THE LIBRARY OF CONGRESS
1800

Class TF200
Book .W4
1922
Copyright No. ______

COPYRIGHT DEPOSIT.

WORKS OF

WALTER LORING WEBB

PUBLISHED BY

JOHN WILEY & SONS, Inc.

Railroad Construction.—Theory and Practice.

A Text-book for the Use of Students in Colleges and Technical Schools. Seventh Edition. Rewritten and Enlarged. xvii + 847 pages, 4¼ by 6¾; 225 figures and 10 plates. Flexible Binding, $5.00 net.

Technic of Surveying Instruments and Methods.

Including General and Detailed Instructions for Field and Office Work of Extended Students' Surveys. In collaboration with Prof. J. C. L. Fish. xiv + 319 pages, 4 by 6¾; 59 figures. Fexible Binding; $2.50 net.

The American Civil Engineers' Pocket Book.

(*Author of Section on Railroads.*)

4¼ by 7. Flexible Binding, $6.00 net.

RAILROAD CONSTRUCTION

THEORY AND PRACTICE

A TEXT-BOOK FOR THE USE OF STUDENTS
IN COLLEGES AND TECHNICAL SCHOOLS,

AND

A HAND-BOOK FOR THE USE OF ENGINEERS
IN FIELD AND OFFICE,

BY

WALTER LORING WEBB, C.E.,

Member American Society of Civil Engineers; Member American Railway Engineering Association; Assistant Professor of Civil-Engineering (Railroad Engineering) in the University of Pennsylvania, 1893–1901 Major, Engineer Corps, U. S. A., 1917–1920; etc.

SEVENTH EDITION, REVISED AND ENLARGED

TOTAL ISSUE, SEVENTEEN THOUSAND

NEW YORK
JOHN WILEY & SONS, Inc.
London: CHAPMAN & HALL, Limited
1922

TF200
W4
1922

Copyright, 1899, 1903, 1908, 1913, 1917, 1922
BY
WALTER LORING WEBB.

22-20055

PRESS OF
BRAUNWORTH & CO.
BOOK MANUFACTURERS
BROOKLYN, N. Y.

OCT 16 '22
© C1 A683736

PREFACE TO SEVENTH EDITION

THE author wishes to reiterate, with even greater emphasis, the statement made in the second paragraph of the preface to the sixth edition. There are few, outside of railroad circles, who realize the great work which is being accomplished by the American Railway Engineering Association. Much of this work has been done during the past five years. One of the notable features is the work of the Special Committee on "Stresses in Track." A very condensed account of the work of this Committee is given in the new added Chapter XXV. Numerous corrections and revisions have also been made throughout this edition to make it conform to the decisions of the recent conventions of the Association.

Some of the more important changes, additions, or developments of subjects, which have been made in this edition, are as follows:

(*a*) The shrinkage of embankments and the subsidence of subsoil under them—Chapter III.

(*b*) Laws governing the life of ties; developments in substitutes for wooden ties—Chapter VIII.

(*c*) Rails; present status of specifications; testing; life of rails; failures; intensity of pressure; rail wear—Chapter IX.

(*d*) Rail joints; causes of failures—Chapter X.

(*e*) Water tanks; principles of construction—Chapter XII.

(*f*) Yards and terminals; hump yards; grades—Chapter XIII (nearly rewritten).

(*g*) Train resistance; resistance of passenger cars, freight cars; resistance through switches—Chapter XVI.

(*h*) Stresses in track, in rails, ties and ballast; static and dynamic stresses—Chapter XXV (new).

WALTER LORING WEBB.

PHILADELPHIA, PA.,
Dec., 1921.

5.00 net.

PREFACE TO SIXTH EDITION.

THE revision of the fifth edition has been so extensive that it has almost amounted to a rewriting of the book. Comparatively few pages have been left without some revision.

The last few years have seen a greater advance in the science of railroad construction than any similar period in its previous history. This has been largely due to the combined work of the several Standing Committees of the American Railway Engineering Association. The writer has received special permission to quote from the Association's publications and has availed himself of the privilege, because he considers that the decisions of such an Association are, in general, the highest authority obtainable.

Considerable new matter has been added on the general subject of railroad surveys, and the handling of surveying parties. One feature of the additions has been the emergency medical and surgical treatment which the engineer-in-charge, as responsible head of the party, must sometimes supply when regular professional advice is absolutely unobtainable and the engineer must choose between seeing the victim die (or become permanently injured), or assuming the unwelcome responsibility of applying simple instructions plus common sense. It usually means choosing the lesser of two evils. The author wishes to acknowledge his indebtedness to his friends, Dr. G. Victor Janvier and Dr. Henry P. DeForest, for advice and the revision of these sections, which may thus be depended on to be technically correct.

Those familiar with the former editions of this work will note that the computations previously given for the unit values of saving one foot (or mile) of distance, one degree of curvature, or one foot of rise-and-fall, have now been omitted. This is due to the belief, as expressed by the Economics Committee of the

Am. Rwy. Eng. Assoc., that all previously published methods of making such calculations are unreliable since they ignore certain operating conditions peculiar to each road, and that the application of such unit figures may lead to unwarranted conclusions. It may be that a method will be sometime devised by which some simple and satisfactory form of unit value may be used. At present, the most practicable method yet proposed is to compute the costs of operating two suggested routes on the basis of an assumed amount and kind of traffic and compare the results.

WALTER LORING WEBB.

PHILADELPHIA, PA.,
Nov., 1916.

TABLE OF CONTENTS.

CHAPTER I.

RAILROAD SURVEYS.

CHAPTER II.

ALINEMENT.

CHAPTER III.

EARTHWORK.

CHAPTER IV.

TRESTLES.

CHAPTER V.

TUNNELS.

CHAPTER VI.

CULVERTS AND MINOR BRIDGES.

CHAPTER VII.

BALLAST.

CHAPTER VIII.

TIES AND OTHER FORMS OF RAIL SUPPORT.

CHAPTER IX.

RAILS.

CHAPTER X.

RAIL-FASTENINGS.

CHAPTER XI.

SWITCHES AND CROSSINGS.

CHAPTER XII.

MISCELLANEOUS STRUCTURES AND BUILDINGS.

CHAPTER XIII.

YARDS AND TERMINALS.

CHAPTER XIV.

BLOCK SIGNALING.

CHAPTER XV.

ROLLING STOCK.

LOCOMOTIVES.

CARS.

TRAIN-BRAKES.

CHAPTER XVI.

TRAIN RESISTANCE.

CHAPTER XVII.

COST OF RAILROADS.

CHAPTER XVIII.

THE POWER OF A LOCOMOTIVE.

CHAPTER XIX.

THE PROMOTION OF RAILROAD PROJECTS.

CHAPTER XX.

OPERATING EXPENSES.

CHAPTER XXI.

DISTANCE.

CHAPTER XXII.

CURVATURE.

CHAPTER XXIII.

GRADE.

CHAPTER XXIV.

THE IMPROVEMENT OF OLD LINES.

CHAPTER XXV.

STRESSES IN TRACK.

RAILROAD CONSTRUCTION.

CHAPTER I.

RAILROAD SURVEYS.

The proper conduct of railroad surveys presupposes an adequate knowledge of almost the whole subject of railroad engineering, and particularly of some of the complicated questions of Railroad Economics, which are not generally studied except at the latter part of a course in railroad engineering, if at all. This chapter will therefore be chiefly devoted to methods of instrumental work, and the problem of choosing a general route will be considered only as it is influenced by the topography or by the application of those elementary principles of Railroad Economics which are self-evident or which may be accepted by the student until he has had an opportunity of studying those principles in detail

The student-engineer should be warned against the hasty and inadequate surveying which has resulted in so much misconstruction in this country. This kind of surveying was especially common forty or fifty years ago, and the methods have more or less continued. The demand for railroad facilities was then so urgent that lax methods were tolerated. A general route would be selected which, at first sight, seemed most obvious and it would be immediately staked out in a manner suitable to a location survey. After correcting some of the most glaring faults, the survey was considered complete and the road was constructed accordingly. The cost of such a survey is comparatively small, but it is almost inevitable that the line is not as good as could have been obtained with a greater amount of examination and study. The cost of construction and the future cost of operating such a line is always unnecessarily high. The money wasted in construction, plus the capitalized value of the annual waste in future operating expenses, is frequently a hundred times the cost of the extra study and surveying which would have avoided these faults. This has been unquestionably proved by the innumerable cases of reconstruction of portions of old lines which could have been constructed originally on the lines as revised at even less cost. The engineer is not always responsible for ill-advised hasty work. An impatient Board of Directors often insists on commencing to "throw dirt" before a proper survey has been made. The engineer should make, if necessary, the most earnest representations and even strenuous demands, that he be given the requisite time, opportunity and money to conduct his survey in such a manner as to investigate thoroughly every possibility for improving the alinement.

A railroad survey ordinarily consists of three parts: (*a*) the reconnoissance; (*b*) the preliminary survey, and (*c*) the definite location. As explained later, circumstances may modify the relative importance of these divisions, but under ordinary circumstances all three are necessary.

RECONNOISSANCE SURVEYS.

1. Character of a reconnoissance survey. A reconnoissance survey is a very hasty examination of a belt of country to determine which of all possible or suggested routes is the most promising and best worthy of a more detailed survey. It is essentially very rough and rapid. It aims to discover those salient features which instantly stamp one route as distinctly superior to another and so narrow the choice to routes which are so nearly equal in value that a more detailed survey is necessary to decide between them.

A map should be prepared, at a scale not smaller than one mile to the inch, which should show all general routes which are conceivably possible. It is particularly important that the mere lack of data should not exclude consideration of some general route which might be superior to the one or more obvious routes which have already been picked out.

2. Selection of a general route. The general question of running a railroad between two towns is frequently a financial rather than an engineering question. Financial considerations usually determine that a road must pass through certain more or less important towns between its termini. It is also possible that there may be certain topographical features in any route between two determined towns on the line, such as a low saddle in crossing a ridge or a difficult crossing of a large river, which, with the towns, may be considered as **control points,** and the problem may be narrowed down to the determination of the best route between these consecutive control points. But care should be taken that control points are not too hastily considered as fixed and unalterable, especially if it results in very unfavorable grades and alinement between consecutive points.

The reconnoissance survey should include the determination of the location and relative elevations of all these control points. These data should be obtained with sufficient accuracy to compute the necessary ruling grade and the general character of the alinement, and the map as thus amplified should be studied by comparing the several possible routes and eliminating all those which are unquestionably less favorable than others.

The engineer should avoid, especially in a rough and wooded country, the influence that an existing highway, or even a path through the woods or of a clearing of the trees, may have in determining the choice of routes. Mere ease of travel, as long as it is not glaringly wrong, has caused many prepossessions in favor of a certain route, when a much better line could be obtained by plunging through the woods or over swampy or rocky ground. As a first trial in selecting the route, the bearing of a line joining two consecutive control points should be determined and then an effort should be made to find a general route which will have the least possible variation from that straight line, without sacrificing the limits of ruling grade, curvature and general type or cost of construction which may have been fixed for the road.

A difficult line between two control points should be studied by beginning at either end for two independent studies. The very obvious route, starting from *A* toward *B*, may lead into very difficult construction, which may be avoided by commencing at B and finally reaching A on a route which, while practicable, would not be considered attractive when starting from A.

When a railroad runs through a thickly settled and very flat country, where, from a topographical standpoint, the road may be run by any desired route, the "right-of-way agent" sometimes has a greater influence in locating the road than the engineer. But such modifications of alinement, on account of business considerations, are foreign to the engineer's side of the subject, and it will be hereafter assumed that topography alone determines the location of the line. The consideration of those larger questions combining finance and engineering (such as passing by a town on account of the necessary introduction of heavy grades in order to reach it), will be considered in later chapters.

3. Valley route. This is perhaps the simplest problem. If two control points to be connected lie in the same valley, it is frequently only necessary to run a line which shall have a nearly uniform grade. The reconnoissance problem consists largely in determining the difference of elevation of the two termini of this division and the approximate horizontal distance so that the proper grade may be chosen. If there is a large river running through the valley, the road will probably remain on one side or the other throughout the whole distance, and both banks should be examined by the reconnoissance party to determine which is preferable. If the river may be easily bridged, both banks may be alternately used, especially when better alinement is thereby secured. A river valley has usually a steeper slope in the upper part than in the lower part. A uniform grade throughout the valley will therefore require that the road climbs up the side slopes in the lower part of the valley. In case the "ruling grade"* for the whole road is as great as or greater than the steepest natural valley slope, more freedom may be used in adopting that alinement which has the least cost—regardless of grade. The natural slope of large rivers is almost invariably so low that grade has no influence in determining the choice of location. When bridging is necessary, the river

* The *ruling grade* may here be loosely defined as the maximum grade which is permissible. This definition is not strictly true, as may be seen later when studying Railroad Economics, but it may here serve the purpose.

banks should be examined for suitable locations for abutments and piers. If the soil is soft and treacherous, much difficulty may be experienced and the choice of route may be largely determined by the difficulty of bridging the river except at certain favorable places.

4. **Cross-country route.** A cross-country route always has one or more summits to be crossed. The problem becomes more complex on account of the greater number of possible solutions and the difficulty of properly weighing the advantages and disadvantages of each. The general aim should be to choose the lowest summits and the highest stream crossings, provided that by so doing the grades between these determining points shall be as low as possible and shall not be greater than the ruling grade of the road. Nearly all railroads combine cross-country and valley routes to some extent. Usually the steepest natural slopes are to be found on the cross-country routes, and also the greatest difficulty in securing a low through grade. An approximate determination of the ruling grade is usually made during the reconnoissance. If the ruling grade has been previously decided on by other considerations, the leading feature of the reconnoissance survey will be the determination of a general route along which it will be possible to survey a line whose maximum grade shall not exceed the ruling grade.

5. **Mountain route.** The streams of a mountainous region frequently have a slope exceeding the desired ruling grade. In such cases there is no possibility of securing the desired grade by following the streams. The penetration of such a region may only be accomplished by "development"—accompanied perhaps by tunneling. "Development" consists in deliberately increasing the length of the road between two extremes of elevation so that the rate of grade shall be as low as desired. The usual method of accomplishing this is to take advantage of some convenient formation of the ground to introduce some lateral deviation. The methods may be somewhat classified as follows:

(a) Running the line up a convenient lateral valley, turning a sharp curve and working back up the opposite slope. As shown in Fig. 1, the considerable rise between *A* and *B* was surmounted by starting off in a very different direction from the general direction of the road; then, when about one-half of the desired rise had been obtained, the line crossed the valley and continued the climb along the opposite slope. (b) *Switchback.* On the steep side-hill *BCD* (Fig. 1) a very considerable gain in elevation was accomplished by the switchback *CD*. The gain in elevation from *B* to *D* is very great. On the other hand, the speed must always be slow; there are two complete stoppages of the train for each run; all trains must run backward from *C* to *D*. (c) *Bridge spiral.* When a valley is so narrow at some point that a bridge or viaduct of reasonable length can span the valley at a considerable elevation above the

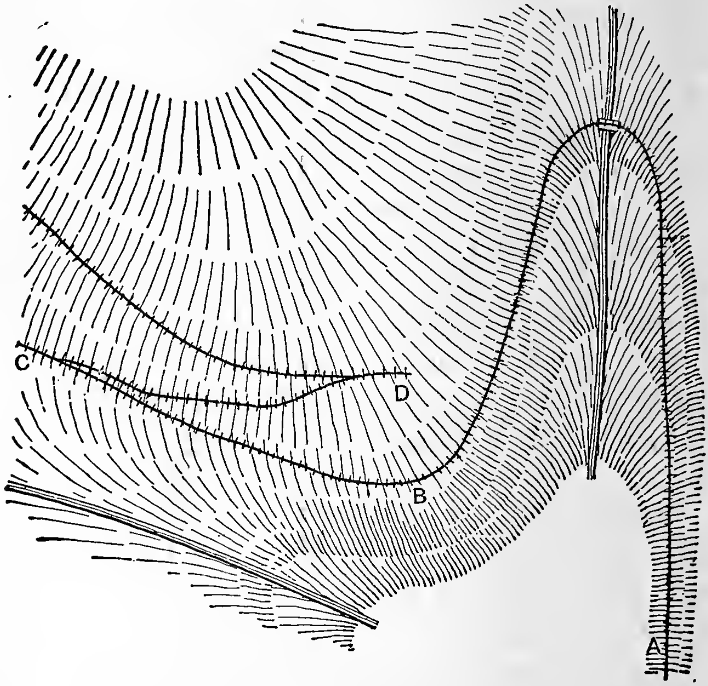
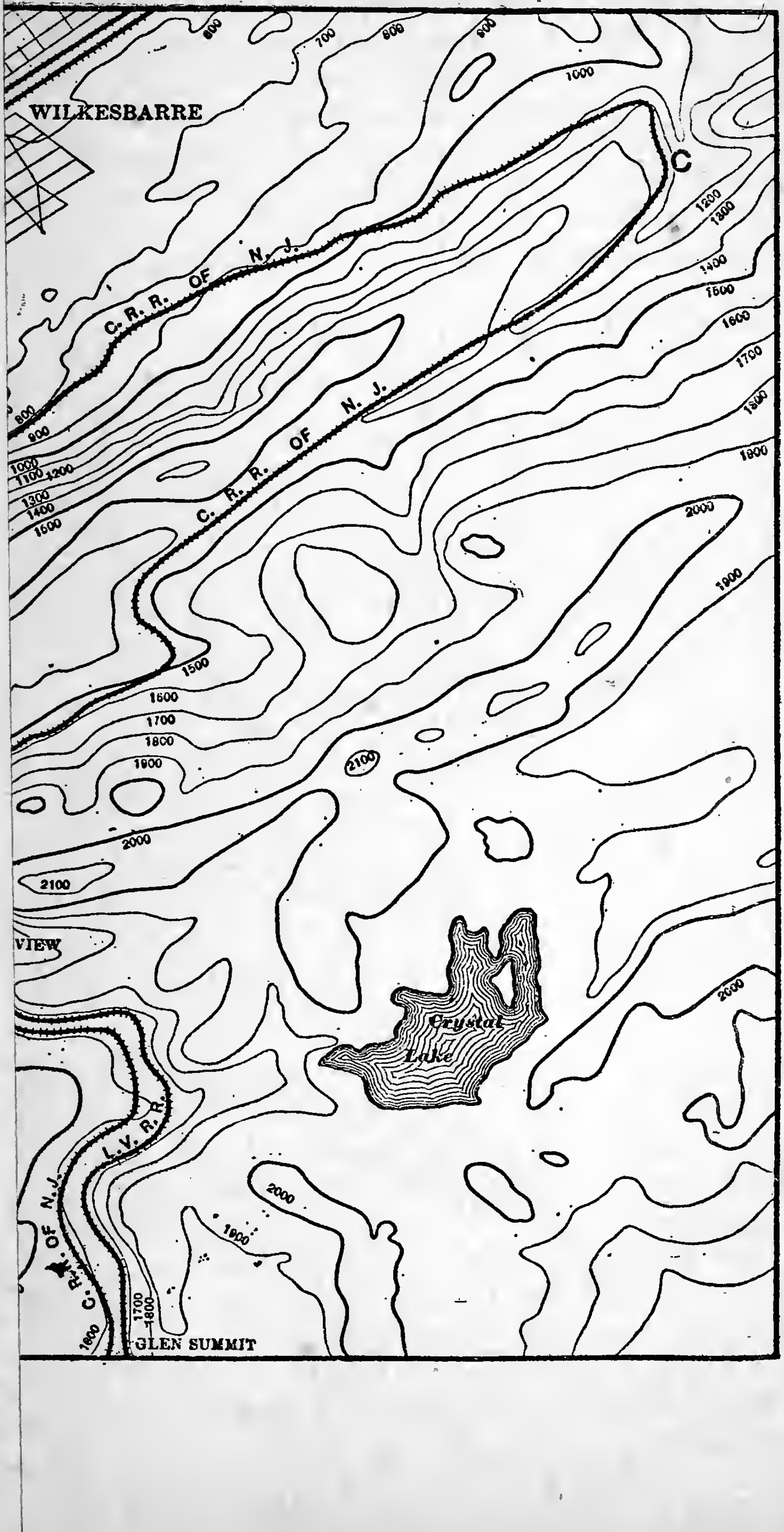
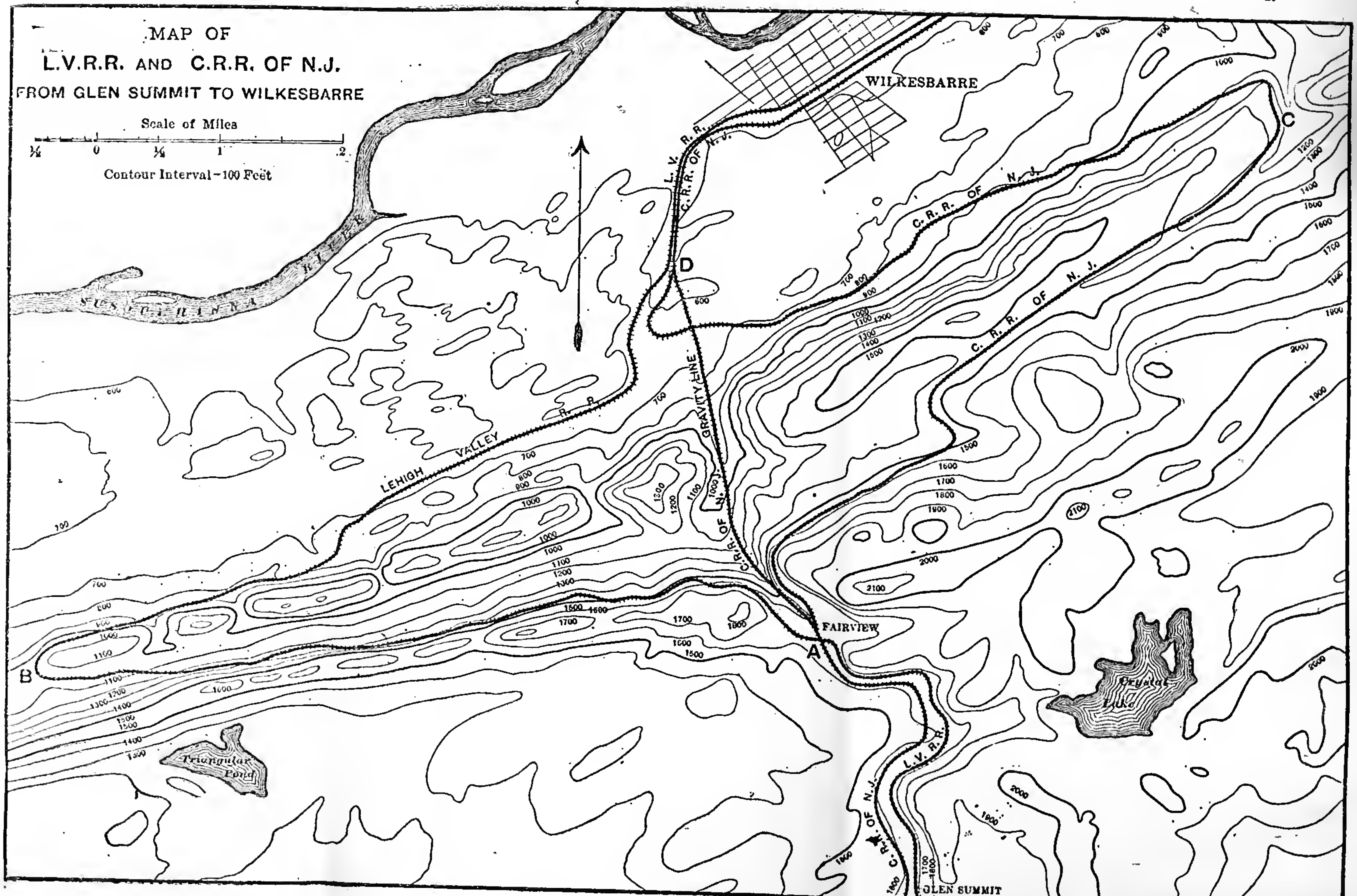


Fig. 1.

bottom of the valley, a bridge spiral may be desirable. In Fig. 2 the line ascends the stream valley past *A*, crosses the stream at *B*, works back to the narrow place at *C*, and there crosses itself, having gained perhaps 100 feet in elevation. (d) *Tunnel spiral* (Fig. 3). This is the reverse of the previous plan. It implies a thin steep ridge, so thin at some place that a tunnel through it will not be excessively long. Switchbacks and spirals are sometimes necessary in mountainous countries, but they should not be considered as normal types of construction. A region must be very difficult if these devices cannot be avoided.

PLATE I.


WILKESBARRE
C. R. R. OF N. J.
C. R. R. OF N. J.
C
Crystal Lake
VIEW
L. V. R. R.
C. R. R. OF N. J.
GLEN SUMMIT
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100



(*To face page 6.*)

On Plate I are shown three separate ways (as actually constructed) of running a railroad between two points a little over three miles apart and having a difference of elevation of nearly 1100 feet. At *A* the Central R. R. of New Jersey runs *under* the Lehigh Valley R. R. and soon turns off to the northeast for about six miles, then doubles back, reaching *D*, a fall of about 1050 feet with a track distance of about 12.7 miles. The L. V. R. R. at *A* runs to the westward for six to seven miles,

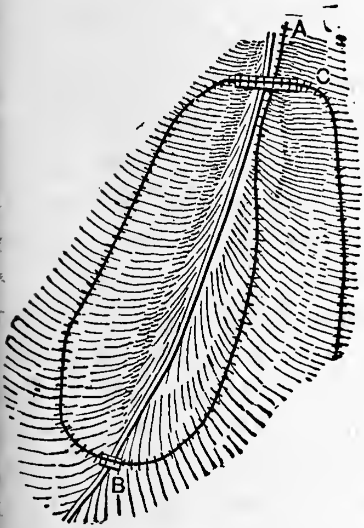


Fig. 2.

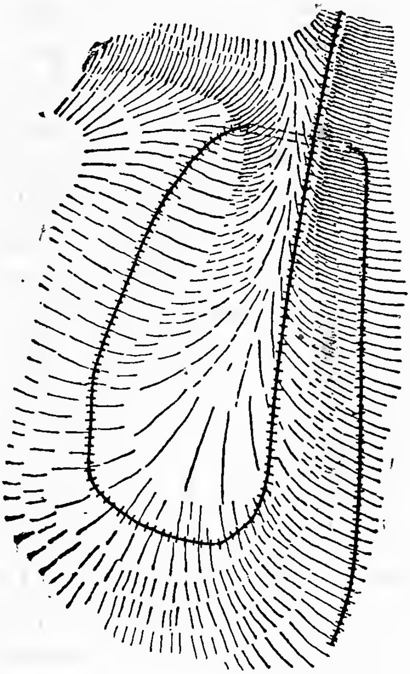


Fig. 3.

then turns back until the roads are again close together at *D*. The track distance is about 14 miles and the drop a little greater, since at *A* the L. V. R. R. crosses *over* the other, while at *D* they are at practically the same level. From *B* to *C* the distance is over eleven miles. From *A* directly down to *D* the C. R. R. of N. J. runs a "gravity" road, used exclusively for freight, on which cars alone are hauled by cable. The main-line routes are remarkable examples of sheer "development." Even as constructed the L. V. R. R. has a grade of about 95 feet per mile, and this grade has proved so excessive for freight work that the company has constructed a cut-off (not shown on the map) which leaves the main line at *A*, nearly parallels the

C. R. R. to *C*, and then running in a northeasterly direction again joins the main line beyond Wilkesbarre. The grade is thereby cut down to 65 feet per mile.

Rack railways and cable roads, although types of mountain railroad construction, will not be here considered.

6. Existing maps. The maps of the U. S. Geological Survey are exceedingly valuable as far as they have been completed. So far as topographical considerations are concerned, they almost dispense with the necessity for the reconnoissance and "first preliminary" surveys. Some of the State Survey maps will give practically the same information. County and township maps can often be used for considerable information as to the relative *horizontal* position of governing points, and even some approximate data regarding elevations may be obtained by a study of the streams. Of course such information will not dispense with surveys, but will assist in so planning them as to obtain the best information with the least work. When the relative horizontal positions of points are reliably indicated on a map, the reconnoissance may be reduced to the determination of the relative elevations of the governing points of the route.

7. Determination of relative elevations. A recent description of European methods includes spirit-leveling in the reconnoissance work. This may be due to the fact that, as indicated above, previous topographical surveys have rendered unnecessary the "exploratory" survey which is required in a new country, and that their reconnoissance really corresponds more nearly to our preliminary.

The perfection to which barometrical methods have been brought has rendered it possible to determine differences of elevation with sufficient accuracy for reconnoissance purposes by the combined use of a mercurial and an aneroid barometer. The mercurial barometer should be kept at "headquarters," and readings should be taken on it at such frequent intervals that any fluctuation is noted, and throughout the period that observations with the aneroid are taken in the field. At each observation there should also be recorded the time, the reading of the attached thermometer, and the temperature of the external air. For uniformity, the mercurial readings should then be "reduced to 32° F." The form of notes for the mercurial barometer readings should be as follows:

Time.	Merc. Barom.	Attached Therm.	Reduction to 32° F.	External Therm.	Corrected reading.
7:00 A. M.	29.872	72°	—.117	73°	29.755
:15	.866	73.5	.121	75	.745
:30	.858	75	.125	76	.733
:45	.850	76	.127	77	.723

The corrections in column 4 are derived from Table XI by interpolation.

Before starting out, a reading of the aneroid should be taken at headquarters coincident with a reading of the mercurial. The difference is one value of the correction to the aneroid. As soon as the aneroid is brought back another comparison of readings should be made. Even though there has been considerable rise or fall of pressure in the interval, the *difference* in readings (the correction) should be substantially the same provided the aneroid is a good instrument. If the difference of elevation is excessive (as when climbing a high mountain) even the best aneroid will "lag" and not recover its normal reading for several hours, but this does not apply to such differences of elevation as are met with in railroad work. The best aneroids read directly to $\frac{1}{100}$ of an inch of mercury and may be estimated to $\frac{1}{1000}$ of an inch—which corresponds to about 0.9 foot difference of elevation. In the field there should be read, at each point whose elevation is desired, the aneroid, the time, and the temperature. These readings, corrected by the mean value of the correction between the aneroid and the mercurial, should then be combined with the reading of the mercurial (interpolated if necessary) for the times of the aneroid observations and the difference of elevation obtained. The field notes for the aneroid should be taken as shown in the first four columns of the tabular form. The "corrected aneroid" readings of column 5 are found by correcting the readings of column 3 by the mean difference between the mercurial and aneroid when compared at morning and night Column 6 is a copy of the "corrected readings" from the office notes, interpolated when necessary for the proper time. Column 7 is similarly obtained. Col. 8 is obtained from cols. 4 and 5, and col. 9 from cols. 6 and 7, with the aid of Table XII. The correction for temperature (col. 11), which is generally small unless the difference of elevation is large, is obtained with the

(Left-hand page of Notes.)

Time.	Place.	Aneroid.	Therm.	Corr. Aner.	Corr. Merc.
7:00	Office	29.628	73°	....	29.755
7:10	$\Delta 0$	29.662	72°	29.789	29.748
7:30	saddle-back	29.374	63°	29.501	29.733
7:50	river cross.	29.548	70°	29.675	29.720

aid of Table XIII. The elevations in Table XII are elevations above an assumed datum plane, where under the given atmospheric conditions the mercurial reading would be 30″. Of course the position of this assumed plane changes with varying atmospheric conditions and so the elevations are to be considered as *relative* and their difference taken. See "Technic of Surveying Instruments and Methods," Prob. **28**, by Webb and Fish; John Wiley & Sons. Important points should be observed more than once if possible. Such duplicate observations will be found to give surprisingly concordant results even when a general fluctuation of atmospheric pressure so modifies the tabulated readings that an agreement is not at first apparent. Variations of pressure produced by high winds, thunder-storms, etc., will generally vitiate possible accuracy by this method. By "headquarters" is meant any place whose elevation above any given datum is known and where the mercurial may be placed and observed while observations within a range of several miles are made with the aneroid. If necessary, the elevation of a new headquarters may be determined by the above method, but there should be if possible several independent observations whose accordance will give a fair idea of their accuracy.

The above method should be neither slighted nor used for more than it is worth. When properly used, the errors are compensating rather than cumulative. When used, for example, to determine that a pass B is 260 feet higher than a determined bridge crossing at A which is six miles distant, and that another pass C is 310 feet higher than A and is ten miles distant, the figures, even with all necessary allowances for inaccuracy, will give an engineer a good idea as to the choice of route especially as affected by ruling grade. There is no comparison between the time and labor involved in obtaining the above information by barometric and by spirit-leveling methods, and *for recon-*

(Right-hand page of Notes.)

Temp. at headqu.	Approx. field read.	Approx. headq. read.	Diff.	Corr. for temp.	Diff. elev.
—	—	—	—	—	—
75°	192	230	− 38	−(+ 2)	− 40
76	457	244	+213	+(+10)	+223
77	297	256	+ 41	+(+ 2)	+ 43

noissance purposes the added accuracy of the spirit-leveling method is hardly worth its cost.

8. Horizontal measurements, bearings, etc. When reliable maps are unobtainable, rapid exploratory surveys become essential. Since accuracy is sacrificed for rapidity in such surveys, more or less approximate methods are used. "An experienced saddle-horse, whose speeds at his various gaits have been learned accurately by previous timing," is quoted from Beahan * as one means of rapidly measuring distances. The percentage of probable error is evidently large. A **pedometer** (or pace-measurer) is probably more accurate, but its accuracy depends on a knowledge of the average length of the observer's pace. Due allowance must be made for the fact that the length of pace will vary very greatly depending on whether the surface is smooth and level, or is plowed ground, or marshy, or slippery, or consists of rough boulders covered with moss, or is a wilderness of brambles, fallen trees, bogs, etc. It will also depend on whether the observer is fatigued or is in fresh physical condition. Under such a variety of conditions the counting of steps for long distances is sometimes a farce. Even when the surface is fairly smooth and easy, precautions must be taken that paces are not counted during the pauses at important points while bearings are being taken and other data recorded. An **odometer** which records the revolutions of a wheel of known circumference is far more accurate. Such a machine has been made so that it may be trundled like a wheelbarrow and thus go through the woods and over ground that would be impassable to any horse-drawn vehicle. The attachment of an odometer to the wheels of a wagon is very tempting, since it permits the engineer to ride, but it is probably an unreliable method for the reason men-

* "The Field Practice of Railway Location," p. 34.

tioned in Art. 2—permitting the ease of travel over a road practicable for a horse and vehicle to deflect the engineer from his true course, which is perhaps over rough ground which is impassable for a vehicle.

When the country is quite open and clear of underbrush, very rapid work may be done by the **stadia method**, which is many times more accurate than any of the methods previously mentioned. Some of the accuracy possible with stadia may be sacrificed for extreme rapidity and sights may be made 1200 and even 2000 feet long. By taking very few, if any, "side-shots," the progress is very rapid and many miles per day may be covered, with the advantage that the three elements of distance, azimuth and relative elevation may be obtained with as great accuracy as is necessary for an exploratory survey. The method of using the stadia will be described later.

The **bearings** of the various lines forming the skeleton of the survey, and also the bearings of the courses of streams and of side lines from the stations on the skeleton line, may be taken most easily with a **prismatic compass.** This instrument has a circular card, or sometimes a metal ring, attached to the needle. The edge of the card is graduated into degrees and is usually numbered consecutively (instead of by quadrants), from 0° up to 360°. This is advantageous since the one number, without any qualifying letters, *NE* or *NW*, determines the quadrant definitely without danger of confusion or error. The observer sights through a narrow slit in the desired direction and, by means of the prismatic reflector, can read directly the number of degrees, measured *to the right*, and usually from the magnetic *South.* The makers of prismatic compasses do not always number the graduations in the same manner, and, therefore, the engineer, who is accustomed to one particular instrument, should carefully study the markings of any new instrument. In any case it should be remembered that the prism reflects the numbers on that side of the movable card or ring which is *toward the observer* rather than on the side toward the object sighted at. The prismatic compass has the special advantage that, like a sextant, it can be used when supported only by hand, while an ordinary sight compass of equal accuracy would require a tripod, or, at least, a Jacob's staff. The declination of the needle in that section of the country can be readily determined with sufficient accuracy for the purposes of such a survey. Usually the declination may be ignored. Any errors due to local attraction are never cumulative, but apply only to the point where those individual observations are taken. The angle between two lines radiating from any station may be obtained by subtracting one bearing from the other.

Relative elevations may be obtained systematically, using a barometer, as already explained, but much filling in may be done with the use of a hand-level. Experience soon teaches an engineer that there are many optical illusions about the slopes of ground which have the practical effect of making the apparent slope different from the actual, and, in the case of low grade, may make an actual down grade appear as an up grade. For example, when looking along an actual but slight down grade, especially if there are no obstructions or natural objects which the eye can use as a comparative scale, the eye is apt to foreshorten the distance, which has the effect of lessening the apparent down grade and perhaps of making it appear as a slight up grade. The hand level will immediately detect such errors and its frequent use by a reconnoissance engineer will not only enable him to avoid many errors he might otherwise make, but will also be an effective means of training him to guard against such optical illusions. Such a simple and effective instrument should always be at hand and it should be tested with sufficient frequency to know that it is always as accurate as such an instrument can be. The bubble should be as sensitive as is practicable for an instrument which is held in the hand. A well-made hand level has a bubble of the right sensitiveness, but even a super-sensitive level may be utilized and still better work done by supporting it steadily on the top of a light wooden stick about five feet long.

9. **Importance of a good reconnoissance.** The foregoing instruments and methods should be considered only as aids in exercising an educated common sense, without which a proper location cannot be made. The reconnoissance survey should command the best talent and the greatest experience available. If the general route is properly chosen, a comparatively low order of engineering skill can fill in a location which will prove a paying railroad property; but if the general route is so chosen that the ruling grades are high and the business obtained is small and subject to excessive competition, no amount of perfection in

detailed alinement or roadbed construction can make the road a profitable investment.

PRELIMINARY SURVEYS.

10. **Character of survey.** A preliminary railroad survey is properly a topographical survey of a belt of country which has been selected during the reconnoissance and within which it is estimated that the located line will lie. The width of this belt will depend on the character of the country. When a railroad is to follow a river having very steep banks the choice of location is sometimes limited at places to a very few feet of width and the belt to be surveyed may be correspondingly narrowed.

But even in such a case, the width surveyed should be sufficient to include not only every possible location of "slope-stakes" but also should indicate the contours and nature of any soil which might give trouble by sliding, after an excavation has been made at the base. It is justifiable and proper to survey a belt considerably wider than it is expected to use, for experience shows that, while there is generally but little or no direct utilization of the extra area surveyed, it frequently becomes essential to know something of the character of the ground considerably to one side of where it was expected to run the line and the inclusion of this area in the original survey has saved an expensive trip to obtain a very small amount of data.

In very flat country the desired width may be only limited by the ability to survey points with sufficient accuracy at a considerable distance from what may be called the "backbone line" of the survey.

11. **Cross-section method.** This is the only feasible method in a wooded country, and is employed by many for all kinds of country. The backbone line is surveyed either by observing magnetic bearings with a compass or by carrying forward absolute azimuths with a transit. The compass method has the disadvantages of limited accuracy and the possibility of considerable local error owing to local attraction. On the other hand there are the advantages of greater simplicity, no necessity for a back rodman, and the fact that the errors are purely local and not cumulative, and may be so limited, with care, that

they will cause no vital error in the subsequent location survey. The transit method is essentially more accurate, but is liable to be more laborious and troublesome. If a large tree is encountered, either it must be cut down or a troublesome operation of offsetting must be used. If the compass is employed

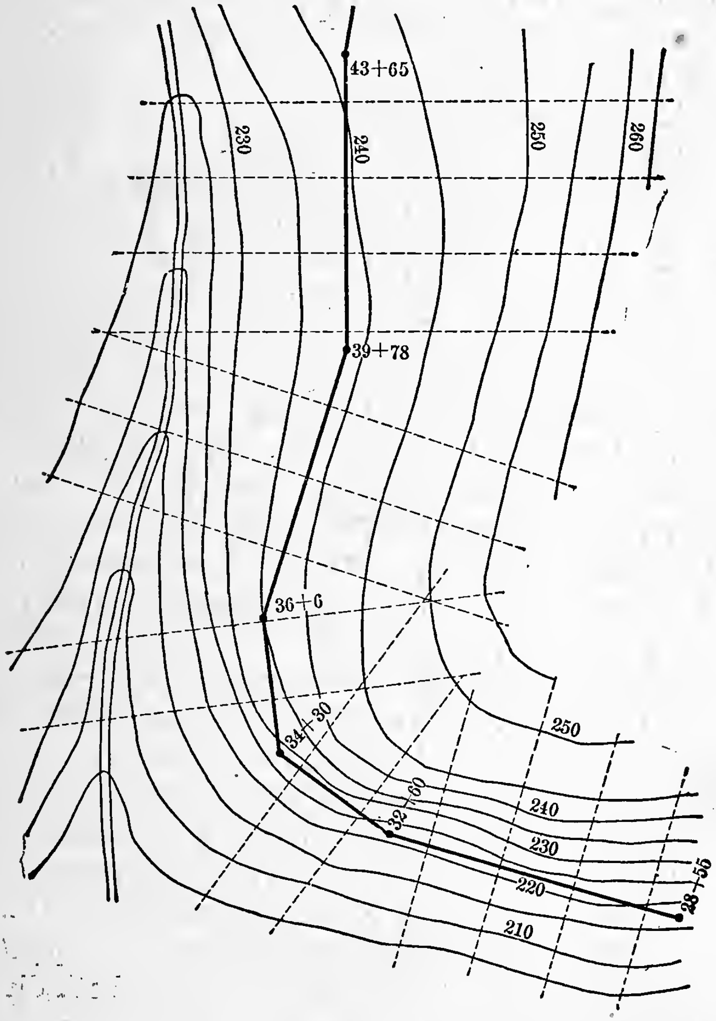


Fig. 4.

under these circumstances, it need only be set up on the far side of the tree and the former bearing produced. An error in reading a transit azimuth will be carried on throughout the survey. An error of only five minutes of arc will cause an offset of nearly eight feet in a mile. Large azimuth errors may, however, be avoided by immediately checking each new azimuth with a needle reading. It is advisable to obtain true azimuth at the beginning of the survey by an observation on the sun* or Polaris, and to check the azimuths every few miles by azimuth observations. Distances along the backbone line should be measured with a chain or steel tape and stakes set every 100 feet. When a course ends at a substation, as is usually the case, the remaining portion of the 100 feet should be measured along the next course. The level party should immediately obtain the elevations (to the nearest tenth of a foot) of all stations, and also of the lowest points of all streams crossed and even of dry gullies which would require culverts.

12. **Cross-sectioning.** It is usually desirable to obtain contours at five-foot intervals This may readily be done by the use of a Locke level (which should be held on top of a simple five-foot stick), a tape, and a rod ten feet in length graduated to feet and tenths. The method of use may perhaps be best explained by an example. Let Fig. 5 represent a section *perpendicular* to the survey line—such a section as would be made by the dotted lines in Fig. 4. *C* represents the station point. Its elevation as determined by the level is, say, 158.3 above datum. When the Locke level on its five-foot rod is placed at *C*, the level has an elevation of 163.3. Therefore when a point is found (as at *a*) where the level will read 3.3 on the rod, that point has an elevation of 160.0 and its distance from the center gives the position of the 160-foot contour. Leaving the long rod at that point (*a*), carry the level to some point (*b*) such that the level will sight at the *top* of the rod. *b* is then on the 165-foot contour, and the *horizontal* distance *ab* added to the horizontal distance *ac* gives the position of that contour from the center. The contours on the lower side are found similarly. The first rod reading will be 8.3, giving the 155-foot contour. Plot the results in a note-book which is ruled in quarter-inch squares, using a scale of 100 feet per inch in both directions. Plot the work UP the page; then when looking ahead along the line, the work is properly oriented. When a contour crosses the survey line, the place of crossing may be similarly determined. If the ground flattens out so that five-foot contours are very far apart, the absolute elevations of points at even fifty-foot distances from the center should be determined. The

* The method of making such observations is given in the Appendix.

method is exceedingly rapid. Whatever error or inaccuracy occurs is confined in its effect to the one station where it occurs. The work being thus plotted in the field, unusually irregular topography may be plotted with greater certainty and no great error can occur without detection. It would even be possible by this method to detect a gross error that might have been made bv the level party.

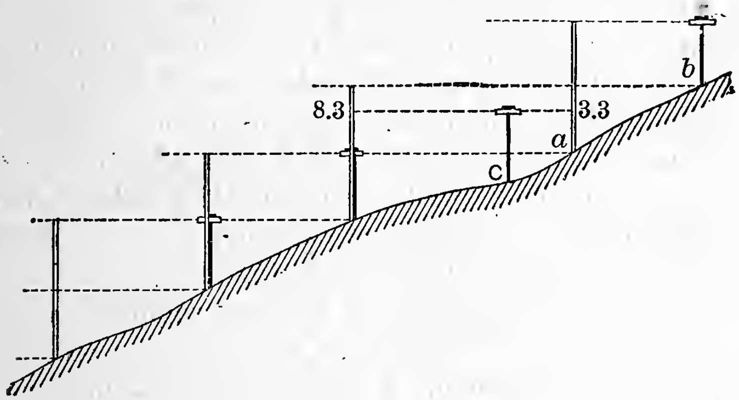


FIG. 5.

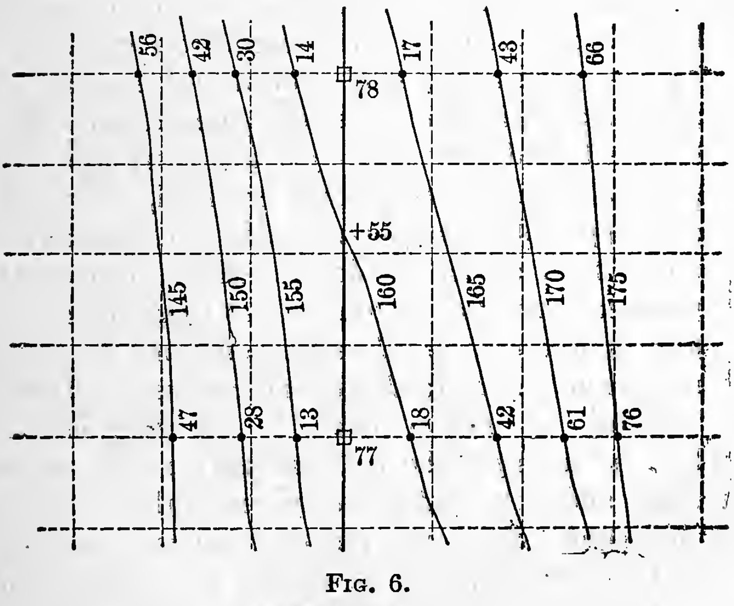


FIG. 6.

13. Stadia method. This method is best adapted to fairly open country where a "shot" to any desired point may be taken without clearing. The *backbone* survey line is the same as in the previous method except that each course is limited to the practicable length of a stadia sight. The distance between stations should be checked by foresight and backsight—also the vertical angle. Azimuths should be checked by the needle. Considering the vital importance of leveling on a railroad survey it might be considered desirable to run a line of levels over the stadia stations in order that the leveling may be as precise as possible; but when it is considered that a preliminary survey is a somewhat hasty survey of a route that *may* be abandoned, and that the errors of leveling by the stadia method (which are compensating) may be so minimized that no proposed route would be abandoned on account of such small error, and that the effect of such an error may be usually neutralized by a slight change in the location, it may be seen that excessive care in the leveling of the preliminary survey is hardly justifiable.

A stadia party should include a locating engineer (or chief of party), and perhaps an assistant, a transitman, a recorder and four rodmen, beside axemen. The transitman should have nothing to do but attend to his instrument. After setting up the transit at an advanced station, a backsight should be taken to the previous station. If the vertical circle is full 360°, the telescope should be plunged and sighted on the backsight with vernier *A* reading the same as the foresight to the station occupied. If the vertical arc is semi-circular (or less), no vertical angle can be taken with the telescope plunged and, therefore, vernier A should read 180° more (or less) than the foresight. The lower plate should be very firmly clamped, and then, after loosening the upper plate, a reference sight and reading on some well-defined natural object should be taken. If there is any reason to suspect that the instrument has been disturbed while occupying that station, the reference point can be sighted at and the instrument can be re-alined, and re-leveled, if necessary, without sending a rodman back to the previous station. When taking a backsight the rod reading for distance should be taken first and immediately compared with the previously recorded foresight. Since the distance between stations will always be taken with especial care so as to avoid "blunders" of an even 10, 20 or perhaps 100 feet, the foresights and backsights should agree to within the proper limits of the stadia method. Similarly the vertical angle should agree with the previous reading, *but with opposite sign.* If especial care is taken in leveling the instrument immediately before taking both foresights and backsights, these readings should agree to within one minute, or even 30 seconds, with a good transit. The height of the telescope above the ground at the new station must be measured, and the middle wire sighted at that reading on the rod (called the *H. I.*), when taking any vertical angle. Theoretically the rod reading for distance should be taken when the telescope is pointing at the proper vertical angle for that shot, but this will mean, in general, that both the upper and lower cross wires will read odd amounts and that an inconvenient subtraction must be made to get the difference, which is the "rod reading." But it may be demonstrated that no error of distance, amounting to the lowest practicable unit of measurement, can result if the telescope is raised or lowered just enough to set it on the nearest even foot mark. The routine of observing a shot is therefore as follows: (*a*) swing the instrument (the upper plate) horizontally until the telescope sights at the rod and clamp the horizontal motion—but very lightly and perhaps not at all; (*b*) raise or lower the telescope until the middle cross wire is sighting at the H. I., reading on the rod; a target on the rod may be set at the H. I. reading for each set-up and it will facilitate the work; (*c*) read the vertical angle and report it to the recorder, standing at hand; (*d*) raise or lower the telescope just enough so that the lower wire is on the nearest even foot mark and read (calling it out to the recorder) the number of even feet of interval from the lower to the upper wire and the odd amount at the top at the reading of the upper wire; (*e*) dismiss the rodman, who is then directed to another point by the chief of party; (*f*) read the azimuth on the horizontal plate. By that time another rodman has been located at a point where an observation is required, and the routine is repeated. The work of the transitman is thus very strenuous, without any recording work, and the progress of the party depends on him. He, therefore, should not be required to direct the party or even to record his notes, since every moment spent in that way delays the entire party by that amount. The recorder also has all that he can do to record the notes (with perhaps some sketches), as fast as the transitman calls them off. Usually four rodmen can be kept very busy, and they must be on the run between the successive points at which they hold their rods. One of the rodmen or one of the axemen, if axemen are employed, carries and drives the stakes, which are only required at the instrument points. One or more axemen are generally useful in lopping off branches or cutting down saplings which interfere with desirable sights. The chief of party has plenty to do in directing the rodmen and axemen so that shots may be taken at points which will give the most significant information, and also in picking out the proper location for the advance station at some place from which a maximum of information may be observed with one set-up of the transit. A well-drilled organization and "team work" are necessary. The best work is done when every man is kept busy. Several hundred shots per day can be observed when it is considered advisable to obtain much detailed information and the average number of shots per set-up is large. On the other hand, when the stadia method is used for a rapid exploratory survey, only a few side shots (at some stations perhaps none at all) will be taken at each station. In such a case, the total number of shots taken during a day will be comparatively small, but the progress will be very rapid, and the salient features of several miles of a proposed route can be obtained in a day.

14. Form for stadia notes.

[Left-hand page.]

Inst. at	Azim.	Rod	Vert. angle	Diff. elev.	Elev.	Sighting at
Δ24.	264° 27′	622	−0° 18′			Δ23
HI = 4.9	83° 10′	528	+1° 16′			Δ25
El = 629.2. . .	184° 23′	264	−2° 18′			bend in creek
. . . .	5° 47′	218(175)	+26° 20′			top of bluff

The usual six-column note-book can be utilized by ruling an extra line (shown dotted in the Form of Stadia Notes), in the fifth column, since the column is wide enough for both the "difference of elevation" and the "elevation." The "rod reading" (3d column) as recorded should include the $(f+c)$, which in almost all American transits equals 1.0 to 1.3 feet. Since the wire-interval ratio is almost invariably 1 : 100, the rod interval in hundredths of a foot is considered as the number of feet of distance, except that one even foot is added for the $(f+c)$. The sample figures given above are typical of all that needs to be taken in the field. The "difference of elevation" and the "elevation" are computed and entered later.

The "difference of elevation" may be mathematically computed from the formula

$$D = k\,r\,\tfrac{1}{2}\sin 2\alpha + (f+c)\sin\alpha,$$

in which D is the difference of elevation, k is a constant, usually 100, r is the rod intercept and α is the angle of elevation—or depression. The mathematical solution of such an equation for every shot that is taken (except the very few shots which are level) is very laborious and impracticable. But the work of reduction can be shortened by a justifiable approximation. By changing the factor of $(f+c)$ from $\sin\alpha$ to $\frac{1}{2}\sin 2\alpha$, the formula may be written

$$D' = [kr + (f+c)]\tfrac{1}{2}\sin 2\alpha.$$

The first term (that within the bracket) is the number recorded under "Rod" in the Form of Notes (622, 528, etc.). The second term ($\frac{1}{2}\sin 2\alpha$) may be taken from "Stadia Tables," of which many are published, although the tables usually give these numbers merely as the factors by which the distance is to be multiplied in order to obtain the "Difference of Elevation," and do not mention that the factor is really $\frac{1}{2}\sin 2\alpha$. The error of the approximation (when $(f+c)=1$ foot) is less than 0.01 foot for a vertical angle of 15° and less than 0.1 foot for the unusual angle of 30°. Since 0.1 foot is the usual lowest unit of measurement for stadia elevations, probably 99% of all stadia work can use such an approximation without appreciable error. The special cases with high angles can be computed separately if it is considered necessary. The algebraic sign of the vertical angle should *always* be recorded, even if it is plus, or upward; the sign + is a positive statement that it *is* plus and that the sign was not forgotten. The difference of elevation likewise should always have a + or − sign. Adding the difference of elevation to the elevation of the station (or subtracting it), gives the elevation of each point.

Theoretically the true horizontal distance for all inclined sights is always less than the nominal distance, as given by the rod reading. The formula for true distance is

$$L = kr\cos^2\alpha + (f+c)\cos\alpha.$$

As before, we may use the approximation of combining the $(f+c)$ with the kr and say that

$$L' = [kr + (f+c)] \cos^2 \alpha,$$

and that the *correction*, which is subtracted from $[kr+(f+c)]$, and *not* from kr, is

$$\text{Corr.} = [kr + (f+c)] \sin^2 \alpha.$$

The error of this approximation is usually insignificant, as illustrated below. Since $\sin^2 \alpha$ is very much less than $\cos^2 \alpha$ for the usual small values of α, it is easier and more accurate to compute the smaller quantity and mentally subtract it from the nominal reading. When the vertical angle and the distance are both small, the horizontal correction is within the lowest unit of measurement (one foot), and should, therefore, be ignored. The engineer soon learns the approximate limits at which the combination of vertical angle and distance will make a correction necessary. In the above notes no correction is necessary except in the last case, the angle being 26° 20′. The exact mathematical computation is as follows, the rod interval being 2.17 and $(f+c)=1$,

$$L = 217 \cos^2 26° \, 20' + 1 \cos 26° \, 20' = 175.20.$$

Using the approximate rule, the correction $= 218 \sin^2 26° \, 20' = 42.90$.

$$218 - 42.90 = 175.10.$$

The above calculations have been carried to hundredths of a foot for the sole purpose of illustrating that the discrepancy between the approximate and the theoretical value is only 0.10 foot, even for this unusually large angle, and considering that the rod interval is read only to the nearest 0.01 foot, which corresponds to one foot of distance, this discrepancy is utterly inappreciable.

15. **The reduction of stadia observations** is most easily accomplished by using a stadia slide rule, which has one logarithmic scale for distances and for the computed differences of elevation or corrections to distance, and also two other scales one of which gives values for $\frac{1}{2} \sin 2\alpha$, and the other gives values

for $\sin^2 \alpha$. Some scales give values of $\cos^2 \alpha$. To illustrate the difference, in the above case, it is evidently easier to read 43 (two significant figures) than to read 218, which has three figures. When the distance is over 1000 (four figures), the difficulty is even greater. The necessity for subtracting the correction is of no appreciable importance. In this case, the correction would be read from the slide rule as 43, and mentally subtracting 43 from 218, we write at once 175, which is recorded in parenthesis in the Rod column. The draftsman, when plotting the notes, uses this distance (175) instead of 218. Using a slide rule, two men can very quickly compute the differences of elevation for the entire day's work in a very short time. A very little practice will enable them to run down the list, picking out the observations, usually less than 10% of the total number, where the combination of distance and vertical angle is sufficiently great to make it necessary to compute a horizontal correction. The stadia slide rule is so small that it may readily be carried into the field and used there if desired, in which respect it has a great advantage over diagrams, which are sometimes used for the same purpose.

16. Stadia method vs. cross-section method. There is still a difference of opinion among engineers as to the choice of these two methods. When a large part of the route is thickly wooded, the cross-section method is preferable. In open country the stadia method is more rapid and more economical. Although it would be inadvisable to change from one method to the other every mile or so, a very considerable economy is possible by alternating the two methods according to the character of the country. The locating engineer can plan such change of method during his reconnoissance. The real efficiency of the stadia method is due to the fact that the preliminary survey should be considered as the topographical survey of an area or belt, and not the survey of a line, and that in open country the stadia method is the most efficient method of obtaining such topographical data. But the efficiency depends on the handling of the party. When a valley widens out with easy slopes and the possible area in which the location may lie is correspondingly widened, it is far easier and more accurate to widen the belt surveyed by stadia shots of 1000 feet if necessary.

17. "First" and "Second" preliminary surveys. Some engineers advocate two preliminary surveys. When this is done, the first is a very rapid survey, made perhaps with a compass, and is only a better grade of reconnoissance. Its aim is to rapidly develop the facts which will decide for or against any proposed route, so that if a route is found to be unfavorable another more or less modified route may be adopted without having wasted considerable time in the survey of useless details. By this time the student should have grasped the fundamental idea that both the reconnoissance and preliminary surveys are not surveys of *lines* but of *areas*, that their aim is to survey only those topographical features which would have a determining influence on any railroad line which might be constructed through that particular territory, and that the value of a locating engineer is largely measured by his ability to recognize those determining influences with the least amount of work from his surveying corps. Frequently too little time is spent on the comparative study of preliminary lines. A line will be hastily decided on after very little study; it will then be surveyed with minute detail and estimates carefully worked up, and the claims of any other suggested route will then be handicapped, if not disregarded, owing to an unwillingness to discredit and throw away a large amount of detailed surveying. The cost of two or three extra preliminary surveys (*at critical sections* and not over the whole line) is utterly insignificant compared with the probable improvement in the "operating value" of a line located after such a comparative study of preliminary lines.

LOCATION SURVEYS.

18. "Paper location." When the preliminary survey has been plotted to a proper scale (usually 200 feet per inch), and the contours drawn in, a study may be made for the location survey. Disregarding for the present the effect on location of transition curves, the alinement may be said to consist of straight lines (or "tangents") and circular curves. The "paper location" therefore, consists in plotting on the preliminary map a succession of straight lines which are tangent to the circular curves connecting them. It may be assumed that the general route of the preliminary survey has been so well selected, as the result of the reconnoissance survey, that it is possible to construct a line without excessive earthwork between consecutive control points, and that the grades are within the ruling grade. If the preliminary survey has been run by locating stations every 100 or 200 feet (see § 11 and Fig. 4), the profile of this line gives the first approximation toward the rate of grade, and from this may be determined whether one uniform grade between the control points is

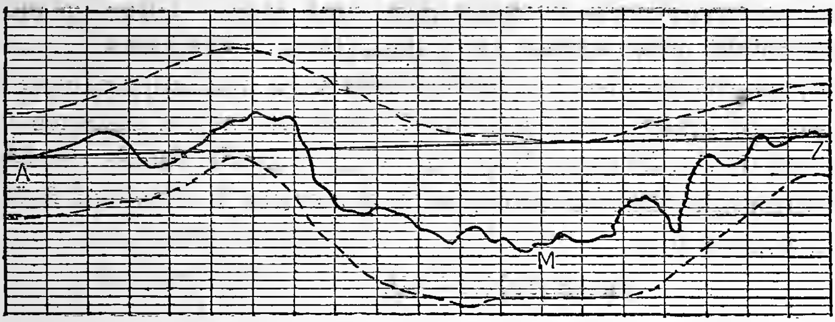


Fig. 7. Single Grade Between Control Points.

practicable, or whether two or more different grades must be used. If the stadia method was used, the profile of a line running through the station points will serve the same purpose. In Fig. 7 let *AMZ* represent, on a very small scale, the surface profile between two control points, *A* and *Z*, which are, perhaps,

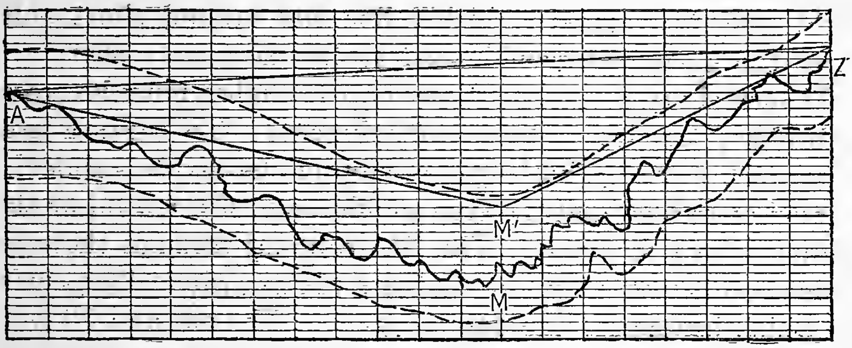


Fig. 8. Two Grades Between Control Points.

two miles apart. The upper dotted line shows the elevations of the highest points in the surveyed belt at each of the several stations, and the lower line the corresponding lowest points. If the straight line *AZ* does not go outside of these dotted lines, it indicates that the uniform grade *AZ* will have "supporting ground" for the entire distance and that such a grade is practicable and should be tentatively selected (or at least investigated) for that stretch. If the straight line AZ passes outside the belt of the dotted lines, as in Fig. 8, it implies that there was some definite reason why no higher supporting ground could be found near M', or the preliminary survey, if properly made, would have covered that ground. It then becomes necessary to adopt two grades, such as AM' and $M'Z$. Three or more grades might prove necessary or desirable in some cases.

Having determined, at least tentatively and approximately, the rate of grade, set a pair of dividers at such a distance (to scale) that the distance times the rate of grade equals the contour interval. For example, with a contour interval of 5 feet and a 2% grade,

$$\text{distance} \times .02 = 5,$$

or

$$\text{distance} = 5 \div .02 = 250.$$

Then, with dividers set at 250 feet, put one leg where the line previously located crosses a contour and put the other leg where it reaches the contour next above—or below, if a down grade. Then step to the next contour and so on. If the desired starting point is not on a contour, the distance for the *first* step should be proportionately shortened. A strict application of this method would probably make a sidehill line run around short gullies where the curvature would need to be excessively sharp. To avoid such sharp curvature, these narrow gullies must be crossed by bridges, trestles or high embankments. To carry a grade across such a place, the length of step of the dividers should be doubled or trebled and the step should be to the second or third contour above or below. The line running through these successive points located on the contours will be practically a surface line which has nearly the desired grade. The cut and fill would be almost nothing—except "side-hill work," and the crossing of gullies. No accuracy need be expected on this preliminary trial since the distance is somewhat greater than the air-line distance AZ. It would, in general, be impossible to run a practicable combination of tangents and proper curves through these points, but such a line is very suggestive of a proper alinement which will fulfill the grade and curvature conditions and along which the cut and fill will be reasonably small.

If there are long stretches where, in each case, the line joining a group of consecutive points is nearly straight, the tangents will predominate and should be located first and then connected by curves. If the line has numerous and long bends, it may be preferable to select the curves first and then connect them with tangents. For such work a series of curves, drawn to proper scale, varying by even degrees from 1° up to 15° or 20°, or whatever is the maximum allowable curvature, and drawn on any transparent material such as tracing cloth, celluloid or glass, is very useful, since different curves may be tried in turn until the curve which best fits the ground is discovered. The contours and other fixed features should have been inked in and then the trial lines and curves may be marked in lightly with a *soft* pencil, so that trial lines may be easily erased until a satisfactory line is obtained. The number of possible combinations is infinite, but certain conditions must be fulfilled which narrows the choice. (1) The connecting tangents must not be too short; 100, 200 and even 300 feet are used as limits. (2) The curvature must be within the adopted limit. If two consecutive curves, which are connected by a very short tangent, bend in the same direction, it is preferable that they should be combined into one simple curve, or into two branches of a compound curve, rather than to make a "broken-backed" curve. If they bend in opposite directions (making a reverse), even 300 feet is none too long for the transition curves which should be used, especially if the curves are sharp. Actual reverse curves (changing the direction of curvature without any separating tangent) should *never* be used, except on switch work and track where the speed is always slow. It would be far preferable to sharpen the curvature enough to introduce a tangent at least 100 feet long. The following considerations should be kept in mind.*

"(1) If the location could follow the grade line [or surface line] precisely, there would be no cuts or fills (practically speaking) on the center line.

"(2) Whenever the location lies on the $\left\{\begin{matrix}\text{down-hill}\\ \text{up-hill}\end{matrix}\right\}$ side of the grade contour [or surface line] there will be $\left\{\begin{matrix}\text{fill}\\ \text{cut.}\end{matrix}\right\}$

"(3) The further the location departs from the grade contour the greater will be the cut or fill, as the case may be."

---

* Art. 50, Part IV, "Technic of Surveying Instruments and Methods," by Webb and Fish. John Wiley & Sons.

After a location line has been selected which seems satisfactory from the standpoints of easy curvature, not too short tangents, a proper balance of cut and fill, and not too great cuts and fills, as will be approximately indicated by its distance from the surface line, the volume of earthwork may be estimated with sufficient accuracy for comparative purposes by drawing a profile of the surface location line and its roadbed line. Considering the ease with which such lines may be drawn on the preliminary map, it is frequently advisable, after making such a paper location, to begin all over, draw a new line over some specially difficult section and compare results. Profiles of such lines may be readily drawn by noting their intersection with each contour crossed. Drawing on each profile the required grade line will furnish an approximate idea of the *comparative* amount of earthwork required. A comparison of the areas of cut and fill on the profile will show the approximate balance in volume of cut and fill. If it is considered necessary to compute the volume with greater accuracy, it may be done by the use of Table XVII (see also § 126), applying the latter part of the table correctively to allow for side slope. After deciding on the paper location, the length of each tangent, the central angle (see § 51), and the radius of each curve should be measured as accurately as possible. Frequent tie lines and angles should be determined between the plotted location line and the preliminary line. When the preliminary line has been properly run, its "backbone" line will lie very near the location line and will probably cross it at frequent intervals, thus rendering it easy to obtain short and numerous tie lines.

19. Preparation of the notes. This and the actual transfer of the paper location to the ground is a problem in surveying which is so varied in its character that the ingenuity of the engineer is required to use the best method adapted to each particular case, but a few principles may profitably be kept in mind. (1) The scale of the paper location drawing is probably 200 feet per inch, unless the difficulties of the problem demand a larger scale for a particular stretch of the road, so that the paper location may be more accurate. Since a variation of 1/200 inch in the drawing means a variation of one foot on the ground, no close checking of the line on any tie-point need be expected. (2) Since a very small variation in alinement would, if persisted in, throw the alinement very far from its desired location, it must be expected that there will be more or less adjustment of the paper location alinement (numerically) on nearly every tangent and curve. (3) The intersection of the preliminary line by a paper-location tangent (or the tangent produced) gives a possible tie-point. The position of this tie-point on the preliminary line must be scaled and the angle between the lines determined by measuring the chord of a long arc with its center at the point of intersection or by scaling the sine (or tangent) produced by a perpendicular from one line to the other from a point whose distance from the intersection is a convenient unit length. (4) When there is no intersection at some place where a tie is desired, a perpendicular offset from the preliminary line may be necessary. (5) When the paper location crosses the preliminary line at frequent intervals (say 500 to 1000 feet), it may be more simple to locate the tie-point intersections on the preliminary line and work from one to the other, taking up the inevitable inaccuracies by slight variations in the length of tangents or curves or by some one of the various methods detailed in § 63. When no practicable tie can be obtained for a considerable distance (say one-half mile), it may be desirable to determine the ordinates (latitudes and departures) of all the points on the preliminary and on the paper location between two consecutive intersections. In such a case the precision would depend entirely on the accuracy of scaling the positions of the two intersections and on the accuracy of the preliminary survey. While such a method requires considerable office computation, even that is cheaper than an extensive revision of a located line in the field. For a further development of this method, the student is referred to a course of instruction originally written by Prof. J. C. L. Fish, of Stanford University, and included in "Technic of Surveying Instruments and Methods," by Webb and Fish, published by Wiley & Sons.

As previously stated, the above method has been developed as if the final located line were to be made up only of tangents and circular curves. But transition curves between the tangents and circular curves are essential for the easy operation of trains. Anticipating the more complete demonstration of the subject, § 71, *et seq.*, it may be stated that the effect of the transition curve, or "spiral," is to move the curve inward, or toward its center, or to move the tangent outward. The effect of this is equivalent to offsetting the tangent outward, or offsetting the curve inward, and then connecting the tangent and circular curve by a transition curve which gradually crosses the offsetted distance. The amount of the offset varies with the degree of the central curve and the desired length of the transition curve, but it is seldom more than three or four feet, and is usually much less. No consideration need be given to these offsets when comparing several trial locations. It is only after the paper location has been settled and it is time to transfer this to the ground that it is necessary to compute these offsets and adjust the lines accordingly. Even then the offsets will seldom be so large that they would appreciably affect the paper location, but when the alinement is actually located on the ground, the proper offsets should be used and the alinement laid out as described in detail in § 80.

20. Surveying methods. A transit should be used for alinement, and only precise work is allowable. The transit stations should be centered with tacks and should be tied to witness-stakes, which should be located outside of the range of the earthwork, so that they will neither be dug up nor covered up. All original property lines lying within the limits of the right of way should be surveyed with reference to the location line, so that the right-of-way agent may have a proper basis for settlement. When the property lines do not extend far outside of the required right of way they are frequently surveyed completely.

The leveler usually reads the target to the nearest thousandth of a foot on turning-points and bench-marks, but reads to the nearest tenth of a foot for the elevation of the ground at stations. Considering that $\frac{1}{1000}$ of a foot has an angular value of about one second at a distance of 200 feet, and that one division of a level-bubble is usually about 30 seconds, it may be seen that it is a useless refinement to read to thousandths unless corresponding care is taken in the use of the level. The leveler should also locate his bench-marks outside of the range of earthwork. A knob of rock protruding from the ground affords an excellent mark. A large nail, driven in the roots of a tree, which is not to be disturbed, is also a good mark. These marks should be clearly described in the note-book. The leveler should obtain the elevation of the ground at all station-points; also at all sudden breaks in the profile line, determining also the distance of these breaks from the previous even station. This will include the position and elevation of all streams, and even dry gullies, which are crossed

Measurements should preferably be made with a steel tape, care being taken on steep ground to insure horizontal measurements. Stakes are set each 100 feet, and also at the beginning and end of all curves. Transit-points (sometimes called "plugs" or "hubs") should be driven flush with the ground, and a "witness-stake," having the "number" of the station, should be set three feet to the right. For example, the witness-stake might have on one side "137 + 69.92," and on the other side "P C 4° R," which would signify that the transit hub is 69.92 feet beyond station 137, or 13769.92 feet from the beginning of the line, and also that it is the "point of curve" of a "4° curve" which turns to the *right*.

Alinement. The alinement is evidently a part of the location survey, but, on account of the magnitude and importance of the subject, it will be treated in a separate chapter.

21. Form of Notes. Although the Form of Notes cannot be thoroughly understood until after curves are studied, it is here introduced as being the most convenient place. The right-hand page should have a sketch showing all roads, streams, and property lines crossed with the bearings of those lines. This should be drawn to a scale of 100 feet per inch—the quarter-inch squares which are usually ruled in note-books giving convenient 25-foot spaces. This sketch will always be more or less distorted on curves, since the center line is always shown as *straight* regardless of curves. The station points ("Sta." in first column, left-hand page) should be placed opposite to their sketched positions, which means that even stations will be recorded on every *fourth* line. This allows three intermediate lines for substations, which is ordinarily more than sufficient. The notes should read UP the page, so that the sketch will be properly oriented when looking ahead along the line The other columns on the left-hand page will be self-explanatory when the subject of curves is understood. If the "calculated bearings" are based on azimuthal observations, their agreement (or *constant* difference) with the needle readings will form a valuable check on the curve calculations and the instrumental work.

22. Number of men required in surveying parties. No fixed rules can be given. The general rule of economy and efficiency

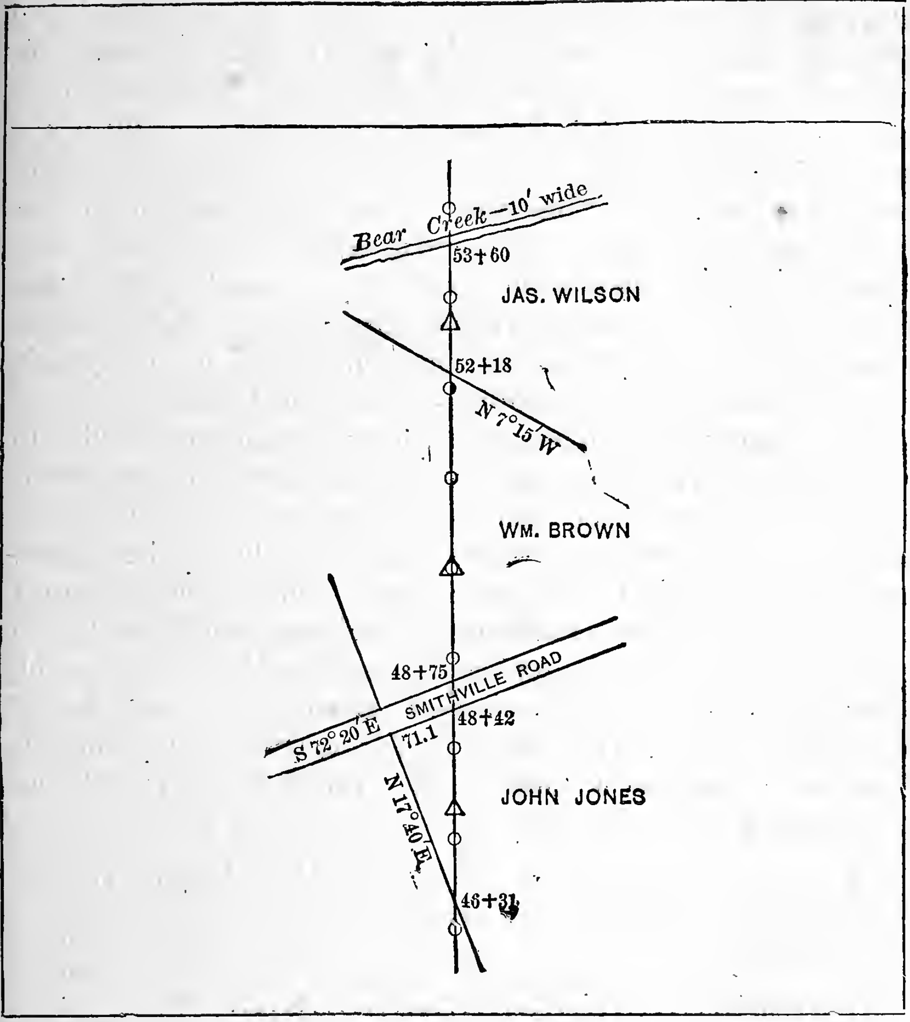
FORM OF NOTES.

[Left-hand page.]

Sta.	Aline-ment.	Vernier.	Tangential Deflection.	Calculated Bearing.	Needle.
54					
⊙ 53 +72.2	P.T.	9° 11′	18° 22′	N 54° 48′ E	N 62° 15′ E
52		7 57			
51		6 15			
⊙ 50	[3° 24′ curve to right for 18° 22′; tang. dist., 272.5]	4 33			
49		2 51			
48		1 09			
⊙ 47 +32	P.C.	0°			
46				N 36° 26′ E	N 44° 0′ E

should govern, and that is, that the organization should be such that all desired data can be obtained at a minimum of cost. This general rule may be subject to the modification that the early completion of the survey is sometimes financially so important as to justify the maximum speed, almost regardless of expense. A common violation of the general rule of economy is the use of too few men, with the mistaken idea that it is economical. This requires the high-priced efficient men to waste their time on work which men at one-half (or even one-third) their salary could do sufficiently well, thus delaying the completion of the work or depreciating its quality by undue haste

[Right-hand page.]



or by neglect to obtain complete data. The work should be so organized that each man is constantly busy at the kind of work for which he is especially qualified, and that no men shall have to wait for others to complete their co-ordinate work. Even if 100% efficiency is unobtainable, it is very uneconomical to have nearly the whole party idle while one or two high-priced men do some work which must be done before the party can proceed but which could have been done by some extra lower-grade men without delaying the party. **Reconnoissance.** When the territory of the general route has been mapped by the U. S. Geol. Survey, there may be no need of instrumental work on the reconnoissance, since the approximate ruling grades and general route may perhaps be determined directly from the map, and the purpose of the reconnoissance is the examination of physical features which would affect or modify the general route. In such a case the engineer does his technical work alone and only needs a guide and cook in case camping is necessary. When the reconnoissance partakes more of the nature of a hasty preliminary, distances, elevations and the necessary side topography being determined by rapid approximate methods, more men should be added, keeping in mind that the work should be so organized that each member of the party is kept busy at his own co-ordinate work, and that the chief engineer is not delayed in his own special work by spending his valuable time on a cheaper grade of work which an assistant could do sufficiently well. In other words, it is economical to add to the party an extra assistant whenever the work that he can do will so facilitate the work of the party as a whole that the value of the salaries and expenses saved will more than offset the assistant's salary and expenses. **Preliminary surveys.** No fixed list of members of a party is applicable to all conditions. The following list, with monthly salaries, is given by Mr. Fred Lavis* as having been used on each of five parties in surveying the Choctaw, Oklahoma & Gulf R. R. The list is very full but justifiably so.

Locating engineer	$150	to	$175
Assistant locating engineer	115		125
Transitman	90		100
Levelman	80		90
Draftsman	80		90
Topographers, two	80		90
Level rodman	50		
Head chainman	50		
Rear chainman	40		
Tapemen, two	30		
Back flagman	30		
Stake marker	30		
Axemen, three to five	25	to	30
Cook	50		
Cook's helper	20		
Double teams and driver, furnish their own feed, driver boarded in camp	65	to	90

* Methods of Railroad Location on the Choctaw, Oklahoma & Gulf R.R. Trans. Am. Soc. C. E., Vol. LIV, page 104.

Other organizations sometimes combine the first two positions on this list and possibly call him "chief of party." For the above work, the locating engineer was relieved altogether from the detailed direction of the party, which was handled by the assistant, and spent nearly all his time in studying the country so as to determine how the line should advance. In nearly all cases, such expense is justified, perhaps many times over, (1) by the saving of uselessly surveying an improper route, (2) by an improvement in the operating value of the route selected, or (3) by an improvement in route which makes a decrease in construction cost. Sometimes those controlling the financial side of the project insist that the chief of party shall also run the transit, as a measure of "economy." Such a policy cannot be too strongly condemned. The work of a transitman requires every instant of his time and every minute that he turns from his transit to direct the party or study the proper route is a minute delay for the entire party. It generally means also a deterioration in the quality of his work as a leader and as a transitman, in his effort to hastily do at one time work which requires the concentrated efforts of two men. In this survey (described by Mr. Lavis), the skeleton or backbone line was a broken line with angles every few hundred feet, and the topography was taken by right-angled offsets every hundred feet or oftener, substantially as described in § 11 and Fig. 4. These offsets were determined by a hand level and pacing by one of the two topographers. The other topographer, using a transit, with the other two tapemen "determined drainage areas, located property lines and section corners, got names of property owners, etc." When, as is usually the case, such essential work cannot be done by the main party without delaying their progress, there is a real economy in adding to the party these comparatively low-priced assistants. It may be noted that the above party includes two chainmen, back flagman and stake-marker, beside three to five axemen. The proper number of axemen manifestly depends on the amount of necessary cutting, but the chainmen or the stake-marker should not be depended on for such work. The steady march of the party should not be halted while a stake-marker or chainman stops his regular work to cut down a tree. One of the duties of the chief of party is to foresee the necessities of tree-cutting and clearing, so far in advance that, by the time the surveying members of the party have reached the spot, the area is cleared. It is likewise false economy to dispense with the stake-marker and require the head chainman to do such work. A full corps of such men, properly drilled, can add 20 to 50% to the daily progress of the party and much more than save their cost.

MAINTENANCE OF SURVEY PARTIES.

23. Economy and efficiency. When considering the treatment and maintenance of surveying parties, it should be remembered that a false idea of economy is frequently responsible for making the parties too small, overworking the men, depriving them of physical comforts and even necessities, and that the result is a greater net cost and a great deterioration in the quality of the results. A party may cost $40 to $65 per day in salaries and expenses. Any policy which depreciates the net output of their work 20 to 50% (which is easily possible) in order to save a few dollars per day is manifestly poor policy. The men, especially those who must use their brains and who presumably have a finer nervous organism, have only a quite definite sum total of nervous energy. If a considerable part of that energy is spent in needlessly long tramps both morning and evening to and from work, or if that nervous energy is not maintained by plentiful and appetizing food and by sufficient and comfortable rest, there is a reduction in efficiency which is often far greater than any possible saving in expenses. This idea of developing the maximum efficiency of the party is the justification of the recommendations made below regarding outfit, equipment, and other details about managing a party.

24. Country hotels and farm houses. In settled sections of the country, country hotels and even farm houses are sometimes available where men can be provided with living facilities which are unobtainable in camp life and at less total expense. Such accommodations have the advantage that they obviate a considerable capital expenditure to purchase sufficient camp outfit. But if suitable accommodations are unobtainable over a considerable portion of the route and such accommodations as there are on the remaining distance are inconvenient and inadequate, it may be preferable to provide a camping outfit at once. Considering the fact that there is a real economy in making a survey with a large party and that such a party can seldom if ever be accommodated in a single farmhouse, and that there is a lack of efficiency if the party is separated, the farmhouse plan is frequently impractical. But when villages are so located that there is always one within five miles of any point of the line, the house plan may be preferable, since the party may be taken to and from work in conveyances. The economy of employing conveyances may be judged by comparing the cost of the vehicles and the value of the time and energy saved. A five-mile tramp, carrying an instrument, following a full day's work surveying, will frequently incapacitate a man from doing effective work in the night-work which the higher grade men of the party must generally do. The day's work in the field must be begun later and ended earlier or else the time and strength spent in the morning and evening tramps are uneconomical drains on their total nervous energy.

25. Camping Outfits: Tents. The Choctaw, Oklahoma & Gulf R.R. survey, previously referred to, provided for each party one office tent, with fly, 14×16 feet, three tents, evidently without flies, 14×16 feet, and one cook tent 16×20 feet. The office tent had 5-foot walls; the others 4-foot. H. M. Wilson ("Topographical Surveying," p. 817) recommends 9×9 foot tents, with 4-foot walls. These are easier to erect but have only 36% of the floor area of the 14×16-foot tents and it would require 15 such tents to equal the floor area of the 5 tents described above. For a small party the smaller tents would be preferable. The canvas should be mildew-proof and free from sizing. A "sod-flap" about 8 inches wide, should be attached to the bottom of the wall. When this flap is weighted down with stones or heavy sticks the wind and weather is kept out. Dirt or sod should *not* be used for weights, since they rot the canvas. It pays to use tents which conform to the U. S. Army specifications. Some of the specifications as to material and workmanship are here quoted:

"*Materials.*—Body of tent to be made of Army standard $12\frac{4}{10}$ ounce cotton duck, $29\frac{1}{2}$ inches wide and the sod cloth of Army standard 8-ounce cotton duck, $28\frac{1}{2}$ inches wide.

"*Workmanship.*—To be made by machine in a workmanlike manner, all seams to be stitched with two rows of stitching, not less than six stitches to the inch, with three-cord twelve-thread Sea Island cotton, white.

"In making tents by hand, to have not less than two and one-half stitches of equal length to the inch, made with a double thread of five-fold cotton twine, drab, well waxed.

"The seams should be not less than 1 inch in width, flat stitched, and no slack taken in them.

"*Grommet holes.*—Made with malleable iron rings, galvanized, to be worked with four-thread five-fold cotton twine, well waxed.

"*Sod cloth.*—To be 8 inches in width in the clear from the tabling, into which it is inserted 1 inch and extending from door seam to door seam around the tent.

"*Tabling.*—On foot of tent when finished to be $2\frac{1}{2}$ inches in width." (Adopted July 14, 1911.)

A ditch should be dug outside the tent, at least on the up-hill side, if the ground is at all inclined. This will prevent rain-water from draining through the tent. Of course, the bottom of the ditch should have a uniform slope draining to an outfall amply clear of the tent.

26. Tent floors. Dry floors are almost essential to health. Sectional floors, about 3×9 feet per section, made by fastening boards to cross cleats, provide a perfectly dry floor and often repay their transportation. A mere layer of canvas, cut to proper shape and bound on the edges, is worth providing if the ground is dry when the tent is erected and can be kept from getting rainsoaked by proper outside drainage.

27. Tent stoves. For winter work, tents may be made quite comfortable with stoves. Oil stoves are convenient when the oil can be purchased without excessive cost for transportation. "Sibley" stoves, burning wood, are commonly used but they require smoke pipes which must pass through the canvas and this means that the holes must be properly protected with metal or asbestos. If a pipe elbow is provided, the pipe may be taken out through one end of the tent. This obviates a hole in the roof of the tent (and also the fly); it avoids a direct pour of rain on the fire or leakage into the tent around the pipe, and also the danger of sparks dropping on the canvas. A "Sibley" stove for mere heating is a sheet-iron frustum of a cone, about 3 feet high; diameter at bottom 18 to 30 inches; diameter at top $4\frac{1}{2}$ to 6 inches, or so as to fit the stovepipe which is to be used. It has no bottom, or in other words, the bare earth forms the base. A door, large enough for the insertion of such fuel as it is designed to use, is placed in the side. Three or four lengths of pipe, one of which should have a damper, and an elbow, should be provided. Draft at the bottom is obtained, and may be easily controlled, by packing earth around the base, leaving a small opening which may be easily enlarged or diminished to control the draft. **Cook stove.** A regular 6-hole cooking range, perhaps made of wrought-iron or sheet-steel, is essential to cook meals for twenty or more hearty men. Sporting outfitters supply all sizes of stoves, which must always be selected with due regard for the facilities for transportation. Oil stoves are commonly used. For still smaller parties, or when no cook stove can be permitted in the baggage, a primitive grid may be made from four sticks of *green* timber about 6 inches in diameter and 2 to 4 feet long. Notch two of them, each with a pair of notches about 10 inches apart. Place the other two sticks across the notches and they will steadily support a kettle or a frying pan. If the sticks are sufficiently green and the fuel quite dry the grid will last some time. A folding grid of iron bars may be obtained, which is but a small addition to the weight of the baggage. Another method is to suspend a kettle by a chain or long hook either from a tripod of sticks or from a horizontal stick lying in two forked sticks on each side of the fire.

28. Dining tables. These are justifiable for a large party when the baggage is necessarily great and camp wagons are a part of the equipment. Mr. Lavis, in the article previously referred to, describes a very good table from the standpoint of transportation. The table top consists of three loose planks $1\frac{3}{8}'' \times 12'' \times 18'\ 0''$. Two similar boards are used for seats. During transportation these boards are placed on the bottom of the wagon and, of course, project from the back where they form a support for stoves, etc., which can be roped on. These boards are supported on three trestles or horses, made as shown. For a much smaller party, a table may be improvised by utilizing two "mess-boxes," which carry the cooking utensils and tableware. These mess-boxes are about 20 inches wide and high and from 24 to 30 inches long. The covers are made to open 180° and may be fastened horizontally. An "inside cover," which can be utilized as a bread board, covers the entire inside area of the box. Two such boxes, set together and with the tops opened out, provide a fairly even surface four times the area of one box.

29. Cooking utensils, table-ware, tools, etc. The size of the party, the individual preferences of the person designing the outfit and the facilities for transportation, vary such lists almost indefinitely. Agate ware has replaced china for plates and cups. Aluminum ware, although expensive, is preferable from a cooking standpoint and has the advantage of a very material reduction in weight. Out of the very great number of lists which have been published, the following list of articles is quoted as suggestive: Plates, cups, saucers, steel knives and forks, German-silver spoons, large and small, carving knives and forks, large cooking forks and spoons, pepper and salt boxes, tin pans about

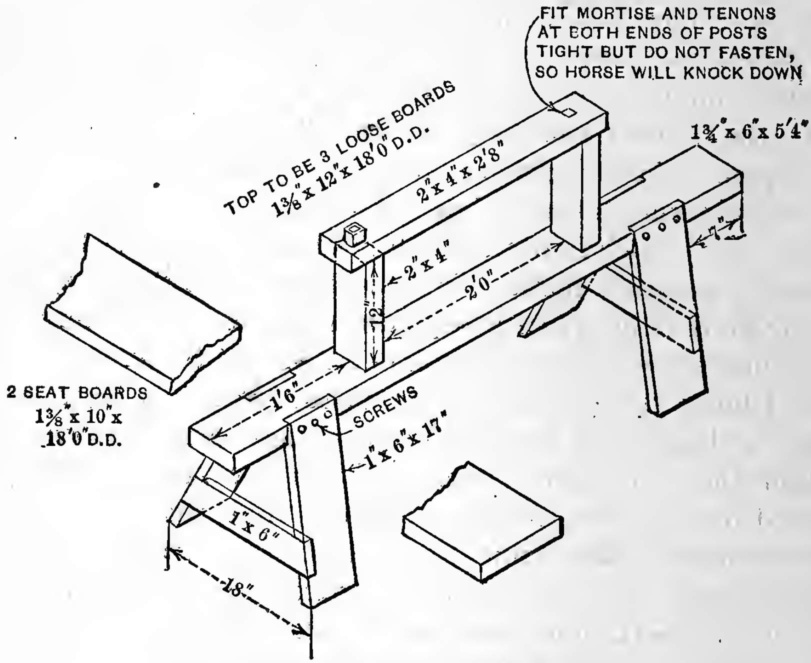


FIG. 9.—CAMP DINING TABLE.

6 inches diameter by 1½ inches deep, utilized for serving soup, cereal, etc., pans and kettles of varying sizes which will "nest" and thus facilitate packing, tea kettle, coffee pot, frying pan, griddle, cake turner, pie plates, dripping pan, chopping bowl and chopper, colander, flour sieve, coffee mill, broiler, corkscrew and can opener, rolling pin, folding table (similar to the drawing table described below), wash basins, kerosene oil can, alarm clock, spring balance. The last two articles are important. The cook is the first man up in the morning—usually before daylight—and may need the alarm clock. A single delay, of even ten minutes of such a party, would cost more than a very valuable clock. A spring balance is very essential to the proper

and economical use of provisions without waste. It pays to have a cook who is able to compute, weigh out and use an amount

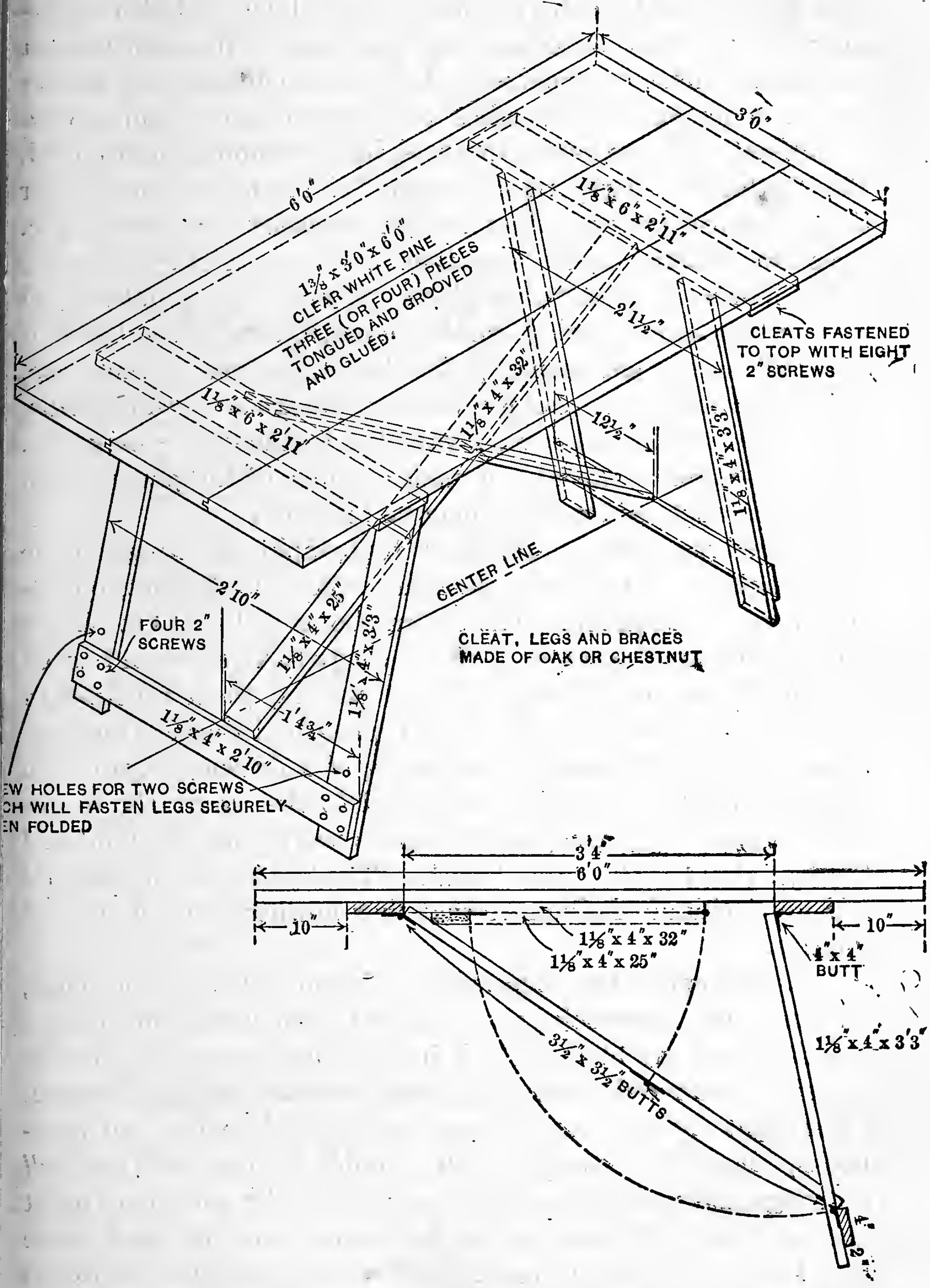


Fig. 10.—Folding Drafting Table.

of each kind of provisions so that there will be sufficient, but no waste. Besides the above, dish towels are practically essential and tablecloths and napkins are easily carried. A table oilcloth may replace the ordinary tablecloth. Wash tubs and wash board facilitate the washing of table linen and also underwear, so essential to clean, healthy living. Illumination for night work must be provided. Reflecting lanterns will answer for all tents except the office tent, where good lamps, with cylindrical wick and center draft, or similar, should be provided. The farther the party travels from "civilization" the greater the necessity for providing for emergencies, breakages, etc. Axes are essential, apart from their use in the surveying work. Extra handles should be provided. A saw, brace and several sizes of bits, screw drivers, monkey wrench, files, pliers, hatchet, assorted screws and nails, pick, shovel, crowbar, whetstone, rope in various sizes, sailor's needles, palm and sewing twine, will all be useful and even invaluable in times of emergency. Canvas-covered canteens, for each member of the party, when passing through arid regions, may be essential.

30. Drawing tables. Complete topographic drawings, made in the field, are absolutely essential. Suitable drawing boards are, therefore, required. The design shown in Fig. 10 fulfills all the working requirements; it also is easily handled when packed up and is not readily broken. By packing them together in pairs, face to face, the surfaces are protected during transportation. The table consists essentially of a drawing board with stiffening cleats. The legs are hinged to the cleats, the braces for each pair of legs being of just such a length that when opened the legs stand at the desired angle. The braces are hinged and fold up, jackknife fashion, so that they nowhere project beyond the legs.

31. Stationery and map chest. Considering that the maps, drawings and notebooks may represent thousands of dollars, and that they are likely to be injured, if not irreparably ruined, by rain, when moving camp or during a cyclonic storm, a strong, water-tight chest, of ample capacity for all drawings and notebooks, should be provided. It should be required that *all* drawings and notebooks should be kept in the chest over night and at all other times, except such drawings and notebooks as are in actual use. The net inside length should be a little in excess of the longest roll or drawing, which is perhaps 36 inches. There should be a tray in the top with numerous compartments or boxes for the multitudinous small articles required by a draftsman. Handles should be provided for convenience and it should have a lock. A good "steamer" trunk of requisite size will answer the purpose, provided it is waterproof, and it would perhaps be cheaper than a chest of similar size, made to order.

32. **Provisions.** A "ration" is the estimated amount of food required per man per day. For men engaged in strenuous outdoor work, the food required is far more than that eaten ordinarily. Ration lists should average about 5 to 6 pounds of food per day per man. The amount that must be *transported* may be considerably less than this, in view of the fact that e.g., dried vegetables may be substituted for fresh vegetables in the ratio of 1 lb. of dried for 3 lbs. of fresh, the water used in cooking providing the other two pounds. For explorers, who carry their own provisions, and who must cut down every possible ounce of baggage, still further concentrations are possible.

Article	100 rations
Fresh meat, including fish and poultry, (*a*)	100 lbs.
Cured meat, canned meat, or cheese (*b*)	50 "
Lard	15 "
Flour, bread or crackers	80 "
Corn meal, cereals, macaroni, sago, or cornstarch	15 "
Baking powder or yeast cakes	5 "
Sugar	40 "
Molasses	1 gal.
Coffee	12 lbs.
Tea, chocolate or cocoa	2 "
Milk, condensed (*c*)	10 cans
Butter	10 lbs.
Dried fruits (*d*)	20 "
Rice or beans	20 "
Potatoes, or other fresh vegetables (*e*)	100 "
Canned vegetables or fruit	30 "
Spices	¼ "
Flavoring extracts	¼ "
Pepper or mustard	½ "
Salt	4 "
Pickles	3 qts.
Vinegar	1 "

"(*a*) Eggs may be substituted for fresh meat in the ratio of 8 eggs for 1 lb. of meat.

"(*b*) Fresh meat and cured meat may be interchanged on the basis of 5 lbs. of fresh for 2 lbs. of cured. [This ratio 5:2 is far higher than is usually allowed, 5:3 or even less is usually stated as the equivalent ratio.]

"(*c*) Fresh milk may be substituted for condensed milk in the ratio of 5 quarts of fresh for 1 can of condensed.

"(*d*) Fresh fruit may be substituted for dried fruit in the ratio of 5 lbs. of fresh for 1 of dried.

"(*e*) Dried vegetables may be substituted for fresh vegetables in the ratio of 3 lbs. of fresh for 1 lb. of dried."

The list at bottom of p. 43 is given by H. M. Wilson ("Topographic Surveying") as the ration list of the U. S. Geol. Survey. The quantities are those required to make up 100 rations, or the food for 5 men for 20 days, or for 100 men for one day. They are considered maximum. The sum total is about 525 lbs. or $5\frac{1}{4}$ lbs. per day per man.

Wilson states that the cost of the above list of rations should not average more than 45 to 55 cents per day for average conditions and with a maximum of 75 cents, but considering that this statement was written in 1900, some allowance may need to be made for higher prices since then.

The list given below represents the provisions actually supplied to a mining camp in British Columbia. The list has been reduced to the average quantity actually consumed per man per day. The food supply averaged nearly 6 lbs. per day per man.

Meat, etc.:		
Fresh beef	1.89	lbs.
Bacon	.076	"
Ham	.060	"
Codfish	.007	"
Canned salmon	.014	can
Breads, etc.:		
Pilot bread	.007	lb.
Flour	.894	"
Baking powder	.016	"
Corn meal	.037	"
Vegetables:		
Potatoes	1.421	lbs.
Turnips	.010	"
Carrots	.047	"
Beets	.016	"
Parsnips	.023	"
Rice	.043	"
Cabbage	.101	"
Dehydrated onions	.0014	"
" rhubarb	.0029	"
White beans	.0014	"
Bayo "	.027	"
Lima "	.013	"
Split peas	.006	"
Rowan "	.0014	"
Canned tomatoes	.016	can
" beans	.0043	"
" peas	.0014	"
Cereals:		
Pearl barley	.0004	lb.
Rolled oats	.117	"
Beverages:		
Tea	.021	lb.
Coffee	.036	"
Milk, condensed	.137	can

Fruit:		
Dried apples	.040	lb.
" pears	.033	"
" peaches	.029	"
" prunes	.020	"
" apricots	.007	"
" figs	.030	"
Dehydrated cranberries	.004	"
Currants	.021	"
Jam	.001	pint
Condiments, etc:		
Mustard	.001	lb.
Salt	.036	"
Pepper	.001	"
Vinegar, Klondyke	.0003	pint
Worcestershire sauce	.0043	"
Catsup	.0029	gal.
Miscellaneous:		
Sugar	.594	lb.
Lard	.030	"
Cheese	.016	"
Cornstarch	.007	"
Extract	.049	"
Curry powder	.0007	"
Cinnamon	.0009	"
Hops	.0001	"
Nutmeg	.0009	"
Ginger	.0014	"
Mapleine	.0011	oz.
Candied peel	.004	lb.
Butter	.014	"
Macaroni	.003	"
Sago	.011	"
Tapioca	.003	"
Baker's chocolate	.0014	"
Cocoanut	.0003	"
Pickles	.003	gal.

Supplies: candles, .03 lb.; gold dust, .003 lb.; soap, .024 bar.

The following list of provisions was bought to start a camp of 20 to 25 men on the Choctaw, Oklahoma & Gulf R. R. Survey. (F. Lavis, Trans. Am. Soc. C. E., Vol. LIV, p. 104.)

6 hams	100 cakes soap
6 pieces of bacon	1 gal. molasses
50 lbs. fresh beef	1 case condensed milk
1 case eggs	1 doz. tomato catsup
25 lbs. butter	¼ " Worcestershire sauce
25 " lard	1 gal. pickles
100 " flour, hard wheat	¼ doz. lemon extract
100 " flour, soft wheat	¼ " vanilla extract
100 " sugar	1 box dried prunes
5 " baking powder	5 lbs. raisins
2 " tea	4 doz. assorted canned fruits
50 " coffee	1 case tomatoes
50 " navy beans	1 bushel potatoes
25 " lima beans	1 kit salt mackerel
12 " buckwheat flour	20 lbs. salt
5 " macaroni	¼ " mustard
35 " cornmeal	1 " pepper
1 cheese, about 15 lbs.	1 qt. vinegar
12 packages oatmeal	½ doz. yeast cakes
10 lbs. rice	

In addition to the above, there must be provided plenty of matches, kerosene oil and perhaps candles. As a matter of health conservation, and the prevention of piles, it is wise to provide toilet paper and to insist, if necessary, on its use. There is economy, when it is practicable, in making wholesale contracts for all provisions, rather than to buy haphazard from small local sources.

33. Beds. When baggage wagons accompany the party, as is virtually necessary to transport other essential equipment, it is desirable that they also transport army cots. These fold up so as to be easily transportable. It is a wise economy to obtain the regular army blankets, since they are what long experience has approved. Bedding rolls should be provided for the bedding. This is essential to keep the bedding in even reasonably cleanly condition, especially while moving. The policy of requiring each member of the party to provide himself with cot, bedding and cover, and to care for them, is debatable. As a matter of business economy, the company should buy all cots and bedding wholesale. Requiring each one to purchase his own is virtually a reduction of salary, for, if a man leaves the party, he usually does not care to take his bedding with him, except in the hope of realizing something on it. But as all this is considered when accepting employment, the company virtually pays for the bedding by an increase of salary over what they would have to pay if bedding were provided. There is the same reason for owning bedding as for owning dishes, etc. Sterilizing bedding by means of a formaldehyde candle, especially after a man has left the party, is a wise sanitary precaution and nullifies one of the strongest reasons for individual ownership.

34. **Transportation.** The route of travel of a mining engineer, a topographical engineer or an explorer, may be over country with every variety of surface and slope. But, since a practicable railroad route is necessarily on a low grade, except as it may pass over a ridge or mountain to be pierced by a tunnel, the question of grade does not ordinarily influence the method of transportation and wagons can ordinarily be used, provided the nature of the surface will permit. Strong and heavy wagons can usually pick their way between the camping places, even though long detours must be made to avoid swamps or other obstructions. The parties surveying the Choctaw, Oklahoma & Gulf R. R., previously referred to, used two teams regularly, one of which stayed with the topographical party. They used a third team for hauling supplies. Two teams of horses can help each other over a particularly bad place in the trail or in the case of accident. The wagons should have canvas tops, as a protection against rain, especially while moving. Transportation by dogs and sledges is only applicable under very limited and unusual conditions. It implies winter work, which is always uneconomical and inefficient compared with summer work, but in a very swampy country, where the transportation of any considerable amount of baggage is very difficult, and where it freezes during the winter to a comparatively smooth surface, such a method may be preferable in spite of short daylight hours and other disadvantages. "The Duluth, South Shore & Atlantic Railway employed toboggans during the construction of its road throughout the season of 1887." The description of this work, and much other useful information is given in a paper by Chas. H. Snow, Vol. XXIX, p. 164, in the Trans. Am. Inst. Mining Eng'rs. A reconnoissance through a comparatively unexplored country, made with the object of discovering a practicable low-grade route through a mountainous section, might require that all baggage shall be reduced to what may be handled in packs carried by horses, mules, Indian ponies or even by men. The question of the necessary method of transportation must always be studied before beginning a survey, since the entire question

of subsistence, and even many features of the method of work, must depend on what can be included in the baggage.

35. **Clothing.** While it may seem an unwarranted interference with personal liberty to control the clothing worn by members of the party, it becomes justifiable when the efficiency and progress of the party is impaired by bad health or disability, which is plainly due to neglect of proper precautions in the way of clothing or personal sanitation. Sore feet are responsible for a large part of the disablement of men. Washing the feet *every night,* especially when they have become wet, will often obviate blisters. Stockings should be heavy, made of "natural wool" and should fit tightly enough so that wrinkles will not form. Shoes should have heavy soles and should be made of such tough leather that they will not easily tear. Rubber boots should *not* be worn; they make the feet tender. Although a surveying trip is usually considered as the opportunity to use up discarded clothing, ordinary clothing is usually very unsuitable and quickly becomes unwearable. When camping conditions are rough and the work must last for several months, and possibly years, clothing made of specially suitable material is economical. The material should be tough, so that it will not easily be torn by brambles, etc. It should be waterproof so as to shed rain and yet should be porous. It should be so thoroughy shrunken that moisture cannot appreciably shrink it further. "Mackinaw" is a soft, rough cloth, all wool, thoroughly shrunken, light, warm and waterproof. It is especially suitable for cold weather. "Pontiac" is similar. "Khaki" is a twilled cotton and is especially suitable for warm weather clothing. "Jungle cloth" is somewhat similar, but is particularly noted for its toughness and durability.

Especial care should be taken in the choice of underclothing, so as to avoid sudden chills after becoming overheated. Woolen underclothing is almost essential. "Cholera bands," made of wool, should *always* be worn about the abdomen in tropical countries.

MEDICAL AND SURGICAL TREATMENT.

36. **Responsibility of engineer-in-charge.** Throughout any surveying trip, where camping is necessary, professional medical aid is usually unobtainable. There rests upon the engineer-in-

charge, as the head of the expedition, some measure of responsibility for the health and care of the party. When some member of the party is seriously injured by accident, bitten by a poisonous snake or insect, or stricken with a sudden and violent attack of disease, and competent medical assistance is absolutely unobtainable for several days or even weeks, the head of the party must choose between seeing the victim die or boldly performing some simple surgical operation or giving medical treatment which he would not dream of doing otherwise. It is the lesser of two evils and the engineer must not shirk his duty. Even though a doctor is *perhaps* obtainable after many days delay by despatching a messenger 50 miles for him, common sense first-aid work and the intelligent use of a few simple methods and remedies may save life or prevent or mitigate permanent disablement. The outfit should include a sufficient supply of the medicines and medical appliances which would most probably be required. All bottles should be carried in cases to prevent breakage and the corks or stoppers secured tightly. When practicable, the drugs should be in tablet form, rather than liquid, and a normal dose should be marked on each bottle or package. They should be doubly labeled and the labels varnished to prevent their coming off in a damp climate. All adhesive plasters, antiseptic gauze, and such appliances, should be kept carefully wrapped up and protected from air and moisture.

37. **Appliances.** The very simplest medical outfit should include a pair of good scissors, which can be made antiseptically clean by wiping off with alcohol; a knife with two razor-sharp blades; a probe; a small saw; dentist's forceps; a pair of mouse-tooth forceps; a hypodermic syringe and two needles, or the more modern individual hypodermic syringe packages; also individual needles and cat-gut "No. 2 chromic" in curved vacuum tubes; a two-quart fountain syringe; supplies of sterilized gauze, adhesive plaster, needles, safety pins. The engineer should thoroughly familiarize himself with the working and manner of use of these. Any engineer who is preparing to head an expedition into a region where medical attention is unobtainable should consider that he can very wisely spend time with some doctor friend in learning the elements of the use of all these appliances.

38. **Antiseptics.** The engineer should warn his men of the danger from the infection of even slight wounds and scratches, especially in hot climates. The best emergency treatment for

any scratch, nail gouge, or nail in the foot, is to apply pure tincture of iodine at the *base* of the wound by cotton on the end of a small stick or probe. A more modern safe-guard against tetanus, or "lock-jaw," is "tetanus antitoxin," put up in individual syringe packages. A few of the many effective antiseptics are here mentioned: **Boric ointment**; one part of powdered boric acid added to nine parts of vaseline. **Carbolic ointment**; one part of carbolic acid to nineteen parts of vaseline. **Iodoform** powder promotes rapid healing of sores and wounds; one part in eight parts of vaseline is a good healing ointment. **Permanganate of potash**; one grain gives a purple color to a gallon of water; if the water is impure, the purple color changes rapidly to brown and this is a rough test of organic impurity; the crystals are soluble in 20 parts of water; it is especially useful in the treatment of snake bites. In a snake-infested country, it is wise for each man to carry permanganate of potash crystals with him, for use in emergency. See "Snake bites," § 44.

39. **Drinking water.** Every chief of party should see to it that his party has a pure supply of drinking water and especially that this supply is not contaminated by excrement from the camp draining into it. If there is any doubt about the purity of the supply (especially if so indicated by the permanganate-of-potash test) it should be part of the duty of the camp cook to maintain a liberal supply of boiled and cooled water. A neglect of such a precaution might easily result in an epidemic of typhoid. In a region where all streams are contaminated, perhaps by decaying vegetation or other natural cause, it may be wise to provide canteens, which the cook should furnish each morning filled with sterilized water.

40. **Bleeding** from an artery or vein can sometimes be stopped by pressing the vessel with sufficient pressure to stop the flow and continuing the pressure until the blood coagulates. If the vein or artery is actually severed but is not too large, the bleeding may be stopped by the use of a pair of forceps; grasp and pinch the vessel and twist it around three or four times. In about ten minutes the forceps may be removed. If the vein or artery is larger, and especially when it is an artery, which may be recognized by spurts of bright red blood, it may be necessary to tie the vessel. This may be done with catgut ligature, which should previously be boiled to prevent infection. While preparing for this, bleeding should be stopped by temporary pres-

sure. This is most easily done when the bleeding vessel may be pressed against a bone. A tourniquet can be improvised for pressing a pad (or even a stone) against the vein or artery of a limb by using a stick and a piece of cloth, or, perhaps, a rope and a small block of wood. Fasten the cloth or rope into a loose loop around the limb and run the stick through the loop; then twist it so that the pad is pressed down as desired. The rope can be so disposed as to press the block, which in turn presses the pad against the vein or artery.

41. Ailments and diseases; medicines; treatment.

Colic or cramp. **Essence of ginger,** 5 to 20 drops, in a small amount of very hot water.

Diarrhœa. Remove the bowel irritant by a castor-oil purge; then, if diarrhœa continues, give one-half teaspoonful of **bismuth sub-carbonate** every two or three hours until relieved.

Purgatives. **Epsom salts;** dose, two teaspoonsful in a small glass of hot water. **Calomel;** dose, two to five grains; should be followed by **Epsom** salts. **Cascara sagrada;** dose, two to six grains. **Castor oil;** dose, one to three tablespoonsful, which may be made more palatable by mixing with an equal amount of glycerine, and then putting the mixture into a glass of lemonade. Any tendency to constipation, which leads to intestinal poisoning and appendicitis, may be avoided by using a laxative, made as effective as necessary, about once a week.

Emetics. **Common salt** (two tablespoonsful), or **mustard** (one tablespoonful) or **Ipecacuanha** (30 grains) or **Zinc Sulphate** (30 grains), dissolved in a glass of water. Tickling the throat with a feather may sometimes be effective. Strong "Ivory" soap suds is excellent.

Malaria. Five grains of **Quinine** as a preventive; ten grains, three times a day, as an ordinary maximum dose. Larger doses are often given but it is dangerous unless under the care of a physician.

Cold-in-head. **Rhinitis** tablets, given as directed on bottle, are effective to break up an incipient cold. **"Dover's powder";** dose, five to ten grains. Keep patient warm, with hot-water bottles and hot drinks.

42. Drowning; electric shock, asphyxiation. The trouble and the remedy is essentially the same in all three cases; respiration has been temporarily suspended and *must* be promptly restored by artificial means. Loosen the patient's clothing, especially about the neck. In a drowning case, lay the patient on the ground, face down, straddle him and raise him at the hips so that the water in the air passages will drain out. Remove from the mouth any tobacco, false teeth or anything else that might obstruct breathing. Draw the tongue forward with forceps or a handkerchief. Then lay him face down, but with the face turned to one side so as to facilitate breathing, and with the arms extended forward. Then the operator, kneeling astride the patient, facing his head, and with the hands pressing on the lower ribs, *gradually* presses down so as to expel the air from the lungs. Then he suddenly removes the pressure by swinging back, and thus allows air to enter the lungs. Repeat the movements every four or five seconds, until natural breathing commences. Considering the fact that this method has successfully restored breathing after some *hours* of unsuccessful effort, and also that, in those cases, the patient would have died except for the persistency of the effort, the operator must not be discouraged because his efforts are not immediately successful. Promptness in beginning such treatment is so important that it is better to commence at once (even outdoors) rather than allow any material delay in order to get the patient to a house. The patient should be allowed plenty of air; crowding around him should be avoided. A blanket, extra clothing, hot bricks or stones, or hot-water bags, to restore heat to the body, will be of assistance, provided they do not interfere with the respiration operations. Do not attempt to make the patient swallow anything (e. g., a stimulant), until he is fully conscious; otherwise he will choke.

43. **Fractures.** Obtain medical aid if possible, but if this is unobtainable, except after a delay of many days or weeks, and it is uncertain even then, it may be preferable to take the chances of common-sense treatment, even if unskilled, rather than the certain permanent injury due to neglect of all treatment. Fractures are (a) **simple,** when the skin is not broken; (b) **compound,** when the skin is so broken that the fractured bone is more or less exposed to the air; and (c) **comminuted,** when there are two or more breaks of the same bone; a comminuted fracture may be simple or compound. Great care should be used in handling the patient immediately after the accident so that a simple fracture does not become compound. A broken limb should be

carefully straightened out and bound temporarily with the best improvised splints which are available until the patient can be removed to a bed. Even if amateur bone setting is decided to be advisable, setting should not be attempted if there is excessive swelling or tenderness. Apply ice or evaporating lotions to reduce any swelling. Splints should be made which are of proper length and are so rounded and padded with cloth that they cannot produce any concentrated pressure. Usually the dislocated bones are forced past each other, especially if the fracture is oblique rather than perpendicular, and it is always necessary to use considerable force, especially if it is a broken leg, to pull the bones back into position. The amateur must use his best common sense and knowledge of skeleton anatomy to restore the fragments to the same relative position they had previously, and then to secure them rigidly stiff with splints. Comparison with an unbroken arm or leg will be made even by a skilled surgeon, and such a comparison should be carefully studied by the amateur. While the binding should be as firm as it is safe to make it, it may be so tight as to produce swelling and even ulceration, and then the binding must be loosened. Compound fractures require the care of the flesh and skin wound in addition to the bone setting. The wound should be treated as described for wounds, but the splints and binding should be designed so that the wound can be properly dressed without loosening the splints. If the broken bone protrudes through the wound, it *must* be drawn back so that the wound can heal externally, even though the bone setting is beyond the skill of the amateur surgeon. Setting usually requires about six weeks, but, in the case of a limb, the joints above and below the break should be very carefully moved after about three weeks, so as to avoid stiff joints, special care being taken that there is no strain on the healing bone.

44. **Snake or insect bites.** The majority of snake bites occur on the limbs. In such a case (1) **tie a cord or bandage** about the limb just above the wound as promptly as possible, so as to prevent the poisoned blood from getting into the system; (2) **cut into the wound** so as to induce free bleeding; (3) **suck the wound** to aid in drawing out the poisoned blood; there is little or no danger in this, provided the mouth is free from sores, and provided the mouth is immediately rinsed out, preferably with an antiseptic solution, such as a light purple solution of **per-**

manganate of potash; (4) inject into the wound a strong solution of **permanganate of potash,** which may be done hypodermically or, perhaps, even by rubbing into the wound crystals of the drug. When the case is very serious, on account of the known deadly character of the poison, and when no permanganate of potash is obtainable, heroic measures are sometimes necessary. Pure **carbolic acid,** or **caustic,** may be used, if available. Cauterizing the wound with white-hot iron, exploding a pinch of gunpowder over the wound, shooting away the infected part with a gun, or even summary amputation with a hatchet, may sometimes be considered the lesser of two evils. If the limb has been tightly tied, it will, of course, produce great pain, discoloration and swelling, which must not be continued too long. A second ligature should be tied a few inches above the first. When the limb becomes very swelled and painful, loosen the first ligature for about ten seconds and again tighten, and then loosen the second ligature for ten seconds and again tighten. After fifteen minutes, repeat the loosening and tightening. After about eight repetitions, the ligatures may be removed altogether. If the poison is partly sucked out, the remainder partly neutralized with chemicals, and does not get fully into the system for two hours, the danger is greatly diminished. Of course bites on the face or body cannot be tied up and can only be treated by sucking out the poison and by chemicals. Stimulation of the heart is usually essential, which may be done with one teaspoonful of **aromatic spirits of ammonia** in two tablespoonsful of water, or with alcoholic liquor, preferably whiskey. One 1-30th grain **strychnine** tablets, dissolved in two tablespoonsful of water, is also a stimulant. If a hypodermic is available, one tablet may be dissolved in thirty drops of sterile water and inserted in the back or arm, well under the skin.

45. **Wounds.** First, last and all the time, **prevent infection.** The marvelous success of modern surgery is due largely to antiseptic methods. Neglect of cleanliness almost inevitably induces blood poisoning. A perfectly clean cut, after being washed and sterilized with iodine, may be closed with adhesive plaster, taking stitches, if necessary, with sterilized catgut or silk or linen thread. The stitches may be removed in a week. But when the flesh is torn and, especially, when dirt and other matter, which is possibly poisonous or infectious, has been forced into the wound, there is great danger of blood poisoning, and

the wound must be cleansed. First, cover the wound itself with a pad which has been soaked in an antiseptic solution and then wash the skin (shaving off all hair), all around the wound, using first soap and then an antiseptic solution. Then cleanse out all foreign matter from the wound, using antiseptics and pack the wound with strip gauze, soaked in the antiseptic, so as to extend from the deepest part of it to the outside. This will drain the discharges. The dressing should be renewed every day, or even three times per day, according to the severity of the wound, until the wound shows a tendency to heal. A gaping torn wound should not be sewed up, except to bring the edges together temporarily.

45a. Medical outfit to be carried. The quantity of medicine which should be carried is necessarily guess-work. If the party has great good luck, it might bring back the entire supply untouched. On the other hand severe sickness might exhaust some of the medicines long before the survey is complete. But the following list has been estimated as a reasonably proper supply for a party of 25 men which may be out of reach of an adequate source of medical supplies for a period of six months. The list should be varied somewhat according to the climate. The probabilities of disease, snake-bites, etc., in a cold climate are not the same as those of the tropics. Some of the following articles, those commonly required for "first-aid" work, should always be provided, even when the party will never be more than a few hours distance from medical assistance.

Boric acid, powdered, 5 lbs.
Carbolic acid, pure, 1 oz.
Iodoform powder, 2 oz.
Permanganate of potash, 8 oz.
Essence of ginger, 2 oz.
Epsom salts, 50 lbs.
Calomel, 1000 $\frac{1}{2}$-gr. tablets.
Cascara sagrada, 1000 5-gr. tablets.
Castor oil, 4 quarts.
Glycerine, 4 quarts.
Ipecacuanha, 6 oz.
Individual hypoder. syr. packages; Tetanus antitoxin, 12 units; Morphine ($\frac{1}{4}$ gr.), Atropine ($\frac{1}{150}$ gr.); (for agonizing pain); 24 units; Strychnia ($\frac{1}{20}$ gr.); 24 units; Camphorated oil; 24 units (for profound shock); Digalen (20 drops); 24 units (for acute heart trouble).
Bismuth sub-carbonate, 2 lbs.
Zinc sulphate, 4 oz.
Quinine 1000 5-gr. tablets.
Rhinitis, 2000 5-gr. tablets.
Dover's powder, 1000 5-gr. tablets.
Caustic, $AgNO_3$, 24 sticks.
Aromatic sp'ts of ammonia, 1 pint.
Strychnine tablets, 1000 $\frac{1}{30}$ gr.
Carbolized vaseline, 12 1-oz. jars.
Sterilized gauze, 5 doz. individual 1-yard rolls.
Adhesive plaster, 3 5-yard rolls, 12 inches wide.
Needles and catgut, No. 2 chromic, in curved vacuum tubes, 12 packages.
Needles, safety pins, etc.
Instruments, etc., as listed in § 37.

CHAPTER II.

ALINEMENT

IN this chapter the alinement of the *center line* only of a pair of rails is considered. When a railroad is crossing a summit in the grade line, although the horizontal projection of the alinement may be straight, the vertical projection will consist of two sloping lines joined by a curve. When a curve is on a grade, the center line is really a spiral, a curve of double curvature, although its horizontal projection is a circle. The center line therefore consists of straight lines and curves of single and double curvature. The simplest method of treating them is to consider their horizontal and vertical projections separately. In treating simple, compound, and transition curves, only the horizontal projections of those curves will be considered.

SIMPLE CURVES.

46. Designation of curves. A curve may be designated either by its radius or by the angle subtended by a chord of unit length. Such an angle is known as the "degree of curve" and is indicated by D. Since the curves that are practically used have very long radii, it is generally impracticable to make any use of the actual center, and the curve is located without reference to it. If AB in Fig. 11 represents a unit chord (C) of a curve of radius R, then by the above definition the angle AOB equals D. Then

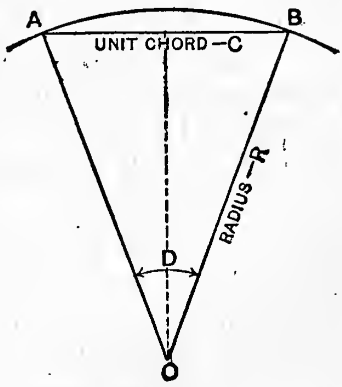


FIG. 11.

$$AO \sin \tfrac{1}{2}D = \tfrac{1}{2}AB = \tfrac{1}{2}C.$$

$$R = \frac{\frac{1}{2}C}{\sin \frac{1}{2}D}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

or, by inversion,

$$\sin \tfrac{1}{2}D = \frac{C}{2R}. \quad \ldots \ldots \ldots \quad (2)$$

The unit chord is variously taken throughout the world as 100 feet, 66 feet, and 20 meters. In the United States 100 feet is invariably used as the unit chord length, and throughout this work it will be so considered. Table I has been computed on this basis. It gives the radius, with its logarithm, of all curves from a 0° 01′ curve up to a 10° curve, varying by single minutes. The sharper curves, which are seldom used, are given with larger intervals.

An approximate value of R may be readily found from the following simple rule, which should be memorized:

$$R = \frac{5730}{D}.$$

Although such values are not mathematically correct, since R does not strictly vary inversely as D, yet the resulting value is within a tenth of one per cent for all commonly used values of R, and is sufficiently close for many purposes, as will be shown later.

47. Metric Curves. The unit chord for railroad curves on the metric system is 20 meters. If a curve has a 100-foot chord and a central angle of 5°, the radius would, of course, be 1146.3 feet. Since 20 meters $=65.6174$ feet, a 20-meter chord between those same radial lines would subtend an arc with a radius of $.656174 \times 1146.3$ feet, or 752.16 feet. But this radius, measured in meters, would be $(.656174 \times 1146.3) \div 3.28087 = 229.26$ meters, which is $1146.3 \times .20$. In other words, the radius of any metric curve, measured in meters, is *numerically* one-fifth of the radius, measured in feet, of the same degree curve, but in actual length is a little less than two-thirds. This practically means that a 10° curve, metric, is actually very much sharper than a 10° curve, using foot-measure, or that the radius is about 66% as much. Therefore, in selecting curves for location, an engineer, who is accustomed to the foot-measure system, should remember that a 10° curve metric, for example, has approximately the same radius as a 15° curve, using foot-measure. While it is more convenient for an engineer, who is constantly using the metric system for curves, to have tables computed directly on this basis, an engineer need not be dependent on such tables, since it is only necessary to divide the tabular quantities in the foot-table by 5 to obtain the corresponding quantities for the metric system. This applies not only to radii, but also to tangents, external distances and long chords for a 1° curve. A desired logarithm may be obtained by subtracting 0.6989700 from the foot-table logarithm.

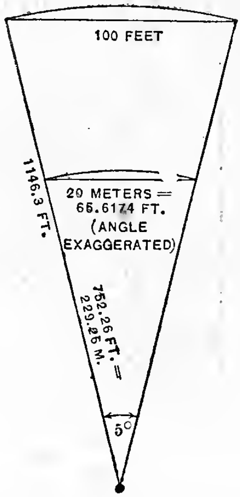


FIG. 12.

For example, anticipating the explanation in Art. 53, what is the tangent distance of a 6° metric curve, when the central angle is 32° 40′. From Table II, we find that by the foot-system the tangent distance for a 1° curve when the central angle is 32° 40′ is 1679.1 feet; then for a 6° curve it is $1679.1 \div 6 = 279.85$ feet; for a 6° metric curve it is $279.85 \div 5 = 55.97$ meters. The radius of the 6° metric curve $= 955.37 \div 5 = 191.074$ meters, which is in actual length about 66% of 955.37 feet.

As another illustration of the transformation from the foot-system to the metric system, or vice versa, the degree of a curve, by the foot system, may be multiplied by .66 and obtain approximately the degree of the equivalent curve by the metric system. For example, a 6° curve, foot system, has about the same actual radius as a $6 \times .66 = 3.96°$ metric curve, or about a 4° curve.

48. Length of a subchord. Since it is impracticable to measure along a curved arc, curves are always measured by laying off 100-foot chord lengths. This means that the actual arc is always a little longer than the chord. It also means that a *subchord* (a chord shorter than the unit length), will be a little longer than the ratio of the angles subtended would call for. The truth of this may be seen without calculation by noting that two equal subchords, each subtending the angle $\frac{1}{2}D$, will evidently be slightly longer than 50 feet each. If c be the length of a subchord subtending the angle d, then, as in Eq. 2,

$$\sin \tfrac{1}{2}d = \frac{c}{2R},$$

or, by inversion, $$c = 2R \sin \tfrac{1}{2}d. \quad \quad (3)$$

The *nominal length* of a subchord $= 100\frac{d}{D}$. For example, a *nominal* subchord of 40 feet will subtend an angle of $\frac{40}{100}$ of $D°$; its *true length* will be slightly more than 40 feet, and may be computed by Eq. 3. The *difference* between the nominal and true lengths is maximum when the subchord is about 57 feet long, but with the low degrees of curvature ordinarily used the difference may be neglected. With a 10° curve and a nominal chord length of 60 feet, the true length is 60.049 feet. Very sharp curves should be laid off with 50-foot or even 25-foot chords (nominal length). In such cases especially the true lengths of these subchords should be computed and used instead of the nominal lengths.

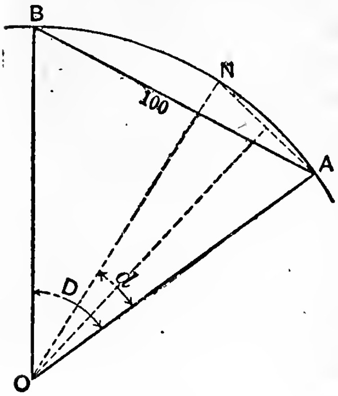


FIG. 13.

For example, assume that a 12° curve begins at Sta. 26+30. The first subchord will be nominally 70 feet and actually 70.066 feet. Assume that the central angle between the tangents is 39° 36′. Then the nominal length of curve is $39.6° \div 12° = 3.30$ stations. $3.30 - .70 = 2.60$, the nominal length of curve beyond the first station point on the curve. The final subchord is nominally 60 feet, but its actual length is 60.070 feet.

The values of these subchords for even degrees between 5° and 30°, and for nominal chord lengths of 10, 20, 30, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90 and 95 feet, are given in Table IIa. The excess values increase approximately as the square of the degree of curvature, but for intervals of 1° simple interpolation will be sufficiently accurate for intermediate values.

49. Length of a curve. The actual mean length of the two rails will be more than the nominal length of the curve, as defined above, and even more than the sum of the full 100-foot lengths and the true lengths of the subchord lengths at the ends. In the above numerical case the mean rail length is

$$39.6° \times \frac{\pi}{180°} \times R = 39.6° \times \frac{\pi}{180°} \times 478.34 = 330.604.$$

The sum of the two full-chord lengths and the two subchords is 70.066+200+60.070=330.136. A large part of the excess (330.604−330.136=.468) is the excess length (.183) of each arc of a 12° curve over the 100-foot chord. The remainder is the excess of the 70-foot and 60-foot arcs over the true chord lengths. But this excess length is of little practical importance. In the above case (a 12° curve) it adds about 0.2% to the length of rail that must be bought. The excess varies approximately as the square of the degree of curvature. The percentage of excess for the entire length of a road is utterly insignificant and is swallowed up by the 2% excess which is usually allowed for wastage in rail cutting.

50. Curve notation. The notation adopted by the Amer. Rwy. Eng. Assoc. indicates any point where there is a change of alinement by two letters, the first of which denotes the alinement on the side toward station zero and the second that away from station zero. Thus, the beginning of a curve, or the change from a tangent to a simple curve, is noted as *TC*; the other end of the curve, or the change from a simple curve to a tangent is noted as *CT*. But, since the use of two letters to indicate a point, or the use of four letters to indicate a line joining the two points, is cumbersome in the algebraic solutions and demonstrations which follow (demonstrations which the A. R. E. A. do not give), the author has decided to retain the old notation, rather than to try to conform to the A. R. E. A. notation. The A. R. E. A. system also indicates the central angle of a curve, or the angle between the two tangents, by *I*. In the first edition of this work, the author, following Searles, indicated the central angle by Δ. To make even this change, for the sake of conformity, would require a change in all the mathematical work and figures involving curves throughout the book. In Fig. 14 both notations are given, the A. R. E. A. notations being given in parentheses. Both notations are also shown in Fig. 36, which illustrates a transition curve or spiral. It should be noted that some of the notations coincide for some of the elements.

51. Elements of a curve. Considering the line as running from *A* toward *B*, the beginning of the curve, at *A*, is called the *point of curve* (*PC*). The other end of the *curve*, at *B*, is called the *point of tangency* (*PT*). The intersection of the tangents is called the *vertex* (*V*). The angle made by the tangents at V, which equals the angle made by the radii to the extremities of the curve, is called the *central angle* (Δ). AV and BV, the two equal tangents from the vertex to the PC and T, are called the *tangent distances* (T). The chord AB is called the *long chord* (LC). The intercept HG from the middle of the long chord to the middle of the arc is called the *middle ordinate* (M). That part of the secant GV from

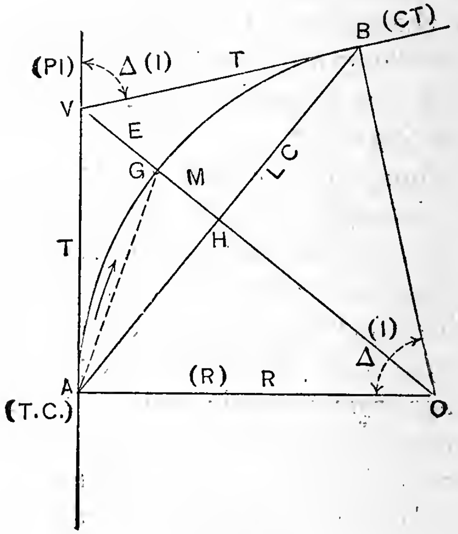


FIG. 14.

the middle of the arc to the vertex is called the *external distance* (E). From the figure it is very easy to derive the following frequently used relations:

$$T = R \tan \tfrac{1}{2}\Delta. \qquad (4)$$

$$LC = 2R \sin \tfrac{1}{2}\Delta. \qquad (5)$$

$$M = R \operatorname{vers} \tfrac{1}{2}\Delta. \qquad (6)$$

$$E = R \operatorname{exsec} \tfrac{1}{2}\Delta. \qquad (7)$$

52. Relation between T, E, and Δ. Join A and G in Fig. 14. The angle $VAG = \frac{1}{4}\Delta$, since it is measured by one half of the arc AG between the secant and tangent.

$$AGO = 90° - \tfrac{1}{4}\Delta.$$

$$AV : VG :: \sin AGV : \sin VAG;$$

$$\sin AGV = \sin AGO = \cos \tfrac{1}{4}\Delta;$$

$$T : E :: \cos \tfrac{1}{4}\Delta : \sin \tfrac{1}{4}\Delta;$$

$$T = E \cot \tfrac{1}{4}\Delta. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The same relation may be obtained by dividing Eq. 4 by Eq. 7, since $\tan a \div \operatorname{exsec} a = \cot \tfrac{1}{2}a$.

53. **Elements of a 1° curve.** From Eqs. 1 to 8 it is seen that the elements of a curve vary directly as R. It is also seen to be very nearly true that R varies inversely as D. If the elements of a 1° curve for various central angles are calculated and tabulated, the elements of a curve of $D°$ curvature may be approximately found by dividing by D the corresponding elements of a 1° curve having the same central angle. For small central angles and low degrees of curvature the errors involved by the approximation are insignificant, and even for larger angles the errors are so small that *for many purposes* they may be disregarded

In Table II is given the value of the tangent distances, external distances, and long chords for a 1° curve for various central angles The student should familiarize himself with the degree of approximation involved by solving a large number of cases under various conditions by the exact and by the approximate methods, in order that he may know when the approximate method is sufficiently exact for the intended purpose. The approximate method also gives a ready check on the exact method.

A closer value may be obtained by using the "Corrective Table" found at the end of the main table. The correction is *always* additive and is usually very small and often even too insignificant for attention. A glance at the corrective table will show whether a correction need be made and an easily computed interpolation will show its amount. For example, what is the tangent distance for a 6° curve having a central angle of 42° 15'? Interpolating between 2209.0 and 2218.6, we have 2213.8 as the tangent distance for a 1° curve. Dividing by 6, we have 368.97 as the approximate tangent distance. Interpolating in the corrective table, we have .14 as the correction for a 5° curve and a central angle of 42° 15′, and .28 as the correction for a 10° curve. Interpolating for 6° between these values of .14 and .28, we have .17, which added to 368.97 equals 369.14. The precise value, computed from Eq. 4, is 369.12. If the approximate value, even after correction, is not considered sufficiently accurate, Eq. 4 should be used. The student should appreciate that the discrepancy of even .02 in the above calculation is not due to any real error in the main table or the corrective table, but is due to the fact that the tangent distances are only computed to the nearest tenth of a foot for values over 1000 feet, and this will produce such discrepancies. The table should not be used where precise values are required.

54. Exercises. (*a*) What is the tangent distance of a 4° 20′ curve having a central angle of 18° 24′?

(*b*) Given a 3° 30′ curve and a central angle of 16° 20′, how far will the curve pass from the vertex? [Use Eq. 7.]

(*c*) An 18° curve is to be laid off using 25-foot (nominal) chord lengths. What is the true length of the subchords?

(*d*) Given two tangents making a central angle of 15° 24′. It is desired to connect these tangents by a curve which shall pass 16.2 feet from their intersection. How far down the tangent will the curve begin and what will be its radius? (Use Eq. 8 and then use Eq. 4 inverted.)

55. Curve location by deflections. The angle between a secant and a tangent (or between two secants intersecting on an arc) is measured by one half of the intercepted arc. Beginning at the *PC* (*A* in Fig. 15), if the first chord is to be a full chord we may deflect an angle *VAa* ($=\frac{1}{2}D$), and the point *a*, which is 100 feet from *A*, is a point on the curve. For the next station, *b*, deflect an *additional* angle *bAa* ($=\frac{1}{2}D$) and, with one end of the tape at *a*, swing the other end until the 100-foot point is on the line *Ab*. The point *b* is then on the curve. If the final chord *cB* is a subchord, its *additional deflection* ($\frac{1}{2}d$) is something less than $\frac{1}{2}D$. The last *deflection* (*BAV*) is

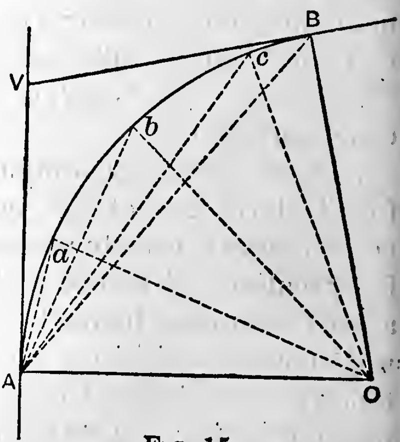


FIG. 15.

of course $\frac{1}{2}\Delta$. It is particularly important, when a curve begins or ends with a subchord and the deflections are odd quantities, that the last additional deflection should be carefully computed and added to the previous deflection, to check the mathematical work by the agreement of this last computed deflection with $\frac{1}{2}\Delta$.

Example. Given a 3° 24′ curve having a central angle of 18° 22′ and beginning at sta. 47+32, to compute the deflections. The nominal length of curve is 18° 22′ ÷ 3° 24′ = 18.367 ÷ 3.40 = 5.402 stations or 540.2 feet. The curve therefore ends at sta. 52+72.2. The deflection for sta. 48 is $\frac{68}{100}\times\frac{1}{2}(3°\ 24')$ $=0.68\times1°.7=1°.156=1°\ 09'$ nearly. For each additional 100 feet it is 1° 42′ additional. The final additional deflection for the final subchord of 72.2 feet is

$$\frac{72.2}{100}\times\frac{1}{2}(3°\ 24')=1°.2274=1°\ 14'\text{ nearly.}$$

The deflections are

P. C	Sta. 47+32		0°
	48	0°	+ 1° 09′ = 1° 09′
	49	1° 09′	+ 1° 42′ = 2° 51′
	50	2° 51′	+ 1° 42′ = 4° 33′
	51	4° 33′	+ 1° 42′ = 6° 15′
	52	6° 15′	+ 1° 42′ = 7° 57′
P. T.	52+72.2	7° 57′	+ 1° 14′ = 9° 11′

As a check 9° 11′ = $\frac{1}{2}$(18° 22′) = $\frac{1}{2}\Delta$. (See the Form of Notes in § 21.)

56. Instrumental work. It is generally impracticable to locate more than 500 to 600 feet of a curve from one station. Obstructions will sometimes require that the transit be moved up every 200 or 300 feet. There are two methods of setting off the angles when the transit has been moved up from the *PC.*

(a) The transit may be sighted at the previous transit station with a reading on the plates equal to the deflection angle from that station to the station occupied, but with the angle set off on the *other* side of 0°, so that when the telescope is turned to 0° it will sight along the tangent at the station occupied. Plunging the telescope, the forward stations may be set off by deflecting the proper deflections from the tangent at the station occupied.

This is a very common method and, when the degree of curvature is an even number of degrees and when the transit is only set at even stations, there is but little objection to it. But the degree of curvature is sometimes an odd quantity, and the exigencies of difficult location frequently require that substations be occupied as transit stations. Method (*a*) will then require the recalculation of all deflections for each new station occupied. The mathematical work is largely increased and the probability of error is very greatly increased and not so easily detected. Method (*b*) is just as simple as method (*a*) even for the most simple cases, and for the more difficult cases just referred to the superiority is very great.

(**b**) Calculate the deflection for each station and substation throughout the curve as though the whole curve were to be located from the *PC*. The computations may thus be completed and *checked* (as above) before beginning the instrumental work. If it unexpectedly becomes necessary to introduce a substation at any point, its deflection from the *PC* may be readily interpolated. The stations actually set from the *PC* are located as usual. RULE. **When the transit is set on any forward station, backsight to ANY previous station with the plates set at the deflection angle for the station sighted at. Plunge the telescope and sight at any forward station with the deflection angle originally computed for that station.** When the plates read the deflection angle for the station occupied, the telescope is sighting along the tangent at that station—which is the method of getting the forward tangent when occupying the *PT*. Even though the station occupied is an unexpected substation, when the instrument is properly oriented at that station, the angle reading for *any* station, forward or back, is that originally computed for it from the *PC*. In difficult work, where there are obstructions, a valuable check on the accuracy may be found by sighting backward at *any* visible station and noting whether

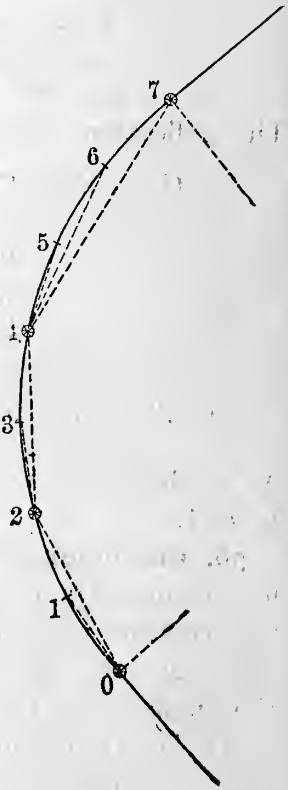


FIG. 16.

its deflection agrees with that originally computed. As a numerical illustration, assume a 4° curve, with 28° curvature, with stations 0, 2, 4, and 7 occupied. After setting stations 1 and 2, set up the transit at sta. 2 and backsight to sta. 0 with the deflection for sta. 0, which is 0°. The reading on sta. 1 is 2°; when the reading is 4° the telescope is tangent to the curve, and when sighting at 3 and 4 the deflections will be 6° and 8°. Occupy 4; sight to 2 with a reading of 4°. When the reading is 8° the telescope is tangent to the curve and, by plunging the telescope, 5, 6, and 7 may be located with the originally computed deflections of 10°, 12°, and 14°. When occupying 7 a backsight may be taken to any visible station with the plates reading the deflection for that station; then when

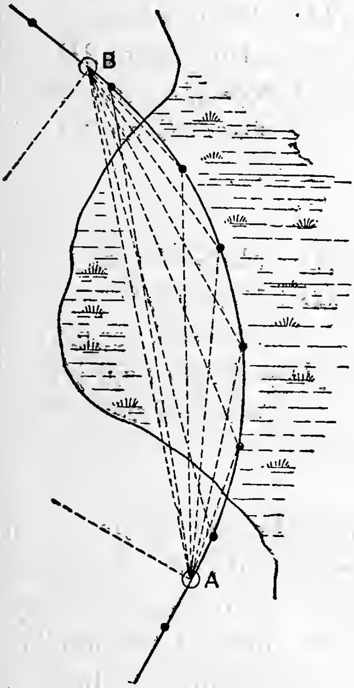


FIG. 17.

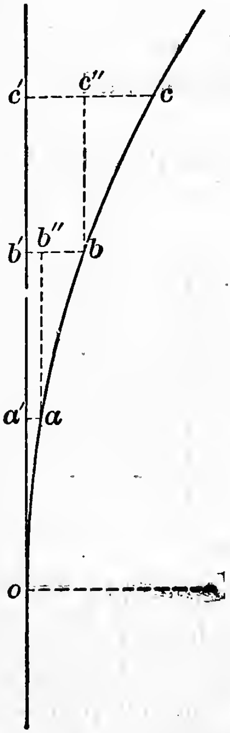


FIG. 18.

the plates read 14° the telescope will point along the forward tangent.

The location of curves by deflection angles is the normal method. A few other methods, to be described, should be considered as exceptional.

57. Curve location by two transits. A curve might be locate[d] more or less on a swamp where accurate chaining would b[e] exceedingly difficult if not impossible. The long chord *A*[B] (Fig. 17) may be determined by triangulation or otherwis[e] and the elements of the curve computed, including (possibly) subchords at each end. The deflection from *A* and *B* to eac[h] point may be computed. A rodman may then be sent (b[y] whatever means) to locate long stakes at points determine[d] by the simultaneous sightings of the two transits.

58. Curve location by tangential offsets. When a curve [is] very flat and no transit is at hand the following method may b[e] used (see Fig. 18): Produce the back tangent as far forward [as] necessary. Compute the ordinates Oa', Ob', Oc', etc., and th[e] abscissæ $a'a$, $b'b$, $c'c$, etc. If Oa is a full station (100 feet), the[n]

$$\left.\begin{aligned}
Oa' &= Oa' &&= 100 \cos \tfrac{1}{2}D, \text{ also} = R \sin D; \\
Ob' &= Oa' + a'b' &&= 100 \cos \tfrac{1}{2}D + 100 \cos \tfrac{3}{2}D, \\
& && \qquad \text{also} = R \sin 2D; \\
Oc' &= Oa' + a'b' + b'c' &&= 100(\cos \tfrac{1}{2}D + \cos \tfrac{3}{2}D + \cos \tfrac{5}{2}D), \\
& && \qquad \text{also} = R \sin 3D;
\end{aligned}\right\} \quad (9$$

etc.

$$\left.\begin{aligned}
a'a &= &&100 \sin \tfrac{1}{2}D, \text{ also} = R \operatorname{vers} D; \\
b'b &= a'a + b''b &&= 100 \sin \tfrac{1}{2}D + 100 \sin \tfrac{3}{2}D, \\
& && \qquad \text{also} = R \operatorname{vers} 2D; \\
c'c &= b'b + c''c &&= 100(\sin \tfrac{1}{2}D + \sin \tfrac{3}{2}D + \sin \tfrac{5}{2}D), \\
& && \qquad \text{also} = R \operatorname{vers} 3D;
\end{aligned}\right\} \quad (10$$

etc.

The functions $\frac{1}{2}D$, $\frac{3}{2}D$, etc., may be more conveniently use[d] *without* logarithms, by adding the several *natural* trigonometrica[l] functions and pointing off two decimal places. It may also b[e] noted that Ob' (for example) is one half of the long chord fo[r] four stations; also that $b'b$ is the middle ordinate for fou[r] stations. If the engineer is provided with tables giving the lon[g] chords and middle ordinates for various degrees of curvature these quantities may be taken (perhaps by interpolation) fro[m] such tables.

If the curve begins or ends at a substation, the angles an[d] terms will be correspondingly altered. The modifications ma[y] be readily deduced on the same principles as above, and should be worked out as an exercise by the student.

In Table II are given the long chords for a 1° curve for various values of Δ. Dividing the value as given by the degree of the curve, we have an approximate value which is amply close for low degrees of curvature, especially for laying out curves without a transit. For example, given a 4° 30′ curve, required the ordinate Oc'. This is evidently one half of a chord of six stations, with $\Delta=27°$. Dividing 2675.1 (which is the long chord of a 1° curve with $\Delta=27°$) by 4.5 we have 594.47; one half of this is the required ordinate, $Oc'=297.23$. The exact value is 297.31, an excess of .08, or less than .03 of 1%. The true values are always slightly in excess of the value as computed from Table II.

Exercise. A 3° 40′ curve begins at sta. 18+70 and runs to sta. 23+60. Required the tangential offsets and their corresponding ordinates. The first ordinate $=30 \cos \frac{1}{2}(\frac{30}{100}\times 3° 40') = 30\times .99995=29.9985$; the offset $=30 \sin 0° 33'=30\times .0096=0.288$. For the second full station (sta. 20) the ordinate $=\frac{1}{2}$ long chord for $\Delta=2(1° 06'+3° 40')$ with $D=3° 40'$. Dividing 476.12, from Table II, by $3\frac{2}{3}$, we have 129.85. Otherwise, by Eq. 9, the ordinate $=30\times\cos 0° 33'+100 \cos (1° 06'+1° 50') =30.00+99.87=129.87$. The offset for sta. $20=30 \sin 0° 33'+100 \sin (1° 06'+1° 50')=0.288+5.12=5.41$. Work out similarly the ordinates and offsets for sta. 21, 22, 23, and 23+60.

59. Curve location by middle ordinates. Take first the simpler case when the curve begins at an even station. If we consider (in Fig. 19) the curve produced back to z, the chord $za=2\times 100 \cos \frac{1}{2}D$, $A'a=100 \cos \frac{1}{2}D$, and $A'A=am=zn=100 \sin \frac{1}{2}D$. Set off AA' perpendicular to the tangent and $A'a$ parallel to the tangent. $AA'=aa'=bb'=cc'$, etc. $=100 \sin \frac{1}{2}D$. Set off aa' perpendicular to $a'A$. Produce Aa' until $a'b=A'a$, thus determining b. Succeeding points of the curve may thus be determined indefinitely.

Suppose the curve begins with a subchord. As before $ra=Am'=c' \cos \frac{1}{2}d'$, and $rA=am'=c' \sin \frac{1}{2}d'$. Also $sz=An'=c'' \cos \frac{1}{2}d''$, and $sA=zn'=c'' \sin \frac{1}{2}d''$, in which $(d'+d'')=D$. The points z and a being determined on the ground, aa' may be computed and set off as before and the curve continued in full stations. A subchord atthe end of the curve may be locate[d] by a similar process.

60. Curve location by offsets from the long chord. (Fig. 21.) Consider at once the general case in which the curve commence[s] with a subchord (curvature, d'), continues with one or more fu[ll]

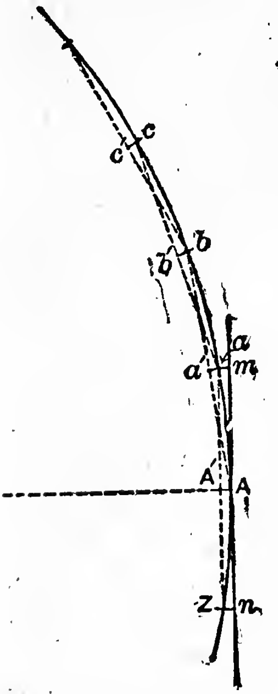


FIG. 19.

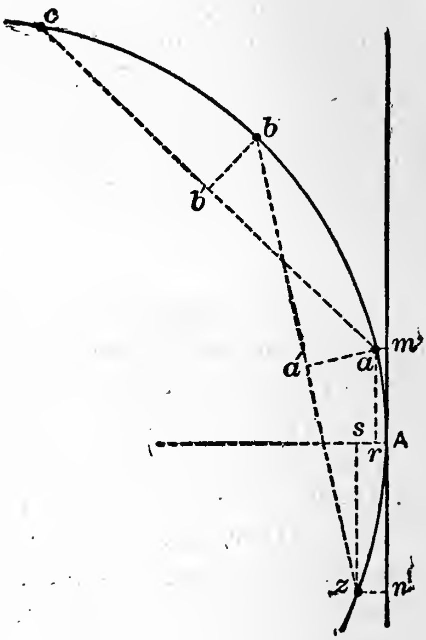


FIG. 20.

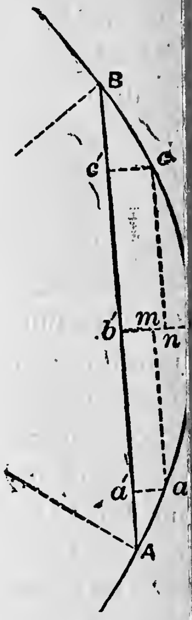


FIG. 21.

chords (curvature of each, D), and ends with a subchord with curvature d''. The numerical work consists in computing first AB, then the various abscissæ and ordinates. $AB = 2R \sin \frac{1}{2}\Delta$.

$$\left.\begin{aligned}
Aa' &= Aa' &&= c' \cos \tfrac{1}{2}(\Delta - d'); \\
Ab' &= Aa' + a'b' &&= c' \cos \tfrac{1}{2}(\Delta - d') + 100 \cos \tfrac{1}{2}(\Delta - 2d' - D); \\
Ac' &= Aa' + a'b' + b'c' &&= c' \cos \tfrac{1}{2}(\Delta - d') + 100 \cos \tfrac{1}{2}(\Delta - 2d' - D) \\
& && \quad + 100 \cos \tfrac{1}{2}(\Delta - 2d'' - D); \\
\text{also} & \\
&= AB - Bc' &&= 2R \sin \tfrac{1}{2}\Delta - c'' \cos \tfrac{1}{2}(\Delta - d'').
\end{aligned}\right\} \quad (11)$$

$$\left.\begin{aligned}
a'a &= a'a &&= c' \sin \tfrac{1}{2}(\Delta - d'); \\
b'b &= a'a + mb &&= c' \sin \tfrac{1}{2}(\Delta - d') + 100 \sin \tfrac{1}{2}(\Delta - 2d' - D); \\
c'c &= b'b - nb &&= c' \sin \tfrac{1}{2}(\Delta - d') + 100 \sin \tfrac{1}{2}(\Delta - 2d' - D) \\
& && \quad - 100 \sin \tfrac{1}{2}(\Delta - 2d'' - D); \\
\text{also} & &&= c'' \sin \tfrac{1}{2}(\Delta - d'').
\end{aligned}\right\} \quad (12)$$

The above formulæ are considerably simplified when the curve begins and ends at even stations. When the curve is very long a regular law becomes very apparent in the formation of all terms between the first and last. There are too few terms in the above equations to show the law.

61. Use and value of the above methods. The chief value of the above methods lies in the possibility of doing the work without a transit. The same principles are sometimes employed, even when a transit is used, when obstacles prevent the use of the normal method (see § 62, *c*). If the terminal tangents have already been accurately determined, these methods are useful to locate points of the curve when rigid accuracy is not essential. Track foremen frequently use such methods to lay out unimportant sidings, especially when the engineer and his transit are not at hand. Location by tangential offsets (or by offsets from the long chord) is to be preferred when the curve is flat (i.e., has a small central angle Δ) and there is no obstruction along the tangent, or long chord. Location by middle ordinates may be employed regardless of the length of the curve, and in cases when both the tangents and the long chord are obstructed. The above methods are but samples of a large number of similar methods which have been devised. The choice of the particular method to be adopted must be determined by the local conditions.

62. Obstacles to location. In this section will be given only a few of the principles involved in this class of problems, with illustrations. The engineer must decide, in each case, which is the best method to use. It is frequently advisable to devise a special solution for some particular case.

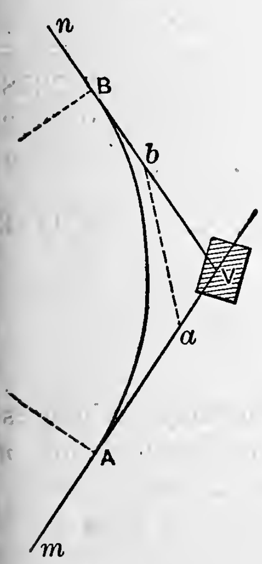


FIG. 22.

a. When the vertex is inaccessible. As shown in § 56, it is not absolutely essential that the vertex of a curve should be located on the ground. But it is very evident that the angle between the terminal tangents is determined with far less probable error if it is measured by a single measurement at the vertex rather than as the result of numerous angle measurements along the curve, involving several positions of the transit and comparatively short sights. Sometimes the location of the tangents is already determined on the ground (as by *bn* and *am*, Fig. 22), and it is required to join the tangents by a curve of given radius. *Method*: Measure *ab* and the angles *Vba* and *baV*. Δ is the sum of these angles. The distances *bV* and *aV* are computable from the above data. Given Δ and *R*, the tangent distances are computable, and then *Bb* and *aA* are found by subtracting *bV* and *aV* from the tangent distances. The curve may then be run from *A*, and the work may be checked by noting whether the curve as run ends at *B*—previously located from *b*.

Example. Assume $ab=546.82$; angle $a=15°\,18'$; angle $b=18°\,22'$; $D=3°\,40'$; required *aA* and *bB*.

$\Delta=15°\,18'+18°\,22'=33°\,40'$

Eq. (4)	$R \quad (3°\,40')$	$3.1939\bar{2}$
	$\tan\frac{1}{2}\Delta=\tan 16°\,50'$	9.48080
	$T=472.85$	$2.6747\bar{2}$

$aV=ab\dfrac{\sin 18°\,22'}{\sin 33°\,40'}$	*ab*	$2.7378\bar{4}$
	log sin 18° 22′	$9.4984\bar{4}$
	co-log sin 33° 40′	0.25621
	$aV=310.81$	2.49250
	$AV=472.85$	
	$aA=162.04$	

$bV=ab\dfrac{\sin 15°\,18'}{\sin 33°\,40'}$	*ab*	$2.7378\bar{4}$
	log sin 15° 18′	$9.4213\bar{9}$
	co-log sin 33° 40′	0.25621
	$bV=260.29$	2.41545
	$BV=472.85$	
	$bB=212.56$	

b. When the point of curve (or point of tangency) is inaccessible. At some distance (*As*, Fig. 23) an unobstructed line *pn* may be run parallel with *AV*. $nv=py=As=R \text{ vers } a$.

$$\therefore \text{vers } a=As\div R.$$

$$ns=ps=R\sin a.$$

At y, which is at a distance ps back from the *computed* position of A, make an offset sA to p. Run pn parallel to the tangent. A tangent to the curve at n makes an angle of a with np. From n the curve is run in as usual.

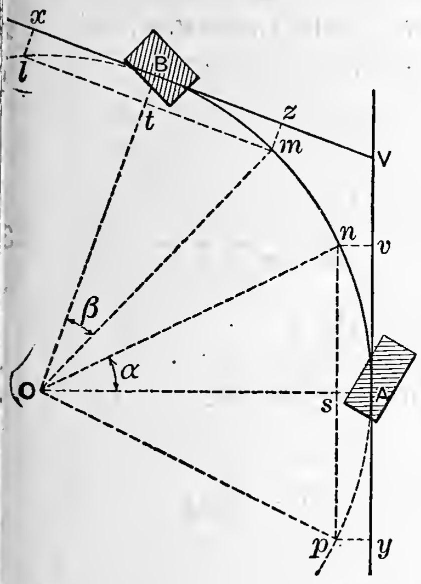


FIG. 23.

If the point of tangency is obstructed, a similar process, somewhat reversed, may be used. β is that portion of Δ still to be laid off when m is reached. $tm = tl = R \sin \beta$. $mz = tB = lx = R$ vers β.

c. When the central part of the curve is obstructed. a is the central angle between two points of the curve between which a chord may be run. a may equal *any* angle, but it is preferable that a should be a multiple of D, the degree of curve, and that the points m and n should be on even stations. $mn = 2R \sin \frac{1}{2}a$. A point s may be located by an offset ks from the chord mn by a similar method to that outlined in § 60.

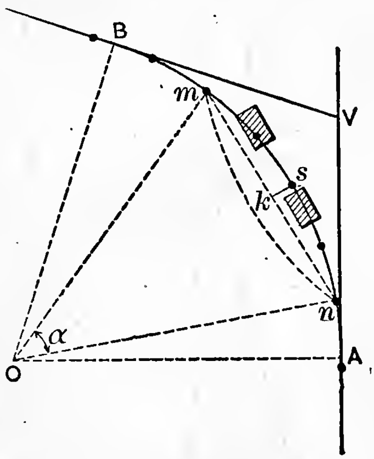


FIG. 24.

The device of introducing the dotted curve mn having the same radius of curvature as the other, although neither necessary nor advisable in the case shown in Fig. 24, is sometimes the best method of surveying around an obstacle. The offset from any point on the dotted curve to the corresponding point on the true curve is twice the "ordinate to the long cord," as computed in § 60.

63. Modifications of location. The following methods may be used in allowing for the discrepancies between the "paper location" based on a more or less rough preliminary survey and the more accurate instrumental location. (See § 18.) They are also frequently used in locating new parallel tracks and modifying old tracks.

a. To move the forward tangent parallel to itself a distance x the point of curve (A) remaining fixed. (Fig. 25.)

$$V'h = B'r = x'.$$

$$VV' = \frac{V'h}{\sin hVV'} = \frac{x}{\sin \Delta}. \quad . \quad . \quad . \quad . \quad . \quad (13)$$

$$AV' = AV + VV'.$$

The triangle BmB' is isosceles and $Bm = B'm$.

$$R' - R = O'O = mB = \frac{B'r}{\text{vers } B'mB} = \frac{x'}{\text{vers } \Delta}.$$

$$\therefore \; R' = R + \frac{x'}{\text{vers } \Delta}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The solution is very similar in case the tangent is moved inward to $V''B''$. Note that this method necessarily changes the

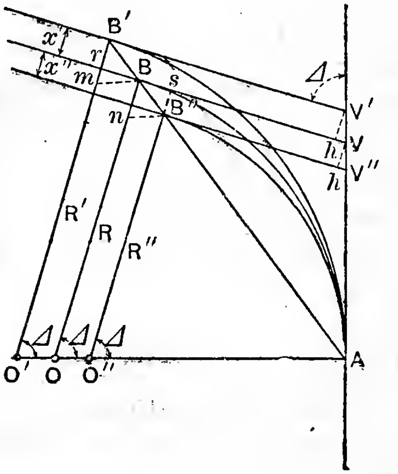


Fig. 25.

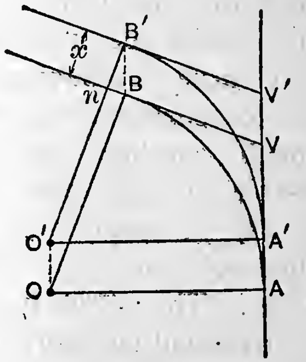


Fig. 26.

radius. If the radius is not to be changed, the point of curve must be altered as follows:

b. To move the forward tangent parallel to itself a distance x, the radius being unchanged. (Fig. 26.) In this case the whole curve is moved bodily a distance $OO' = AA' = VV' = BB'$, and moved parallel to the first tangent AV

$$BB' = \frac{B'n}{\sin nBB'} = \frac{x}{\sin \Delta} = AA'. \quad . \quad . \quad . \quad (15)$$

c. To change the direction of the forward tangent at the point of tangency. (Fig. 27.) This problem involves a change (a) in the central angle and also requires a new radius. An error in the determination of the central angle furnishes an occasion for its use.

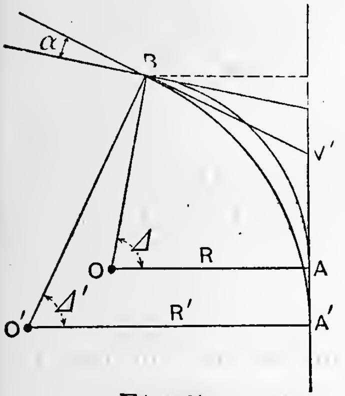


Fig. 27.

R, Δ, a, AV, and BV are known.

$$\Delta' = \Delta - a.$$

$$Bs = R \text{ vers } \Delta. \qquad Bs = R' \text{ vers } \Delta'.$$

$$\therefore R' = R \frac{\text{vers } \Delta}{\text{vers } (\Delta - a)}. \quad . \quad (16)$$

$$As = R \sin \Delta. \quad A's = R' \sin \Delta'.$$

$$\therefore AA' = A's - As = R' \sin \Delta' - R \sin \Delta. \quad . \quad . \quad (17)$$

The above solutions are given to illustrate a large class of problems which are constantly arising. All of the ordinary problems can be solved by the application of elementary geometry and trigonometry.

64. Limitations in location. It may be required to run a curve that shall join two given tangents and also pass through a given point The point (P, Fig. 28) is assumed to be determined by its distance (VP) from the vertex and by the angle $AVP = \beta$.

It is required to determine the radius (R) and the tangent distance (AV). Δ is known.

$$PVG = \tfrac{1}{2}(180° - \Delta) - \beta$$
$$= 90° - (\tfrac{1}{2}\Delta + \beta).$$
$$PP' = 2VP \sin PVG$$
$$= 2VP \cos (\tfrac{1}{2}\Delta + \beta).$$
$$PSV = \tfrac{1}{2}\Delta.$$
$$\therefore SP = VP \frac{\sin \beta}{\sin \frac{1}{2}\Delta}.$$

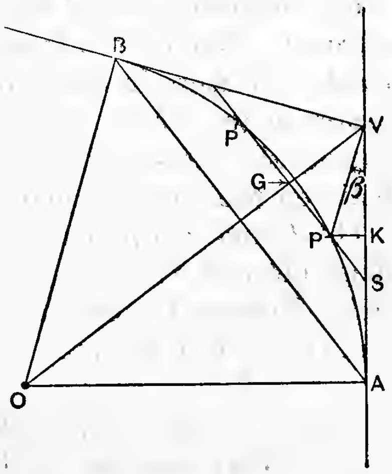


Fig. 28.

$$AS=\sqrt{SP\times SP'}=\sqrt{SP(SP+PP')}$$

$$=\sqrt{VP\frac{\sin\beta}{\sin\frac{1}{2}\Delta}\left[VP\frac{\sin\beta}{\sin\frac{1}{2}\Delta}+2VP\cos\left(\tfrac{1}{2}\Delta+\beta\right)\right]}$$

$$=VP\sqrt{\frac{\sin^2\beta}{\sin^2\frac{1}{2}\Delta}+\frac{2\sin\beta\cos\left(\frac{1}{2}\Delta+\beta\right)}{\sin\frac{1}{2}\Delta}}.$$

$$SV=VP\frac{\sin\left(\frac{1}{2}\Delta+\beta\right)}{\sin\frac{1}{2}\Delta}.$$

$$AV=AS+SV$$

$$=\frac{VP}{\sin\frac{1}{2}\Delta}\left[\sin\left(\tfrac{1}{2}\Delta+\beta\right)+\sqrt{\sin^2\beta+2\sin\beta\sin\tfrac{1}{2}\Delta\cos\left(\tfrac{1}{2}\Delta+\beta\right)}\right]. \quad (18)$$

$$R=AV\cot\tfrac{1}{2}\Delta.$$

In the special case in which P is on the median line OV, $\beta=90°-\frac{1}{2}\Delta$, and $(\frac{1}{2}\Delta+\beta)=90°$. Eq. 18 then reduces to

$$AV=\frac{VP}{\sin\frac{1}{2}\Delta}\left(1+\cos\tfrac{1}{2}\Delta\right)=VP\cot\tfrac{1}{4}\Delta,$$

as might have been immediately derived from Eq. 8.

In case the point P is given by the offset PK and by the distance VK, the triangle PKV may be readily solved, giving the distance VP and the angle β, and the remainder of the solution will be as above.

65. Determination of the curvature of existing track. (a) *Using a transit.* Set up the transit at any point in the center of the track. Measure in each direction 100 feet to points also in the center of the track. Sight on one point with the plates at 0°. Plunge the telescope and sight at the other point. The angle between the chords equals the degree of curvature.

(b) *Using a tape and string.* Stretch a string (say 50 feet long) between two points on the inside of the head of the outer rail. Measure the ordinate (x) between the *middle* of the string and the head of the rail. Then

$$R=\frac{\text{chord}^2}{8x}\text{(very nearly).} \quad . \quad . \quad . \quad . \quad (19)$$

For, in Fig. 29, since the triangles AOE and ADC are similar,

$AO : AE :: AD : DC$ or $R = \frac{1}{2}\overline{AD}^2 \div x$. When, as is usual, the arc is very short compared with the radius, $AD = \frac{1}{2}AB$, very nearly. Making this substitution we have Eq. 19. With a chord of 50 feet and a 10° curve, the resulting difference in x is .0025 of an inch—far within the possible accuracy of such a method. The above method gives the radius of the inner head of the outer rail. It should be diminished by $\frac{1}{2}g$ for the radius of the center of the track. With easy curvature, however, this will not affect the result by more than one or two tenths of one per cent.

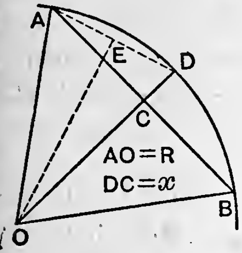


FIG. 29.

The inversion of this formula gives the required middle ordinate for a rail on a given curve. For example, the middle ordinate of a 30-foot rail, bent for a 6° curve, is

$$x = 900 \div (8 \times 955) = .118 \text{ foot} = 1.4 \text{ inches.}$$

Another much used rule is to require the foreman to have a string, knotted at the center, of such length that the middle ordinate, measured in inches, equals the degree of curve. To find that length, substitute (in Eq. 19) $5730 \div D$ for R and $D \div 12$ for x. Solving for *chord*, we obtain *chord* = 61.8 feet. The rule is not theoretically exact, but, considering the uncertain stretching of the string, the error is insignificant. In fact, the distance usually given is 62 feet, which is close enough for all purposes for which such a method should be used.

66. Problems. A systematic method of setting down the solution of a problem simplifies the work. Logarithms should always be used, and *all* the work should be so set down that a revision of the work to find a supposed error may be readily done. The value of such systematic work will become more apparent as the problems become more complicated. The two solutions given below will illustrate such work.

a. Given a 3° curve beginning at Sta. 27 + 60 and running to Sta. 32 + 45. Compute the ordinates and offsets used in locating the curve by tangential offsets.

b. With the same data as above, compute the distances to locate the curve by offsets from the long chord.

c. Assume that in Fig. 22 *ab* is measured as 217.6 feet, the angle $abV = 17° 42'$, and the angle $baV = 21° 14'$. Join the tangents by a 4° 30′ curve. Determine bB and aA.

d. Assume that in a case similar to Fig. 23 it was noted that a distance (As) equal to 12 feet would clear the building. Assume that $\Delta = 38° 20'$ and that $D = 4° 40'$. Required the value of a and the position of n. *Solution:*

vers $a = As \div R$	$As = 12$	log = 1.07918
	R (for 4° 40′ curve)	log = $3.0892\bar{3}$
	$a = 8° 01'$	log vers $a = 7.9899\bar{4}$
$ns = R \sin a$		log sin $a = 9.1444\bar{5}$
		log $R = 3.0892\bar{3}$
	$ns = 171.27$	log = 2.23369

e. Assume that the forward tangent of a 3° 20′ curve having a central angle of 16° 50′ must be moved 3.62 feet *inward*, without altering the $P.C.$ Required the change in radius.

f. Given two tangents making an angle of 36° 18′. It is required to pass a curve through a point 93.2 feet from the vertex, the line from the vertex to the point making an angle of 42° 21′ with the tangent. Required the radius and tangent distance. *Solution:* Applying Eq. 18, we have

	2	log = 0.30103
	$\beta = 42° 21'$	log sin = 9.82844
	$\frac{1}{2}\Delta = 18° 09'$	log sin = $9.4934\bar{6}$
	$(\frac{1}{2}\Delta + \beta) = 60° 30'$	log cos = 9.69234
	.20667	$9.3152\bar{7}$
log $\sin^2 \beta = 9.65688$	.45382	
2|9.81987	.66049	
$9.9099\bar{3}$	.81271	
nat. sin 60° 30′	$.870\bar{3}$	
	$1.683\bar{0}$	log = 0.22610
$VP = 93.2$		log = $1.9694\bar{1}$
		$2.1955\bar{1}$
		log sin $\frac{1}{2}\Delta = 9.4934\bar{6}$
Tang. dist. $AV = 503.36$		log = 2.70205
		log cot $\frac{1}{2}\Delta = 10.48437$
$R = 1536.1$		log = 3.18642
$D = 3° 44'$		

COMPOUND CURVES.

67. **Nature and use.** Compound curves are formed by a succession of two or more simple curves of different curvature. The curves must have a common tangent at the point of compound curvature (*P.C.C.*). In mountainous regions there is frequently a necessity for compound curves having several changes of curvature. Such curves may be located separately as a succession of simple curves, but a combination of two simple curves has special properties which are worth investigating and utilizing. In the following demonstrations R_2 always represents the *longer* radius and R_1 the *shorter*, no matter which succeeds the other. T_1 is the tangent adjacent to the curve of shorter radius (R_1), and is invariably the shorter tangent. Δ_1 is the central angle of the curve of radius R_1, but it may be greater or less than Δ_2

68. **Mutual relations of the parts of a compound curve having two branches.** In Fig. 30, AC and CB are the two branches of

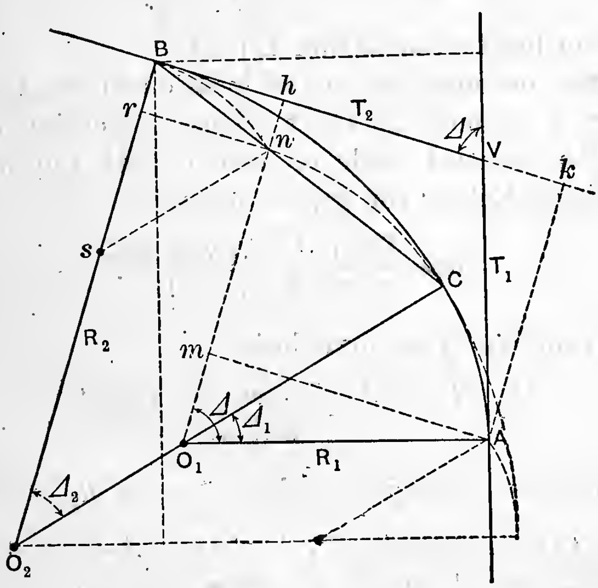


FIG. 30.

the compound curve having radii of R_1 and R_2 and central angles of Δ_1 and Δ_2. Produce the arc AC to n so that $AO_1n = \Delta$. The chord Cn produced *must* intersect B. The line ns, parallel to CO_2, will intersect BO_2 so that $Bs = sn = O_2O_1 = R_2 - R_1$. Draw Am perpendicular to O_1n. It will be parallel to hk.

$$Br = sn \text{ vers } Bsn \quad = (R_2 - R_1) \text{ vers } \Delta_2;$$
$$mn = AO_1 \text{ vers } AO_1n = R_1 \text{ vers } \Delta;$$
$$Ak = AV \sin AVk \quad = T_1 \sin \Delta;$$
$$Ak = hm = mn + nh = mn + Br.$$
$$\therefore \; T_1 \sin \Delta = R_1 \text{ vers } \Delta + (R_2 - R_1) \text{ vers } \Delta_2. \quad . \quad . \quad (20)$$

Similarly it may be shown that

$$T_2 \sin \Delta = R_2 \text{ vers } \Delta - (R_2 - R_1) \text{ vers } \Delta_1. \quad . \quad . \quad (21)$$

The mutual relations of the elements of compound curves may be solved by these two equations. For example, assume the tangents as fixed (Δ therefore known) and that a curve of given radius R_1 shall start from a given point at a distance T_1 from the vertex, and that the curve shall continue through a given angle Δ_1. Required the other parts of the curve. From Eq. 20 we have

$$R_2 - R_1 = \frac{T_1 \sin \Delta - R_1 \text{ vers } \Delta}{\text{vers } \Delta_2}.$$

$$\therefore \; R_2 = R_1 + \frac{T_1 \sin \Delta - R_1 \text{ vers } \Delta}{\text{vers } (\Delta - \Delta_1)}. \quad . \quad . \quad . \quad . \quad . \quad (22)$$

T_2 may then be obtained from Eq. 21.

As another problem, given the location of the two tangents, with the two tangent distances (thereby locating the *PC* and *PT*), and the central angle of each curve; required the two radii. Solving Eq. 20 for R_1, we have

$$R_1 = \frac{T_1 \sin \Delta - R_2 \text{ vers } \Delta_2}{\text{vers } \Delta - \text{vers } \Delta_2}.$$

Similarly from Eq. 21 we may derive

$$R_1 = \frac{T_2 \sin \Delta - R_2(\text{vers } \Delta - \text{vers } \Delta_1)}{\text{vers } \Delta_1}.$$

Equating these, reducing, and solving for R_2, we have

$$R_2 = \frac{T_1 \sin \Delta \text{ vers } \Delta_1 - T_2 \sin \Delta \text{ (vers } \Delta - \text{vers } \Delta_2)}{\text{vers } \Delta_2 \text{ vers } \Delta_1 - (\text{vers } \Delta - \text{vers } \Delta_1)(\text{vers } \Delta - \text{vers } \Delta_2)}. \quad (23)$$

Although the various elements may be chosen as above with considerable freedom, there are limitations. For example, in Eq. 22, since R_2 is always greater than R_1, the term to be added to R_1 must be essentially positive—i.e., $T_1 \sin \Delta$ must be greater than R_1 vers Δ. This means that $T_1 > R_1 \frac{\text{vers } \Delta}{\sin \Delta}$, or that

$T_1 > R_1 \tan \frac{1}{2}\Delta$, or that T_1 is greater than the corresponding tangent on a simple curve. Similarly it may be shown that T_2 is *less* than $R_2 \tan \frac{1}{2}\Delta$ or *less* than the corresponding tangent on a simple curve. Nevertheless T_2 is always greater than T_1. In the limiting case when $R_2 = R_1$, $T_2 = T_1$, and $\Delta_2 = \Delta_1$.

69. Modifications of location. Some of these modifications may be solved by the methods used for simple curves. For example:

a. It is desired to move the tangent VB, Fig. 31, parallel to itself to $V'B'$. Run a new curve from the $P.C.C.$ which shall reach the new tangent at B', where the chord of the old curve

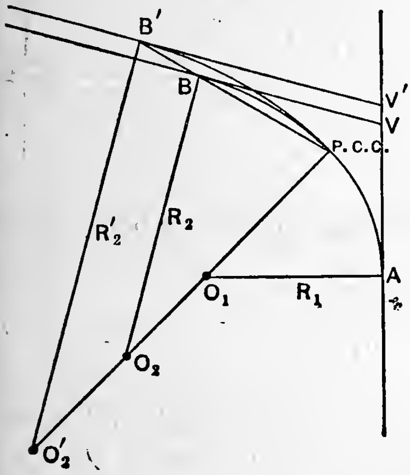


FIG. 31.

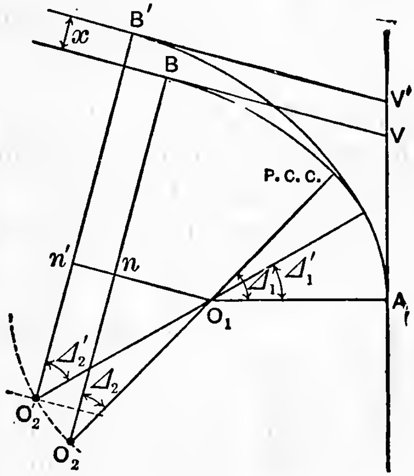


FIG. 32.

intersects the new tangent. The solution is almost identical with that in § 63, *a*.

b. Assume that it is desired to change the forward tangent (as above) but to retain the same radius. In Fig. 32

$$(R_2 - R_1) \cos \Delta_2 = O_2 n;$$
$$(R_2 - R_1) \cos \Delta_2' = O_2' n'.$$
$$x = O_2 n - O_2' n' = (R_2 - R_1)(\cos \Delta_2 - \cos \Delta_2').$$

$$\cos \Delta_2' = \cos \Delta_2 - \frac{x}{R_2 - R_1} \quad \text{. . . . . . .} \quad (24)$$

The $P.C.C.$ is moved *backward* along the sharper curve an angular distance of $\Delta_2' - \Delta_2 = \Delta_1 - \Delta_1'$.

In case the tangent is moved inward rather than outward, the solution will apply by transposing Δ_2 and Δ_2'. Then we shall have

$$\cos \Delta_2' = \cos \Delta_2 + \frac{x}{R_2 - R_1} \quad \text{. . . . . . .} \quad (25)$$

The *P.C.C.* is then moved *forward.*

c. Assume the same case as (**b**) except that the larger radius comes first and that the tangent adjacent to the smaller radius is moved. In Fig. 33

$$(R_2-R_1)\cos \Delta_1 = O_1n;$$

$$(R_2-R_1)\cos \Delta_1' = O_1'n'.$$

$$x = O_1'n' - O_1n$$
$$= (R_2-R_1)(\cos \Delta_1' - \cos \Delta_1).$$

$$\cos \Delta_1' = \cos \Delta_1 + \frac{x}{R_2-R_1}. \qquad (26)$$

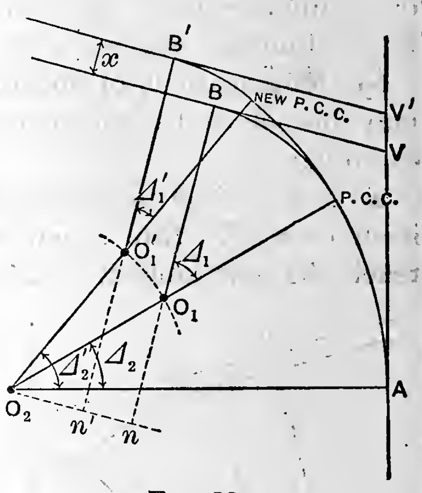


FIG. 33.

The *P.C.C.* is moved *forward* along the easier curve an angular distance of $\Delta_1' - \Delta_1 = \Delta_2 - \Delta_2'$.

In case the tangent is moved *inward*, transpose as before and we have

$$\cos \Delta_1' = \cos \Delta_1 - \frac{x}{R_2-R_1}. \quad . \quad . \quad . \quad . \quad . \quad (27)$$

The *P.C.C.* is moved *backward*

d. Assume that the radius of one curve is to be altered without changing either tangent. Assume conditions as in Fig. 34. For the diagrammatic solution assume that R_2 is to be increased by O_2S. Then, since R_2' must pass through O_1 and extend beyond O_1 a distance O_1S, the locus of the new center must lie on the arc drawn about O_1 as center and with O_1S as radius. The locus of O_2' is also given by a line $O_2'p$ parallel to BV and at a distance of R_2' (equal to $S \ldots P.C.C.$) from it. The new center is therefore at the intersection O_2'. An arc with radius R_2' will therefore be tangent at B' and tangent to the old curve *produced* at NEW *P.C.C.* Draw O_1n' perpendicular to O_2B.

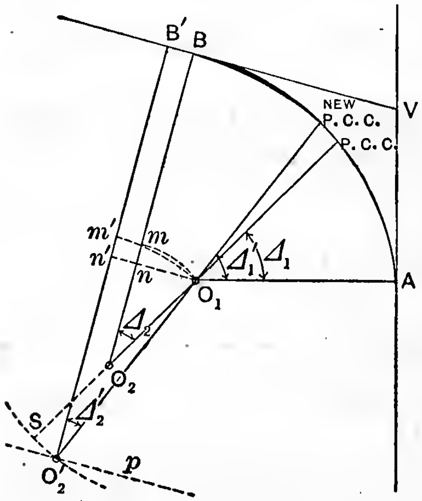


FIG. 34.

With O_2 as center draw the arc O_1m, and with O_2' as center draw the arc O_1m'. $mB = m'B' = R_1$.

$$\therefore\ mn = m'n' = (R_2' - R_1) \text{ vers } \Delta_2' = (R_2 - R_1) \text{ vers } \Delta_2.$$

$$\therefore\ \text{vers } \Delta_2' = \frac{(R_2 - R_1)}{(R_2' - R_1)} \text{ vers } \Delta_2. \quad . \quad . \quad . \quad . \quad (28)$$

$$O_1n = (R_2 - R_1) \sin \Delta_2;$$

$$O_1n' = (R_2' - R_1) \sin \Delta_2'.$$

$$BB' = O_1n' - O_1n = (R_2' - R_1) \sin \Delta_2' - (R_2 - R_1) \sin \Delta_2. \quad (29)$$

This problem may be further modified by assuming that the radius of the curve is decreased rather than increased, or that the smaller radius follows the larger. The solution is similar and is suggested as a profitable exercise.

It might also be assumed that, instead of making a given change in the radius R_2, a given change BB' is to be made. Δ_2' and R_2' are required. Eliminate R_2' from Eqs. 28 and 29 and solve the resulting equation for Δ_2'. Then determine R_2' by a suitable inversion of either Eq. 28 or 29.

As in §§ 62 and 63, the above problems are but a few, although perhaps the most common, of the problems the engineer may meet with in compound curves. All of the ordinary problems may be solved by these and similar methods.

70. Problems. *a.* Assume that the two tangents of a compound curve are to be 348 feet and 624 feet, and that $\Delta_1 = 22° 16'$ and $\Delta_2 = 28° 20'$. Required the radii.

[*Ans.* $R_1 = 326.92$; $R_2 = 1574.85$.]

b. A line crosses a valley by a compound curve which is first a 6° curve for 46° 30′ and then a 9° 30′ curve for 84° 16′. It is afterward decided that the last tangent should be 6 feet farther up the hill. What are the required changes? [*Note.* The second tangent is evidently moved *outward.* The solution corresponds to that in the first part of § 69, *c.* The *P.C.C.* is moved forward 16.39 feet. If it is desired to know how far the *P.T.* is moved in the direction of the tangent (i.e., the *projection* of BB', Fig. 33, on $V'B'$), it may be found by observing that it is equal to $nn' = (R_2 - R_1)(\sin \Delta_1 - \sin \Delta_1')$. In this case it equals 0.65 foot, which is very small because Δ_1 is nearly 90°. The value of Δ_2 (46° 30′) is not used, since the solution is independent of the value of Δ_2. The student should learn to recognize which quantities are mutually related and therefore essential to a solution, and which are independent and non-essential.

TRANSITION CURVES.

71. Superelevation of the outer rail on curves. When a mass is moved in a circular path it requires a centripetal force to keep it moving in that path. By the principles of mechanics we know that this force equals $Gv^2 \div gR$, in which G is the weight, v the velocity in feet per second, g the acceleration of gravity in feet per second in a second, and R the radius of curvature. If the two rails of a curved track were laid on a level (transversely), this centripetal force could only be furnished by the pressure of the wheel-flanges against the rails. As this is very objectionable; the outer rail is elevated so that the reaction of the rails against the wheels shall contain a horizontal component equal to the required centripetal force. In Fig. 35, if ob represents the reaction, oc will represent the weight G, and ao will represent the required centripetal force. From similar triangles we may write $sn : sm :: ao : oc$. Call $g = 32.17$. Call $R = 5730 \div D$, which is sufficiently accurate for this purpose (see § 46). Call $v = 5280V \div 3600$, in which V is the velocity in miles per hour. mn is the distance between rail centers, which, for an 80-lb. rail and standard gauge, is 4.916 feet sm is slightly less than this. As an average value we may call it 4.900, which is its exact value when the superelevation is $4\frac{3}{4}$ inches. Calling $sn = e$, measured in feet, we have

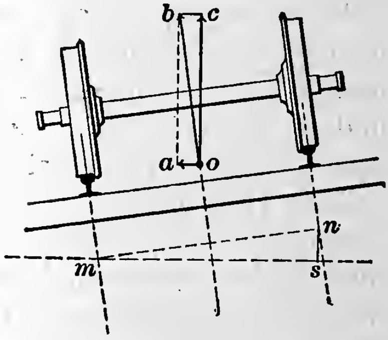


FIG. 35.

$$e = sm\frac{ao}{oc} = 4.9\frac{Gv^2}{gR}\frac{1}{G} = \frac{4.9 \times 5280^2 V^2 D}{32.17 \times 3600^2 \times 5730}.$$

$$e = .0000572V^2D. \qquad (30)$$

It should be noticed that, according to this formula, the required superelevation varies as the *square* of the velocity, which means that a change of velocity of only 10% would call for a change of superelevation of 21%. Since the velocities of trains over any road are extremely variable, it is impossible to adopt any superelevation which will fit all velocities even approximately. The above fact also shows why any over-refinement in the calculations is useless and why the above approximations, which are really small, are amply justifiable. For example, the above formula contains the approximation that $R = 5730 \div D$. In the extreme case of a 10° curve the error involved would be about 1%. A change of about ½ of 1% in the velocity, or say from 40 to 40.2 miles per hour, would mean as much. The error in e due to the assumed constant value of sm is never more than a very small fraction of 1%. The rail-laying is not done closer than this. Table XIX is based on Eq. (30):

TABLE XIX. SUPERELEVATION OF THE OUTER RAIL (IN FEET) FOR VARIOUS VELOCITIES AND DEGREES OF CURVATURE.

Velocity in Miles per Hour.	Degree of Curve.									
	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°
30	.05	.10	.15	.20	.26	.31	.36	.41	.46	.51
40	.09	.18	.27	.37	.46	.55	.64	.73	.82	.92
50	.14	.29	.43	.57	.71	.86	1.00	1.14	1.29	
60	.20	.41	.62	.82	1.03					

72. Practical rules for superelevation. A much used rule for superelevation is to "elevate one half an inch for each degree of curvature." The rule is rational in that e in Eq. 30 varies directly as D. The above rule therefore agrees with Eq. 30 when V is about 27 miles per hour. However applicable the rule may have been in the days of low velocities, the elevation thus computed is too small now. The rule to elevate one inch for each degree of curvature is also used and is precisely similar in its nature to the above rule. It agrees with Eq. 30 when the velocity is about 38 miles per hour, which is more nearly the average speed of trains.

Another (and better) rule is to "elevate for the speed of the fastest trains." This rule is further justified by the fact that a four-wheeled truck, having two parallel axles, will always tend to run to the outer rail and will require considerable flange pressure to guide it along the curve. The effect of an excess of superelevation on the slower trains will only be to relieve this flange pressure somewhat. This rule is coupled with the limitation that the elevation should never exceed a limit of six inches—sometimes eight inches. This limitation implies that locomotive engineers must reduce the speed of fast trains around sharp curves until the speed does not exceed that for which the actual superelevation used is suitable. The heavy line in Table XIX shows the six-inch limitation.

Some roads furnish their track foremen with a list of the superelevations to be used on each curve in their sections. This method has the advantage that each location may be separately studied, and the proper velocity, as affected by local conditions (*e.g.*, proximity to a stopping-place for all trains), may be determined and applied.

Another method is to allow the foremen to determine the superelevation for each curve by a simple measurement taken at the curve. The rule is developed as follows: By an inversion of Eq. 19 we have

$$x = chord^2 \div 8R. \quad \ldots \ldots \ldots \quad (31)$$

Putting x equal to e in Eq. 30 and solving for "*chord*," we have

$$chord^2 = .0000572V^2D \times 8R$$
$$= 2.621V^2.$$
$$chord = 1.62V. \quad \ldots \ldots \ldots \ldots \quad (32)$$

To apply the rule, assume that 50 miles per hour is fixed as the velocity from which the superelevation is to be computed. Then $1.62V = 1.62 \times 50 = 81$ feet, which is the distance given to the trackmen. Stretch a tape (or even a string) with a length of 81 feet between two points on the concave side of the head of either the inner or the outer rail. The ordinate at the middle point then equals the superelevation. The values of this chord length for varying velocities are given in the accompanying tabular form.

Velocity in miles per hour...	20	25	30	35	40	45	50	55	60
Chord length in feet.......	32.4	40.5	48.6	56.7	64.8	72.9	81.0	89.1	97.2

The following tabular form shows the standard (at one time) on the N. Y., N. H. & H. R. R. It should be noted that the elevations do not increase proportionately with the radius, and that they are higher for descending grades than for level or ascending grades. This is on the basis that the velocity on curves and on ascending grades will be less than on descending grades. For example, the superelevation for a 0° 30′ curve on a descending grade corresponds to a velocity of about 54 miles per hour, while for a 4° curve on a level or ascending grade the superelevation corresponds to a velocity of only about 38 miles per hour.

TABLE OF THE SUPERELEVATION OF THE OUTER RAIL ON CURVES.

N. Y., N. H. & H. R. R.

Degree of curve.	Level or ascending grade.	Descending grade.
	inches.	inches.
0° 30′	$0\frac{3}{4}$	1
1 00	$1\frac{1}{2}$	$1\frac{3}{4}$
1 15	$1\frac{3}{4}$	2
1 30	2	$2\frac{1}{4}$
1 45	$2\frac{1}{4}$	$2\frac{1}{2}$
2 00	$2\frac{3}{8}$	$2\frac{3}{4}$
2 15	$2\frac{5}{8}$	3
2 30	$2\frac{7}{8}$	$3\frac{1}{4}$
2 45	3	$3\frac{3}{8}$
3 00	$3\frac{1}{8}$	$3\frac{5}{8}$
3 15	$3\frac{3}{8}$	$3\frac{7}{8}$
3 30	$3\frac{5}{8}$	4
3 45	$3\frac{7}{8}$	$4\frac{1}{8}$
4 00	4	$4\frac{1}{2}$

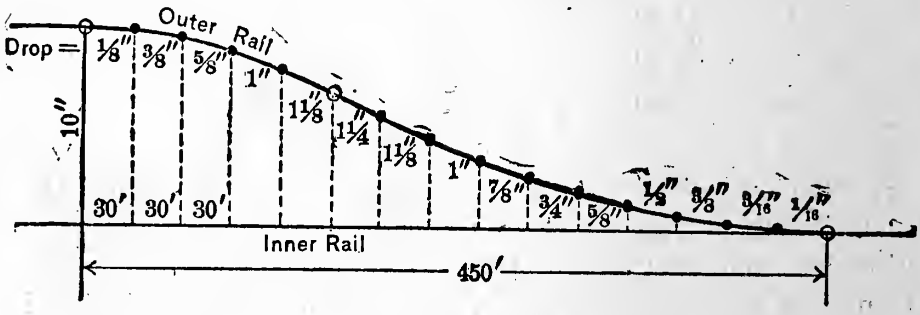
73. **Transition from level to inclined track.** On curves the track is inclined transversely; on tangents it is level. The transition from one condition to the other must be made gradually. If there is no transition curve, there must be either inclined track on the tangent or insufficiently inclined track on the curve or both. Sometimes the full superelevation is continued through the total length of the curve and the "run-off" (having a length of 100 to 400 feet) is located entirely on the tangents at each end. In other practice it is located partly on the tangent and partly on the curve. Whatever the method, the superelevation is correct at only one point of the run-off. At all other points it is too great or too small. This (and other causes) produces objectionable lurches and resistances when entering and leaving curves. The object of transition curves is to obviate these resistances.

On the Lehigh Valley R. R. the run-off is made in the form of a reversed vertical curve, as shown in the accompanying figure. According to this system the length of run-off varies from 120 feet, for a superelevation of one inch, to 450 feet, for a superelevation of ten inches. Such a superelevation as ten inches is very unusual practice, but is successfully operated on that road. The curve is concave upward for two-thirds of its length and then reverses so that it is convex upward.

TABLE FOR RUN-OFF OF ELEVATION OF OUTER RAIL OF CURVES.

Drop in inches for each 30-foot rail commencing at theoretical point of curve.

Elevation.	$\frac{1}{8}''$	$\frac{1}{4}''$	$\frac{3}{8}''$	$\frac{1}{2}''$	$\frac{5}{8}''$	$\frac{3}{4}''$	$\frac{7}{8}''$	1″	$1\frac{1}{8}''$	$1\frac{1}{4}''$	$1\frac{1}{8}''$	1″	$\frac{7}{8}''$	$\frac{3}{4}''$	$\frac{5}{8}''$	$\frac{1}{2}''$	$\frac{3}{8}''$	$\frac{1}{4}''$	$\frac{3}{16}''$	$\frac{1}{8}''$	$\frac{1}{16}''$	Total.
1″	..	30	30	..	..	..	..	..	...	...	...	..	..	..	..	..	..	30	...	30	...	120
2″	..	30	..	..	..	30	..	..	...	...	...	..	..	..	..	30	30	..	...	30	...	150
3″	..	30	..	..	..	30	..	..	...	...	...	..	30	..	30	..	30	..	...	30	...	180
4″	..	30	..	30	..	..	30	..	...	...	...	..	30	..	30	30	..	30	...	30	...	240
5″	..	30	..	30	..	..	..	30	...	...	...	30	..	30	30	30	..	30	...	30	...	270
6″	..	30	..	30	..	..	30	..	30	...	...	30	..	30	30	30	..	30	...	30	...	300
7″	..	30	..	30	..	..	30	..	30	...	30	30	..	30	30	..	30	30	...	30	...	330
8″	..	30	..	30	..	30	..	..	30	30	30	30	..	30	30	..	30	..	30	..	30	360
9″	30	..	..	30	..	30	..	30	30	...	30	30	30	30	30	30	30	..	30	..	30	420
10″	30	..	30	..	30	..	..	30	30	30	30	30	30	30	30	30	30	..	30	..	30	450



The figure (and also the lower line of the tabulated form) shows the drop for each thirty-foot rail length. For shorter lengths of run-off, the drop for each 30 feet is shown by the corresponding lines in the tabular form. Note in each horizontal line that the sum of the drops, under which 30 is found, equals the total superelevation as found in the first column. For example, for 4 inches superelevation, length of curve 240 feet, the successive drops are $\frac{1}{4}''$, $\frac{1}{2}''$, $\frac{7}{8}''$, $\frac{7}{8}''$, $\frac{5}{8}''$, $\frac{1}{2}''$, $\frac{1}{4}''$, and $\frac{1}{8}''$ whose sum is 4 inches. Possibly the more convenient form would be to indicate for each 30-foot point the actual superelevation of the outer rail, which would be for the above case (running from the tangent to the curve) $\frac{1}{8}''$, $\frac{3}{8}''$, $\frac{7}{8}''$, $1\frac{1}{2}''$, $2\frac{3}{8}''$, $3\frac{1}{4}''$, $3\frac{3}{4}''$, 4″.

74. Fundamental principle of transition curves. If a curve has variable curvature, beginning at the tangent with a curve of infinite radius, and the curvature gradually sharpens until it equals the curvature of the required simple curve and there becomes tangent to it, the superelevation of such a transition curve may begin at zero at the tangent, gradually increase to the required superelevation for the simple curve, and yet have at every point the superelevation required by the curvature at that point. Since in Eq. (30) e is directly proportional to D, the required curve must be one in which the degree of curve increases directly as the distance along the curve.

75. Varieties of Transition Curves. A theoretically exact transition curve is very complicated and its mathematical solution very difficult. A committee of the Amer. Rwy. Eng. Assoc. investigated the many systems which have been proposed and reported that all of them seemed to be objectionable for one or more of the following reasons: "(1) If simple approximate formulas were used, they were not sufficiently accurate. (2) Accurate formulas were too complex. (3) The curve could not be expressed by formulas. (4) Formulas were of the endless series class. (5) Complex field methods were required to make the field-work agree with formulas with spirals of large angles." The committee then developed a method which gives results whose accuracy is beyond that of the most careful field-work and yet which is sufficiently simple for practical use. The mathematical development is so elaborate that it will not be detailed here, but the working formulas and a condensation of the table together with an explanation of their practical use and application, will be given, with numerical examples.

The general form of these curves, whatever their precise mathematical character, is shown in Fig. 36. AVB are two tangents, joined by the simple circular curve AMB, having the center O. Assume that the entire curve is moved in the direction MO a distance $OO' = MM' = BB' = AA'$. At some point TS on the tangent, the spiral begins and joins the circular curve tangentially at SC. The other spiral runs from CS to ST. The significance of these symbols may be readily remembered from the letters; T, S, and C signify tangent, spiral and circular curve; TS is the point of change from tangent to spiral, SC, the point of change from spiral to curve, etc. At the other end of the circular curve the letters are in reverse order, the station numbers increasing from A to B. The meaning of the various symbols is indicated in Fig. 36. The student should appreciate the fact of the necessary distortion of the figure in order to make it plain. Based on the figures of the following numerical problem, the distance MM' is about fourteen times its proper amount. Another effect of the distortion is that the dimension U, instead of being

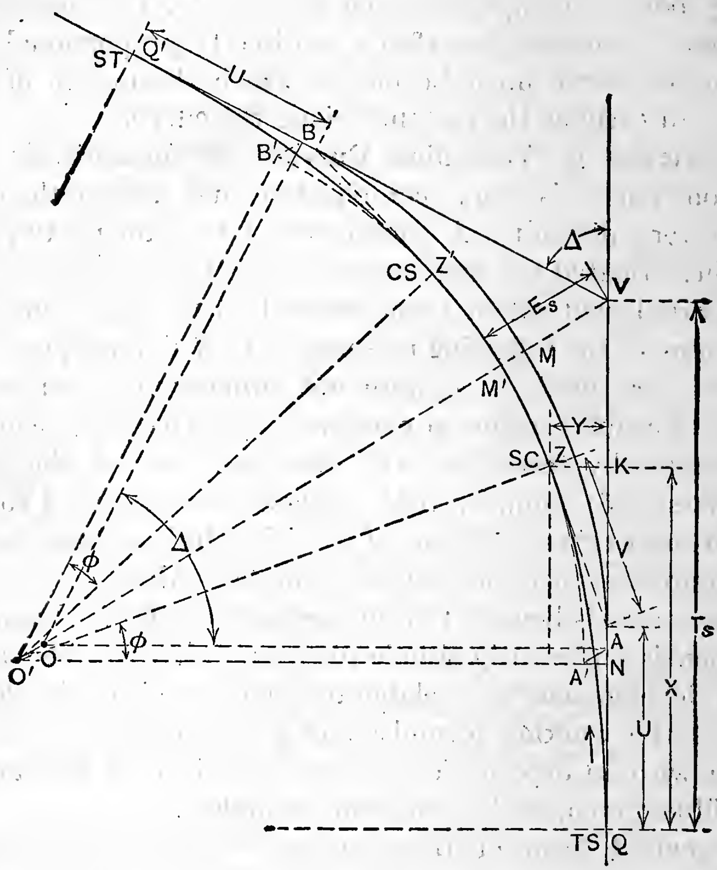


FIG. 36.

nearly twice V, which is usual, as given in Table IV, Part B, is only a little longer than V.

76. Proper length of spiral. This can only be computed on the basis of certain assumptions as to the desired rate of tipping the car, so as to avoid discomfort to passengers, and, of course, this depends on the expected velocity. There is also a maximum limitation, since the sum of the two spiral angles cannot exceed the total central angle of the curve. The *minimum* lengths recommended are as follows:

On curves which limit the speed:

6° and over, 240 feet;

Less than 6°, $5\frac{1}{3}\times$speed in m.p.h. for elevation of 8 inches.

On curves which do not limit the speed:

30 times elevation in inches, or

$\frac{2}{3}\times$ultimate speed in m.p.h.$\times$elevation in inches.

For example. (1) 5° curve which limits speed; speed limit 48 m.p.h. by interpolation in table, § 71; $48\times5\frac{1}{3}=256$ feet minimum length. (2) 3° curve; maximum operating speed 60 m.p.h.; superelevation, .62 feet = 7.44 inches; $30\times7.44=223.2$ feet; or, $\frac{2}{3}\times60\times7.44=297.6$ feet. Of course the higher value should be used, or say 300 feet as the minimum length.

While it is generally true that the longer transition curves give easier riding, the spiral must not reach the center point of the curve. Since it is approximately true that the spiral extends for equal distances on each side of the original point of curve, it is nearly true that two spirals, each having the same length as the original curve, would just meet at the center. The length of a spiral should in general be very much less than the length of the original curve.

77. Symbols. Beside the symbols whose significance is clearly indicated in Fig. 36, the following are defined:

- a The angle between the tangent at the TS and the chord from the TS to *any* point on the spiral; a_1 is the angle to the *first* chord point.
- A The angle between the tangent at the TS and the chord from the TS to the SC.
- D The degree of the central circular curve.
- Δ The central angle of the original circular curve, or the angle between the tangents.
- ϕ The total central angle of the spiral.
- k The increase in degree of curve per station on the spiral.
- L The length of the spiral in feet from the TS to the SC.
- S The length of the spiral in stations from the TS to the SC.
- s The length of the spiral in stations from the TS to any given point.

78. Deflections. The field formulas for deflections are based on the following two equations:

$$a = 10\,ks^2 \text{ minutes},$$

$$A = 10\,kS^2 \text{ minutes}.$$

The first deflection $a_1 = 10\,ks_1^2$ minutes. But k is the increase in degree of curve per station, and since the degree of curve increases as the length, $k = D \div S$, S being expressed in stations. For point 1, since $S = 10s$, $a_1 = 10\left(\frac{D}{10s_1}\right)s_1^2 = Ds_1$, which may be expressed as the degree of the curves times the length of the chord in stations. For example, if the spiral is 400 feet long (which means that $L = 400$ and $S = 4$) and runs on to a 5° curve (then $D = 5$), one chord is 40 feet long and $s = .4$ station. Then $a_1 = 5 \times 0.4 = 2$ minutes of arc for the deflection for the first chord point. And since the deflections are as the square of the number of stations, the deflections from TS to succeeding stations will be 4, 9, 16, 25, 36, 49, 64, 81, and 100 times 2 minutes, these factors being those given in the second vertical column of Part A of Table IV. The last deflection $= A = 100 \times 2' = 200' = 3°\ 20' = \frac{1}{3}\ (10°) = \frac{1}{3}\phi$, ϕ being the total central angle of the spiral. Although it is always nearly true that $A = \frac{1}{3}\phi$, and the error is inappreciable for small angles, the error amounts to 30 seconds of arc when $\phi = 21°\ 30'$, an unusually large angle.

The deflection from any other point of the spiral to any other point, either forward or backward, may be found by multiplying the value of a_1 (in this case 2′), by the coefficients in the proper vertical column of that table.

The spiral angle

$$\phi = \frac{kS^2}{2} = \frac{kL^2}{20000} = \frac{DL}{200} = \frac{5 \times 400}{200} = 10°.$$

Also,

$$\phi = \frac{kS^2}{2} = \frac{DS}{2} = \frac{5 \times 4}{2} = 10°$$

The values of the ratios $U \div L$ and $V \div L$ for even degrees, and for A, $C \div L$, $X \div L$, and $Y \div L$ for half degrees are given in Parts B and C of Table IV. When it is desired to temporarily omit locating the intermediate points of the spiral, the jump from the TS to the SC may be made by measuring the distance U from the TS along the tangent. At that point a deflection ϕ and a measured distance V will give not only the position of SC but also the direction of the tangent at the beginning of the circular curve. Another method of locating the SC without locating the intermediate points is to make the deflection A at the TS

and measure the long chord C. In the above numerical problem this equals $400 \times .998664 = 399.47$, a little over 6 inches short of the full 400 feet. By setting up the transit at the SC, backsighting at the TS, and turning off the angle $(\phi - A)$, which in the above case is $10° - 3° 19' 57'' = 6° 20' 03''$, the direction of the tangent at the SC is obtained. In this case, the three seconds variation from the approximate value is utterly negligible. The other dimensions are easily determined from the tables if desired;

$$X = .996975 \times 400 = 398.79,$$

$$Y = .058053 \times 400 = 23.22,$$

$$U = .667742 \times 400 = 267.10$$

$$V = .334313 \times 400 = 133.73.$$

For greater convenience of notation, the points TS, SC, CS, and ST, in Fig. 36 are also indicated by the letters Q, Z, Z' and Q' respectively. The same letters are used for the corresponding points in Figs. 37 and 38.

79. Location of spirals and circular curve with respect to tangents. See Fig. 36. Let AV and BV be the tangents to be connected by a $D°$ curve, having a suitable spiral at each end. If no spirals were to be used, the problem would be solved as in simple curves giving the curve AMB. Introducing the spiral has the effect of throwing the curve away from the vertex a distance MM' and reducing the central angle of the $D°$ curve by 2ϕ. Continuing the curve beyond Z and Z' to A' and B', we will have $AA' = BB' = MM'$. $ZK =$ the Y ordinate and is therefore known. Call $MM' = m$. $A'N = Y - R \text{ vers } \phi$. Then

$$m = MM' = AA' = \frac{A'N}{\cos \frac{1}{2}\Delta} = \frac{Y - R \text{ vers } \phi}{\cos \frac{1}{2}\Delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

$$NA = AA' \sin \tfrac{1}{2}\Delta = (Y - R \text{ vers } \phi) \tan \tfrac{1}{2}\Delta.$$

$$\begin{aligned} VQ &= QK - KN + NA + AV \\ &= X - R \sin \phi + (Y - R \text{ vers } \phi) \tan \tfrac{1}{2}\Delta + R \tan \tfrac{1}{2}\Delta \\ &= X - R \sin \phi + Y \tan \tfrac{1}{2}\Delta + R \cos \phi \tan \tfrac{1}{2}\Delta. \quad . \quad . \quad . \quad . \quad (34) \end{aligned}$$

When $A'N$ has already been computed, it may be more convenient to write

$$VQ = X + R (\tan \tfrac{1}{2}\Delta - \sin \phi) + A'N \tan \tfrac{1}{2}\Delta. \quad . \quad . \quad . \quad . \quad (35)$$

$$VM' = VM + MM'$$

$$= R \text{ exsec } \tfrac{1}{2}\Delta + \frac{Y}{\cos \frac{1}{2}\Delta} - \frac{R \text{ vers } \phi}{\cos \frac{1}{2}\Delta}. \qquad (36)$$

$$AQ = VQ - AV$$

$$= X - R \sin \phi + (Y - R \text{ vers } \phi) \tan \tfrac{1}{2}\Delta. \qquad (37)$$

Example. To join two tangents making an angle of 34° 20′ by a 5° 40′ curve and suitable spirals. Assume that the spiral is 300 feet long. Then

$$\phi = \frac{DS}{2} = \frac{5.67 \times 3}{2} = 8.5° = 8° \ 30'.$$

Since, from Table IV, Part A, $Y \div L = .049374$ for $\phi = 8° \ 30'$, $Y = 14.812$; similarly, we find $X = 299.344$ and $C = 299.71$.

[Eq. 33]			R	3.00497
			vers ϕ	8.04076
		11.110		1.04573
		Y = 14.812		
		$A'N$ = 3.702		0.56843
			cos $\frac{1}{2}\Delta$	9.98021
		$m = MM' = AA'$ = 3.875		0.58822
[Eq. 36]			R	3.00497
			exsec $\frac{1}{2}\Delta$	8.66863
		VM = 47.164		1.67360
		m = 3.875		
		VM' = 51.039		
[Eq. 35]	X = 299.344	nat. tan $\frac{1}{2}\Delta$ = .30891		
		nat. sin ϕ = .14781		
		.16110		9.20709
			R	3.00497
	162.954			2.21206
		[See above]	$A'N$	0.56843
			tan $\frac{1}{2}\Delta$	9.48984
	1.144		AN	0.05827
	VQ = 463.442			
[Eq. 37]			R	3.00497
			tan $\frac{1}{2}\Delta$	9.48984
	312.471		AV	2.49481
	AQ = 150.971			

It should be noted that AQ is within a foot of equaling one-half the length of the spiral, which illustrates the general fact that a spiral begins at approximately one-half its length from the P.C. of the simple curve. All approximate systems of spirals assume this to be exactly true.

80. Field-work. When the spiral is designed during the original location, the tangent distance VQ should be computed and the point Q located. It is hardly necessary to locate all of the points of the spiral until the track is to be laid. The extremities should be located, and as there will usually be two or more full station points on the spiral, these should also be located. Z may be located by setting off $QK=X$ and $KZ=Y$, or else by the tabular deflection for Z from Q and the distance ZQ, which is the long chord c. Setting up the instrument at Z and sighting back at Q with the proper deflection, the tangent at Z may be found and the circular curve located as usual, its central angle being $\Delta-2\phi$. A similar operation will locate Q' from Z'.

To locate points on the spiral. Set up at Q, with the plates reading 0° when the telescope sights along VQ. Set off from Q the deflections computed from Table IV for the instrument at Q, using a chord length of $L\div10$, the process being like the method for simple curves except that the deflections are variable. If a full station-point occurs within the spiral, interpolate between the deflections for the adjacent spiral-points. For example, a 400-foot spiral running on to a 3° 31′ curve begins at Sta. 56+15. The spiral points are 40 feet apart. Sta. 57 comes 5 feet beyond the second spiral point. The first deflection $a_1 = Ds = 3.5\times.4 = 1.4$ min. The deflection to point 2 is $4\times1.4 = 5.6$ min. and that to point 3 is $9\times1.4=12.6$ min. Then the deflection to Sta. 57 is $\frac{5}{40}\times(12.6-5.6)+5.6=6.47$ min.

This method is not theoretically accurate, but the error is small. Arriving at Z, the forward alinement may be obtained by sighting back at Q (or at any other point) with the proper deflection for that point from the station occupied. Then when the plates read 0° the telescope will be tangent to the spiral and to the succeeding curve. All rear points should be checked from Z. If it is necessary to occupy an intermediate station, use the deflections given for that station, orienting as just explained for Z, checking the back points and locating all forward points up to Z if possible.

After the center curve has been located and Z' is reached, the other spiral must be located but *in reverse order*, i.e., the sharp curvature of the spiral is at Z' and the curvature decreases toward Q'.

81. To replace a simple curve by a curve with spirals. This *may* be done by the method of § 79, but it involves shifting the whole track a distance m, which in the given example equals 3.87 feet. Besides this the track is appreciably shortened,

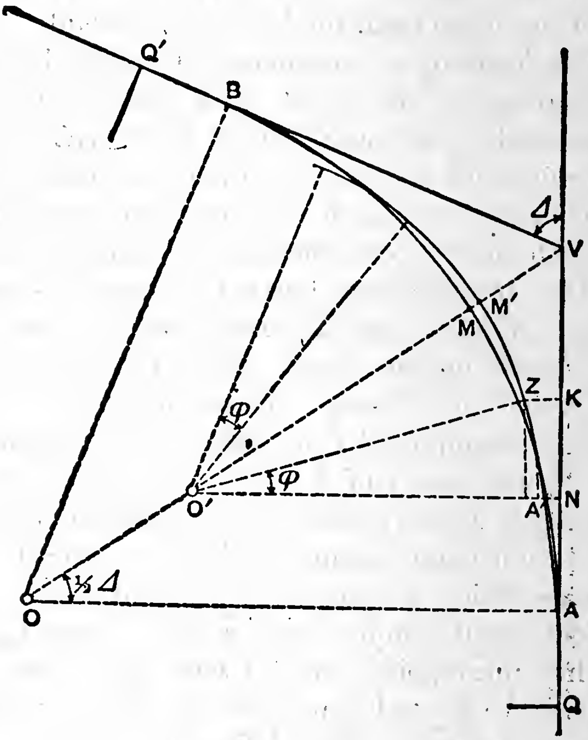


Fig. 37.

which would require rail-cutting. But the track may be kept at practically the same length and the lateral deviation from the old track may be made very small by slightly sharpening the curvature of the old track, moving the new curve so that it is wholly or partially *outside* of the old curve, the remainder of it with the spirals being *inside* of the old curve. It is found by experience that a decrease in radius of from 5% to 10% will answer the purpose. The larger the central angle the less the change. The solution is as indicated in Fig. 37.

$$O'N = R' \cos \phi + Y.$$
$$O'V = O'N \sec \tfrac{1}{2}\Delta$$
$$= R' \cos \phi \sec \tfrac{1}{2}\Delta + Y \sec \tfrac{1}{2}\Delta.$$

$$m = MM' = MV - M'V$$
$$= R \text{ exsec } \tfrac{1}{2}\Delta - (O'V - R')$$
$$= R \text{ exsec } \tfrac{1}{2}\Delta - R' \cos\phi \sec \tfrac{1}{2}\Delta - Y \sec \tfrac{1}{2}\Delta + R'. \quad . \quad . \quad (38)$$

$$AQ = QK - KN + NV - VA$$
$$= X - R' \sin\phi + (R' \cos\phi + Y) \tan \tfrac{1}{2}\Delta - R \tan \tfrac{1}{2}\Delta$$
$$= X - R' \sin\phi + R' \cos\phi \tan \tfrac{1}{2}\Delta - (R - Y) \tan \tfrac{1}{2}\Delta. \quad . \quad . \quad (39)$$

The length of the old curve from Q to $Q' = 2AQ + 100\,\dfrac{\Delta}{D}$.

The length of the new curve from Q to $Q' = 2L + 100\,\dfrac{\Delta - 2\phi}{D'}$,

in which L is the length of each spiral.

Example. Suppose the old curve is a 7° 30′ curve with a central angle of 38° 40′. As a trial, compute the relative length of a new 8° 20′ curve with spirals 240 feet long. $\tfrac{1}{2}\Delta = 19° 20'$; R (for the 7° 30′ curve) $= 764.49$; R' (for the 8° 20′ curve) $= 688.16$; $\phi = 10° 0'$; $Y = 13.933$; $X = 239.274$.

[Eq. 38]			R	2.88337
			exsec $\frac{1}{2}\Delta$	8.77642
	45.687	. . . .		1.65979
	R' = 688.16			
	733.847		R'	2.83768
			$\cos\phi$	9.99335
			$\sec \frac{1}{2}\Delta$	0.02521
		718.200	. . . .	2.85624
			Y	1.14405
			$\sec \frac{1}{2}\Delta$	0.02521
		14.766	. . . .	1.16926
	732.966	732.966		
	m = 0.881			
			R'	2.83768
[Eq. 39]	X = 239.274		$\sin\phi$	9.23967
		119.497	. . . .	2.07735
			R'	2.83768
			$\cos\phi$	9.99335
			$\tan \frac{1}{2}\Delta$	9.54512
	237.770	. . . .		2.37615
			R = 764.49	
			Y = 13.93	
			750.56	2.87538
			$\tan \frac{1}{2}\Delta$	9.54512
	477.044	263.333	. . . .	2.42050
	382.830	382.830		
	AQ = 94.214			

The length of the old curve from Q to Q' is

$$100\frac{\Delta}{D}=100\frac{38.667}{7.5}= \quad \ldots\ldots\ldots \quad 515.556$$

$$2AQ=2\times 94.214= \quad \ldots\ldots\ldots \quad \underline{188.428}$$

$$703.984$$

$$\text{New curve: } 100\frac{\Delta-2\phi}{D'}=100\frac{38.667-20.000}{8.33}=224.000$$

$$2L=2\times 240 \qquad =\underline{480.000}$$

$$704.000 \qquad \underline{704.000}$$

$$\text{Difference in length} = \quad 0.016$$

Considering that this difference may be divided among 21 joints (using 33-foot rails) no rail-cutting would be necessary. If the difference is too large, a slight variation in the value of the new radius R' will reduce the difference as much as necessary. A truer comparison of the lengths would be found by comparing the lengths of the arcs.

82. Application of transition curves to compound curves. Since compound curves are only employed when the location is limited by local conditions, the elements of the compound curve should be determined (as in §§ 68 and 69) regardless of the transition curves, depending on the fact that the lateral shifting of the curve when transition curves are introduced is very small. If the limitations are very close, an estimated allowance may be made for them.

Methods have been devised for inserting transition curves between the branches of a compound curve, but the device is complicated and usually needless, since when the train is once on a curve the wheels press against the outer rail steadily and a change in curvature will not produce a serious jar even though the superelevation is temporarily a little more or less than it should be.

If the easier curve of the compound curve is less than 3° or 4°, there may be no need for a transition curve off from that branch. This problem then has two cases according as transition curves are used at both ends or at one end only.

a. *With transition curves at both ends.* Adopting the method of § 79, calling $\Delta_1=\frac{1}{2}\Delta$, we may compute $m_1=MM_1'$. Similarly, calling $\Delta_2=\frac{1}{2}\Delta$, we may compute $m_2=MM_2'$. But M_1' and M_2' must be made to coincide. This may be done by moving the curve $Z'M_1'$ and its transition curve parallel to $Q'V$ a distance $M_1'M_3$, and the other curve parallel to QV a distance $M_2'M_3$.

In the triangle $M_1'M_3M_2'$, the angle at $M_1'=90°-\Delta_1$, the angle at $M_2'=90°-\Delta_2$, and the angle at $M_3=\Delta$.

$$\left.\begin{aligned}\text{Then } M_1'M_3 &= M_1'M_2'\frac{\sin(90°-\Delta_2)}{\sin\Delta}=(m_1-m_2)\frac{\cos\Delta_2}{\sin\Delta}.\\ \text{Similarly } M_2'M_3 &= M_1'M_2'\frac{\sin(90°-\Delta_1)}{\sin\Delta}=(m_1-m_2)\frac{\cos\Delta_1}{\sin\Delta}.\end{aligned}\right\}\quad(40)$$

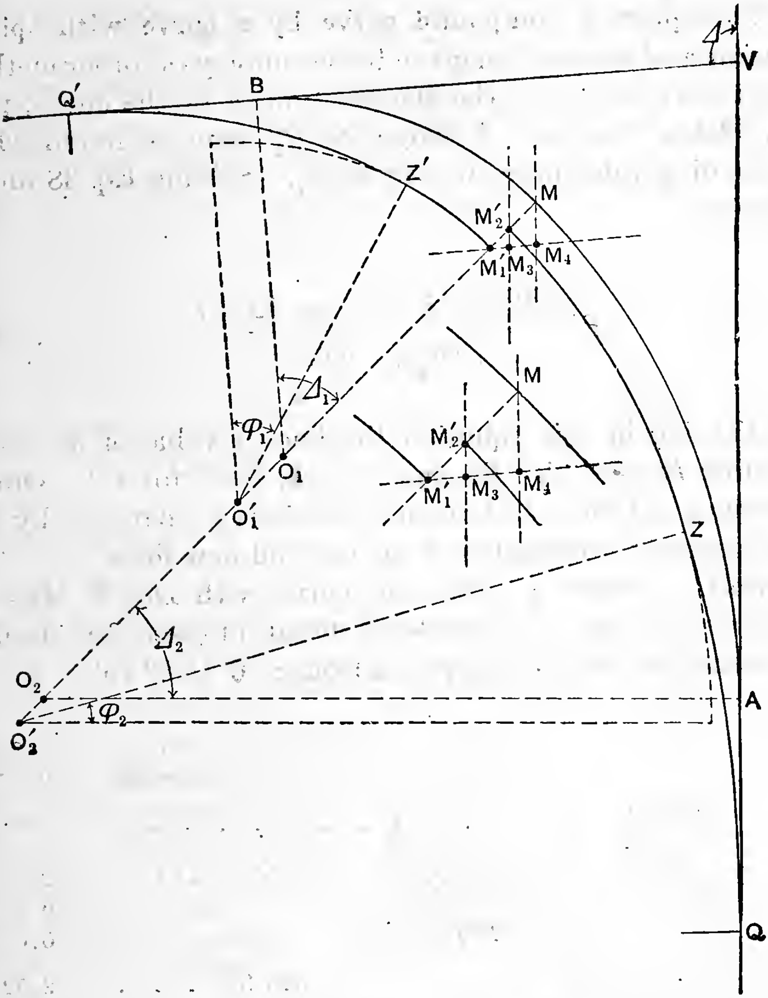


FIG. 38.

b. *With a transition curve on the sharper curve only.* Compute $m_1=MM_1'$ as before; then move the curve Z_1M_1' parallel to $Q'V$ a distance of

$$M_1'M_4=m_1\frac{\cos\Delta_2}{\sin\Delta}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (41)$$

The simple curve MA is moved parallel to VA a distance of

$$MM_4 = m_1 \frac{\cos \Delta_1}{\sin \Delta}. \quad \ldots \quad (42)$$

If Δ_1 and Δ_2 are both small, $M_1'M_4$ and MM_4 may be more than m_1, but the lateral deviation of the new curve from the old will always be less than m_1.

83. To replace a compound curve by a curve with spirals. The numerical illustration given below employs another method. We first solve for m_1 for the sharper branch of the curve, placing $\Delta_1 = \frac{1}{2}\Delta$ in Eq. 38. A value for R_2' may be found whose corresponding value of m_2 will equal m_1. Solving Eq. 38 for R', we obtain

$$R' = \frac{R \text{ vers } \frac{1}{2}\Delta - m \cos \frac{1}{2}\Delta - Y}{\cos \phi - \cos \frac{1}{2}\Delta}. \quad \ldots \quad (43)$$

Substituting in this equation the known value of m_1 $(= m_2)$ and calling $R' = R_2'$, $R = R_2$, and $\Delta_2 = \frac{1}{2}\Delta$, solve for R_2'. Obtain the value of AQ for each branch of the curve separately by Eq. 39, and compare the lengths of the old and new lines.

Example. Assume a compound curve with $D_1 = 8°$, $D_2 = 4°$, $\Delta_1 = 36°$, and $\Delta_2 = 32°$. Use 240-foot spirals at each end. Assume that the sharper curve is sharpened from 8° 0′ to 8° 15′.

Eq. 38		R_1	2.85538
		exsec 36°	9.37303
169.21	. . . .		2.22842
695.09			
864.30	$\phi_1 = \frac{8.25 \times 240}{2}$	R_1' (8° 15′)	2.84204
		$\cos \phi_1$	9.99348
	$= 9.^\circ 9 = 9° 54'$	$\sec \Delta_1$	0.09204
		846.39	2.92757
	$Y_1 = 240 \times .05747$	Y_1	1.13969
	$= 13.79$	$\sec \Delta_1$	0.09204
		17.05	1.23173
863.44		863.44	
$m_1 =$ 0.86			

[Eq. 43]	$\phi_2 = \frac{4.05 \times 2.4}{2.}$	R_2	3.15615
		vers 32°	9.18170
	$= 4°.86 = 4°51'.6$		
	217.700		2.33785
	$Y_2 = .02826 \times 240.$	$m_1 = 0.86$	9.93450
	$= 6.782$	cos 32°	9.92842
		0.729	9.86292
		$Y_2 = 6.782$	
	7.511	7.511	
	210.189		2.32261
		nat. cos ϕ_2 = .99640	
		nat. cos Δ_2 = .84805	
		.14835	9.17129
	$R_2' = 1416.84$ [4° 2′ 41″]		3.15132
Eq. 39]	$X_1 =$ 239.286 $X_1 = .997024 \times 240$		
	$= 239.286$	R_1'	2.84204
		sin ϕ_1	9.23535
		119.505	2.07739
		R_1'	2.84204
		cos ϕ_1	9.99348
		tan $\frac{1}{2}\Delta[\Delta_1 = 36°]$	9.86126
	497.489		2.69678
		$R_1 = 716.78$	
		$Y_1 = 13.70$	
		703.08	2.84700
	736.775	tan $\frac{1}{2}\Delta$	9.86126
	630.325	510.820	2.70826
	$AQ_1 = 106.450$	630.325	
[Eq. 39]		R_2'	3.15132
	$X_2 = .999284 \times 240$	sin ϕ_2	8.92799
	$= 239.828$	120.035	2.07931
		R_2'	3.15132
		cos ϕ_2	9.99843
		tan $\frac{1}{2}\Delta(\Delta_2 = 32°)$	9.79579
	882.145		2.94554
		$R_2 = 1432.7$	
		$Y_2 = 6.8$	
		1425.9	3.15400
		tan $\frac{1}{2}\Delta$	9.79579
		891.00	2.94988
	1121.973	1011.03	
	1011.03		
	$AQ_2 = 110.94$		

For the length of the old track we have:

$$100\frac{\Delta_1}{D_1} = 100\frac{36^\circ}{8^\circ} = 450.$$

$$100\frac{\Delta_2}{D_2} = 100\frac{32^\circ}{4^\circ} = 800.$$

$$AQ_1 = 106.45$$

$$AQ_2 = 110.94$$

$$= 1467.39$$

For the length of the new track we have:

$$100\frac{\Delta_1 - \phi_1}{D'_1} = 100\frac{26^\circ.1}{8^\circ.25} = 316.36$$

$$100\frac{\Delta_2 - \phi_2}{D'_2} = 100\frac{27.14}{4^\circ.044} = 671.11$$

Spiral on 8° 15′ curve = 240.00

Spiral on 4° 02′ 41″ curve = 240.00

Length of new track = 1467.47

Length of old track = 1467.39

Excess in length of new track = 0.08 feet.

Since the new track is slightly longer than the old, it shows that the new track runs too far *outside* the old track at the *P.C.C.* On the other hand the offset m is only 0.86. The maximum amount by which the new track comes *inside* of the old track at two points, presumably not far from Z' and Z, is very difficult to determine exactly. Since it is desirable that the maximum offsets (inside and outside) should be made as nearly equal as possible, this feature should not be sacrificed to an effort to make the two lines of precisely equal length so that the rails need not be cut. Therefore, if it is found that the offsets inside the old track are nearly equal to m (0.86), the above figures should stand. Otherwise m may be diminished (and the above excess in length of track diminished) by *increasing* R_1' very slightly and making the necessary consequent changes.

VERTICAL CURVES

84. Necessity for their use. Whenever there is a change in the rate of grade, it is necessary to eliminate the angle that would be formed at the point of change and to connect the two grades by a curve. This is especially necessary at a sag between two grades, since the shock caused by abruptly forcing an upward motion to a rapidly moving heavy train is very severe both to the track and to the rolling stock. The necessity for vertical curves was even greater in the days when link couplers were in universal use and the "slack" in a long train was very great.

Under such circumstances, when a train was moving down a heavy grade the cars would crowd ahead against the engine. Reaching the sag, the engine would begin to pull out, rapidly taking out the slack. Six inches of slack on each car would amount to several feet on a long train, and the resulting jerk on the couplers, especially those near the rear of the train, has frequently resulted in broken couplers or even derailments. A vertical curve will practically eliminate this danger if the curve is made long enough.

85. Required length. Theoretically the length should depend on the change in the rate of grade and on the length of the longest train on the road. A sharp change in the rate of grade requires a long curve; a long train requires a long curve; but since the longest trains are found on roads with light grades and small changes of grade, the required length is thus somewhat equalized. The A.R.E.A. rule is: "On class A roads (see § 234) rates of change of 0.1 per cent per station on summits and 0.05 per cent per station in sags should not be exceeded. On minor roads 0.2 per cent per station on summits and 0.1 per cent per station in sags may be used." When changing from a down grade to an up grade (or vice versa) the change of grade equals the numerical sum of the two rates of grade. For example, if a 0.5 per cent down grade is followed by a 0.7 per cent up grade, the road being a "minor" road, then, by the above rule the length of the curve should be at least $[0.5-(-0.7)]\div 0.1=12$ stations or 1200 feet. Added length increases the amount of earthwork required both in cuts and fills, but the resulting saving in operating expenses will always justify a considerable increase.

86. Form of curve. In Fig. 39 assume that A and C, equi-

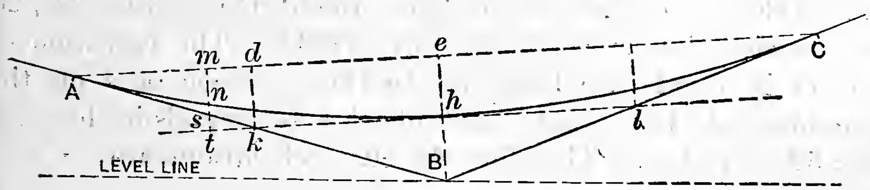


FIG. 39.

distant from B, are the extremities of the vertical curve. Bisect AC at e; draw Be and bisect it at h. Bisect AB and BC at k and l. The line kl will pass through h. A parabola may be drawn with its vertex at h which will be tangent to AB and BC at A and C. It may readily be shown * from the properties of

* See note at end of this chapter.

a parabola that if an ordinate be drawn at *any* point (as at *n*) we will have

$$sn : eh \text{ (or } hB) :: \overline{Am}^2 : \overline{Ae},^2$$

or

$$sn = eh\frac{\overline{Am}^2}{\overline{Ae}^2} \quad \ldots \ldots \ldots \quad (44)$$

In Fig. 39 the grades are necessarily exaggerated enormously. With the proportions found in practice we may assume that ordinates (such as *mt*, *eB*, etc.) are perpendicular to either grade, as may suit our convenience, without any appreciable error. In the numerical case given below, the variation of these ordinates from the vertical is 0° 07′, while the effect of this variation on the calculations in this case (as in the most extreme cases) is absolutely inappreciable. It may easily be shown that the angle CAB = half the *algebraic difference* of the rates of grade. Call the difference, expressed in per cent of grade, r; then $CAB = \frac{1}{2}r$. Let l = length (in "stations" of 100 feet) of the line AC, which is practically equal to the horizontal measurement. Since the angle CAB is one-half the total change of grade at B, it follows that $Be = \frac{1}{2}l \times \frac{1}{2}r$ Therefore

$$Bh = \tfrac{1}{8}lr. \quad \ldots \ldots \ldots \quad (45)$$

Since Bh (or eh) and Ae are constant for any one curve, the correction sn at any point (see Eq. 44) equals a constant times Am^2.

87. Numerical example. Assume that B is located at Sta. 16+20; that the grade of AB is −0.5%, and of BC +0.7%; also that the elevation of B above the datum plane is 162.6. Then the algebraic difference of the grades, r, $= 0.7-(-0.5) = 1.2$; $l = 12$. $Bh = \frac{1}{8}lr = \frac{1}{8} \times 12 \times 1.2 = 1.8$. A is at Sta. 10+20 and its elevation is $162.6+(6\times0.5)=165.6$; C is at Sta. 22+20 and its elevation is $162.6+(6\times0.7)=166.8$. The elevation of Sta. 11 is found by adding sn to the elevation of s on the straight grade line. The constant $(eh \div \overline{Ae}^2)$ equals in this case $1.8 \div 600^2 = \frac{1}{200000}$. Therefore the curve elevations are

A, Sta.	10+20,	$162.6+(6.00\times0.5)$	$=165.60$
	11	$165.6-(0.80\times0.5)+\frac{1}{200000}\,80^2$	$=165.23$
	12	$165.6-(1.80\times0.5)+\frac{1}{200000}\,180^2$	$=164.86$
	13	$165.6-(2.80\times0.5)+\frac{1}{200000}\,280^2$	$=164.59$
	14	$165.6-(3.80\times0.5)+\frac{1}{200000}\,380^2$	$=164.42$
	15	$165.6-(4.80\times0.5)+\frac{1}{200000}\,480^2$	$=164.35$
	16	$165.6-(5.80\times0.5)+\frac{1}{200000}\,580^2$	$=164.38$

B,	16+20,	162.6+ 1.80	=164.40
	17	166.8 −(5.20×0.7) + $\frac{1}{200000}$ 520²	=164.51
	18	166.8 −(4.20×0.7) + $\frac{1}{200000}$ 420²	=164.74
	19	166.8 −(3.20×0.7) + $\frac{1}{200000}$ 320²	=165.07
	20	166.8 −(2.20×0.7) + $\frac{1}{200000}$ 220²	=165.50
	21	166.8 −(1.20×0.7) + $\frac{1}{200000}$ 120²	=166.03
	22	166.8 −(0.20×0.7) + $\frac{1}{200000}$ 20²	=166.66
C,	22+20,	162.6+(6.00×0.7)	=166.80

DEMONSTRATION OF EQ. 44.

The general equation of a parabola passing through the point n (Fig. 36) may be written

$$y^2 + y_n^2 = 2p(x + x_n),$$

from which

$$x_n = \frac{y^2}{2p} + \frac{y_n^2}{2p} - x.$$

When $x = x_A$, $y = y_A$, and we have

$$x_n = \frac{y_A^2}{2p} + \frac{y_n^2}{2p} - x_A.$$

The general equation of a tangent passing through the point A may be written

$$yy_A = p(x + x_A),$$

from which

$$x = \frac{yy_A}{p} - x_A.$$

When $x = x_s$, $y = y_s[= y_n]$, and we have

$$x_s = \frac{y_n y_A}{p} - x_A.$$

$$\overline{sn} = x_n - x_s = \frac{y_A^2 + y_n^2 - 2y_n y_A}{2p}$$

$$= \frac{(y_A - y_n)^2}{2p} = \frac{\overline{Am}^2}{2p},$$

$$2p = \frac{y_A^2}{x_A} = \frac{\overline{Ae}^2}{\overline{eh}}.$$

$$\therefore \quad \overline{sn} = \overline{eh}\frac{\overline{Am}^2}{\overline{Ae}^2}.$$

This proves the general proposition that if secants are drawn parallel to the axis of x, intersecting a parabola and a tangent to it, the intercepts between the tangent and the parabola are proportional to the square of the distances (measured parallel to y) from the tangent point.

CHAPTER III.

EARTHWORK.

FORM OF EXCAVATIONS AND EMBANKMENTS.

88. Usual form of cross-section in cut or fill. The normal form of cross-section in cut is as shown in Fig. 40, in which *e* . . . *g* represents the natural surface of the ground, no matter

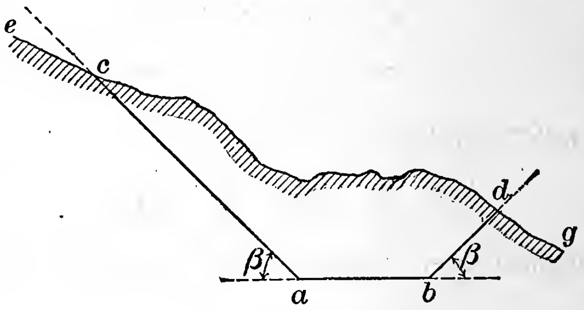


Fig. 40.

how irregular; *ab* represents the position and width of the required roadbed; *ac* and *bd* represent the "side slopes" which begin at *a* and *b* and which intersect the natural surface at such

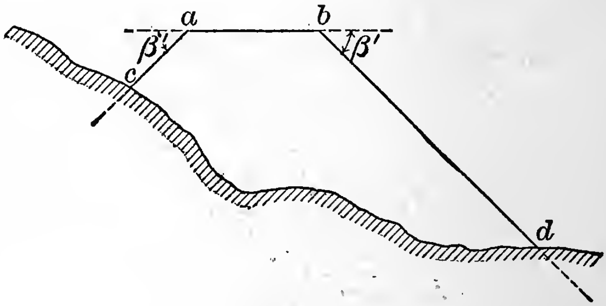


Fig. 41.

points (*c* and *d*) as will be determined by the required slope angle (β).

The normal section in fill is as shown in Fig. 41. The points *c* and *d* are likewise determined by the intersection of the required side slopes with the natural surface. In case the required roadbed (*ab* in Fig. 42) intersects the natural surface, both cut

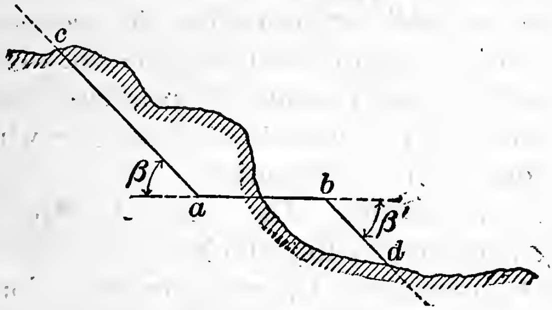


FIG. 42.

and fill are required, and the points *c* and *d* are determined as before. Note that β and β' are not necessarily equal. Their proper values will be discussed later.

89. Terminal pyramids and wedges. Fig. 43 illustrates the general form of cross-sections when there is a transition from cut to fill. *a . . . g* represents the grade line of the road which

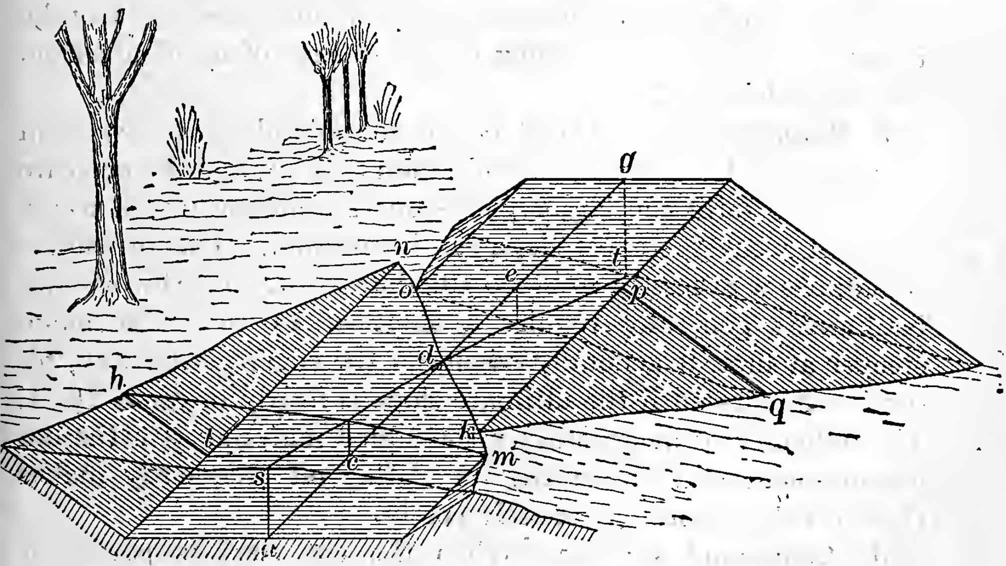


FIG. 43.

passes from cut to fill at *d*. *sdt* represents the surface profile. A cross-section taken at the point where either side of the roadbed *first* cuts the surface (the point *m* in this case) will usually be triangular if the ground is regular. A similar cross-section should be taken at *o*, where the other side of the roadbed cuts the surface. In general the earthwork of cut and fill terminates in two pyramids. In Fig. 43 the pyramid vertices are at *n* and *k*, and the bases are *lhm* and *opq*. The roadbed is generally wider in cut than in fill, and therefore the section *lhm* and the altitude *ln* are generally greater than the section *opq* and the altitude *pk*. When the line of intersection of the roadbed and natural surface (*nodkm*) becomes perpendicular to the axis of the roadbed (*ag*) the pyramids become wedges whose bases are the nearest convenient cross-sections.

90. Slopes. a. Cuttings. The required slopes for cuttings vary from perpendicular cuts, which may be used in hard rock which will not disintegrate by exposure, to a slope of perhaps 4 horizontal to 1 vertical in a soft material like quicksand or in a clayey soil which flows easily when saturated. For earthy materials a slope of 1 : 1 is the maximum allowable, and even this should only be used for firm material not easily affected by saturation. A slope of 1½ horizontal to 1 vertical is a safer slope for average earthwork. It is a frequent blunder that slopes in cuts are made too steep, and it results in excessive work in clearing out from the ditches the material that slides down, at a much higher cost per yard than it would have cost to take it out at first, to say nothing of the danger of accidents from possible landslides.

b. Embankments. The slopes of an embankment vary from 1 : 1 to 1.5 : 1. A rock fill will stand at 1 : 1, and if some care is taken to form the larger pieces on the outside into a rough dry wall, a much steeper slope can be allowed. This method is sometimes a necessity in steep side-hill work. Earthwork embankments generally require a slope of 1½ to 1. If made steeper at first, it generally results in the edges giving way, requiring repairs until the ultimate slope is nearly or quite 1½ : 1. The difficulty of incorporating the added material with the old embankment and preventing its sliding off frequently makes these repairs disproportionately costly.

91. Compound sections. When the cut consists partly of earth and partly of rock, a compound cross-section must be made. If borings have been made so that the contour of the rock surface is accurately known, then the true cross-section may be determined. The rock and earth should be calculated separately, and this will require an accurate knowledge of where the rock "runs out"—a difficult matter when it must be determined by boring. During construction the center part of the earth cut would be taken out first and the cut widened until a sufficient width of rock surface had been exposed so that the rock cut would have its proper width and side slopes. Then the earth slopes could be cut down at the proper angle. A "berm" of about three feet should be left on the edges of the rock cut as

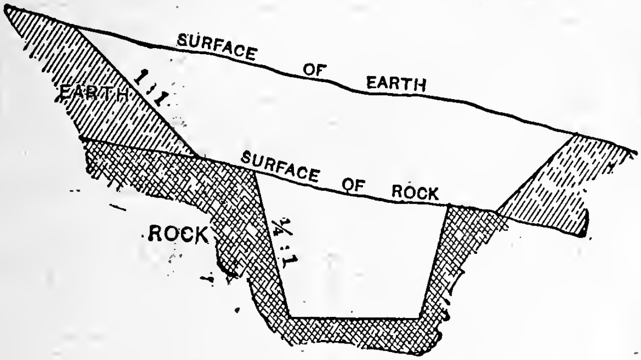


Fig. 44.

a margin of safety against a possible sliding of the earth slopes. After the work is done, the amount of excavation that has been made is readily computable, but accurate preliminary estimates are difficult. The area of the cross-section of earth in the figure must be determined by a method similar to that developed for borrow-pits (see § 120).

92. Width of roadbed. Owing to the large and often disproportionate addition to volume of cut or fill caused by the addition of even one foot to the width of roadbed, there is a natural tendency to reduce the width until embankments become unsafe and cuts are too narrow for proper drainage. The cost of maintenance of roadbed is so largely dependent on the drainage of the roadbed that there is true economy in making an ample allowance for it. The practice of some of the leading railroads of the country in this respect is given in the following table, in which are also given some data belonging more properly to the subject of superstructure.

It may be noted from the table that the average width for an *earthwork* cut, single track, is about 24.7 feet, with a minimum of 19 feet 2 inches. The widths of fills, single track, average over 18 feet, with numerous minimums of 16 feet. The widths for double track may be found by adding the distance between track centers, which is usually 13 feet.

WIDTH OF ROADBED FOR SINGLE AND DOUBLE TRACK—SLOPE RATIOS—DISTANCES BETWEEN TRACK CENTERS.

Road.	Single Track.		Double Track.		Slope Ratios.		Distance Between Track Centers.
	Cut.	Fill.	Cut.	Fill.	Cut.	Fill.	
A., T. & Santa Fé	28′ earth	20	....	....	1 : 1	1.5 : 1	
	22′ rock	....	....	....	$\frac{1}{4}$: 1		
Chicago, Burlington & Quincy	14+(2×5)*	16	28+(2×5)	30	1.5 : 1	1.5 : 1	14′
Chicago, Milwaukee & St. Paul	18+(2×6)	20 to 24	31+(2×6)	33 to 37	1.5 : 1	1.5 : 1	13′
C., C., C. & St. Louis	20+(2×4)	20	33+(2×4)	33	1.5 : 1	1.5 : 1	13′
Illinois Central	32.5	18	....	....	1.5 : 1	1.5 : 1	
Erie	20′ 8½″	20′ 8½″	33′ 8½″	33′ 8½″	1.5 : 1	1.5 : 1	13′
Lehigh Valley	14+(2×3.5)	16	27+(2×3.5)	30	1 : 1	1.5 : 1	13′
Lake Shore & Michigan Southern	....	....	33+(2×7.25)	32	1.5 : 1	1.5 : 1	13′
Louisville & Nashville	13+(2×4.5)	16	....	....	1 : 1	1.5 : 1	
Michigan Central	....	....	(33+2×2.5)	33	1.5 : 1	1.5 : 1	13′
N. Y., N. H. & H.	....	....	30	30	1.5 : 1	1.5 : 1	12′
Norfolk & Western	21′ 2″ earth	17′ 2″	34′ 2″ earth	30′ 2″	1.5 : 1	1.5 : 1	13′
	16′ rock	....	29′ rock	....	$\frac{1}{4}$: 1 $\frac{1}{2}$: 1	....	13′
Pennsylvania	19′ 2″ light traffic	19′ 2″					
	27′ 2″ heavy "	19′ 2″	31′ 4″+(2×4)	31′ 4″	1.5 : 1	1.5 : 1	12′ 2″
Union Pacific	14+(2×3.5)	16	....	....	1 : 1	1.5 : 1	

* (2×5) signifies two ditches each 5 feet wide; the following cases should be interpreted similarly.

Am. Rwy. Eng. Assoc. standard for Class A roads, 20 feet for single track fill, 20+width of ditches for cut; 16 feet for Class B roads and 14 feet for Class C roads. See § 234 for classification. In theory, the track, in excavation, rests on a low embankment. By adding the width of side ditches, in excavations, there are uniform conditions, immediately under the track, throughout the line.

93. Form of subgrade. Specifications (or the cross-section drawings) formerly required that the subgrade should have a curved form, convex upward, or that it should slope outward from a slight ridge in the center, with the evident purpose of draining to the sides all water which might percolate through the ballast. If the subsoil were hard and impenetrable by the ballast, the method might answer, but experience has shown that, with ordinary subsoils, the ballast immediately under each rail is forced a little deeper into the subsoil by the passage of each train. Periodical retamping of ballast under the ends of the ties, and little or no tamping under the center, only adds to the accumulation under each rail. A cross-section of a very old roadbed will frequently show twice as much depth of ballast under the rails as there is under the center. This method of tamping quickly obliterates the original line of demarcation between ballast and subsoil and any expected improvement in drainage due to sloping subsoil is not realized. Therefore the A.R.E.A. specifications call for *flat* subgrades.

94. Ditches. "The stability of the track depends upon the strength and permanence of the roadbed and structures upon which it rests; whatever will protect them from damage or prevent premature decay should be carefully observed. The worst enemy is WATER, and the further it can be kept away from the track, or the sooner it can be diverted from it, the better the track will be protected. Cold is damaging only by reason of the water which it freezes; therefore the first and most important provision for good track is drainage." (Rules of the Road Department, Illinois Central R. R.)

The form of ditch generally prescribed has a flat bottom 12″ to 24″ wide and with sides having a minimum slope, except in rock-work, of 1 : 1, more generally 1.5 : 1 and sometimes 2 : 1. Sometimes the ditches are made V-shaped, which is objectionable unless the slopes are low The best form is evidently that which will cause the greatest flow for a given slope, and this will evidently be the form in which the ratio of area to wetted perimeter is the largest. The semicircle fulfills this condition better than any other form, but the nearly vertical sides would be difficult to maintain. (See Fig. 45.) A ditch, with a flat bottom and such

FIG. 45.

slopes as the soil requires, which approximates to the circular form will therefore be the best.

When the flow will probably be large and at times rapid it will be advisable to pave the ditches with stone, especially if the soil is easily washed away. Six-inch tile drains, placed 2′ under the ditches, are prescribed on some roads. (See Fig. 46.) No better method could be devised to insure a dry subsoil. The ditches through cuts should be led off at the end of the cut so that the adjacent embankment will not be injured.

Wherever there is danger that the drainage from the land above a cut will drain down into the cut, a ditch should be made near the edge of the cut to intercept this drainage, and this ditch should be continued, and paved if necessary, to a point where the outflow will be harmless. Neglect of these simple and inexpensive precautions frequently causes the soil to be loosened on the shoulders of the slopes during the progress of a heavy rain, and results in a landslide which will cost more to repair than the ditches which would have prevented it for all time.

Ditches should be formed along the bases of embankments; they facilitate the drainage of water from the embankment, and may prevent a costly slip and disintegration of the embankment.

95. Effect of sodding the slopes, etc. Engineers are unanimously in favor of rounding off the shoulders and toes of embankments and slopes, sodding the slopes, paving the ditches, and providing tile drains for subsurface drainage, all to be put in during original construction. (See Fig. 46.) Some of the highest grade specifications call for the removal of the top layer of vegetable soil from cuts and from under proposed fills to some convenient place, from which it may be afterwards spread on the slopes, thus facilitating the formation of sod from grass-seed. But while engineers favor these measures and their economic value may be readily demonstrated, it is generally impossible to obtain the authorization of such specifications from railroad directors and promoters. The addition to the original cost of the roadbed is considerable, but is by no means as great as the capitalized value of the extra cost of maintenance resulting from the usual practice. Fig. 46 is a copy of designs * presented at a convention of the Ameiican Society of Civil Enginecrs by Mr. D. J. Whittemore, Past President of the Society and Chief Enginecr of the Chi., Mil. & St. Paul

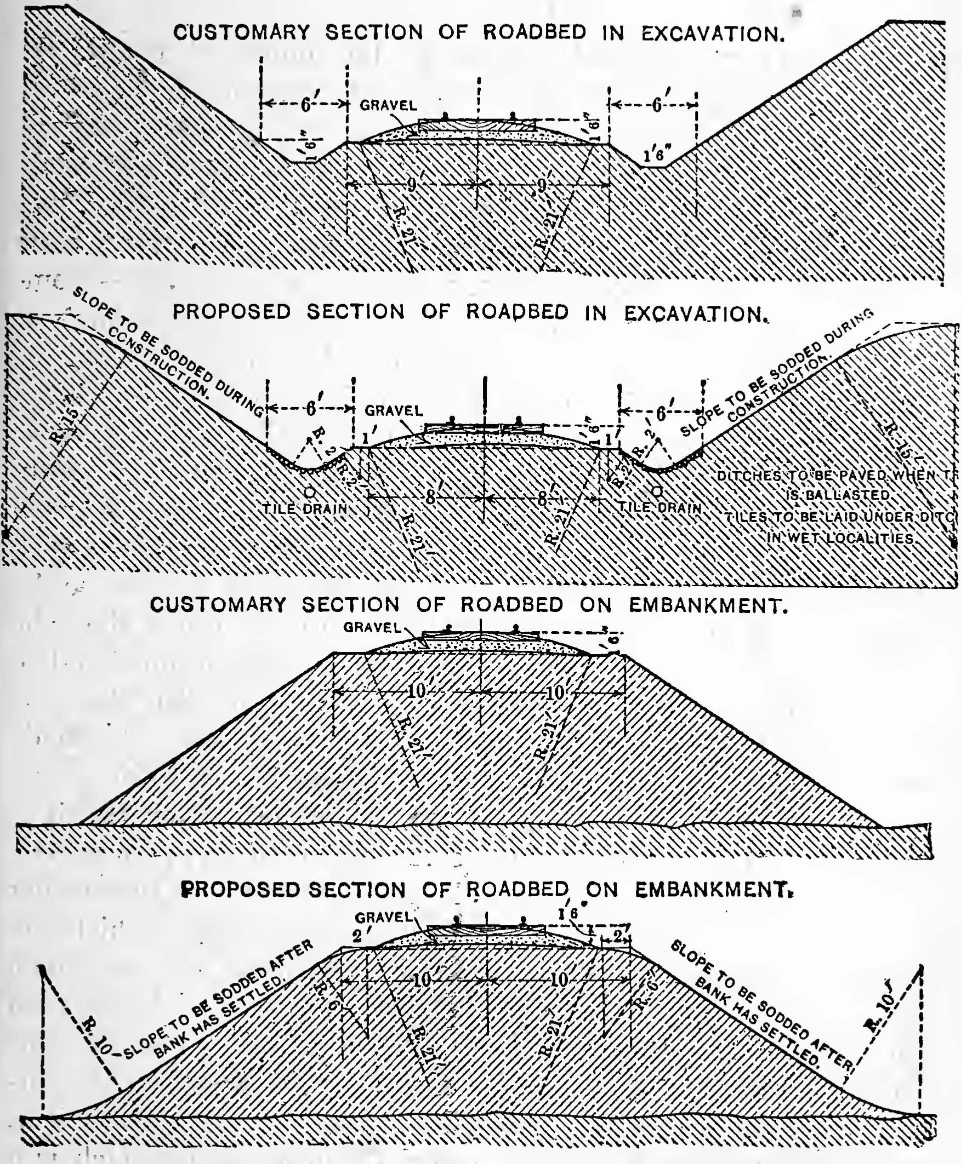


FIG. 46.—"WHITTEMORE ON RAILWAY EXCAVATION AND EMBANKMENTS" Trans. Am. Soc. C. E., Sept. 1894.

R. R. The "customary sections" represent what is, with some variations of detail, the practice of many railroads. The "pro-

---

* Trans. Am. Soc. Civil Eng., Sept. 1894.

posed sections" elicited unanimous approval. They should be adopted when not prohibited by financial considerations.

EARTHWORK SURVEYS.

96. Relation of actual volume to the numerical result. It should be realized at the outset that the accuracy of the result of computations of the volume of any given mass of earthwork has but little relation to the accuracy of the mere numerical work. The process of obtaining the volume consists of two distinct parts. In the first place it is assumed that the volume of the earthwork may be represented by a more or less complicated geometrical form, and then, secondly, the volume of such a geometrical form is computed. A desire for simplicity (or a frank willingness to accept approximate results) will often cause the cross-section men to assume that the volume may be represented by a very simple geometrical form which is really only a very rough approximation to the true volume. In such a case, it is only a waste of time to compute the volume with minute numerical accuracy. One of the first lessons to be learned is that economy of time and effort requires that the accuracy of the numerical work should be kept proportional to the accuracy of the cross-sectioning work, and also that the accuracy of both should be proportional to the use to be made of the results. The subject is discussed further in § 125.

97. Prismoids. To compute the volume of earthwork, it is necessary to assume that it has some geometric form whose volume is readily determinable. The general method is to consider the volume as consisting of a series of *prismoids*, which are solids having parallel plane ends and bounded by surfaces which may be formed by lines moving continuously along the edges of the bases These surfaces may also be considered as the surfaces generated by lines moving along the edges joining the corresponding points of the bases, these edges being the directrices, and the lines being always parallel to either base, which is a plane director. The surfaces thus developed may or may not be planes. The volume of such a prismoid is readily determinable (as explained in § 108 *et seq.*), while its definition is so very general that it may be applied to very rough ground. The "two plane ends" are sections perpendicular to the axis of the road. The roadbed and side slopes (also plane) form three of the side surfaces. The only approximation lies in the degree of accuracy with which the plane (or warped) surfaces coincide with the actual surface of the ground between these two sections. This accuracy will depend (*a*) on the number of points which are taken in each cross-section and the accuracy with which the lines joining these points coincide with the actual cross-sections; (*b*) on the skill shown in selecting places for the cross-sections so that the warped surfaces shall coincide as nearly as possible with the surface of the ground. In fairly smooth country, cross-sections every 100 feet, placed at the even stations, are sufficiently accurate, and such a method simplifies the computations greatly; but in rough country cross-sections must be interpolated as the surface demands. As will be explained later, carelessness or lack of judgment in cross-sectioning will introduce errors of such magnitude that all refinements in the computations are utterly wasted.

98. Cross-sectioning. The process of cross-sectioning consists in determining at any place the intersection by a vertical plane of the prism of earth lying between the roadbed, the side slopes, and the natural surface. The intersection with the road-

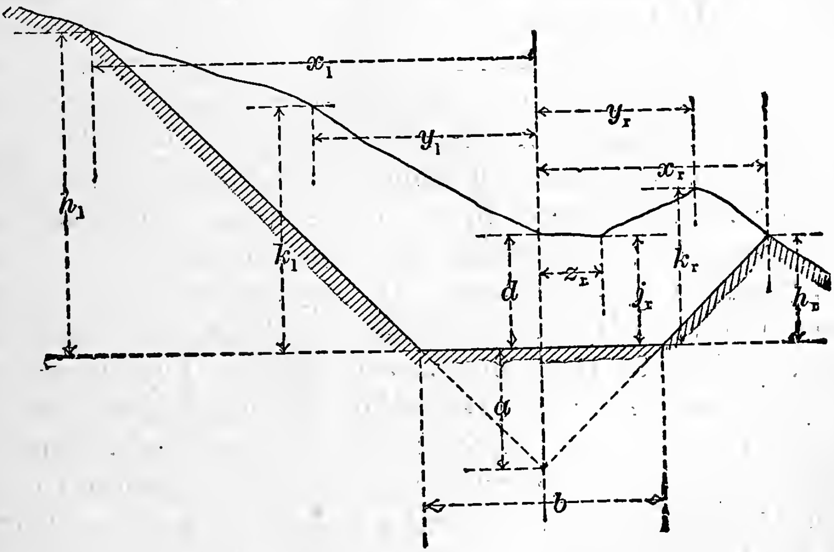


FIG. 47.

bed and side slopes gives three straight lines. The intersection with the natural surface is in general an irregular line. On smooth regular ground or when approximate results are acceptable this line is assumed to be straight. According to the irregularity of the ground and the accuracy desired more and more "intermediate points" are taken.

The distance (d in Fig. 47) of the roadbed below (or above) the natural surface at the center is known or determined from the profile or by the computed establishment of the grade line. The distances out from the center of all "breaks" are determined with a tape. To determine the elevations for a cut, set up a level at any convenient point so that the line of sight is higher than any point of the cross-section, and take a rod reading on the center point. This rod reading added to d gives the height of the instrument (H. I.) above the roadbed. Subtracting from H. I. the rod reading at any "break" gives the height of that point above the roadbed (h_l, k_l, h_r, etc.). This is true for all cases in excavation. For fill, the rod reading at center minus d equals the H. I., which may be positive or negative. When negative, add to the "H. I." the rod readings of the intermediate points to get their depths below "grade"; when positive, subtract the "H. I." from the rod readings.

The heights or depths of these intermediate points above or below grade need only be taken to the nearest tenth of a foot, and the distances out from the center will frequently be sufficiently exact when taken to the nearest foot. The roughness of the surface of farming land or woodland generally renders useless any attempt to compute the volume with any greater accuracy than these figures would imply unless the form of the ridges and hollows is especially well defined. The position of the slope-stake points is considered in the next section. Additional discussion regarding cross-sectioning is found in § 118.

99. Position of slope-stakes. The slope-stakes are set at the intersection of the required side slopes with the natural surface, which depends on the center cut or fill (d). The distance of the slope-stake from the center for the lower side is $x = \frac{1}{2}b + s(d+y)$; for the up-hill side it is $x' = \frac{1}{2}b + s(d-y')$. s is the "slope ratio" for the side slopes, the ratio of horizontal to vertical. In the above equation both x and y are unknown. Therefore some position must be found by trial which will satisfy the equation. As a preliminary, the value of x for the point $a = \frac{1}{2}b + sd$, which is the value of x for *level* cross-sections. In the case of fills on sloping ground the value of x on the *down-hill* side is *greater* than this; on the *up-hill* side it is *less*. The difference in distance is s times the difference of elevation. Take a numerical case corresponding with Fig. 48. The rod reading on c is 2.9; $d=4.2$; therefore the telescope is $4.2-2.9=1.3$ *below* grade. $s=1.5:1$, $b=16$. Hence for the point a (or for level ground) $x=\frac{1}{2}\times 16+1.5\times 4.2=14.3$. At a distance out of 14.3 the ground is seen to be about 3 feet lower, which will not only require $1.5\times 3=4.5$ more, but enough additional distance so that the added distance shall be 1.5 times the additional drop. As a first trial the rod may be held at 24 feet out and a reading of, say, 8.3 is obtained. $8.3+1.3=9.6$, the depth of the point below grade. The point on the slope line (n) which has this depth below grade is at a distance from the center

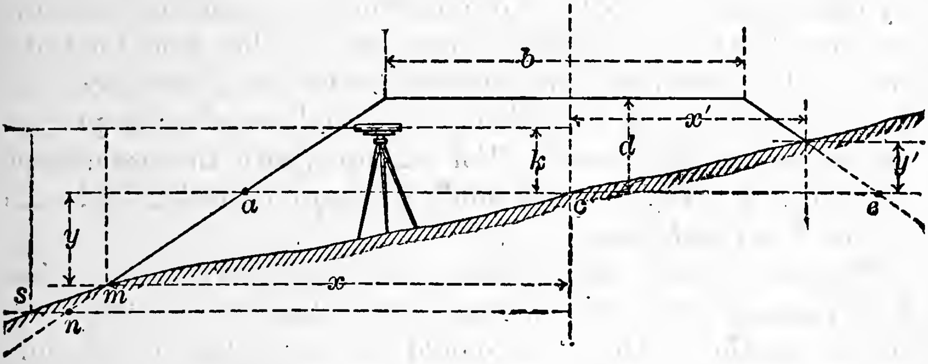


FIG. 48.

$x=8+1.5\times 9.6=22.4$. The point on the surface (s) having that depth is 24 feet out. Therefore the true point (m) is nearer the center. A second trial at 20.5 feet out gives a rod reading of, say, 7.1 or a depth of 8.4 below grade. This corresponds to a distance out of 20.6. Since the natural soil (especially in farming lands or woods) is generally so rough that a difference of elevation of a tenth or so may be readily found by slightly varying the location of the rod (even though the distance from the center is the same), it is useless to attempt too much refinement, and so in a case like the above the combination of 8.4 below grade and 20.6 out from center may be taken to indicate the proper position of the slope-stake. This is usually indicated in the form of a fraction, the distance out being the denominator and the height above (or below) grade being the numerator; the fact of *cut* or *fill* may be indicated by C or F. Ordinarily a second trial will be sufficient to determine with sufficient accuracy the true position of the slope-stake. Experienced men will frequently estimate the required distance out to within a few tenths at the first trial. The left-hand pages of the note-book should have the station number, surface elevation, grade elevation, center cut or fill, and rate of grade. The right-hand pages should be divided in the center and show the distances out and heights above grade of all points, as is illustrated in §109. The notes should read UP the page, so that when looking ahead along the line the figures are in their proper relative position. The "fractions" farthest from the center line represent the slope-stake points.

100. Setting slope-stakes by means of "automatic" slope-stake rods. The equipment consists of a specially graduated tape and a specially constructed rod. The tape may readily be prepared by marking on the *back* side of an ordinary 50-foot tape which is graduated to feet and tenths. Mark **"0"** at "$\frac{1}{2}b$" from the tape-ring. Then graduate from the zero backward, at true scale, to the ring. Mark off "feet" and "tenths" on a scale proportionate to the slope ratio. For example, with the usual slope ratio of 1.5:1 each "foot" would measure 18 inches and each "tenth" in proportion.

The rod, 10 feet long, is shod at each end and has an endless tape passing within the shoes at each end and over pulleys—to reduce friction. The tape should be graduated in feet and tenths, from 0 to 20 feet—the 0 and 20 coinciding. By moving the tape so that 0 is at the bottom of the rod—or (practically) so that the 1-foot mark on the tape is one foot above the bottom of the shoe, an index mark may be placed on the back of the rod (say at 15—on the tape) and this readily indicates when the tape is "set at zero."

The method of use may best be explained from the figure and from the explicit rules as stated. The proof is given for two assumed positions of the level.

(1) Set up the level so that it is higher than the "center" and (if possible) higher than both slope-stakes, but not more than a rod-length higher. On very steep ground this may be impossible and each slope-stake must be set by separate positions of the level.

(2) Set the rod-tape at zero (i.e., so that the 15-foot mark on the *back* is at the index mark).

(3) Hold the rod at the center-stake (B) and note the reading (n_1 or n_2). Consider n to be always plus; consider d to be plus for cut and minus for fill.

(4) *Raise* the tape on the *face* side of the rod $(n+d)$. Applied literally (and algebraically), when the level is *below* the roadbed (only possible for fill), $(n+d)=(n_2+(-d_f))=n_2-d_f$. This being numerically negative, the tape is *lowered* (d_f-n_2). With level at (1), for fill, $(n+d)=(n_1+(-d_f))=(n_1-d_f)$; this being positive, the tape is raised. With level at (1), for cut, the tape is raised (n_1+d_c). In every case the effect is the same as if the telescope were set at the elevation of the roadbed.

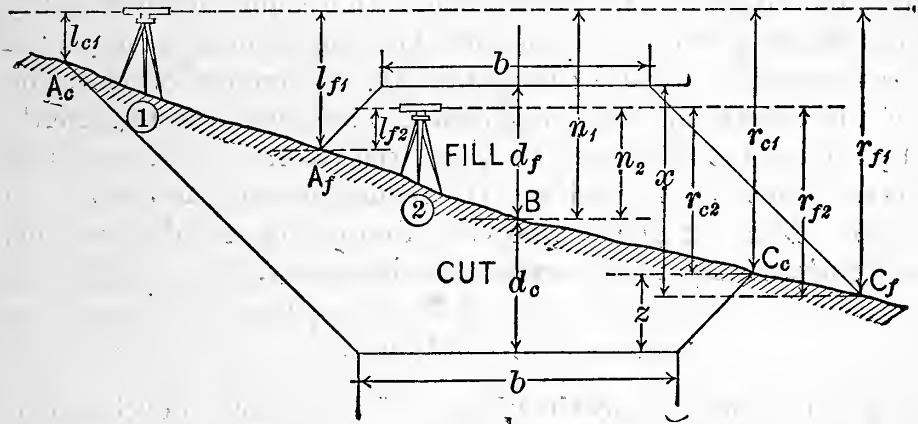


FIG. 49.

(5) With the special distance-tape, so held that its zero is $\frac{1}{2}b$ from the center, carry the rod out until the rod reading equals the reading indicated by the tape. Since in cut the tape is raised $(n+d)$, the zero of the rod-tape is always higher than the level (unless the rod is held at or below the elevation of the roadbed—which is only possible on side-hill work), and the reading at either slope-stake is necessarily *negative.* The reading for slope-stakes in fill is always positive.

(6) Record the rod-tape reading as the numerator of a fraction and the *actual distance* out (read directly from the *other* side of the distance-tape) as the denominator of the fraction.

Proof. Fill. Level at (1). Tape is raised (n_1-d_f). When rod is held at C_f, the rod reading is $+x$, which $=r_{f1}-(n_1-d_f)$. But the reading on the back side of the distance-tape is also x.

Fill. Level at (2). Tape is raised (n_2-d_f), i.e., it is *lowered* (d_f-n_2). When rod is held at C_f, the rod reading is $+x$, which similarly $= r_{f2}-(n_2-d_f) = r_{f2}+(d_f-n_2)$. Distance-tape as before.

Cut Level at (1). Tape is raised (n_1+d_c). When rod is held at C_c the rod reading is $-z$, which $= r_{c1}-(n_1+d_c)$, i.e., $z=(n_1+d_c)-r_{c1}$. The distance-tape will read z.

Side-hill work. It is easily demonstrated that the method, when followed literally, may be applied to side-hill work. although there is considerable chance for confusion and error, when, as is usual, $\frac{1}{2}b$ and the slope ratio are different for cut and for fill.

The method appears complicated at first, but it becomes mechanical and a time-saver when thoroughly learned. The advantages are especially great when the ground is fairly level transversely, but decrease when the difference of elevation of the center and the slope-stake is more than the rod length. By setting the rod-tape "at zero," the rod may always be used as an ordinary level rod and the regular method adopted, as in § 99. Many engineers who have thoroughly tested these rods are enthusiastic in their praise as a time-saver.

COMPUTATION OF VOLUME

§ 101. **Simple approximations.** The principles developed in §§ 96 and 97 show that, except where the ground is abnormally smooth and level, the earthwork to be excavated has a geometrical form whose volume cannot be *accurately* computed by any simple rule. The usual method is to consider that the volume is approximately measured by the product of the mean of the areas of two consecutive sections and the distance between those sections. When the ground is so regular that the error of such an approximation may be tolerated, or when only a rough approximation is necessary, such a computation may be accepted without correction. In any case, the "volume by averaging end areas" is computed as a first approximation and then correction is computed if desired. It should, therefore, be remembered that this approximate method, which is so common that it is often accepted without correction as the true volume, is never mathematically correct except under conditions which practically never exist. Whether a correction should be computed depends on the percentage of accuracy required, on the irregularity of the ground, and on the differences in the depth of adjacent center cuts—or fills. Experience gives the engineer such an idea of the probable amount of this correction under any given conditions that he may judge when it is necessary to compute the correction in order to obtain the true volume with any desired degree of accuracy. The methods of computing this correction will be given later.

102. Approximate volume, level sections. When the country is very level or when only approximate preliminary results

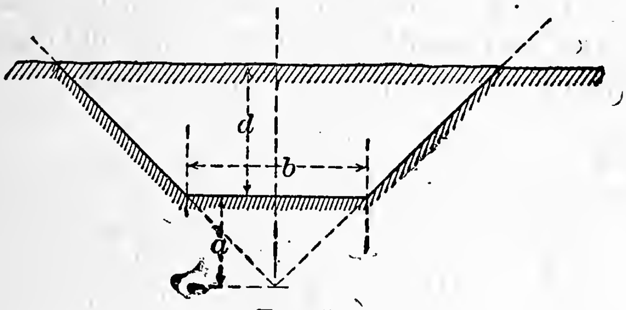


FIG. 50.

are required, it is sometimes assumed that the cross-sections are level. The area of the cross-section may be written

$$(a+d)^2s-\frac{ab}{2}. \quad \ldots \ldots \ldots \quad (46)$$

in which a, b and d are dimensions as indicated by the figure and s is the "slope ratio" or the ratio of the horizontal projection of the slope to the vertical. A table is very readily formed giving the area in square feet of a section of given depth and for any given width of roadbed and ratio of side slopes. Usually these tables give a number which equals that area times 100 and divided by 27, which is the volume in cubic yards of a prism 100 feet long and with that cross-sectional area. Table XVII is such a table.

The volume may also be readily determined (as illustrated in the following example), without the use of such a table; a table of squares will facilitate the work. Assuming the cross-sections at equal distances ($=l$) apart, the total approximate volume for any distance will be

$$\frac{l}{2}[A_0+2(A_1+A_2+\ldots A_{n-1})+A_n]. \quad \ldots \ldots \quad (47)$$

103. Numerical example: level sections. Given the following center heights for the same number of consecutive stations 100 feet apart; width of roadbed 18 feet; slope $1\frac{1}{2}$ to 1.

The products in the fifth column may be obtained very readily and with sufficient accuracy by the use of the slide-rule described in § 106. The products should be considered as $(a+d)(a+d)\div\frac{1}{s}$. In this problem $s=1\frac{1}{2}$, $\frac{1}{s}=.6667$. To apply the rule to the first case above, place 6667 on scale B over 89 on scale A, then opposite 89 on scale B will be found 118.8 on scale A. The position of the decimal point will be evident from an approximate mental solution of the problem.

Sta.	Center Height.	$a+d$	$(a+d)^2$	$(a+d)^2s$	Areas.
17	2.9	8.9	79.21	118.81	118.81
18	4.7	10.7	114.49	171.74	×2 = 343.48
19	6.8	12.8	163.84	245.76	×2 = 491.52
20	11.7	17.7	313.29	469.93	×2 = 939.86
21	4.2	10.2	104.04	156.06	×2 = 312.12
22	1.6	7.6	57.76	86.64	86.64

$$\frac{ab}{2}=\frac{6\times 18}{2}=54$$

2292.43
$10\times 54 =$ 540
1752.43

$$\frac{1752.43\times 100}{2\times 27}=3245 \text{ cub. yards}=\text{approx. vol.}$$

104. Equivalent sections. When sections are very irregular the following method may be used, especially if great accuracy

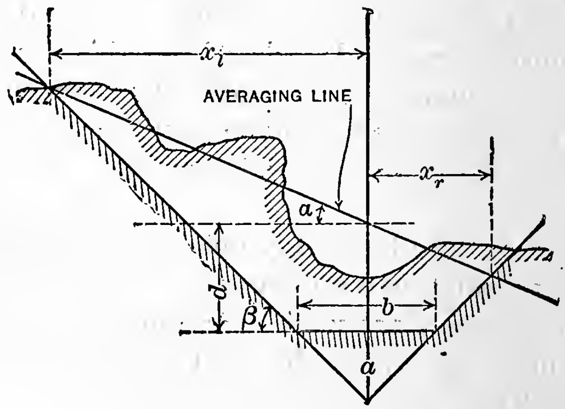


FIG. 51.—EQUIVALENT SECTION.

is not required. The sections are plotted to scale and then a uniform slope line is obtained by stretching a thread so that the undulations are averaged and an *equivalent section* is obtained. Measure the distances (x_l and x_r) from the center. The area may then be obtained independent of the center depth as follows: Let s = the slope ratio of the side slopes $=\cot\beta=\frac{b}{2a}$. (See Fig. 51.) Then the

$$\text{Area}=\frac{1}{2}\left(\frac{x_l+x_r}{s}\right)(x_l+x_r)-\frac{x_r}{s}\frac{x_r}{2}-\frac{x_l}{s}\frac{x_l}{2}-\frac{ab}{2}$$

$$=\frac{x_l x_r}{s}-\frac{ab}{2}. \qquad (48)$$

These approximate methods are particularly useful for rapidly making up monthly estimates, realizing that the inaccuracies, plus and minus, will be wiped out when the final computation is made by a more accurate method.

105. Three-level sections. The next method of cross-sectioning in the order of complexity, and therefore in the order of

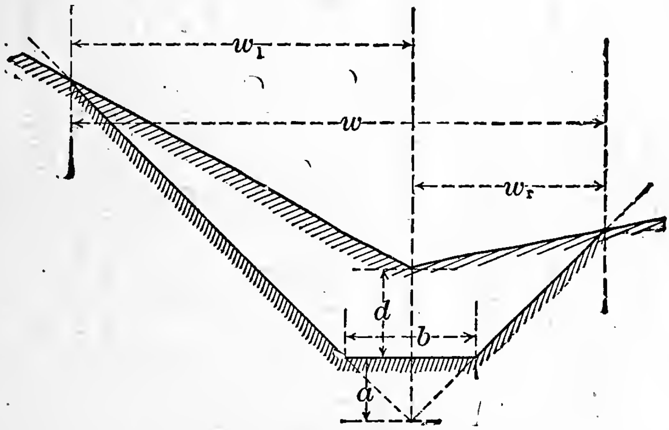


FIG. 52.

accuracy, is the method of three-level sections. The area of the section is $\frac{1}{2}(a+d)(w_r+w_l)-\frac{ab}{2}$, which may be written $\frac{1}{2}(a+d)w-\frac{ab}{2}$, in which $w=w_r+w_l$. If the volume is computed by averaging end areas, it will equal

$$\frac{l}{4}[(a+d')w'-ab+(a+d'')w''-ab]. \qquad (49)$$

Notes.				Approx. Volume.				* Prismoidal correction.			Curvature Correction.†		
Station.	Center.	Left.	Right.	$a+d$	w	Yards.		$d'-d''$	$w''-w'$	Pris. Corr.	$x_l \sim x_r$	$\frac{V(x_l \sim x_r)}{3R}$	Curv. Corr.*
17	$2.6F$	$\frac{10.6F}{22.9}$	$\frac{0.8F}{8.2}$	7.3	31.1	210					14.7	+1	
18	$8.1F$	$\frac{15.8F}{30.7}$	$\frac{3.4F}{12.1}$	12.8	42.8	507	595	−5.5	+11.7	−20	18.6	+3	+4
+ 40	$10.7F$	$\frac{20.2F}{37.3}$	$\frac{4.8F}{14.2}$	15.4	51.5	734	448	−2.6	+ 8.7	− 3	23.1	+6	+4
19	$6.4F$	$\frac{14.0F}{28.0}$	$\frac{2.1F}{10.1}$	11.1	38.1	392	602	+4.3	−13.4	−11	17.9	+2	+5
20	$3.7F$	$\frac{5.8F}{15.7}$	$\frac{0.2F}{7.3}$	8.4	23.0	179	449	+2.7	−15.1	−13	8.4	+1	+3
										−47			+16

Roadbed, 14′ wide in fill.
Slope $1\frac{1}{2}$ to 1.

$$a = \frac{b}{2s} = \frac{14}{3} = 4.7$$

$$\frac{25}{27}ab = 61.$$

Approx. Vol. = 2094
* Pris. corr. = 47

True Vol. = 2047 (disregarding curv. corr.)†

* For the method of computing the prismoidal correction see § 114.

† For the derivation of the curvature correction, see § 124.

If we divide by 27 to reduce to cubic yards, we have, when $l=100$

$$\text{Vol}_{(\prime \ldots \prime\prime)} = \tfrac{25}{27}(a+d')w' - \tfrac{25}{27}ab + \tfrac{25}{27}(a+d'')w'' - \tfrac{25}{27}ab.$$

For the next section

$$\text{Vol}_{(\prime\prime \ldots \prime\prime\prime)} = \tfrac{25}{27}(a+d'')w'' - \tfrac{25}{27}ab + \tfrac{25}{27}(a+d''')w''' - \tfrac{25}{27}ab.$$

For a partial station length compute as usual and multiply result by $\dfrac{\text{length in feet}}{100}$.

The following example is given to illustrate the method of three-level sections.

In the first column of yards

$$210 = \tfrac{25}{27}(a+d)w = \tfrac{25}{27} \times 7.3 \times 31.1;$$

507, 734, etc., are found similarly;

$$595 = 210 - 61 + 507 - 61;$$

$$448 = \tfrac{40}{100}(507 - 61 + 734 - 61);$$

$$602 = \tfrac{60}{100}(734 - 61 + 392 - 61);$$

$$449 = 392 - 61 + 179 - 61.$$

The "*F*" in the columns of center heights, as well as the columns of "right" and "left" are inserted to indicate *fill* for all those points. Cut would be indicated by "*C.*"

106. Computation of products. The quantities $\dfrac{25}{27}(a+d)w$ and $\dfrac{25}{27}ab$ represent in each case the product of two variable terms and a constant. These products are sometimes obtained from tables which are calculated for all ordinary ranges of the variable terms as arguments. A similar table computed for $\dfrac{25}{81}(d'-d'')(w''-w')$ will assist similarly in computing the prismoidal correction, see § 114. Prof. Charles L. Crandall, of Cornell University, is believed to be the first to prepare such a set of tables, which were first published in 1886 "Tables for the Computation of Railway and Other Earthwork." Another easy method of obtaining these products is by the use of a slide-rule. Any slide-rule, from which may be read directly three significant figures and from which the fourth may be read by estimation, can be utilized for this purpose. The Thacher or the Stanley cylindrical rules are still more accurate. To illustrate its use, suppose $(a+d)=28.2$, and $w=62.4$; then

$$\frac{25}{27}(a+d)w=\frac{28.2\times62.4}{1.08}.$$

Set 108 (which, being a constant of frequent use, may be specially marked) on the sliding scale (B) opposite 282 on the other scale (A), and then opposite 624 on scale B will be found 1629 on scale A, the 162 being read directly and the 9 read by estimation. Although strict rules may be followed for pointing off the final result, it only requires a very simple mental calculation to know that the result must be 1629 rather than 162.9 or 16290. For products less than 1000 cubic yards the result may be read directly from the scale; for products between 1000 and 5000 the result may be read directly to the nearest 10 yards, and the tenths of a division estimated. Between 5000 and 10,000 yards the result may be read directly to the nearest 20 yards, and the fraction estimated; but prisms of such volume will never be found as simple triangular prisms—at least, an assumption that any mass of ground was as regular as this would probably involve more error than would occur from faulty estimation of fractional parts. Facilities for reading as high as 10,000 cubic yards would not have been put on the scale except for the necessity of finding such products as $\frac{25}{27}(9.1\times9.5)$, for example. This product would be read off from the same part of the rule as $\frac{25}{27}(91\times95)$. In the first case the product (80.0) could be read directly to the nearest .2 of a cubic yard, which is unnecessarily accurate. In the other case, the product (8004) could only be obtained by estimating $\frac{4}{20}$ of a division.

The computation for the prismoidal correction (see § 114), may be made similarly except that the divisor is 3.24 instead of 1.08. For example, $\frac{25}{81}(5.5\times11.7)=\frac{5.5\times11.7}{3.24}$. Set the 324 on scale B (also specially marked like 108) opposite 55 on scale A, and proceed as before.

107. Approximate volume. Irregular sections. In cross-sectioning irregular sections, the distance from the center and the elevation above "grade" of every "break" in the cross-section must be observed. The area of the irregular section may be obtained by computing the area of the trapezoids (*five*, in Fig. 53) and subtracting the two external triangles. For Fig. 53 the area would be

$$\frac{h_l+k_l}{2}(x_l-y_l)+\frac{k_l+d}{2}y_l+\frac{d+j_r}{2}z_r+\frac{j_r+k_r}{2}(y_r-z_r)$$
$$+\frac{k_r+h_r}{2}(x_r-y_r)-\frac{h_l}{2}\left(x_l-\frac{b}{2}\right)-\frac{h_r}{2}\left(x_r-\frac{b}{2}\right).$$

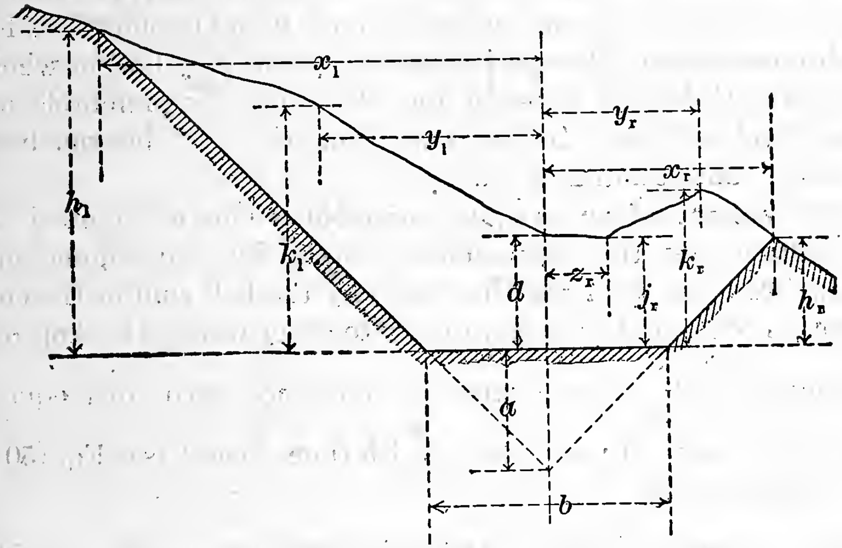


FIG. 53.

Expanding this and collecting terms, of which many will cancel, we obtain

$$\text{AREA}=\frac{1}{2}\Big[x_lk_l+y_l(d-h_l)+x_rk_r+y_r(j_r-h_r)$$
$$+z_r(d-k_r)+\frac{b}{2}(h_l+h_r)\Big]. \quad . \quad . \quad . \quad (50)$$

An examination of this formula will show a perfect regularity in its formation which will enable one to write out a similar formula for any section, no matter how irregular or how many points there are, without any of the preliminary work. The formula may be expressed in words as follows:

AREA equals one-half the sum of products obtained as follows:

the distance to each slope-stake times the height above grade of the point next inside the slope-stake;

the distance to each intermediate point in turn times the height of the point just inside minus the height of the point just outside;

finally, one-half the width of the roadbed times the sum of the slope-stake heights.

If one of the sides is perfectly regular from center to slope-stake, it is easy to show that the rule holds literally good. The "point next inside the slope-stake" in this case is the center; the intermediate terms for that side vanish. The *last term* must always be used. The rule holds good for three-level sections, in which case there are three terms, which may be reduced to two. Since these two terms are both variable quantities for each cross-section, the special method, given in § 105, in which one term ($\frac{1}{2}ab$) is a constant for all sections, is preferable for three-level sections. In the general method, each intermediate "break" adds another term.

108. Volume of an irregular prismoid. This is obtained by computing first the approximate volume by "averaging end areas" or by multiplying the length by the half sum of the end areas, as computed from Eq. (50). In other words, the Approx. volume $= \frac{100}{27} \times \frac{1}{2}$ (area$'$ + area$''$). But since each area equals *one-half* the sum of products of width times height (see Eq. (50)) we may say that

$$\text{Approx. volume} = \frac{25}{27} \text{ (summation of } \textit{width} \text{ times } \textit{height}) \quad . \quad (51)$$

the terms of width times height being like those found within the bracket of Eq. (50).

As before, for partial station lengths, multiply the result by (length in feet ÷ 100). There will be no constant subtractive term, $\frac{25}{27}ab$, as in § 105.

109. Numerical example; approximate volume; irregular sections. Assume the earthwork notes as given below where the roadbed is 18 feet wide in cut and the slope is $1\frac{1}{2}$ to 1. Note that the stations read UP the page and that when the surveyor is looking ahead along the line the several combinations of *heights* and *distances out* have approximately the same relative position on the notebook as they have on the ground. For example, beginning at the bottom line (Sta. 16), the combination $\frac{8.9c}{21.4}$ means that the extreme left-hand point of that section (the "slope-stake") is 22.4 feet horizontally from the center and that it is 8.9 feet above the required roadbed. The cut (c) *would be* 8.9 feet to reach the roadbed, but of course the actual cutting is zero at the slope stake. The next point is 12.0 feet horizontally from the center and 7.6 feet above the roadbed. The cut at the center is 6.8 feet. The combinations of dimensions on the right-hand side are to be interpreted similarly.

Sta.	Center {cut or fill.	Left.			Right.	
19	0.6*c*	$\frac{3.6c}{14.4}$			$\frac{0.1c}{4.2}$	$\frac{0.4c}{9.6}$
18	2.3*c*	$\frac{4.2c}{15.3}$	$\frac{6.8c}{8.4}$	$\frac{3.2c}{5.2}$		$\frac{1.2c}{10.8}$
17	7.6*c*	$\frac{8.2c}{21.3}$	$\frac{10.2c}{17.4}$	$\frac{8.0c}{6.1}$		$\frac{4.2c}{15.3}$
+42	10.2*c*	$\frac{12.2c}{27.3}$		$\frac{12.6c}{8.2}$	$\frac{6.2c}{7.5}$	$\frac{8.4c}{21.6}$
16	6.8*c*	$\frac{8.9c}{22.4}$		$\frac{7.6c}{12.0}$	$\frac{3.2c}{4.1}$	$\frac{2.6c}{12.9}$

The numerical computation is greatly facilitated by a systematic form as given below. For Sta. 16, the first term is "the distance to the left slope stake" (22.4) times "the height above grade of the point next inside" (the height being 7.6), and we place this pair of figures in the columns of "width" and "height." The "distance to the point next inside" is 12.0 and the "height of the point just inside (6.8) minus the height of the point just outside" (8.9) equals (−2.1) and these are the next pair of widths and heights. Taking $\frac{25}{27}$ of the product of each pair of numbers we have the numbers in the first column of "yards." The sum of all these numbers in the first and second groups multiplied by $\frac{42}{100}$ (that section being only 42 feet long) equals 378 cubic yards, the volume by averaging end areas. The determination of center heights and total widths and the application of Eq. (54), to obtain the approximate prismoidal correction (see § 114), is self-evident.

110. Prismoidal correction. The foregoing methods of calculation have been called approximate, although under many

VOLUME OF IRREGULAR PRISMOID, WITH APPROXIMATE PRISMOIDAL CORRECTION.

Sta.	W'th	H'ght	Yards.		Cen. Height.	Total width	$d'-d''$	$w''-w'$	Approx. pris. corr.
	22.4	7.6	158		+6.8	35.3			
	12.0	−2.1	−23						
16	12.9	3.2	40						
	4.1	4.2	16						
	9.0	11.5	96						
	27.3	12.6	319		+10.2	48.9	−3.4	+13.6	−14
	8.2	−2.0	−15						
+42	21.6	6.2	124						
	7.5	1.8	13						
	9.0	20.6	172	378					(−6)
	21.3	10.2	201		+ 7.6	36.6	+2.6	−12.3	−10
	17.4	−0.2	− 3						
17	6.1	−2.6	−14						
	15.3	7.6	107						
	9.0	12.4	103	584					(−6)
	15.3	6.8	95		+ 2.3	26.1	+5.3	−10.5	−17
	8.4	−1.0	− 7						
18	5.2	−4.5	−22						
	10.8	2.3	23						
	9.0	5.4	45	528					(−17)
	14.4	0.6	8		+ 0.6	24.0	+1.7	−2.1	−1
19	9.6	0.1	1						
	4.2	0.2	1						
	9 0	4.0	33	177					(−1)

Approx. volume = 1667 —30
Approx. pris. corr. = −30

Corrected volume = 1637 cubic yards

conditions such results are considered to be sufficiently accurate to serve as final. In any case the approximate result is first computed and then the "prismoidal correction" is computed if necessary. The mathematical necessity for a correction may be at once appreciated from the consideration that the volume of a prismoid having dissimilar and unequal ends is NOT equal to the length times the average of the end areas but is usually somewhat less. In an extreme case the correction is one-third of the approximate volume, or one-half of the true volume. The amount of the prismoidal correction for a triangular prism will be first determined and from that the correction for any kind of prism may be deduced.

Let Fig. 54 represent a triangular prismoid. The two triangles forming the ends lie in *parallel* planes, but since the angles of one triangle are not equal to the corresponding angles of the other triangle, at least two of the surfaces must be *warped.* If a section, parallel to the bases, is made at any point at a dis-

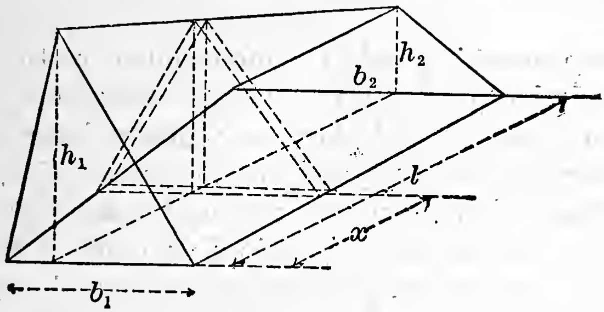


FIG. 54.

tance x from one end, the area of the section will evidently be

$$A_x = \tfrac{1}{2}b_x h_x = \tfrac{1}{2}\left[b_1 + (b_2 - b_1)\frac{x}{l}\right]\left[h_1 + (h_2 - h_1)\frac{x}{l}\right].$$

The volume of a section of infinitesimal length will be $A_x dx$, and the total volume of the prismoid will be *

$$\int_0^l A_x dx = \tfrac{1}{2}\int_0^l \left[b_1 + (b_2 - b_1)\frac{x}{l}\right]\left[h_1 + (h_2 - h_1)\frac{x}{l}\right] dx$$

$$= \tfrac{1}{2}\left[b_1 h_1 x + (b_2 - b_1)h_1\frac{x^2}{2l} + b_1(h_2 - h_1)\frac{x^2}{2l} + (b_2 - b_1)(h_2 - h_1)\frac{x^3}{3l^2}\right]_0^l$$

$$= \tfrac{1}{2}\left\{b_1 h_1 l + [(b_2 - b_1)h_1 + b_1(h_2 - h_1)]\frac{l}{2} + (b_2 - b_1)(h_2 - h_1)\frac{l}{3}\right\}$$

$$= \frac{l}{2}[\tfrac{1}{3}b_1 h_1 + \tfrac{1}{6}b_1 h_2 + \tfrac{1}{6}b_2 h_1 + \tfrac{1}{3}b_2 h_2]$$

$$= \frac{l}{6}[\tfrac{1}{2}b_1 h_1 + \tfrac{1}{2}b_1(h_1 + h_2) + \tfrac{1}{2}b_2(h_1 + h_2) + \tfrac{1}{2}b_2 h_2]$$

$$= \frac{l}{6}\left[\tfrac{1}{2}b_1 h_1 + 4\left(\frac{1}{2}\cdot\frac{b_1 + b_2}{2}\cdot\frac{h_1 + h_2}{2}\right) + \tfrac{1}{2}b_2 h_2\right]$$

$$= \frac{l}{6}]A_1 + 4A_m + A_2], \quad \ldots \quad (52)$$

---

* Students unfamiliar with the Integral Calculus may take for granted the fundamental formulæ that $\int dx = x$, that $\int x dx = \frac{1}{2}x^2$, and that $\int x^2 dx = \frac{1}{3}x^3$; also that in integrating between the limits of l and 0 (zero), the value of the integral may be found by simply substituting l for x after integration.

in which A_1, A_2, and A_m are the areas respectively of the two bases and of the middle section. Note that A_m is *not* the *mean* of A_1 and A_2, although it does not necessarily differ very greatly from it.

The above proof is absolutely independent of the values, absolute or relative, of b_1, b_2, h_1, or h_2. For example, h_2 may be zero and the second base reduces to a line and the prismoid becomes wedge-shaped; or b_2 and h_2 may both vanish, the second base becoming a point and the prismoid reduces to a pyramid. Since every prismoid (as defined in § 97) may be reduced to a combination of triangular prismoids, wedges, and pyramids, and since the formula is true for any one of them individually, it is true for all collectively; therefore it may be stated that *

The volume of a prismoid equals one sixth of the perpendicular distance between the bases multiplied by the sum of the areas of the two bases plus four times the area of the middle section.

While it is always possible to compute the volume of any prismoid by the above method, it becomes an extremely complicated and tedious operation to compute the true value of the middle section if the end sections are complicated in form. It therefore becomes a simpler operation to compute volumes by approximate formulæ and apply, if necessary, a correction. The most common methods are as follows:

111. Correction for triangular prismoid. The volume of the triangular prismoid (Fig. 54), computed by averaging end areas, is $\frac{l}{2}[\frac{1}{2}b_1h_1+\frac{1}{2}b_2h_2]$. Subtracting this from the true volume (as given in the equation above Eq. 52), we obtain the correction

$$\frac{l}{12}[(b_1-b_2)(h_2-h_1)]. \quad . \quad . \quad . \quad . \quad . \quad (53)$$

This shows that if either the h's or b's are equal, the correction vanishes; it also shows that if the bases are roughly similar and b varies roughly with h (which *usually* occurs, as will be seen later), the correction will be *negative*, which means that the method of averaging end areas *usually* gives *too large* results.

If the " base " at one end vanishes to a point, making a trian-

* The student should note that the derivation of equation (52) does not complete the proof, but that the statements in the following paragraph are logically necessary for a general proof.

gular pyramid, then b_1 and h_1 each equal zero and the correction reduces to

$$\frac{l}{12}[(-b_2)(h_2)] = -\frac{lb_2h_2}{12}.$$

But the volume of a triangular prismoid is one-third of the altitude times the area of the base or $\frac{1}{3}l(\frac{1}{2}b_2h_2) = \frac{1}{6}lb_2h_2$. The approximate volume, by averaging end areas, applying the rule strictly, is $\frac{1}{2}l(\frac{1}{2}b_2h_2 + 0) = \frac{1}{4}lb_2h_2$. The correction is therefore one-third of the approximate volume, or one-half of the true volume, in this extreme case. Therefore, when computing the volume of terminal pyramids and wedges (see § 89 and Fig. 43), by the method of averaging end areas, it must be remembered that, although the gross volume is comparatively small, the prismoidal correction is relatively very large.

112. Correction for level sections. Absolutely level sections are practically unknown, and the error involved in assuming any given sections as truly level will ordinarily be greater than the computed correction. If greater accuracy is required, more points should be obtained in the cross-sectioning, which will generally show that the sections are not truly level. But it may be easily computed that the correction equals

$$-\frac{l}{12}\frac{b}{a}\Sigma(d' \sim d'')^2.$$

The squares of the differences of center depth of consecutive sections are always positive, regardless of whether the differences are positive or negative. Therefore the correction is *always* negative, showing that the method of averaging end areas, when the sections are level, *always* gives too large results.

113. Prismoidal correction for "equivalent sections." It is a simple although tedious problem in mathematics to compute algebraically the true and approximate volumes of a prismoid when the areas are determined on the basis of "equivalent sections," § 104, and from thence to derive a formula for the prismoidal correction, but it is generally true that the errors due to such an approximate method of getting the area are so great that it is a needless refinement to compute the correction.

114. Prismoidal correction for three-level sections. The prismoidal correction may be obtained by applying Eq. 53 to each side in turn. For the left side we have

$$\frac{l}{12}[(a+d')-(a+d'')](w_l''-w_l'), \text{ which equals}$$

$$\frac{l}{12}(d'-d'')(w_l''-w_l').$$

For the right side we have, similarly,

$$\frac{l}{12}(d'-d'')(w_r''-w_r').$$

The total correction therefore equals

$$\frac{l}{12}(d'-d'')[(w_l''+w_r'')-(w_l'+w_r')]$$

$$=\frac{l}{12}(d'-d'')(w''-w').$$

Reduced to cubic yards, and with $l=100$,

$$\text{Pris. Corr.}=\tfrac{25}{81}(d'-d'')(w''-w'). \quad . \quad . \quad . \quad (54)$$

Applying this formula to the numerical problem worked out in § 105, the several values of $(d'-d'')$ and $w''-w')$ are computed as given in the first two columns under Prismoidal Correction. Then, for example,

$$-20=\tfrac{25}{81}(d'-d'')(w''-w')=\tfrac{25}{81}(2.6-8.1)(42.8-31.1)$$
$$=\tfrac{25}{81}(-5.5)(+11.7).$$

For the next line, $-3=\frac{40}{100}[\frac{25}{81}(-2.6)(+8.7)]$, and similarly for the rest. For this typical case, the correction is over 2% of the volume and is, as usual, negative, or in other words, the approximate method, if used without correction, allows a contractor in this case 2% too much.

115. Prismoidal correction; irregular sections. For reasons given in the next article, the correction is computed as if the sections were "three-level" sections. This method was used in the numerical problem worked out in § 109. Instead of considering the heights and widths of the separate triangles, the center height and total width for each section is recorded in two columns and the differences $(d'-d'')$ and $(w''-w')$ are computed. $(-3.4)\times(+13.6)\div3.24=-14$, which would be the correction for a section 100 feet long. For 42 feet the correction is 42% of -14 or -6. Note that the total prismoidal correction for this stretch of 300 feet is negative, as is usual, and that it is a little less than 2%, about the same as the numerical problem of § 105.

116. Magnitude of the probable error of this method. In previous editions of this work, methods were given for computing the mathematically exact volume of a prismoid whose ends coincide with the "irregular sections" as measured, and whose upper surfaces are assumed to coincide with the actual surface of the ground. As in the previous methods, the "approximate volume" is computed by averaging end areas and then a correction is applied. If the end sections have the same number of intermediate points on each side, and if it can be assumed that the corresponding lines in each section are connected by plane or warped surfaces, which coincide with the surface of the ground, then the mathematically exact or "true" correction may be obtained by dividing the volume into elementary triangular prismoids, finding the correction for each and adding the results. Although such a method appears very complicated, it is readily possible to develop a law by means of which the true prismoidal correction may be written out (similarly to writing out the formula for the area, Eq. (50)) without any preliminary calculation. Such a law has a mathematical fascination, but it should be remembered that when the ground surface is so broken up that the cross-sections are "irregular" it is in general correspondingly rough and irregular between the cross-sections, especially when those sections are 100 feet apart. It is also true that the cross-sections do *not* usually have the same number of intermediate points on corresponding sides of the center. In such a case, unless the actual form of the ground between the cross-sections is observed and measured, the exact method cannot be used. An extra point in one cross-section implies an extra ridge (or hollow) which "runs out" or disappears by the time the adjoining section is reached. Theoretically a cross-section should be taken at the point where such a ridge or hollow runs out. In general this point will not be at an even 100-foot station. The attempt to compute the exact prismoidal correction usually gives merely a false appearance of extreme accuracy to the work which is not justified by the results. It should not be forgotten that it is readily possible to spend an amount of time on the surveying and computing which is worth more than the few cubic yards of earth which represents the additional accuracy of the more precise method. The accuracy of the office computation should be kept proportionate to the accuracy of the cross-sectioning in the field. The discussion of the magnitude of the prismoidal correction in §§ 110–115 shows that it is small except when the two ends of the prismoid are very dissimilar. The dissimilarity between the two ends of a prismoid would be substantially the same whether the ends were actually "irregular" or had "three-level" sections, which for each end had the same slope stakes and center heights as the irregular sections. Experience proves that the approximate prismoidal correction, computed by considering the ground as three-level, is so nearly equal to the true prismoidal correction that the difference is perhaps no greater than the *probable* difference between the true volume of earth and the volume of the geometrical prismoid which is assumed to represent that volume. The experienced surveyor will take his cross-sections at such places and so close together that the warped surfaces joining the sections will lie very nearly in the surface or at least will so average the errors that they will substantially neutralize each other.

117. Numerical illustration of the accuracy of the approximate rule. The "true" prismoidal correction for the numerical case given in § 109 was computed by the method outlined above, and on the basis of certain figures as to the vanishing of the ridges and valleys found in one section and not found in the adjacent sections. The various quantities for the volumes between the cross-sections have been tabulated as shown.

	1	2	3	4	5	6	7
Sections.	Approx. vol. by averaging end areas.	True prismoidal correction.	True volume.	Approx. pris. corr. on basis of three-level ground.	Error; Col. 4 – col. 2.	Approx. vol. computed from center and side heights *only*.	Error; Col. 6 – col. 3.
16......16+42	378	– 5	373	– 6	–1	396	–23
16+42..17	584	– 3	581	– 6	–3	577	+ 4
17......18	528	–16	512	–17	–1	463	+49
18......19	177	– 3	174	– 1	+2	147	+27
	1667	–27	1640	–30	–3	1583	+57

There has also been shown in the last two columns the error involved if the "intermediate points" had been ignored in the cross-sectioning. From the tabular form we may learn that

1. The *differences* between the "true" and approximate

corrections is so small that it is *probably* swallowed up by errors resulting from inaccurate cross-sectioning.

2. The error which would have been involved in ignoring the intermediate points is so very large in comparison with the other corresponding errors that (although it proves nothing absolutely definite, being an individual case) the *probabilities* of the relative error from these sources are clearly indicated.

118. Cross-sectioning irregular sections. The slope stake should preferably be determined first, and then the "breaks" between the slope stake and the center. When, as is usual, the ground is not even between the cross-section just taken and the section at the next 100-foot station, a point should be selected for a cross-section such that the lines to the previous section should coincide with the actual surface of the ground as closely as the accuracy of the work demands. § 125 gives a numerical illustration of the magnitude of some of these errors. Although it is possible for a skillful surveyor to so choose his cross-sections in rough and irregular ground that the positive and negative errors will nearly balance, it requires exceptional skill. Frequently the work may be simplified by computing separately the volume of a mound or pit, the existence of which has been ignored in the regular cross-sectioning.

119. Side-hill work. When the natural slope cuts the roadbed there is a necessity for both cut and fill at the same cross-section.

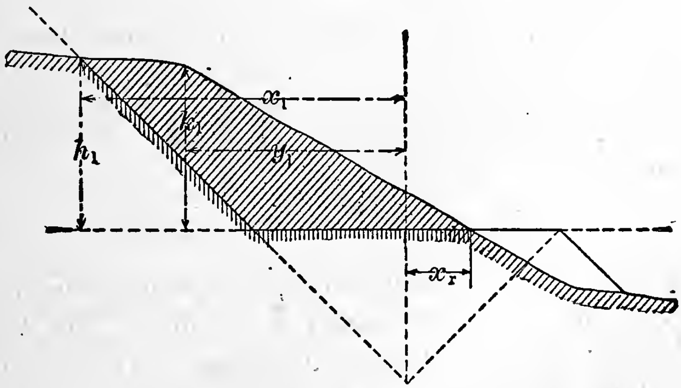


FIG. 55.

When this occurs the cross-sections of both cut and fill are often so nearly triangular that they may be considered as such without great error, and the volumes may be computed separately as triangular prismoids without adopting the more elaborate form of computation so necessary for complicated irregular sections. When the ground is too irregular for this the best plan is to follow the uniform system. In computing the cut, as in Fig. 55, the left side would be as usual; there would be a small center cut and an ordinate of zero at a short distance to the right of the center. Then, *ignoring the fill*, and applying Eq. 56 strictly, we have two terms for the left side, one for the right, and the term involving $\frac{1}{2}b$, which will be $\frac{1}{2}bh_l$ in this case, since $h_r=0$, and the equation becomes

$$\text{Area}_{(\text{Cut})}=\tfrac{1}{2}[x_lk_l+y_l(d-h_l)+x_rd+\tfrac{1}{2}bh_l].$$

The area for fill may also be computed by a strict application of Eq. 50, but for Fig. 56 all distances for the left side are zero and the elevation for the first point out is zero. d also must be

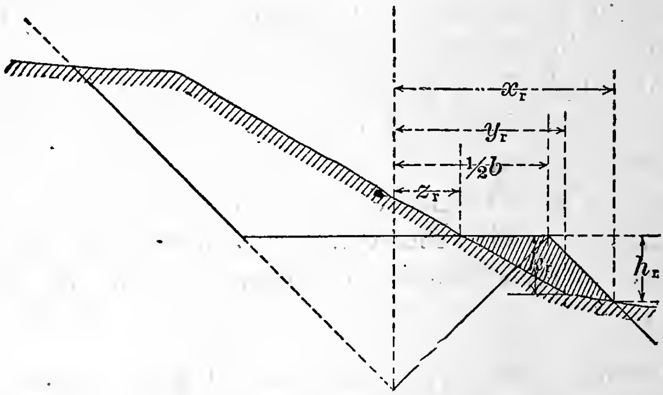


FIG. 56.

considered as zero. Following the rule, § 107, literally, the equation becomes

$$\text{Area}_{(\text{Fill})}=\tfrac{1}{2}[x_rk_r+y_r(o-h_r)+z_r(o-k_r)+\tfrac{1}{2}b(o+h_r)],$$

which reduces to

$$\tfrac{1}{2}[x_rk_r-y_rh_r-z_rk_r+\tfrac{1}{2}bh_r].$$

(*Note* that x_r, h_r, etc., have different significations and values in this and in the preceding paragraphs.) The "terminal pyramids" illustrated in Fig. 43 are instances of side-hill work for very short distances. Since side-hill work always implies *both* cut and fill at the same cross-section, whenever either the cut or fill disappears and the earthwork becomes wholly cut or wholly fill, that point marks the end of the "side-hill work," and a cross-section should be taken at this point.

120. Borrow-pits. The cross-sections of borrow-pits will vary not only on account of the undulations of the surface of the

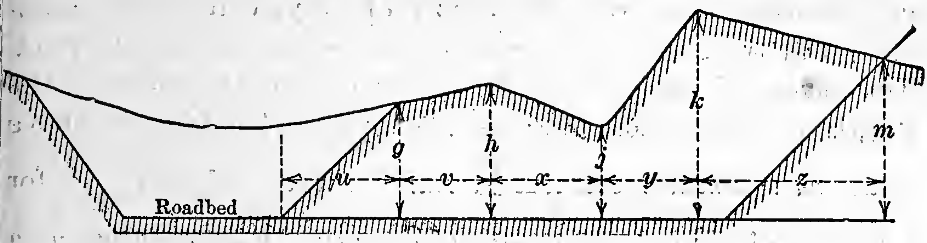


FIG. 57.

ground, but also on the sides, according to whether they are made by widening a convenient cut (as illustrated in Fig. 57) or simply by digging a pit. The sides should always be properly sloped and the cutting made cleanly, so as to avoid unsightly roughness. If the slope ratio on the right-hand side (Fig. 57) is s, the area of the triangle is $\frac{1}{2}sm^2$. The area of the section is $\frac{1}{2}[ug+(g+h)v+(h+j)x+(j+k)y+(k+m)z-sm^2]$. If all the horizontal measurements were referred to one side as an origin, a formula similar to Eq. 50 could readily be developed, but little or no advantage would be gained on account of any simplicity of computation. Since the *exact* volume of the earth borrowed is frequently necessary, the prismoidal correction should be computed; and since such a section as Fig. 57 does not even approximate to a three-level section, the method suggested in § 115 cannot be employed. It will then be necessary to employ the more exact method of dividing the volume into triangular prismoids and taking the summation of their corrections, found according to the general method of § 111.

121. Correction for curvature. The volume of a solid, generated by revolving a plane area about an axis lying in the plane but outside of the area, equals the product of the given area times the length of the path of the center of gravity of the area. If the centers of gravity of all cross-sections lie in the center of the road, where the length of the road is measured, there is absolutely no necessary correction for curvature. If all the cross-sections in any given length were exactly the same and therefore had the same eccentricity, the correction for curvature would be very readily computed according to the above principle. But when both the areas and the eccentricities vary from point to point, as is generally the case, a theoretically exact solution is quite complex, both in its derivation and application. Suppose, for simplicity, a curved section of the road, of uniform cross-sections and with the center of gravity of every cross-section at the same distance e from the center line of the road. The length of the path of the center of gravity will be to the length of the center line as $R \pm e : R$. Therefore we have *True vol.*: *nominal vol.* $:: R \pm e : R$. $\therefore$ *True vol.* $= lA\frac{R \pm e}{R}$ for a volume of uniform area and eccentricity. For any other area and eccentricity we have, similarly, *True vol.'* $= lA'\frac{R \pm e'}{R}$. This shows that the effect of curvature is the same as increasing (or diminishing) the area by a quantity depending on the area and eccentricity, the increased (or diminished) area being found by multiplying the actual area by the ratio $\frac{R \pm e}{R}$. This being independent of the value of l, it is true for infinitesimal lengths. If the eccentricity is assumed to vary uniformly between two sections, the *equivalent area* of a cross-section located midway between the two end cross-sections would be $A_m\frac{\left(R \pm \frac{e'+e''}{2}\right)}{R}$. Therefore the volume of a solid which, when straight, would be $\frac{l}{6}(A'+4A_m+A'')$, would then become

$$\textit{True vol.} = \frac{l}{6R}\left[A'(R \pm e') + 4\,A_m\left(R \pm \frac{e'+e''}{2}\right) + A''(R \pm e'')\right].$$

Subtracting the nominal volume (the true volume when the prismoid is straight), the

$$\textit{Correction} = \pm\frac{l}{6R}\left[(A'+2A_m)e' + (2A_m+A'')e''\right]. \qquad (55)$$

Another demonstration of the same result is given by Prof. C. L. Crandall in his "Tables for the Computation of Railway and other Earthwork," in which is obtained by calculus methods the summation of elementary volumes having variable areas with variable eccentricities. The exact application of Eq. 55 requires that A_m be known, which requires laborious computations, but no error worth considering is involved if the equation is written approximately

$$Curv.\ corr. = \frac{l}{2R}(A'e' + A''e''), \quad . \quad . \quad . \quad . \quad (56)$$

which is the equation generally used. The approximation consists in assuming that the difference between A' and A_m equals the difference between A_m and A'' but with opposite sign. The error due to the approximation is always utterly insignificant.

122. Eccentricity of the center of gravity. The determination of the true positions of the centers of gravity of a long series of irregular cross-sections would be a very laborious operation, but fortunately it is generally sufficiently accurate to consider the cross-sections as three-level ground, or, for side-hill work, to

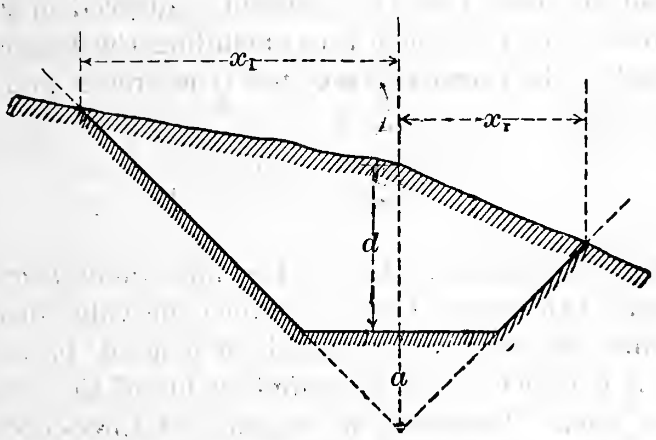


FIG. 58.

be triangular, *for the purpose of this correction.* The eccentricity of the cross-section of Fig. 58 (including the grade triangle) may be written

$$e = \frac{\frac{(a+d)x_l}{2}\frac{x_l}{3} - \frac{(a+d)x_r}{2}\frac{x_r}{3}}{\frac{(a+d)x_l}{2} + \frac{(a+d)x_r}{2}} = \frac{1}{3}\frac{x_l^2 - x_r^2}{x_l + x_r} = \frac{1}{3}(x_l - x_r). \quad . \quad (57)$$

The side toward x_l being considered positive in the above demonstration, if $x_r > x_l$, e would be negative, i.e., the center of gravity would be on the right side. Therefore, for three-level ground, the correction for curvature (see Eq. 56) may be written

$$Correction = \frac{l}{6R}[A'(x_l' - x_r') + A''(x_l'' - x_r'')].$$

Since the approximate volume of the prismoid is

$$\frac{l}{2}(A + A') = \frac{l}{2}A' + \frac{l}{2}A'' = V' + V'',$$

in which V' and V'' represent the number of cubic yards corresponding to the area at each station, we may write

$$Corr.\ in\ cub.\ yds. = \frac{1}{3R}[V'(x_l' - x_r') + V''(x_l'' - x_r'')]. \quad (58)$$

It should be noted that the value of e, derived in Eq. 57, is the eccentricity of the whole area including the triangle under the roadbed. The eccentricity of the true area is greater than this and equals

$$e \times \frac{\text{true area} + \frac{1}{2}ab}{\text{true area}} = e_1.$$

The required quantity ($A'e'$ of Eq. 56) equals *true area* $\times e_1$ which equals (*true area* $+ \frac{1}{2}ab) \times e$. Since the value of e is very simple, while the value of e_1 would, in general, be a complex quantity, it is easier to use the simple value of Eq. 57 and add $\frac{1}{2}ab$ to the area. Therefore, in the case of three-level ground the subtractive term $\frac{25}{27}ab$ (§ 105) should *not* be subtracted in computing this correction. For irregular ground, when computed by the method given in §§ 107 and 108, which does not involve the grade triangle, a term $\frac{25}{27}ab$ must be *added* at every station when computing the quantities V' and V'' for Eq. 58.

It should be noted that the factor $1 \div 3R$, which is constant for the length of the curve, may be computed with all necessary accuracy and without resorting to tables by remembering that

$$R = \frac{5730}{\text{degree of curve}}.$$

Since it is useless to attempt the computation of railroad earthwork closer than the nearest cubic yard, it will frequently be possible to write out all curvature corrections by a simple mental process upon a mere inspection of the computation sheet. Eq. 58 shows that the correction for each station is of the form $\frac{V(x_l-x_r)}{3R}$. $3R$ is generally a large quantity—for a 6° curve it is 2865. (x_l-x_r) is generally small. It may frequently be seen by inspection that the product $V(x_l-x_r)$ is roughly twice or three times $3R$, or perhaps less than half of $3R$, so that the corrective term for that station may be written 2, 3, or 0 cubic yards, the fraction being disregarded. For much larger absolute amounts the correction must be computed with a correspondingly closer percentage of accuracy.

The algebraic sign of the curvature correction is best determined by noting that the center of gravity of the cross-section is on the right or left side of the center according as x_r is greater or less than x_l, and that the correction is *positive* if the center of gravity is on the *outside* of the curve, and *negative* if on the *inside*.

It is frequently found that x_l is uniformly greater (or uniformly less) than x_r throughout the length of the curve. Then the curvature correction for each station is uniformly positive or negative. But in irregular ground the center of gravity is apt

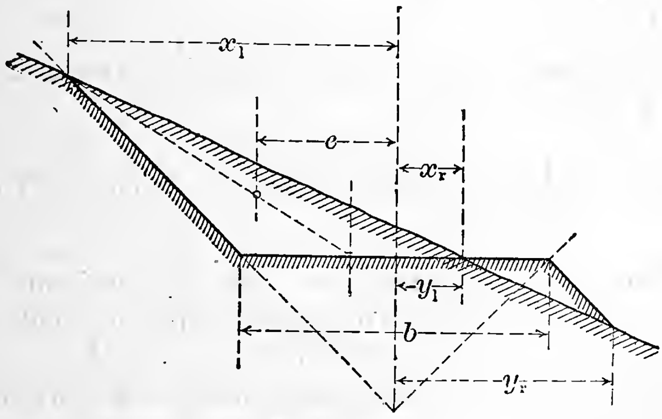


FIG. 59.

to be irregularly on the outside or on the inside of the curve, and the curvature correction will be correspondingly positive or negative. If the curve is to the *right*, the correction will be positive or negative according as (x_l-x_r) is positive or negative; if the curve is to the *left*, the correction will be positive or negative according as $(x_r - x_l)$ is positive or negative. Therefore when computing curves to the *right* use the form $(x_l - x_r)$ in Eqs. 58 and 60; when computing curves to the *left* use the form $(x_r - x_l)$ in these equations; the algebraic sign of the correction will then be strictly in accordance with the results thus obtained.

123. Center of gravity of side-hill sections. In computing the correction for side-hill work the cross-section would be treated as triangular unless the error involved would evidently be too great to be disregarded. The center of gravity of the triangle lies on the line joining the vertex with the middle of the base and at $\frac{1}{3}$ of the length of this line from the base. It is therefore equal to the distance from the center to the foot of this line plus $\frac{1}{3}$ of its horizontal projection. Therefore

$$e = \left[\frac{b}{2} - \frac{1}{2}\left(\frac{b}{2} + x_r\right)\right] + \frac{1}{3}\left[x_l - \left(\frac{b}{2} - \frac{1}{2}\left(\frac{b}{2} + x_r\right)\right)\right]$$

$$= \frac{b}{4} - \frac{x_r}{2} + \frac{x_l}{3} - \frac{b}{12} + \frac{x_r}{6}$$

$$= \frac{b}{6} + \frac{x_l}{3} - \frac{x_r}{3}$$

$$= \frac{1}{3}\left[\frac{b}{2} + (x_l - x_r)\right]. \quad \quad (59)$$

By the same process as that used in § 122 the correction equation may be written

$$\text{Corr. in cub. yds.} = \frac{1}{3R}\left[V'\left(\frac{b}{2} + (x_l' - x_r')\right) + V''\left(\frac{b}{2} + (x_l'' - x_r'')\right)\right]. \quad (60)$$

It should be noted that since the grade triangle is not used in this computation the volume of the grade prism is *not* involved in computing the quantities V' and V''.

The eccentricities of cross-sections in side-hill work are *never* zero, and are frequently quite large. The total volume is generally quite small. It follows that the correction for curvature is generally a vastly larger proportion of the total volume than in ordinary three-level or irregular sections.

If the triangle is wholly to one side of the center, Eq. 59 can still be used. For example, to compute the eccentricity of the triangle of fill, Fig. **59**, denote the two distances to the slope-stakes by y_r and $-y_l$ (note the minus sign). Applying Eq. 59 literally (noting that $\frac{b}{2}$ must here be considered as negative in order to make the notation consistent) we obtain

$$e=\frac{1}{3}\left[-\frac{b}{2}+(-y_l-y_r)\right],$$

which reduces to

$$e=-\frac{1}{3}\left[\frac{b}{2}+y_l+y_r\right]. \quad . \quad . \quad . \quad . \quad . \quad (61)$$

As the algebraic signs tend to create confusion in these formulæ, it is more simple to remember that for a triangle lying on *both* sides of the center e is always numerically equal to $\frac{1}{3}\left[\frac{b}{2}+(x_l \sim x_r)\right]$, and for a triangle entirely on one side, e is numerically equal to $\frac{1}{3}\Big[\frac{b}{2}$ + the numerical *sum* of the two distances out]. The algebraic sign of e is readily determinable as in § 122.

124. Example of curvature correction. Assume that the fill in § 105 occurred on a 6° curve to the *right*. $\frac{1}{3R}=\frac{1}{2865}$. The quantities 210, 507, etc., represent the quantities V', V'', etc., since they include in each case the 61 cubic yards due to the grade prism. Then

$$\frac{V(x_l \sim x_r)}{3R}=\frac{210(22.9-8.2)}{2865}=\frac{3101.7}{2865}=+1.$$

The sign is plus, since the center of gravity of the cross-section is on the left side of the center and the road curves to the right, thus making the true volume larger. For Sta. 18 the correction, computed similarly, is +3, and the correction for the whole section is $1+3=4$. For Sta. 18+40 the correction is computed as 6 yards. Therefore, for the 40 feet, the correction is $\frac{40}{100}(3+6)=3.6$, which is called 4. Computing the others similarly we obtain a total correction of +16 cubic yards.

125. Accuracy of earthwork computations. The preceding methods give the *precise volume* (except where approximations are distinctly admitted) of the prismoids which are *supposed* to represent the volume of the earthwork. To appreciate the accuracy necessary in cross-sectioning to obtain a given accuracy in volume, consider that a fifteen-foot length of the cross-section, which is assumed to be straight, really sags 0.1 foot, so that the cross-section is in error by a triangle 15 feet wide and 0.1 foot high. This sag 0.1 foot high would hardly be detected by the eye, but in a length of 100 feet in each direction it would make an error of volume of 1.4 cubic yards in *each* of the two prismoids, assuming that the sections at the other ends were perfect. If the cross-sections at both ends of a prismoid were in error by this same amount, the volume of that prismoid would be in error by 2.8 cubic yards if the errors of area were both plus or both minus. If one were plus and one minus, the errors would neutralize each other, and it is the compensating character of these errors which permits any confidence in the results as obtained by the usual methods of cross-sectioning. It demonstrates the utter futility of attempting any closer accuracy than the nearest cubic yard. It will thus be seen that if an error really exists at *any* cross-section it involves the prismoids on *both* sides of the section, even though all the other cross-sections are perfect. As a further illustration, suppose that cross-sections were taken by the three-level method (§ 105), and that a cross-section, assumed as uniform from center to side, sags 0.4 foot in a width of 20 feet. Assume an equal error (of same sign) at the other end of a 100-foot section. The error of volume for that one prismoid is 38 cubic yards.

The computations further assume that the warped surface, passing through the end sections, coincides with the surface of the ground. Suppose that the cross-sectioning had been done with mathematical perfection; and, to assume a simple case, suppose a sag of 0.5 foot between the sections, which causes an error equal to the volume of a pyramid having a base of 20 feet (in each cross-section) times 100 feet (between the cross-sections) and a height of 0.5 foot. The volume of this pyramid is $\frac{1}{3}(20\times100)\times0.5=333$ cub. ft. $=12$ cub. yds. And yet this sag or hump of 6 inches would generally be utterly unnoticed, or at least disregarded.

When the ground is very rough and broken it is sometimes practically impossible, even with frequent cross-sections, to locate warped surfaces which will closely coincide with all the sudden irregularities of the ground. In such cases the computations are necessarily more or less approximate and dependence must be placed on the compensating character of the errors.

126. Approximate computations from profiles. When a "paper location" has been laid out on a topographical map having contours, it is possible to compute approximately the amount of earthwork required by some very simple and rapid calculations. A profile may be readily drawn by noting the intersections of the proposed center line with the various contours and plotting the surface line on profile paper. Drawing the grade-line on the profile, the depth of cut or fill may be scaled off at any point. When it is only desired to obtain

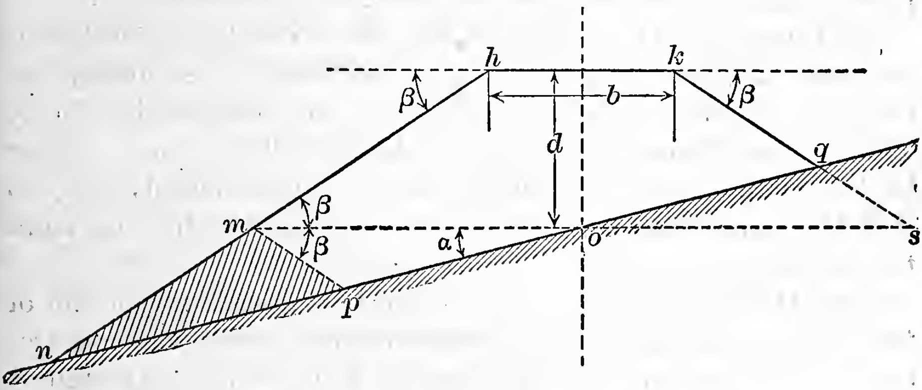


FIG. 60.

very quickly an approximate estimate of the amount of earthwork required on a suggested line, it may be done by the method described in § 103, or by the use of Table XVII. But the assumption that the surface of the ground at each cross-section is level invariably has the effect that the estimated volumes are not as large as those actually required. The difference between the "level section" *hkms* and the actual slope section *hknq* equals the difference between the triangles *mon* and *oqs*, and this difference equals the shaded area *mpn*. The excess volume is proportional to the area of the triangle *mpn*. This area may be expressed by the formula,

$$\text{Area } mpn = 2(\tfrac{1}{2}b + d \cot \beta)^2 \frac{\sin^2\alpha \sin\beta \cos\beta}{\cos 2\alpha - \cos 2\beta}.$$

The percentage of this excess area to the nominal area *hkms* therefore depends on the dimensions b and d and the angles α and β. A solution of this equation for ninety different combinations of various numerical values for these four variables is included in Table XVII for the purpose of making corrections. A study of this correction table points conclusively to the following laws, a thorough understanding of which will enable an engineer to appreciate the degree of accuracy which is attainable by this approximate method:

(*a*) Increasing the *width* of the roadbed (b), the other three factors remaining constant, *increases* the percentage of error, but the increase is comparatively small.

(*b*) Increasing the *depth* of cut or fill (d), *decreases* the percentage of error, but the decrease is almost insignificant.

(*c*) Increasing the angle of the side slopes (β) *decreases* the percentage of error, the decrease being very considerable.

(*d*) Increasing the angle of the slope of the ground (α), *increases* the percentage of error, the percentage rapidly increasing to infinity as the value of α approaches that of β. This is another method of stating the fact that α must always be less than β and, practically, must be considerably less, so that the slope stake shall be within a reasonable distance from the center.

Since the above value for the corrective area is a function of the angle α, which is usually variable and whose value is frequently known only approximately, it is useless to attempt to apply the correction with great precision, and the following rules will usually be found amply accurate, considering the probable lack of precision in the data used.

1. For embankments or cuts, having a slope of 1.5:1, and with a surface slope of 5° (nearly 9%) the excess of true area over nominal area is *about* 2%. There is only a slight variation from this value for all ordinary depths (d) and widths (b) of roadbed. Therefore the nominal volume would be about 2% too *small*. On the other hand, the effect of the prismoidal correction is such that, even with truly level sections, the nominal volume is too *large*. See §§ 103 and 112. The amount of the prismoidal correction depends on the differences between successive center depths. In the very ordinary numerical case given in § 103, the correction was nearly 3%, which more than neutralizes the error due to surface slope. Therefore in

many cases on slightly sloping ground the error due to the surface slope will so nearly neutralize the prismoidal correction that the quantities taken directly from the tables (without correction for either cause) will equal the true volume with as close an approach to accuracy as the precision of the surveying will permit.

2. For a cut with a slope of 1:1, and with a surface slope of 5° the error is about 1%. This will be neutralized by still smaller prismoidal corrections. Therefore, for surface slopes of 5° or less, no allowance should be made for this error unless the prismoidal correction is also considered.

3. When the surface slope is 10° (nearly 18%) the error for a 1.5:1 slope is from 7% to 10% and for a 1:1 slope from 3% to 5%.

4. For a 30° surface slope and 1.5:1 side slopes the excess volume is three or four times the nominal volume. Such a steep surface slope implies the probability of "side-hill work" to which the above corrective rules are not applicable. When the surface slopes are very steep careful work must be done to avoid excessive error. For a 1:1 side slope, the errors are from 50% to 80%.

A still closer approximation, especially for the steeper surface slopes, may be obtained by using, directly or by interpolation, figures from the corrective tabular form which forms part of Table XVII. Unless the surface slope angle is known accurately (especially when large) no great accuracy in the final result is possible. Close accuracy would also require the determination of the prismoidal correction. But if such close accuracy is deemed essential, it can be most easily obtained by accurate cross-sectioning at each station and the adoption of other methods of computation—such as are given in §§ 108 and 109.

When the contours have been drawn in for a sufficient distance on either side to include the position of both slope stakes at every station, as will usually be the case, cross-sections may be obtained by drawing lines on the map at each station perpendicular to the center line—see Fig. 4. The intersection of these lines with the contours will furnish the distances for drawing on cross-section paper the transverse profile at each station. Drawing on the same cross-section the lines representing the roadbed and the side slopes, the cross-section of cut (or fill) is complete and its area may be obtained by scaling from the cross-section paper. If the contours have been located on the map with sufficient accuracy, such a method will determine the cross-sectional area very closely. When cross-sections have been taken with a wye- or hand-level, as described in § 12, the cross-sections as plotted will probably be more accurate than when the contours are run in from points determined by the stadia method. In fact this semi-graphical method is frequently used, in place of the purely numerical methods described in previous sections, to make final estimates of the volume of earthwork.

As a numerical example, an assumed location line was laid out on the contours given in Fig. 4. The volume of cut, as determined by Table XVII for a roadbed 20 feet wide, with side slopes of 1:1, was 5746 cubic yards. The surface slope varied from 3° to 11°. Computing the corrections by a careful interpolation from the corrective table, the total correction was found to be 128 cubic yards, or an average of a little over 2%. On the other hand the negative prismoidal correction amounts to 72 cubic yards, which leaves a net correction of 56 cubic yards—about 1%. It so happens that in this case a correction for curvature would tend further to wipe out this correction. These figures merely verify numerically the general conclusions stated above, although it should not be forgotten that in individual cases the figures taken from Table XVII require ample correction.

The following approximate rule, for which the author is indebted to Mr. W. H. Edinger, is exceedingly useful when it is desired to rapidly determine the approximate volume of earthwork between two points along the road. Its great merit lies in the fact that it only means the memorizing of a comparatively simple rule which will make it possible to make such computations in the field, without the use of tables. The rule is based on the fact that the area of any level section equals $bd+sd^2$; and therefore,

$$\Sigma(\text{vol.}) = (b\Sigma d + s\Sigma d^2)\frac{L}{27},$$

in which L is usually 100 feet. For strict accuracy this would only be the volume provided the total length was an even number of hundred feet, and the various values of d represented the depths which were uniform for hundred foot sections. It makes no allowance for the comparatively large prismoidal error of the pyramidal and wedge-shaped sections usually found at each end of a cut or fill, but where an approximate estimate is desired, in which this inaccuracy may be neglected, the method is very useful. The method of applying this rule without tables may best be illustrated by a simple numerical example. Assume that the levels on a stretch of fairly level ground, which is about 500 feet long, have been taken, the depths being taken at points 100 feet apart, the first and last points being about 40 or 50 feet from the ends of the cut, or fill. The depths are as given in the first column in the tabular form below; the slope is 1.5:1, and the breadth (b) is 14 feet.

d	d^2
1.6	2.56
2.8	7.84
4.5	20.25
3.1	9.61
0.9	.81
$\Sigma d = 12.9$	$\Sigma d^2 = 41.07$
14	adding one half $= 20.53$
$b\Sigma d = 180.6$	$s\Sigma d^2 = 61.60$
61.60	
242.2	

$$24220 \div 27 = 897 \text{ cubic yards.}$$

The 180.6 is the $b\Sigma d$ and the 61.6 is $s\Sigma d^2$; adding these and moving the decimal point two places to multiply by 100, we only have to divide by 27 to obtain the value in cubic yards. Although the above rule requires more work than the employment of earthwork tables, yet it is a very convenient method of estimating the approximate volume of a short section of earthwork when no tables are at hand.

FORMATION OF EMBANKMENTS.

127. Shrinkage of earthwork. The statistical data indicating the amount of shrinkage is very conflicting, a fact which is probably due to the following causes:

1. The various kinds of earthy material act very differently as respects shrinkage. There is a great lack of uniformity in

the *classification of earths* in the tests and experiments which have been made.

2. Very much depends on the *method* of forming an embankment (as will be shown later). Different reports have been based on different methods—often without mention of the method.

3. An embankment requires considerable *time* to shrink to its final volume, and therefore much depends on the time elapsed between construction and the measurement of what is supposed to be the settled volume.

4. A soft subsoil will frequently settle under the weight of a high embankment and apparently indicate a far greater shrinkage than the actual reduction in volume.

5. An embankment of very soft material will sometimes "mush" or widen at the sides, with a consequent settling of the top, due to this cause alone, but such settlement would indicate that unsuitable material had been used to form the embankment.

As a summary of the extensive discussion and wide range of shrinkage factors which might be quoted, the following facts may be stated:

1. The *density* of natural soil increases with its depth below the surface. Some careful and accurate tests of some "clay, loam and gumbo," made on the C. B. & Q. R. R., showed an increase from 70 lbs. per cubic foot at the surface to 121 lbs. per cubic foot (an increase of over 70%) at a depth of 25 feet.

2. Freshly excavated material of whatever character occupies a greater volume in a cart or other conveyor, or when loosely deposited, than it did in the original excavation.

3. After being deposited it usually shrinks more or less from its volume as loose material. This shrinkage increases with age and with the amount of traffic over it. When the material is deposited in small increments from wagons or carts and each layer is subjected to compression from horses' hoofs and from wheels, the contraction during construction is very great and the subsequent shrinkage is comparatively small.

4. Light vegetable mould or "top soil," and, in general, all naturally deposited soil to a depth of 3 to 5 feet, will shrink until its final volume is less than its volume in its original state.

5. On the other hand, compact earth, taken from the bottom of a deep excavation, and also rock, although it may shrink

somewhat from its volume as measured in carts, cars, or other conveyors, will never shrink to its volume in the original excavation, and will always occupy a larger volume in an embankment.

6. An embankment continues to shrink with age, due to the pressure of superincumbent material and also due to the pressure and vibration caused by traffic. This law was clearly indicated by the following figures from the C. B. & Q. R. R. tests, where three embankments were:

(*a*) 17 years old; no traffic............................shrinkage, 6.7%
(*b*) 49 " " abandoned after 32 years of light traffic. " 12.9%
(*c*) 17 " " constantly under heavy traffic......... " 13.6%

7. If an embankment is formed by dropping earth from a trestle, there is no compression during formation and the shrinkage will be long-drawn-out, especially if the material is light and the track continues for some time to be supported by the floor system of the trestle.

8. The mere weight of an embankment, augmented by the vibrating action of heavy traffic, will compress the natural soil on which an embankment is placed. The depth of this compression will vary from zero for a rocky surface to an indefinite and unceasing settlement into a "bottomless bog." This effect, distinct from the shrinkage of the volume of embankment material, is called **subsidence.** It always occurs to some extent on ordinary grazing or agricultural land, which means under the majority of embankments. The *percentage* of subsidence will be greater for a low than for a high embankment, since the area of the base is less and the tamping action of traffic is more direct and effective. Investigation, by borings and the digging of test pits, has shown that there is sometimes as much (or more) deposited material below the original surface line as that in the visible embankment above. This means that when an embankment is to be formed on soft, or even ordinary agricultural ground, considerably more material must be deposited than is called for by the nominal cross-sections above the original surface lines. The extent of such subsidence cannot be accurately predicted. It is even more difficult than to predict the ultimate shrinkage of a volume of excavated material after being formed into an embankment. When subsidence is altogether ignored, the almost inevitable result is a future sag of the grade line on embankments, which can only be restored by comparatively expensive raising of the track under traffic

conditions. Instances are not uncommon where a company has been compelled to change a location after having deposited on a seemingly bottomless bog a volume of material several times the volume of the desired visible embankment. Of course such cases are exceptional, but the engineer must use judgment, aided perhaps by boring into a soft soil, to estimate how much the subsidence will prove to be.

9. A sharp and clear distinction should be made between the *coefficient of extra height* of an embankment and the *coefficient of shrinkage* which determines how many cubic yards of settled embankment may be made from a definite volume of earth or rock measured in the excavation. Even if the coefficient of volume shrinkage were accurately known, the effect of subsidence must still be allowed for, and the coefficient of extra height must be a composite of these two effects. The effect of the method of formation of the embankment must also be considered. If the material is compacted during construction, some of the shrinkage will have been accomplished and some of the subsidence will have taken place by the time the embankment is up to grade line and only the *future* shrinkage and subsidence must be allowed for, although more material has been used than the profile seemed to call for. A rock embankment will not shrink appreciably after formation and in such case only the future subsidence need be allowed for.

10. The very serious expense of raising the grade of a track under traffic may be reduced if not altogether avoided by modifying the normal grade line over an embankment, substantially as shown in Fig. 62. Whatever may be the coefficients of shrinkage and subsidence, the lowering of the grade line by these combined effects will be greater for a high than for a low embankment, and any allowance must be in principle as shown in Fig. 62. From 8% to 15% is sometimes quoted as the required extra height of embankments, although it is strenuously claimed by many that 3% or 2% is sufficient, or even that *no* allowance should be made.

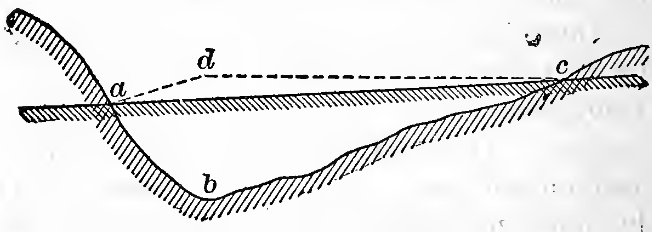


FIG. 62.

128. Proper allowance for shrinkage or subsidence. It follows from the above considerations that no simple and set rules may be prescribed, either for the coefficient of shrinkage (or expansion) or for the coefficient of extra height, since the coefficients will depend on the kind of material, its depth in the cutting, the method of formation of the embankment, the time during which complete settlement is assumed to take place, and even on the intensity of the traffic which will run over the embankment. And also, since an embankment will be formed from materials taken from various depths of excavation, and also from various cuttings containing perhaps several kinds of material, it follows that the real coefficient will be a composite figure whose exact value will be impossible to determine, even if some of the elements could be determined with substantial accuracy. Therefore the allowance to be made when forming any embankment must be estimated according to judgment, after allowing for all of the factors involved. The following figures have the weight of considerable authority and may be used as a guide in making up a composite figure which will best suit any particular case.

Gravel or sand	will shrink about	8%
Clay	" " "	10%
Loam	" " "	12%
Loose vegetable surface soil	" " "	15%
Rock, large pieces	" expand "	40%
" small pieces	" " "	60%

To utilize such figures we might say, for example, that, if some material will shrink 8%, 1000 cubic yards of it, measured in place, will make $1000-80=920$ cubic yards of *settled* embankment. If the material is a mixture of earth and rock, for which a composite figure of 20% expansion is estimated to be correct, 1000 cubic yards of such excavation will make 1200 cubic yards of settled embankment. Even this calculation ignores subsidence, which must be estimated separately.

129. Methods of forming embankments. Embankments of moderate height are sometimes formed by scraping material with drag scrapers from ditches at the sides, especially if there is little or no cutting to be done in the immediate vicinity. Over a low level swampy stretch this method has the double advantage of building an embankment which is well above the general level and also provides generous drainage ditches which keep the embankment dry. Wheeled scrapers may be used economically up to a distance of 400 feet to excavate cuts and deposit the material on low embankments. Such methods have the advantage of compacting the embankments during construction and reducing future shrinkage.

When carts are used, an embankment of any height may be formed by "dumping over the end" and building to the full height (or even higher to allow for shrinkage) as the embankment proceeds. The method is especially applicable when the material comes from a place as high as or higher than the grade-line, so that no up-hill hauling is necessary. Only a small contractor's plant is required for all of these methods.

Trestles capable of carrying carts, or even cars and locomotives, from which excavated material may be dropped, are found to be economical in spite of the fact that their cost is a construction expense. There is the disadvantage that such embankments require a long time to settle, but there are the advantages that the earth may be hauled by the train load from a distance of perhaps several miles, dumped from the

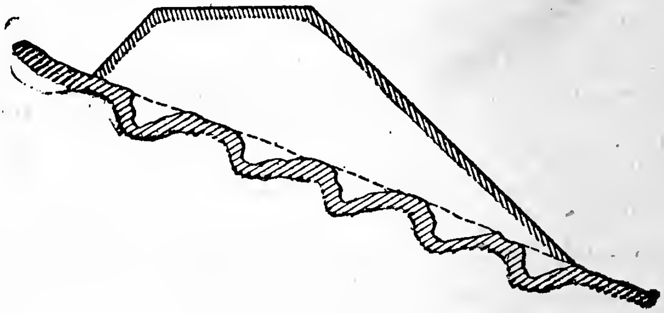


FIG. 63.

cars by train ploughs, or automatically dumped when the material is carried in patent dumping-cars, and all at a comparatively small cost per cubic yard. The disadvantages of slow settlement may be obviated, although at some additional cost, by making the trestle sufficiently strong to support regular traffic until the settlement is complete.

During recent years cableways have been utilized to fill comparatively narrow but deep ravines from material obtainable on either side of the ravine. This method obviates the construction of an excessively high trestle which might otherwise be considered necessary.

When an embankment is to be placed on a steep side hill which has a slippery clay surface, the embankment will sometimes slide down the hill, unless means are taken to prevent it. Some sort of bond between the old surface and the new material becomes necessary. This has sometimes been provided by cutting out steps somewhat as is illustrated in Fig. 63. It is possible that a deep ploughing of the surface would accomplish the result just as effectively and much cheaper. The tendency to slip is generally due not only to the nature of the soil but also to the usual accompanying characteristic that the soil is wet and springy. The sub-surface drainage of such a place with tile drains will still further prevent such slipping, which often proves very troublesome and costly.

COMPUTATION OF HAUL.

130. Nature of subject. As will be shown later when analyzing the cost of earthwork, the most variable item of cost is that depending on the distance hauled. As it is manifestly impracticable to calculate the exact distance to which every individual cartload of earth has been moved, it becomes necessary to devise a means which will give at least an equivalent of the haulage of all the earth moved. Evidently the *average* haul for any mass of earth moved is equal to the distance from the center of gravity of the excavation to the center of gravity of the embankment formed by the excavated material. As a rough approximation the center of gravity of a cut (or fill) may sometimes be considered to coincide with the center of gravity of that part of the profile representing it, but the error is frequently very large. The center of gravity may be determined by various methods, but the method of the "mass diagram" accomplishes the same ultimate purpose (the determination of the haul) with all-sufficient accuracy and also furnishes other valuable information.

131. Mass diagram. In Fig. 64 let $A'B' \ldots G'$ represent a profile and grade line drawn to the usual scales. Assume A' to be a point past which no earthwork will be hauled. Such a point is determined by natural conditions, as, for example, a river crossing, or one end of a long level stretch along which no grading is to be done except the formation of a low embankment from the material excavated from ample drainage ditches on each side. Above the profile draw an indefinite horizontal line (ACn in Fig. 64) which may be called the "zero line." Above every station point in the profile draw an ordinate (above or below the zero line) which will represent the algebraic sum of the cubic yards of cut and fill (calling cut + and fill −) from the point A' to the point considered. The computations of these ordinates should first be made in tabular form as shown below. In doing this shrinkage must be allowed for by considering how much embankment would actually be made by so many cubic yards of excavation of such material. For example, we will assume that 1000 cubic yards of sand or gravel, measured in place (see § 128) will make about 920 cubic yards of embankment; therefore all cuttings in sand or gravel should be discounted in about this proportion. Excavations in rock should be increased in the proper ratio. In short, all excavations should be valued according to the amount of *settled* embankment that could be made from them. Place in the first column a list of the stations; in the second column, the number of cubic yards of cut or fill between each station and the preceding station; in the third and fourth columns, the kind of material and the proper shrinkage factor; in the fifth column, a repetition of the quantities in cubic yards, except that the excavations are diminished (or increased, in the case of rock) to the number of cubic yards of settled embankment which may be made from them. In the sixth column place the *algebraic sum* of the quantities in the fifth column (calling cuts + and fills −) from the starting-point to the station considered. These algebraic sums at each station will be the ordinates, drawn to some scale, of the mass curve. The scale to be used will depend somewhat on whether

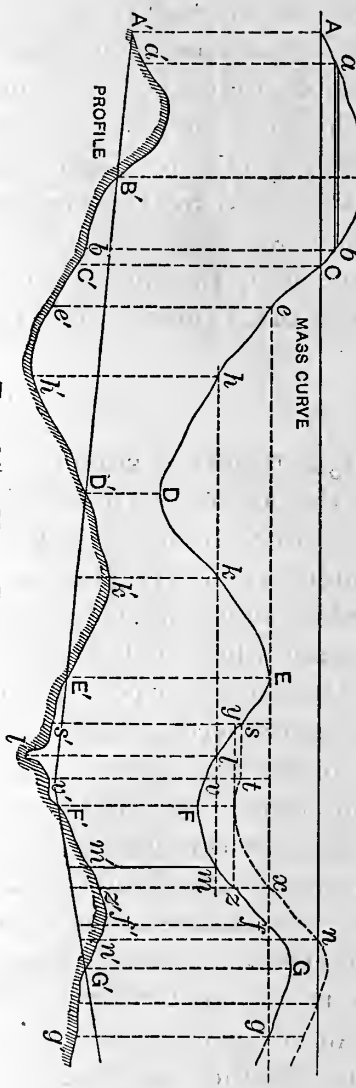


FIG. 64.—MASS DIAGRAM.

the work is heavy or light, but for ordinary cases a scale of 5000 cubic yards per inch may be used. Drawing these ordinates to scale, a curve $A, B, \ldots G$ may be obtained by joining the extremities of the ordinates.

Sta.	Yards { cut + / fill −	Material.	Shrinkage factor.	Yards, reduced for shrinkage.	Ordinate in mass curve.
46 + 70	....	....	....	....	0
47	+ 195	Clayey soil	− 10 per cent	+ 175	+ 175
48	+ 1792	" "	− 10 "	+ 1613	+ 1788
+ 60	+ 614	" "	− 10 "	+ 553	+ 2341
49	− 143	....	....	− 143	+ 2198
50	− 906	....	....	− 906	+ 1292
51	− 1985	....	....	− 1985	− 693
52	− 1721	....	....	− 1721	− 2414
+ 30	− 112	....	....	− 112	− 2526
53	+ 177	Hard rock	+ 60 per cent	+ 283	− 2243
+ 70	+ 180	" "	+ 60 "	+ 289	− 1954
54	− 52	....	....	− 52	− 2006
+ 42	− 71	....	....	− 71	− 2077
55	+ 276	Clayey soil	− 10 per cent	+ 249	− 1828
56	+ 1242	" "	− 10 "	+ 1118	− 710
57	+ 1302	" "	− 10 "	+ 1172	+ 462

132. Properties of the mass curve.

1. The curve will be rising while over cuts and falling while over fills.

2. A tangent to the curve will be horizontal (as at B, D, E, F, and G) when passing from cut to fill or from fill to cut.

3. When the curve is *below* the "zero line" it shows that material must be drawn *backward* (to the left); and *vice versa*, when the curve is *above* the zero line it shows that material must be drawn *forward* (to the right).

4. When the curve crosses the zero line (as at A and C) it shows (in this instance) that the cut between A' and B' will just provide the material required for the fill between B' and C', and that no material should be hauled past C', or, in general, past any intersection of the mass curve and the zero line.

5. If any horizontal line be drawn (as ab), it indicates that the cut and fill between a' and b' will just balance.

6. When the center of gravity of a given volume of material is to be moved a given distance, it makes no difference (at least theoretically) how far each individual load may be hauled or how any individual load may be disposed of. The summation

of the products of each load times the distance hauled will be a constant, whatever the method, and will equal the total volume times the movement of the center of gravity. The *average haul*, which is the movement of the center of gravity, will therefore equal the summation of these products divided by the total volume. If we draw two horizontal parallel lines at an infinitesimal distance dx apart, as at ab, the small increment of cut dx at a' will fill the corresponding increment of fill at b', and this material must be hauled the distance ab. Therefore the product of ab and dx, which is the product of distance times volume, is represented by the area of the infinitesimal rectangle at ab, and the total area ABC represents the summation of volume times distance for all the earth movement between A' and C'. This summation of products divided by the total volume gives the average haul.

7. The horizontal line, tangent at E and cutting the curve at e, f, and g, shows that the cut and fill between e' and E' will just balance, and that a *possible* method of hauling (whether desirable or not) would be to "borrow" earth for the fill between C' and e', use the material between D' and E' for the fill between e' and D', and similarly balance cut and fill between E' and f' and also between f' and g'.

8. Similarly the horizontal line $hklm$ may be drawn cutting the curve, which will show another *possible* method of hauling. According to this plan, the fill between C' and h' would be made by borrowing; the cut and fill between h' and k' would balance; also that between k' and l' and between l' and m'. Since the area $ehDkE$ represents the measure of haul for the earth between e' and E', and the other areas measure the corresponding hauls similarly, it is evident that the sum of the areas $ehDkE$ and $ElFmf$, which is the measure of haul of all the material between e' and f', is largely in excess of the sum of the areas hDk, kEl, and lFm, plus the somewhat uncertain measures of haul due to borrowing material for $e'h'$ and wasting the material between m' and f'. Therefore to make the measure of haul a minimum a line should be drawn which will make the sum of the areas between it and the mass curve a minimum. Of course this is not necessarily the cheapest plan, as it implies more or less borrowing and wasting of material, which *may* cost more than the amount saved in haul. The comparison of the two methods is quite simple, however. Since the amount

of fill between e' and h' is represented by the *difference* of the ordinates at e and h, and similarly for m' and f', it follows that the amount to be borrowed between e' and h' will exactly equal the amount wasted between m' and f'. By the first of the above methods the haul is excessive, but is definitely known from the mass diagram, and all of the material is utilized; by the second method the haul is reduced to about one-half, but there is a known quantity in cubic yards wasted at one place and the same quantity borrowed at another. The length of haul necessary for the borrowed material would need to be ascertained; also the haul necessary to waste the other material at a place where it would be unobjectionable. Frequently this is best done by widening an embankment beyond its necessary width. The computation of the relative cost of the above methods will be discussed later (§ 148).

9. Suppose that it were deemed best, after drawing the mass curve, to introduce a trestle between s' and v', thus saving an amount in fill equal to tv. If such had been the original design, the mass curve would have been a straight horizontal line between s and t and would continue as a curve which would be at all points a distance tv above the curve $vFmzfGg$. If the line Ef is to be used as a zero line, its intersection with the new curve at x will show that the material between E' and z' will just balance if the trestle is used, and that the amount of haul will be measured by the area between the line Ex and the broken line $Estx$. The same computed result may be obtained without drawing the auxiliary curve txn . . . by drawing the horizontal line zy at a distance $xz(=tv)$ below Ex. The amount of the haul can then be obtained by adding the triangular area between Es and the horizontal line Ex, the rectangle between st and Ex, and the irregular area between vFz and y . . . z (which last is evidently equal to the area between tx and E . . . x). The disposal of the material at the right of z' would then be governed by the indications of the profile and mass diagram which would be found at the right of g'. In fact it is difficult to decide with the best of judgment as to the proper disposal of material without having a mass diagram extending to a considerable distance each side of that part of the road under immediate consideration.

133. Area of the mass curve. The area may be computed most readily by means of a planimeter, which is capable with reasonable care of measuring such areas with as great accuracy as is necessary for this work. If no such instrument is obtainable, the area may be obtained by an application of "Simpson's rule." The ordinates will usually be spaced 100 feet apart. Select an *even* number of such spaces, leaving, if necessary, one or more triangles or trapezoids at the ends for separate and independent computation. Let $y_0 \ldots y_n$ be the ordinates, i.e., the number of cubic yards at each station of the mass curve, or the figures of "column six" referred to in § 131. Let the uniform distance between ordinates (=100 feet) be called 1, i.e., one *station*. Then the units of the resulting area will be cubic yards hauled one station. Then the

$$\text{Area} = \tfrac{1}{3}[y_0 + 4(y_1 + y_3 + \ldots y_{(n-1)}) + 2(y_2 + y_4 + \ldots y_{(n-2)}) + y_n]. \quad (62)$$

When an ordinate occurs at a substation, the best plan is to ignore it at first and calculate the area as above. Then, if the difference involved is too great to be neglected, calculate the area of the triangle having the extremity of the ordinate at the substation as an apex, and the extremities of the ordinates at the adjacent stations as the ends of the base. This may be done by finding the ordinate at the substation that would be a proportional between the ordinates at the adjacent full stations. Subtract this from the real ordinate (or *vice versa*) and multiply the difference by $\frac{1}{2} \times 1$. An inspection will often show that the correction thus obtained would be too small to be worthy of consideration. If there is more than one substation between two full stations, the corrective area will consist of two triangles and one or more trapezoids which may be similarly computed, if necessary.

When the zero line (Fig. 64) is shifted to eE, the drop from AC (produced) to E is known in the same units, cubic yards. This constant may be subtracted from the numbers ("column 6," § 131) representing the ordinates, and will thus give, without any scaling from the diagram, the exact value of the modified ordinates.

134. Value of the mass diagram. The great value of the mass diagram lies in the readiness with which different plans for the disposal of material may be examined and compared. When the mass curve is once drawn, it will generally require only a shifting of the horizontal line to show the disposal of the material by any proposed method. The mass diagram also shows the extreme length of haul that will be required by any proposed method of disposal of material. This brings into consideration the "limit of profitable haul," which will be fully discussed in § 148. For the present it may be said that with each method of carrying material there is some limit beyond which the expense of hauling will exceed the loss resulting from borrowing and wasting. With wheelbarrows and scrapers the limit of profitable haul is comparatively short, with carts and tram-cars it is much longer, while with locomotives and cars it may be several miles. If, in Fig. 64, *eE* or *Ef* exceeds the limit of profitable haul, it shows at once that some such line as *hklm* should be drawn and the material disposed of accordingly.

135. Changing the grade line. The formation of the mass curve and the resulting plans as to the disposal of material are based on the mutual relations of the grade line and the surface profile and the amounts of cut and fill which are thereby implied. If the grade line is altered, every cross-section is altered, the amount of cut and fill is altered, and the mass curve is also changed. At the farther limit of the actual change of the grade line the revised mass curve will have (in general) a different ordinate from the previous ordinate at that point. From that point on, the revised mass curve will be parallel to its former position, and the revised curve may be treated similarly to the case previously mentioned in which a trestle was introduced. Since it involves tedious calculations to determine accurately how much the volume of earthwork is altered by a change in grade line, especially through irregular country, the effect on the mass curve of a change in the grade line cannot therefore be readily determined except in an approximate way. Raising the grade line will evidently increase the fills and diminish the cuts, and *vice versa*. Therefore if the mass curve indicated, for example, either an excessively long haul or the necessity for borrowing material (implying a fill) and wasting material farther on (implying a cut), it would be *possible* to diminish the fill (and hence the amount of material to be borrowed) by lowering the grade line near that place, and diminish the cut (and hence the amount of material to be wasted) by raising the grade line at or near the place farther on. Whether the advantage thus gained would compensate for the possibly injurious effect of these changes on the grade line would require patient investigation. But the method outlined shows how the mass curve might be used to indicate a possible change in grade line which might be demonstrated to be profitable.

136. Limit of free haul. It is sometimes specified in contracts for earthwork that *all* material shall be entitled to free haul up to some specified limit, say 500 or 1000 feet, and that all material drawn farther than that shall be entitled to an allowance on the *excess* of distance. It is manifestly impracticable to measure the excess for each load, as much so as to measure the actual haul of each load. The mass diagram also solves this problem very readily. Let Fig. 65 represent a pro-

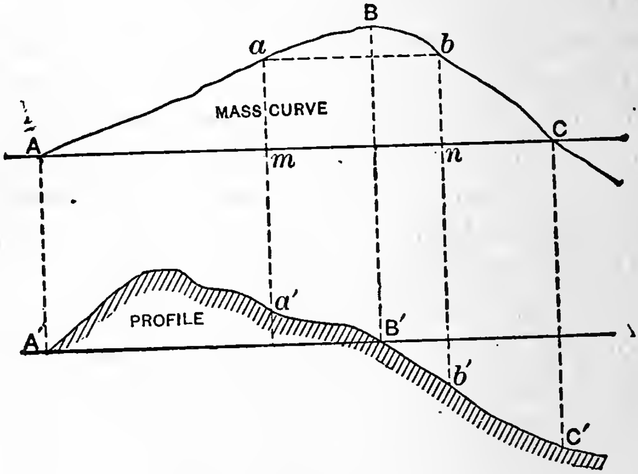


FIG. 65.

file and mass diagram of about 2000 feet of road, and suppose that 800 feet is taken as the limit of free haul. Find two points, a and b, in the mass curve *which are on the same horizontal line* and which are 800 feet apart. Project these points down to a' and b'. Then the cut and fill between a' and b' will just balance, and the cut between A' and a' will be needed for the fill between b' and C'. In the mass curve, the area between the horizontal line ab and the curve aBb represents the haulage of the material between a' and b', which is all free. The rectangle $abmn$ represents the haulage of the material in the cut $A'a'$ across the 800 feet from a' to b'. This is also free. The sum of the two areas Aam and bnC represents the haulage entitled to an allowance, since it is the summation of the products of cubic yards times the *excess* of distance hauled.

If the amount of cut and fill was symmetrical about the point

B', the mass curve would be a symmetrical curve about the vertical line through B, and the two limiting lines of free haul would be placed symmetrically about B and B'. In general there is no such symmetry, and frequently the difference is considerable The area $aBbnm$ will be materially changed according as the two vertical lines am and bn, always 800 feet apart, are shifted to the right or left. It is easy to show that the area $aBbnm$ is a *maximum* when ab is horizontal. The minimum value would be obtained either when m reached A or n reached C, depending on the exact form of the curve. Since the position for the minimum value is manifestly unfair, the best definite value obtainable is the maximum, which must be obtained as above described. Since $aBbnm$ is made maximum, the remainder of the area, which is the allowance for overhaul, becomes a minimum. The areas Aam and bCn may be obtained as in § 120. If the whole area $AaBbCA$ has been previously computed, it may be more convenient to compute the area $aBbnm$ and subtract it from the total area.

Since the intersections of the mass curve and the "zero line" mark limits past which no material is drawn, it follows that there will be no allowance for overhaul except where the distance between consecutive intersections of the zero line and mass curve exceeds the limit of free haul.

Frequently all allowances for overhaul are disregarded; the profiles, estimates of quantities, and the required disposal of material are shown to bidding contractors, and they must then make their own allowances and bid accordingly. This method has the advantage of avoiding possible disputes as to the amount of the overhaul allowance, and is popular with railroad companies on this account. On the other hand the facility with which different plans for the disposal of material may be studied and compared by the mass-curve method facilitates the adoption of the most economical plan, and the elimination of uncertainty will frequently lead to a safe reduction of the bid, and so the method is valuable to both the railroad company and the contractor.

ELEMENTS OF THE COST OF EARTHWORK.

137. Analysis of the total cost into items. The variation in the total cost of excavating earthwork, hauling it a greater or less distance, and forming with it an embankment of definite form or wasting it on a spoil bank, is so great that the only possible method of estimating the cost under certain assumed conditions is to separate the total cost into elementary items. Ellwood Morris was perhaps the first to develop such a method —see *Journal of the Franklin Institute*, September and October, 1841. Trautwine used the same general method with some modifications. The following analysis will follow the same general plan, will quote some of the figures given by Morris and by Trautwine, but will also include facts and figures better adapted to modern conditions. Since every item of cost (except interest on cost of plant and its depreciation) is a direct function of the current price of common labor, all calculations will be based on the simple unit of $1 per day. Then the actual cost may be obtained by multiplying the calculated cost under the given conditions by the current price of day labor. When possible, figures will be quoted giving the cost of all items of work on a loose sandy soil which is the easiest to work and also for the cost of the heaviest soils, such as stiff clay and hard pan. These represent the extremes, excluding rock, which will be treated separately. The cost of intermediate grades may be interpolated between the extreme values according to the judgment of the engineer as to the character of the soil.

The possible division into items varies greatly according to the method adopted, but the differentiation into items given below (which is strictly applicable to the old fashioned simpler methods of work) can usually be applied to any other method by merely combining or eliminating some of the items. The items are

1. Loosening the natural soil.
2. Loading the soil into whatever carrier may be used.
3. Hauling excavated material from excavation to embankment or spoil bank.
4. Spreading or distributing the soil on the embankment.
5. Keeping roadways or tracks in good running order.
6. Trimming cuts to their proper cross-section (sometimes called "sandpapering").
7. Repairs, wear, depreciation, and interest on cost of plant.
8. Superintendence and incidentals.

138. Item 1. Loosening. (a) **Ploughs.** Very light sandy soils can frequently be shovelled without any previous loosening, but it is generally economical, even with very light material, to use a plough. Morris quotes, as the results of experiments, that a three-horse plough would loosen from 250 to 800 cubic yards of earth per day, which at a valuation of $5 per day would make the cost per yard vary from 2 cents to 0.6 cent. Trautwine estimates the cost on the basis of two men handling a two-horse plough at a total cost of $3.87 per day, being $1 each for the men, 75 c. for each horse, and an allowance of 37 c. for the plough, harness, etc. From 200 to 600 cubic yards is estimated as a fair day's work, which makes a cost of 1.9 c. to 0.65 c. per yard, which is substantially the same estimate as above. Extremely heavy soils have sometimes been loosened by means of special ploughs operated by traction-engines.

Gillette estimates that "a two-horse team with a driver and a man holding the plough will loosen 25 cubic yards of fairly tough clay, or 35 cubic yards of gravel and loam per hour." For ten hours per day this would be 250 to 350 cubic yards per day. These values are neither as high nor as low as the extremes above noted. It is probably very seldom that a soil will be so light that a two-horse (or three-horse) plough can loosen as much as 600 (or 800) cubic yards per day.

It is sometimes necessary to plough up a macadamized street. This may be done by using as a plough a pointed steel bar which is fastened to a very strong plough frame. A preliminary hole must be made which will start the bar under the macadam shell. Then, as the plough is drawn ahead, the shell is ripped up. Four or six horses, or even a traction-engine, are used for such work. Gillette quotes two such cases where the cost of such loosening was 2 c. and 6 c. per cubic yard, with common labor at 15 c. per hour. Two-thirds of such figures will reduce them to the $1 per day basis. The cost for ploughing *on the* $1 *per* 10-*hour-day basis* may therefore be summarized as follows:

For very loose sandy soils...........	0.6 c. per cubic yard
" " heavy clay "	2.0 c. " " "
" hard pan and macadam, up to ...	4.0 c. " " "

(b) Picks. When picks are used for loosening the earth, as is frequently necessary and as is often done when ploughing would perhaps be really cheaper, an estimate* for a fair day's

* Trautwine.

work is from 14 to 60 cubic yards, the 14 yards being the estimate for stiff clay or cemented gravel, and the 60 yards the estimate for the lightest soil that would require loosening. At $1 per day this means about 7 c. to 1.7 c. per cubic yard, which is about three times the cost of ploughing. Five feet of the face is estimated * as the least width along the face of a bank that should be allowed to enable each laborer to work with freedom and hence economically.

(c) **Blasting.** Although some of the softer shaly rocks may be loosened with a pick for about 15 to 20 c. per yard, yet rock in general, frozen earth, and sometimes even compact clay are most economically loosened by blasting. The subject of blasting will be taken up later, §§ **149–155.**

(d) **Steam-shovels.** The items of loosening and loading merge together with this method, which will therefore be treated in the next section.

139. Item 2. Loading. **(a) Hand-shovelling.** Much depends on proper management, so that the shovellers need not wait unduly either for material or carts. With the best of management considerable time is thus lost, and yet the intervals of rest need not be considered as entirely lost, as it enables the men to work, while actually loading, at a rate which it would be physically impossible for them to maintain for ten hours. Seven shovellers are sometimes allowed for each cart; otherwise there should be five, two on each side and one in the rear. Economy requires that the number of loads per cart per day should be made as large as possible, and it is therefore wise to employ as many shovellers as can work without mutual interference and without wasting time in waiting for material or carts. The figures obtainable for the cost of this item are unsatisfactory on account of their large disagreements. The following are quoted as the number of cubic yards that can be loaded into a cart by an average laborer in a working day of ten hours, the lower estimate referring to heavy soils, and the higher to light sandy soils: 10 to 14 cubic yards (Morris), 12 to 17 cubic yards (Haskoll), 18 to 22 cubic yards (Hurst), 17 to 24 cubic yards (Trautwine), 16 to 48 cubic yards (Ancelin). As these estimates are generally claimed to be based on actual experience, the discrepancies are probably due to differences of management. If the

* Hurst.

average of 15 to 25 cubic yards be accepted, it means, on the basis of $1 per day, 6.7 c. to 4 c. per cubic yard. These estimates apply only to earth. *Rockwork* costs more, not only because it is harder to handle, but because a cubic yard of solid rock, measured in place, occupies about 1.8 cubic yards when broken up, while a cubic yard of earth will occupy about 1.2 cubic yards. Rockwork will therefore require about 50% more loads to haul a given volume, *measured in place,* than will the same nominal volume of earthwork. The above authorities give estimates for loading rock varying from 6.9 c. to 10 c. per cubic yard. The above estimates apply only to the loading of carts or cars with shovels or by hand (loading masses of rock). The cost of loading wheelbarrows and the cost of scraper work will be treated under the item of hauling.

(b) **Steam-shovels.*** Whenever the magnitude of the work will warrant it there is great economy in the use of steam-shovels. These have a "bucket" or "dipper" on the end of a long beam, the bucket having a capacity varying from ½ to 2½ cubic yards. Steam-shovels handle all kinds of material from the softest earth to shale rock, earthy material containing large boulders, tree-stumps, etc. The record of work done varies from 200 to 1000 cubic yards in 10 hours. They perform all the work of loosening and loading. Their economical working requires that the material shall be hauled away as fast as it can be loaded, which usually means that cars on a track, hauled by horses or mules, or still better by a locomotive, shall be used. The expenses for a steam-shovel, costing about $5000, will average about $1000 per month. Of this the engineer may get $100; the fireman $50; the cranesman $90; repairs perhaps $250 to $300; coal, from 15 to 25 tons, cost very variable on account of expensive hauling; water, a very uncertain amount, sometimes costing $100 per month; about five laborers and a foreman, the laborers getting $1.25 per day and the foreman $2.50 per day, which will amount to $227.50 per month. This gang of laborers is employed in shifting the shovel when necessary, taking up and relaying

* For a thorough treatment of the capabilities, cost, and management of steam-shovels the reader is referred to "Steam-shovels and Steam-shovel Work," by E. A. Hermann. D. Van Nostrand Co., New York.
This book is now out of print. "Earthwork and its Cost," by H. P. Gillette, to which the student is referred for a more elaborate exposition of the subject, has used many of Hermann's cuts.

tracks for the cars, shifting loaded and unloaded cars, etc. In shovelling through a deep cut, the shovel is operated so as to undermine the upper parts of the cut, which then fall down within reach of the shovel, thus increasing the amount of material handled for each new position of the shovel. If the material is too tough to fall down by its own weight, it is sometimes found economical to employ a gang of men to loosen it or even blast it rather than shift the shovel so frequently. Non-condensing engines of 50 horse-power use so much water that the cost of water-supply becomes a serious matter if water is not readily obtainable. The lack of water facilities will often justify the construction of a pipe line from some distant source and the installation of a steam-pump. Hence the seemingly large estimate of $100 per month for water-supply, although under favorable circumstances the cost may almost vanish. The larger steam-shovels will consume nearly a ton of coal per day of 10 hours. The expense of hauling this coal from the nearest railroad or canal to the location of the cut is often a very serious item of expense and may easily double the cost per ton. Some steam-shovels have been constructed to be operated by electricity obtained from a plant perhaps several miles away. Such a method is especially advantageous when fuel and water are difficult to obtain.

The following general requirements and specifications were recommended in 1907 by the American Railway Engineering Association:

Three important cardinal points should be given careful attention in the selection of a steam-shovel. These are in their order

(1) Care in the selection, inspection and acceptance of all material that enters into every part of the machine.

(2) Design for strength.

(3) Design for production.

GENERAL SPECIFICATIONS.

Weight of shovel: Seventy (70) tons.

Capacity of dipper: Two and one-half ($2\frac{1}{2}$) yards.

Steam pressure: One hundred and twenty (120) pounds.

Clear height above rail of shovel track at which dipper should unload: Sixteen (16) feet.

Depth below rail of shovel track at which dipper should dig Four (4) feet.

Number of movements of dipper per minute from time of entering bank to entering bank: Three (3).

Character of hoist: Cable.

Character of swing: Cable.

Character of housing: Permanent for all employés.

Capacity of tank: Two thousand (2000) gallons.

Capacity of coal-bunker: Four (4) tons.

Spread of jack arm: Eighteen (18) feet. A special short arm should be provided.

Form of steam-shovel track: "T" rails on ties.

Length of rails for ordinary work: Six (6) feet.

Form of rail joint: Strap.

Manufacturers of steam-shovels will sometimes "guarantee" that certain of their shovels will excavate, say 3000 cubic yards of earth per day of ten hours. Even if it were possible for a shovel to fill a car at the rate of 5 cubic yards per minute, it is always impracticable to maintain such a speed, since a shovel must always wait for the shifting of cars and for the frequent shifting of the shovel itself. There are also delays due to adjustments and minor breakdowns. The best shovel records are made when the cars are large—other things being equal. The item of interest and depreciation of the plant is very large in steam-shovel work. This will be discussed further later. The cost of loading alone will usually come to between 3 and 4 c. per cubic yard. The cost of shifting the cars so as to place them successively under the shovel, haul them to the dumping place, dump them and haul them back, will generally be as much more. Gillette quotes five jobs on one railroad where the total cost for loading and hauling varied from 5.9 c. to 11.4 c. per cubic yard. But as these figures are based on *car* measurement, the cost per cubic yard in *place* measurement must be increased about one-fourth, or from 7.4 c. to 14.2 c.

140. Item 3. Hauling. The cost of hauling depends on the number of round trips per day that can be made by each vehicle employed. As the cost of each vehicle is practically the same whether it makes many trips or few, it becomes important that the number of trips should be made a maximum, and to that end there should be as little delay as possible in loading and unloading. Therefore devices for facilitating the passage of the vehicles have a real money value.

(a) **Carts.** The average speed of a horse hauling a two-wheeled cart has been found to be 200 feet per minute, a little slower when hauling a load and a little faster when returning empty. This figure has been repeatedly verified. It means an allowance of one minute for each 100 feet (or "station") of "lead—the lead being the distance the earth is hauled." The time lost in loading, dumping, waiting to load, etc., has been found to average 4 minutes per load. Representing the number of stations (100 feet) of lead by s, the number of loads handled in 10 hours (600 minutes) would be $600 \div (s+4)$. The number of loads per cubic yard, measured in the bank, is differentiated by Morris into three classes, viz.:

3 loads per cubic yard in descending hauling;
$3\frac{1}{2}$ " " " " " level hauling; and
4 " " " " " ascending hauling.

Attempts have been made to estimate the effect of the grade of the roadway by a theoretical consideration of its rate, and of the comparative strength of a horse on a level and on various grades. While such computations are always practicable on a railway (even on a temporary construction track), the traction on a temporary earth roadway is always very large and so very variable that any refinements are useless. On railroad earthwork the hauling is generally nearly level or it is *descending*—forming embankments on low ground with material from cuts in high ground. The only common exception occurs when an embankment is formed from borrow-pits on low ground. One method of allowing for ascending grade is to add to the horizontal distance 14 times the difference of elevation for work with carts and 24 times the difference of elevation for work with wheelbarrows, and use that as the lead. For example, using carts, if the lead is 300 feet and there is a difference of elevation of 20 feet, the lead would be considered equivalent to $300+(14\times20)=580$ feet on a level.

Trautwine assumes the average load for all classes of work to be $\frac{1}{3}$ cubic yard, which figure is justified by large experience. Using one figure for all classes of work simplifies the calculations and gives the number of cubic yards carried per day of 10 hours equal to $\frac{600}{3(s+4)}$. Dividing the cost of a cart per day by the number of cubic yards carried gives the cost of hauling per yard. In computing the cost of a cart per day, Trautwine refers to the practice of having one driver manage four carts, thus making a charge of 25 c. per day for each cart for the driver. Although this might be an economical method when the haul is very long, it is not economical for short hauls. A safer estimate is to allow not more than two carts per driver and in many cases a driver for each cart. Some contractors employ a driver for each cart and then require that the drivers shall assist in loading. The policy to be adopted is sometimes dependent on labor union conditions, which may demand that drivers must not assist in loading. The supply of labor and the amount of work on hand have a great influence on the methods of work which a contractor may adopt, for a strike will often disarrange all plans.

The cost of a horse and cart must practically include a charge for the time of the horse on Sundays, rainy days and holidays. The cost of repairs of cart and harness is generally included in this item for simplicity, but, under a strict application of the analysis suggested in § 137, it should properly be included under Item 7, Repairs, etc.

Since the time required for loading loose rock is greater than for earthwork, less loads will be hauled per day. The time allowance for loading, etc., is estimated by Trautwine as 6 minutes instead of 4 as for earth. Considering the great expansion of rock when broken up (see § 128), one cubic yard of solid rock, measured in place, would furnish the equivalent of five loads of earthwork of $\frac{1}{3}$ cubic yard. Therefore, on the basis of five loads per cubic yard, the number of cubic yards handled per ten-hour day per cart would be $\frac{600}{5(s+6)}$.

Let C represent the daily cost of a horse and cart and of the proportional cost of the driver (according to the number of carts handled by one driver), then the cost per cubic yard, *measured in the cut*, for hauling may be given by the formula:

$$\left.\begin{array}{l} \text{Cost per cu. yd. of hauling earth in carts} = \dfrac{C \times 3(s+4)}{600} \\ \text{“ “ “ “ “ “ rock “ “} = \dfrac{C \times 5(s+6)}{600} \end{array}\right\} . \quad (63)$$

(b) **Wagons.** For longer leads (i.e., from $\frac{1}{3}$ to $\frac{2}{3}$ of a mile) wagons drawn by two (or three) horses are more economical. The old-style wagons (about 0.8 cu. yd.) have bottoms of loose thick narrow boards. Raising them individually deposits the load underneath. Modern dump wagons contain from 1.0 to 2.0 cu. yds. The daily cost may be estimated on the same principle as the cost of carts.

The number of wagon trips per 10 hours will depend somewhat on the management of the shovellers. Too many shovellers per wagon is not economical, measured in yards shovelled per man, although it may reduce the time consumed in loading any one wagon. At an average figure of 20 cubic yards, measured in place, per shoveller per 10 hours, seven shovellers would load 14 cubic yards per hour or one cubic yard in 4.3 minutes. This would be the allowance for a wagon with a capacity of about $1\frac{1}{3}$ yards of loose earth. Adding time for unloading, waiting to load and other possible "lost time," there is perhaps a total of six minutes. This figure will vary very considerably according to the number of shovellers per wagon, the capacity of the wagon, the type of wagon (whether self-dumping) and other details in the method of management. Adopting six minutes as the time used for loading, unloading, and other "lost time," the formula becomes.

$$\text{Cost per cubic yard of hauling in wagons} = \frac{C(s+6)}{600\,c}, \quad \ldots \quad (64)$$

in which C is the cost of the wagon, team and driver per day of 10 hours; s is the distance hauled in stations of 100 feet, and c is the capacity of the wagon in cubic yards, *place measurement*, which should be about three fourths of the nominal capacity of the wagon for earth and about sixty per cent when handling rock.

(c) **Wheelbarrows.** Gillette has computed from observations that a man will trundle a wheelbarrow at the rate of 250 feet per minute or 1.25 *stations* of lead per minute for the round trip. The time required for loading is estimated at $2\frac{1}{4}$ minutes and for unloading, adjusting wheeling planks, short rests, etc., $\frac{3}{4}$ minute, or a total of three minutes per trip for all purposes except hauling. Gillette allows for a load only 1/15 cubic yard, measured in place, or about 1/11 yard, 2.5 cubic feet, on the wheelbarrow. With notation as before, and for a ten-hour day,

$$\left.\begin{array}{l}\text{Cost per cubic yard of loading and}\\ \text{hauling earth in wheelbarrows}\end{array}\right\} = \frac{C \times 15(1.25s+3)}{600}. \qquad (65)$$

In this equation C is the cost of both loading and hauling, and usually includes the allowance (Item 7) for the cost, repairs and depreciation of the wheelbarrows, whose service is very short lived. Trautwine estimates this at five cents per day or a total of $1.05 for labor and wheelbarrow.

The number of wheelbarrow loads required for a cubic yard of rock, measured in place, is about twenty-four. The time required for loading should also be increased about one fourth; the time required for all purposes except hauling is therefore about 3.75 minutes, and the corresponding equation becomes

$$\left.\begin{array}{l}\text{Cost per cubic yard of loading and}\\ \text{hauling rock in wheelbarrows}\end{array}\right\} = \frac{C \times 24(1.25s+3.75)}{600}. \qquad (66)$$

(d) **Scrapers.** These are made in three general ways, "buck" scrapers, "drag" scrapers and "wheeled" scrapers. The buck scraper in its original form consisted merely of a wide plank, shod with an iron strap on the lower edge and provided with a pole and a small platform on which the driver may stand to weight it down. The earth is not loaded on to any receptacle and carried, but is merely pushed over the ground. Notwithstanding the apparent inefficiency of the method, its extreme simplicity has caused its occasional adoption for the construction of canal embankments out of material from the bed of the canal. The occasions are rare when their use for railroad work would be practicable, and even then drag scrapers would probably be preferable.

A drag scraper is an immense "scoop shovel" about three feet long and three feet wide. There are usually two handles and a bail in front by which it is dragged by a team of horses. The nominal capacity varies from 7.5 cubic feet for the largest sizes, down to 3 cubic feet for the "one-horse" size, but these figures must be discounted by perhaps 40 or 50% for the actual average volume (as measured in the cut) loaded on during one scoop. The expansion of the earth during loosening is alone responsible for a discount of 25%. These scrapers cost from $10 to $18.

A wheeled scraper is essentially an extra-large drag scraper which may be raised by a lever and carried on a pair of large wheels. Their nominal capacity ranges from 10 to 17 cubic feet, which should usually be liberally discounted when estimating output. They are loaded by dropping the scoop so that it scrapes up its load. The lever raises the scoop so that the load is carried on wheels instead of being dragged. At the dump the scoop is tipped so as to unload it. The movement of the scraper is practically continuous. They cost from $40 to $75. Their advantages over drag scrapers consist (1) in their greater capacity, (2) in the economy of transporting the load on wheels instead of by dragging, and (3) in the far greater length of haul over which the earth may be economically handled.

Morris estimated the speed of drag scrapers to be 140 feet per minute, or 70 feet of *lead* per minute. The "lead" should be here interpreted as the average distance from the center of the pit to the center of the dump. Gillette declares the speed to be 220 feet per minute. Some of this variation may be due to differences in the method of measuring the distance actually travelled, especially when the lead is very short, since the scraper teams must always travel a considerable extra distance at each end in order to turn around most easily. This extra distance is practically constant whether the lead is long or short. Gillette quotes an instance where the length of lead was actually about 20 feet, but the scraper teams travelled about 150 feet for each load carried. On this account Gillette adopts a minimum of 75 feet of lead no matter how short the lead actually may be. Of course the speed depends considerably on how strictly the men are kept to their work and also on the care which may be taken to obtain a full load for each scraper. As a compromise between Morris's and Gillette's estimates we may adopt the convenient rate of speed of 200 feet per minute, or 100 feet of lead per minute. There should also be allowed for the time lost in loading and unloading and for travelling the extra distance travelled by the teams in making the circuit, $1\frac{1}{3}$ minutes. Allowing the average value of seven loads per cubic yard and letting C represent the cost of scraper team and driver per ten-hour day, we have for the cost as follows:

$$\left.\begin{array}{l}\text{Cost per cubic yard of loading and}\\ \quad\text{hauling earth in drag scrapers}\end{array}\right\} = \frac{C \times 7\,(s + 1\tfrac{1}{3})}{600} \quad . \quad . \quad . \quad (67)$$

In this formula C should include the cost of not only the driver, team, and scraper, but also the proper proportion of the wages of an extra man, who assists each driver in loading his scraper, and whose wages should be divided among the two (or three) scrapers to which he is assigned. Scraper work nearly always implies ploughing, the cost of which should be computed as under Item 1.

When a low embankment is formed from borrow-pits on each side of the road, it may be done with scrapers, which move from one borrow-pit to the other, taking a load alternately from each side to the center and making but one half turn for each load carried. This reduces the time lost in turning by one third of a minute and reduces the constant in the numerator in Eq. (67) from $1\frac{1}{3}$ to 1. In this case the lead will usually be not greater than 75 feet, and therefore, if we consider this as a minimum value, s will ordinarily equal .75 and the quantity in the parenthesis will equal 1.75.

When using wheeled scrapers the catalogue capacity, which varies from 9 or 10 feet for a No. 1 scraper to 16 or 17 feet for a No. 3 scraper, must be reduced to 5 loads per cubic yard (place measurement) for a No. 1 scraper and to $2\frac{1}{2}$ loads per cubic yard for a No. 3, not only on account of the expansion of the earth during loosening, but also on account of the impracticability of loading these scrapers to their maximum nominal capacity. When the haul or lead for wheeled scrapers is 300 feet or over, it will be justifiable to employ shovellers to fill up the bowl of the shovel, especially when the soil is tough and when it is impracticable to fill the shovel even approximately full by the ordinary method. A snatch team to assist in loading the scrapers it also economical, especially with the larger scrapers. The proportionate number of snatch teams to the total number of scrapers of course depends on the length of haul. The cost of these extra shovellers and extra snatch teams must be divided proportionally among the number of scrapers assisted, in determining the value C in the formula given below. The extra time to be allowed on account of turning, loading, and dumping is about $1\frac{1}{2}$ minutes. The speed is considered one station of lead per minute as before. If we call C the average daily cost of one scraper and n the capacity of the scraper, or the number of loads per cubic yard, we may write the following formula, on the basis of a ten-hour day:

$$\left.\begin{array}{l}\text{Cost per cubic yard of loading and}\\ \text{hauling earth in wheeled scrapers}\end{array}\right\} = \frac{C \times n(s+1\frac{1}{2})}{600} \quad . \quad . \quad (68)$$

(e) Cars and horses. The items of cost by this method are (*a*) charge for horses employed, (*b*) charge for men employed strictly in hauling, (*c*) charge for shifting rails when necessary, (*d*) repairs, depreciation, and interest on cost of cars and track. Part of this cost should strictly be classified under items 5 and 7, mentioned in § 137, but it is perhaps more convenient to estimate them as follows:

The traction of a car on rails is so very small that grade resistance constitutes a very large part of the total resistance if the grade is 1% or more. For all ordinary grades it is sufficiently accurate to say that the grade resistance is to the gross weight as the rise is to the distance. If the distance is supposed to be measured along the slope, the proportion is strictly true; i.e., on a 1% grade the grade resistance is 1 lb. per 100 of weight or 20 lbs. per ton. If the resistance on a level at the usual velocity is $\frac{1}{120}$, a grade of 1:120 (0.83%) will exactly double it. If the material is hauled *down* a grade of 1:120, the cars will run by gravity after being started. The work of hauling will then consist practically of hauling the empty cars up the grade. The grade resistance depends only on the rate of grade and the weight, but the tractive resistance will be *greater per ton of weight* for the unloaded than for the loaded cars. The tractive power of a horse is less on a grade than on a level, not only because the horse raises his own weight in addition to the load, but is anatomically less capable of pulling on a grade than on a level. In general it will be possible to plan the work so that loaded cars need not be hauled *up* a grade, unless an embankment is to be formed from a low borrow-pit, in which case another method would probably be advisable. These computations are chiefly utilized in designing the method of work—the proportion of horses to cars. An example may be quoted from English practice (Hurst), in which the cars had a capacity of 3⅓ cubic yards, weighing 30 cwt. empty. Two horses took five "wagons" ¾ of a mile on a level railroad and made 15 journeys per day of 10 hours, i.e., they handled 250 yards per day. In addition to those on the "straight road," another horse was employed to make up the train of loaded wagons. With a short lead the straight-road horses were employed for this purpose. In the above example the number of men required to handle these cars, shift the tracks, etc., is not given, and so the exact cost of the above work cannot be analyzed. It may be noticed that the two horses travelled $22\frac{1}{2}$ miles per day, drawing in one direction a load, including the weight of the cars, of about 57,300 lbs., or 28.65 net tons. Allowing $\frac{1}{120}$ as the necessary tractive force, it would require a pull of 477.5 lbs., or 239 lbs. for each horse. With a velocity of 220 feet per minute this would amount to $1\frac{1}{2}$ horse-power per horse, exerted for only a short time, however, and allowing considerable time for rest and for drawing only the empty cars. Gillette claims that the rolling resistance for such cars on a contractor's track should be considered as 40 lbs. per ton (the equivalent of a 2% grade) and quotes many figures to support the assertion. Unquestionably the resistance on tracks with very light rails, light ties with wide spacing and no tamping, would be very great and might readily amount to 40 lbs. per ton. In the above case, the resistance could not have been much if any over $\frac{1}{120}$. A resistance of 40 lbs. per ton would have required each horse to pull about 573 lbs. for nearly five hours per day, beside pulling the empty cars the rest of the time. This is far greater exertion than any ordinary horse can maintain. The cars generally used in this country have a capacity of $1\frac{1}{2}$ cubic yards and cost about $65 apiece. Besides the shovellers and dumping-gang, several men and a foreman will be required to keep the track in order and to make the constant shifts that are necessary. Two trains are generally used, one of which is loaded while the other is run to the dump. Some passing-place is necessary, but this is generally provided by having a switch at the cut and running the trains on each track alternately. This insures a train of cars always at the cut to keep the shovellers employed. The cost of hauling per cubic yard can only be computed when the number of laborers, cars, and horses employed are known, and these will depend on the lead, on the character of the excavation, on the grade, if any, etc., and must be so proportioned that the shovellers need not wait for cars to fill, nor the dumping-gang for material to handle, nor the horses and drivers for cars to haul. Much skill is necessary to keep a large force in smooth running order.

(f) **Cars and locomotives.** 30-lb. rails are the lightest that should be used for this work, and 35- or 40-lb. rails are better. One or two narrow-gauge locomotives (depending on the length of haul), costing about $2500 each, will be necessary to handle two trains of about 15 cars each, the cars having a capacity of about 2 cubic yards and costing about $100 each. Some cars can be obtained as low as $70. A force of about five men and a foreman will be required to shift the tracks. The track-shifters, except the foreman, may be common laborers. The dumping-gang will require about seven men. Even when the material is all taken *down* grade the grades may be too steep for the safe hauling of loaded cars down the grade, or for hauling empty cars up the grade. Under such circumstances temporary trestles are necessary to reduce the grade. When these are used, the uprights and bracing are left in the embankment—only the stringers being removed. This is largely a necessity, but is partially compensated by the fact that the trestle forms a core to the embankment which prevents lateral shifting during settlement. The average speed of the trains may be taken as 10 miles per hour or 5 miles of lead per hour. The time lost in loading and unloading is estimated (Trautwine) as 9 minutes or .15 of an hour. The number of trips per day of 10 hours will equal $\frac{10}{\frac{1}{5}(\text{miles of lead}) + .15}$ or $\frac{50}{(\text{miles of lead}) + .75}$. Of course this quotient *must* be a whole number. Knowing the number of trains and their capacity, the total number of cubic yards handled is known, which, divided into the total daily cost of the trains, will give the cost of hauling per yard. The daily cost of a train will include

(*a*) Wages of engineer, who frequently fires his own engine;

(*b*) Fuel, about $\frac{1}{4}$ to 1 ton of bituminous coal, depending on work done;

(*c*) Water, a very variable item, frequently costing $3 to $5 per day;

(*d*) Repairs, variable, frequently at rate of 50 to 60% per year;

(*e*) Interest on cost and depreciation, 16 to 40%.

To these must be added, to obtain the total cost of haul,

(*f*) Wages of the gang employed in shifting track.

The above calculation for the number of train loads depends on the assumption that 9 minutes is total time lost by a locomotive for each round trip. If the haul is very short it may readily happen that a steam-shovel cannot fill one train of cars before the locomotive has returned with a load of empties and is ready to haul a loaded train away. The estimation of the number of train loads is chiefly useful in planning the work so as to have every tool working at its highest efficiency. Usually the capacity of the steam-shovel or the ability to promptly "spot" the cars under the shovel is the real limiting agent which determines the daily output.

141. Choice of method of haul dependent on distance. In light side-hill work in which material need not be moved more than 12 or 15 feet, i.e., moved *laterally* across the roadbed, the earth may be moved most cheaply by mere shovelling. Beyond 12 feet scrapers are more economical. At about 100 feet drag-scrapers and wheelbarrows are equally economical. Between 100 and 200 feet wheelbarrows are generally cheaper than either carts or drag-scrapers, but wheeled scrapers are always cheaper than wheelbarrows. Beyond 500 feet two-wheeled carts become the most economical up to about 1700 feet; then four-wheeled wagons become more economical up to 3500 feet. Beyond this cars on rails, drawn by horses or by locomotives, become cheaper. The economy of cars on rails becomes evident for distances as small as 300 feet provided the volume of the excavation will justify the outlay. Locomotives will always be cheaper than horses and mules, providing the work to be done is of sufficient magnitude to justify the purchase of the necessary plant and risk the loss in selling the plant ultimately as second-hand equipment, or keeping the plant on hand and idle for an indefinite period waiting for other work. Horses will not be economical for distances much over a mile. For greater distances locomotives are more economical, but the question of "limit of profitable haul" (§ 148) must be closely studied, as the circumstances are certainly not common when it is advisable to haul material much over a mile.

142. Item 4. SPREADING. The cost of spreading varies with the method employed in dumping the load. When the earth is tipped over the edge of an embankment there is little if any necessary work. Trautwine allows about $\frac{1}{4}$ c. per cubic yard for keeping the dumping-places clear and in order. This would represent the wages of one man at $1 per day attending to the unloading of 1200 two-wheeled carts each carrying $\frac{1}{3}$ cubic yard. 1200 carts in 10 hours would mean an average of two per minute, which implies more rapid and efficient work than may be depended on. The allowance is probably too small. When the material is dumped in layers some levelling is required, for which Trautwine allows 50 to 100 cubic yards as a fair day's work, costing from 1 to 2 cents per cubic yard. The cost of spreading will not ordinarily exceed this and is frequently nothing—all depending on the method of unloading. It should be noted that Mr. Morris's examples and computations (Jour. Franklin Inst., Sept. 1841) disregard altogether any special charge for this item.

143. Item 5. Keeping Roadways in Order. This feature is important as a measure of true economy, whatever the system of transportation, but it is often neglected. A petty saving in such matters will cost many times as much in increased labor in hauling and loss of time. With some methods of haul the cost is best combined with that of other items.

(a) **Wheelbarrows.** Wheelbarrows should generally be run on planks laid on the ground. The adjusting and shifting of these planks is done by the wheelers, and the time for it is allowed for in the "$\frac{3}{4}$ minute for short rests, adjusting the wheeling plank, etc." The actual cost of the planks must be added, but it would evidently be a very small addition per cubic yard in a large contract. When the wheelbarrows are run on planks placed on "horses" or on trestles the cost is very appreciable; but the method is frequently used with great economy. The variations in the requirements render any general estimate of such cost impracticable.

(b) **Carts and wagons.** The cost of keeping roadways in order for carts and wagons is sometimes estimated merely as so much per cubic yard, but it is evidently a function of the *lead*. The work consists in draining off puddles, filling up ruts, picking up loose stones that may have fallen off the loads, and in general doing everything that will reduce the traction as much as possible. Temporary inclines, built to avoid excessive grade at some one point, are often measures of true economy. Trautwine suggests $\frac{1}{10}$ c. per cubic yard per 100 feet of lead for earthwork and $\frac{2}{10}$ c. for rockwork, as an estimate for this item when carts are used.

(c) Cars. When cars are used a shifting-gang, consisting of a foreman and several men (say five), are constantly employed in shifting the track so that the material may be loaded and unloaded where it is desired. The average cost of this item may be estimated by dividing the total daily cost of this gang by the number of cubic yards handled in one day.

144. Item 6. **TRIMMING CUTS TO THEIR PROPER CROSS-SECTION.** This process, often called "sand-papering," must be treated as an expense, since the payment received for the very few cubic yards of earth excavated is wholly inadequate to pay for the work involved. Gillette quotes bids of 2 cents per *square* yard of surface trimmed, and from this argues that, for *average* excavations, it adds to the cost *four* cents per cubic yard of the total excavation. The shallower the cut the greater is the proportionate cost. Of course the actual cost to the contractor will depend largely on the accuracy of outline demanded by the engineer or inspector.

145. Item 7. **REPAIRS, WEAR, DEPRECIATION, AND INTEREST ON COST OF PLANT.** The amount of this item evidently depends upon the character of the soil—the harder the soil the worse the wear and depreciation. The *interest on cost* depends on the current borrowing value of money. The estimate for this item has already been included in the allowances for horses, carts, ploughs, harness, wheelbarrows, steam-shovels, etc. Trautwine estimates $\frac{1}{4}$ c. per cubic yard for picks and shovels. Depreciation is generally a large percentage of the cost of earth-working tools, the life of all being limited to a few years, and of many tools to a few months or weeks.

146. Item 8. **SUPERINTENDENCE AND INCIDENTALS.** The incidentals include the cost of water-boys, timekeepers, watchmen, blacksmiths, fences, and other precautions to protect the public from possible injury, cost of casualty insurance for workmen, etc. Although the cost of some of these sub-items may be definitely estimated, others are so uncertain that it is only possible to make a lump estimate and add say 5 to 7% of the sum of the previous items for this item.

147. Contractor's profit and contingencies. The word "contingencies" here refers to the abnormal expenses caused by freshets, continued wet weather, and "hard luck," as distinguished from mere incidentals which are really normal expenses. They are the expenses which literally cannot be foreseen, and on which the contractor must "take chances." They are therefore included with the expected profit. The allowance for these two elements combined is variously estimated up to 25% of the previously estimated cost of the work, according to the sharpness of the competition, the contractor's confidence in the accuracy of his estimates, and the possible uncertainty as to true cost owing to unfavorable circumstances. The contractor's real profit may vary considerably from this. He often pays clerks, boards and lodges the laborers in shanties built for the purpose, or keeps a supply-store, and has various other items both of profit and expense. His profit is largely dependent on skill in so handling the men that all can work effectively without interference or delays in waiting for others. An unusual season of bad weather will often affect the cost very seriously. It is a common occurrence to find that two contractors may be working on the same kind of material and under precisely similar conditions and at the same price, and yet one may be making money and the other losing it—all on account of difference of management.

148. Limit of profitable haul. As intimated in §§ 134 and 141, there is with every method of haul a limit of distance beyond which the expense for excessive hauling will exceed the loss resulting from borrowing and wasting. This distance is somewhat dependent on local conditions, thus requiring an independent solution for each particular case, but the general principles involved will be about as follows: Assume that it has been determined, as in Fig. 64, that the cut and fill will exactly balance between two points, as between e and x, assuming that, as indicated in § 132 (9), a trestle has been introduced between s and t, thus altering the mass curve to $Estxn$ . . . Since there is a balance between A' and C', the material for the fill between C' and e' must be obtained either by "borrowing" in the immediate neighborhood or by transportation from the excavation between z' and n'. If cut and fill have been approximately balanced in the selection of grade line, as is ordinarily done, borrowing material for the fill $C'e'$ implies a wastage of material at the cut $z'n'$. To compare the two methods, we may place against the plan of borrowing and wasting, (*a*) cost, if any, of extra right of way that may be needed from which to obtain earth for the fill $C'e'$; (*b*) cost of loosening, loading, hauling a distance equal to that between the centers of gravity of the borrow-pit and of the fill, and the other expenses incidental to borrowing M cubic yards for the fill $C'e'$; (*c*) cost of loosening, loading, hauling a distance equal to that between the centers of gravity of the cut $z'n'$ and of the spoil-bank, and the other expenses incidental to wasting M cubic yards at the cut $z'n'$: (*d*) cost, if any, of land needed for the spoil-bank. The cost of the other plan will be the cost of loosening, loading, hauling (the hauling being represented by the trapezoidal figure $Cexn$), and the other expenses incidental to making the fill $C'e'$ with the material from the cut $z'n'$, the amount of material being M cubic yards, which is represented in the figure by the vertical ordinate from e to the line Cn. The difference between these costs will be the cost, if any, of land for borrow-pit and spoil-bank *plus* the cost of loosening, loading, etc. (except hauling and roadways) of M cubic yards, *minus* the difference in cost of the excessive haul from Ce to xn and the comparatively short hauls from borrow-pit and to spoil-bank.

As an illustration, taking some of the estimates previously given for operating with average material, the cost of all items, except hauling and roadways, would be about as follows: loosening, with plough, 1.2 c., loading 5.0 c., spreading 1.5 c., wear, depreciation, etc., .25 c., superintendence, etc., 1.5 c.; total 8.95 c. Suppose that the haul for both borrowing and wasting averages 100 feet or 1 station. Then the cost of haul per yard, using carts, would be (§ 140, *a*) $[125\times3(1+4)]\div600=3.125$ c. The cost of roadways would be about 0.1 c. per yard, making a total of 3.225 c. per cubic yard. Assume $M=10000$ cubic yards and the area $Cexn=180000$ yards-stations or the equivalent of 10000 yards hauled 1800 feet. This haul would cost $[125\times3(18+4)]\div600=13.75$ c. per cubic yard. The cost of roadways will be $18\times.1$ or 1.8 c., making a total of 15.55 c. for hauling and roadways. The difference of cost of hauling and roadways will be $15.55-(2\times3.225)=9.10$ c. per yard or $910 for the 10000 yards. Offsetting this is the cost of loosening, etc., 10000 yards, at 8.95 c., costing $895. These figures may be better compared as follows:

LONG HAUL.	Loosening, etc.,	10000 yards,	@ 8.95 c.	$ 895.
	Hauling,	10000 "	@ 15.55 c.	1555.
				$2450.
BORROWING AND WASTING.	Loosening, etc.,	10000 yards (borrowed),	@ 8.95 c.	$895.
	" "	10000 " (wasted),	@ 8.95 c.	895.
	Hauling, etc.,	10000 " (borrowed),	@ 3.225 c.	322.50
	" "	10000 " (wasted),	@ 3.225 c.	322.50
				$2435.00

These costs are practically balanced, but no allowance has been made for right of way. If any considerable amount had to be paid for that, it would decide this particular case in favor of the long haul. This shows that *under these conditions* 1800 feet is *about* the limit of profitable haul, the land costing nothing extra.

BLASTING.

149. **Explosives.** The effect of blasting is due to the extremely rapid expansion of a gas which is developed by the decomposition of a very small amount of solid matter. Blasting compounds may be divided into two general classes, (*a*) slow-burning and (*b*) detonating. Gunpowder is a type of the slow-burning compounds. These are generally ignited by heat; the ignition proceeds from grain to grain; the heat and pressure produced are comparatively low. Nitro-glycerine is a type of the detonating compounds. They are exploded by a shock which *instantaneously* explodes the whole mass. The heat and pressure developed are far in excess of that produced by the explosion of powder. Nitro-glycerine is so easily exploded that it is very dangerous to handle. It was discovered that if the nitro-glycerine was absorbed by a spongy material like infusorial earth, it was much less liable to explode, while its power when actually exploded was practically equal to that of the amount of pure nitro-glycerine contained in the dynamite, which is the name given to the mixture of nitro-glycerine and infusorial earth. Nitro-glycerine is expensive; many other explosive chemical compounds which properly belong to the slow-burning

class are comparatively cheap. It has been conclusively demonstrated that a mixture of nitro-glycerine and some of the cheaper chemicals has a greater explosive force than the sum of the strengths of the component parts when exploded separately. Whatever the reason, the fact seems established. The reason is possibly that the explosion of the nitro-glycerine is sufficiently powerful to produce a *detonation* of the other chemicals, which is impossible to produce by ordinary means, and that this explosion caused by detonation is more powerful than an ordinary explosion. The majority of the explosive compounds and "powders" on the market are of this character—a mixture of 20 to 60 per cent. of nitro-glycerine with variable proportions of one or more of a great variety of explosive chemicals.

The choice of the explosive depends on the character of the rock. A hard brittle rock is most effectively blasted by a detonating compound. The rapidity with which the full force of the explosive is developed has a shattering effect on a brittle substance. On the contrary, some of the softer tougher rocks and indurated clays are but little affected by dynamite. The result is but little more than an enlargement of the blast-hole. Quarrying must generally be done with blasting-powder, as the quicker explosives are too shattering. Although the results obtained by various experimenters are very variable, it may be said that pure nitro-glycerine is eight times as powerful as black powder, dynamite (75% nitro-glycerine) six times, and gun-cotton four to six times as powerful. For open work where time is not particularly valuable, black powder is by far the cheapest, but in tunnel-headings, whose progress determines the progress of the whole work, dynamite is so much more effective and so expedites the work that its use becomes economical.

150. Drilling. Although many very complicated forms of drill-bars have been devised, the best form (with slight modifications to suit circumstances) is as shown in Fig. 66 (*a*), and (*b*). The width should flare at the bottom (*a*) about 15 to 30%. For hard rock the curve of the edge should be somewhat flatter and for soft rock somewhat more curved than shown, Fig. 66, (*a*). Sometimes the angle of the two faces is varied from that given, Fig. 66, (*b*) and occasionally the edge is purposely blunted so as to give a crushing rather than a cutting effect. The drills will require sharpening for each 6 to 18 inches depth of hole, and will require a new edge to be worked every 2 to 4 days.

For drilling vertical holes the *churn-drill* is the most economical. The drill-bar is of iron, about 6 to 8 feet long, 1¼″ in diameter, weighs about 25 to 30 lbs., and is shod with a piece of steel welded on. The bar is lifted a few inches between each blow, turned partially around, and allowed to fall, the impact doing the work. From 5 to 15 feet of holes, depending on the character of the rock, is a fair day's work—10 hours. In very soft rocks even more than this may be done. This method is

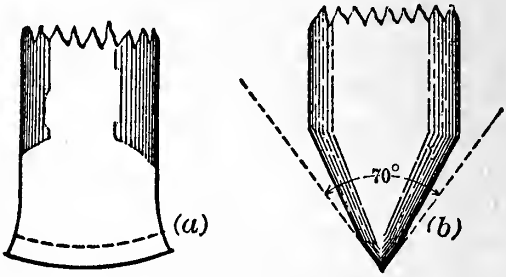
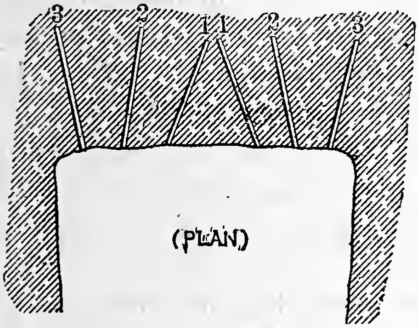


FIG. 66.

inapplicable for inclined holes or even for vertical holes in confined places, such as tunnel-headings. For such places the only practical *hand* method is to use hammers. This may be done by light drills and light hammers (one-man work), or by heavier drills held by one man and struck by one or two men with heavy hammers. The conclusion of an exhaustive investigation as to the relative economy of light or heavy hammers is that the light-hammer method is more economical for the softer rocks, the heavy-hammer method is more economical for the harder rocks, but that the light-hammer method is always more expeditious and hence to be preferred when time is important.

The subject of machine rock-drills is too vast to be treated here. The method is only practicable when the amount of work to be done is large, and especially when time is valuable. The machines are generally operated by compressed air although steam is also used to operate the drills. Gasoline as a motive power is even more economical for a small-scale plant. The cost per foot of hole drilled is quite variable, but is usually somewhat less than that of hand-drilling—sometimes but a small fraction of it.

151. Position and direction of drill-holes. As the cost of drilling holes is the largest single item in the total cost of blasting, it is necessary that skill and judgment should be used in so locating the holes that the blasts will be most effective. The greatest effect of a blast will evidently be in the direction of the "line of least resistance." In a strictly homogeneous material this will be the shortest line from the center of the explosive to the surface. The variations in homogeneity on account of laminations and seams require that each case shall be judged according to experience. In open-pit blasting it is generally easy to obtain two and sometimes three exposed faces to the rock, making it a simple matter to drill holes so that a blast will do effective work. When a solid face of rock must be broken into, as in a tunnel-heading, the work is necessarily ineffectual and expensive. A conical or wedge-shaped mass will first be blown out by simultaneous blasts in the holes marked 1, Fig. 67; blasts in the holes marked 2 and 3 will then complete the cross-section of the heading. A great saving in cost may often be secured by skilfully taking advantage of seams, breaks, and irregularities. When the work is economically done there is but little noise or throwing of rock, a covering of old timbers and branches of trees generally sufficing to confine the smaller pieces which would otherwise fly up.



DRILL HOLES IN TUNNEL HEADING

Fig. 67.

152. Amount of explosive. The amount of explosive required varies as the cube of the line of least resistance. The best results are obtained when the line of least resistance is $\frac{3}{4}$ of the depth of the hole; also when the powder fills about $\frac{1}{3}$ of the hole. For average rock the amount of powder required is as follows:

Line of least resistance............	2 ft.	4 ft.	6 ft.	8 ft.
Weight of powder..................	$\frac{1}{4}$ lb.	2 lbs.	$6\frac{3}{4}$ lbs.	16 lbs.

Strict compliance with all of the above conditions would require that the diameter of the hole should vary for every case. While this is impracticable, there should evidently be some variation in the size of the hole, depending on the work to be done. For example, a 1″ hole, drilled 2′ 8″ deep, with its line of least resistance 2′. and loaded with $\frac{1}{4}$ lb. of powder, would be filled to a depth of $9\frac{1}{2}''$, which is nearly $\frac{1}{3}$ of the depth. A 3″ hole, drilled 8′ deep, with its line of least resistance 6′, and loaded with $6\frac{3}{4}$ lbs. of powder, would be filled to a depth of over 28″, which is also nearly $\frac{1}{3}$ of the depth. One pound of blasting-powder will occupy about 28 cubic inches. Quarrying necessitates the use of numerous and sometimes repeated light charges of powder, as a heavy blast or a powerful explosive like dynamite is apt to shatter the rock. This requires more powder to the cubic yard than blasting for mere excavation, which may usually be done by the use of $\frac{1}{4}$ to $\frac{1}{3}$ lb. of powder per cubic yard of easy open blasting. On account of the great resistance offered by rock when blasted in headings in tunnels, the powder used per cubic yard will run up to 2, 4, and even 6 lbs. per cubic yard. As before stated, nitro-glycerine is about eight times (and dynamite about six times) as powerful as the same *weight* of powder.

153. **Tamping.** Blasting-powder and the slow-burning explosives require thorough tamping. Clay is probably the best, but sand and fine powdered rock are also used. Wooden plugs, inverted expansive cones, etc., are periodically reinvented by enthusiastic inventors, only to be discarded for the simpler methods. Owing to the extreme rapidity of the development of the force of a nitro-glycerine or dynamite explosion, tamping is not so essential with these explosives, although it unquestionably adds to their effectiveness. Blasting under water has been effectively accomplished by merely pouring nitro-glycerine into the drilled holes through a tube and then exploding the charge without any tamping except that furnished by the superincumbent water. It has been found that air-spaces about a charge make a material reduction in the effectiveness of the explosion. It is therefore necessary to carefully ram the explosive into a solid mass. Of course the liquid nitro-glycerine needs no ramming, but dynamite should be rammed with a *wooden* rammer. Iron should be carefully avoided in ramming gunpowder. A copper bar is generally used.

154. **Exploding the charge.** Black powder is generally exploded by means of a fuse which is essentially a cord in which there is a thin vein of gunpowder, the cord being protected by tar, extra linings of hemp, cotton, or even gutta-percha. The fuse is inserted into the middle of the charge, and the tamping carefully packed around it so that it will not be injured. To

produce the detonation required to explode nitro-glycerine and dynamite, there must be an initial explosion of some easily ignited explosive. This is generally accomplished by means of caps containing fulminating-powder which are exploded by electricity. The electricity (in one class of caps) heats a very fine platinum wire to redness, thereby igniting the sensitive powder, or (in another class) a spark is caused to jump through the powder between the ends of two wires suitably separated. Dynamite can also be exploded by using a small cartridge of gunpowder which is itself exploded by an ordinary fuse.

155. Cost. As a rough estimate, the cost of loosening and loading rock work, reduced to the uniform basis of $1.00 per 10-hour day, may be said to vary from 30c. for easy but *brittle* rock and increasing to 80c. per cubic yard when the cutting is shallow, the rock especially tough, and the strata unfavorably placed. For a detailed analysis of cost, which is essential for close estimating, see Gillette's "Rock Excavation, Methods and Cost."

156. Classification of excavated material. The classification of excavated material is a fruitful source of dispute between contractors and railroad companies, owing mainly to the fact that the variation between the softest earth and the hardest rock is so gradual that it is very difficult to describe distinctions between different classifications which are unmistakable and indisputable The classification frequently used is (*a*) earth, (*b*) loose rock, and (*c*) solid rock. As blasting is frequently used to loosen "loose rock" and even "earth" (if it is frozen), the fact that blasting is employed cannot be used as a criterion, especially as this would (if allowed) lead to unnecessary blasting for the sake of classifying material as rock.

Earth. This includes clay, sand, gravel, loam, decomposed rock and slate, boulders or loose stones not greater than 1 cubic foot (3 cubic feet, P. R. R.), and sometimes even "hard-pan." In general it will signify material which *can* be loosened by a plough with two horses, or with which one picker can keep one shoveller busy.

Loose rock. This includes boulders and loose stones of more than one cubic foot and less than one cubic yard; stratified rock, not more than six inches thick, separated by a stratum of clay; also all material (not classified as earth) which may be loosened by pick or bar and which "*can* be quarried without blasting, although blasting may occasionally be resorted to."

Solid rock includes all rock found in masses of over one cubic yard which cannot be removed except by blasting.

It is generally specified that the engineer of the railroad company shall be the judge of the classification of the material, but frequently an appeal is taken from his decisions to the courts.

157. Specifications for earthwork. The following specifications, issued by the Norfolk and Western R. R., represent the average requirements. It should be remembered that very strict specifications invariably increase the cost of the work, and frequently add to the cost more than is gained by improved quality of work.

1. The grading will be estimated and paid for by the cubic yard, and will include clearing and grubbing, and all open excavations, channels, and embankments required for the formation of the roadbed, and for turnouts and sidings; cutting all ditches or drains about or contiguous to the road; digging the foundation-pits of all culverts, bridges, or walls; reconstructing turnpikes or common roads in cases where they are destroyed or interfered with; changing the course or channel of streams; and all other excavations or embankments connected with or incident to the construction of said Railroad.

2. All grading, except where otherwise specified, whether for cuts or fills, will be measured in the excavations and will be classified under the following heads, viz.: Solid Rock, Loose Rock, Hard-pan, and Earth.

Solid Rock shall include all rock occurring in masses which, in the judgment of the said Engineer Maintenance of Way, may be best removed by blasting.

Loose Rock shall include all kinds of shale, soapstone, and other rock which, in the judgment of the said Engineer Maintenance of Way, can be removed by pick and bar, and is soft and loose enough to be removed without blasting, although blasting may be occasionally resorted to; also, detached stone of less than one (1) cubic yard and more than one (1) cubic foot.

Hard-pan shall consist of tough indurated clay or cemented gravel, which requires blasting or other equally expensive means for its removal, or which cannot be ploughed with less than four horses and a railroad plough, or which requires two pickers to a shoveller, the said Engineer Maintenance of Way to be the judge of these conditions.

EARTH shall include all material of an earthy nature, of whatever name or character, not unquestionably loose rock or hard-pan as above defined.

POWDER. The use of powder in cuts will not be considered as a reason for any other classification than earth, unless the material in the cut is clearly other than earth under the above specifications.

3. Earth, gravel, and other materials taken from the excavations, except when otherwise directed by the said Engineer Maintenance of Way or his assistant, shall be deposited in the adjacent embankment; the cost of removing and depositing which, when the distance necessary to be hauled is not more than sixteen hundred (1600) feet, shall be included in the price paid for the excavation.

4. EXTRA HAUL will be estimated and paid for as follows: whenever material from excavations is necessarily hauled a greater distance than sixteen hundred (1600) feet, there shall be paid in addition to the price of excavation the price of extra haul per 100 feet, or part thereof, after the first 1600 feet; the necessary haul to be determined in each case by the said Engineer Maintenance of Way or his assistant, from the profile and cross-sections, and the estimates to be in accordance therewith.

5. All embankments shall be made in layers of such thickness and carried on in such manner as the said Engineer Maintenance of Way or his assistant may prescribe, the stone and heavy materials being placed in slopes and top. And in completing the fills to the proper grade such additional heights and fulness of slope shall be given them, to provide for their settlement, as the said Engineer Maintenance of Way, or his assistant, may direct. Embankments about masonry shall be built at such times and in such manner and of such materials as the said Engineer Maintenance of Way or his assistant may direct.

6. In procuring materials for embankments from without the line of the road, and in wasting materials from cuttings, the place and manner of doing it shall in each case be indicated by the Engineer Maintenance of Way or his assistant; and care must be taken to injure or disfigure the land as little as possible. Borrow-pits and spoil-banks must be left by the Contractor in regular and sightly shape.

7. The lands of the said Railroad Company shall be cleared to the extent required by the said Engineer Maintenance of

Way, or his assistant, of all trees, brushes, logs, and other perishable materials, which shall be destroyed by burning or deposited in heaps as the said Engineer Maintenance of Way, or his assistant, may direct. Large trees must be cut not more than two and one-half (2½) feet from the ground, and under embankments less than four (4) feet high they shall be cut close to the ground. All small trees and bushes shall be cut close to the ground.

8. Clearing shall be estimated and paid for by the acre or fraction of an acre.

9. All stumps, roots, logs, and other obstructions shall be grubbed out, and removed from all places where embankments occur less than two (2) feet in height; also, from all places where excavations occur and from such other places as the said Engineer Maintenance of Way or his assistant may direct.

10. Grubbing shall be estimated and paid for by the acre or fraction of an acre.

11. Contractors, when directed by the said Engineer Maintenance of Way or his assistant in charge of the work, will deposit on the side of the road, or at such convenient points as may be designated, any stone, rock, or other materials that they may excavate; and all materials excavated and deposited as above, together with all timber removed from the line of the road, will be considered the property of the Railroad Company, and the Contractors upon the respective sections will be responsible for its safe-keeping until removed by said Railroad Company, or until their work is finished.

12. Contractors will be accountable for the maintenance of safe and convenient places wherever public or private roads are in any way interfered with by them during the progress of the work. They will also be responsible for fences thrown down, and for gates and bars left open, and for all damages occasioned thereby.

13. Temporary bridges and trestles, erected to facilitate the progress of the work, in case of delays at masonry structures from any cause, or for other reasons, will be at the expense of the Contractor.

14. The line of road or the gradients may be changed in any manner, and at any time, if the said Engineer Maintenance of Way or his assistant shall consider such a change necessary or expedient; but no claim for an increase in prices of excavation

or embankment on the part of the Contractor will be allowed or considered unless made in writing before the work on that part of the section where the alteration has been made shall have been commenced. The said Engineer Maintenance of Way or his assistant may also, on the conditions last recited, increase or diminish the length of any section for the purpose of more nearly equalizing or balancing the excavations and embankments, or for any other reason.

15. The roadbed will be graded as directed by the said Engineer Maintenance of Way or his assistant, and in conformity with such breadths, depths, and slopes of cutting and filling as he may prescribe from time to time, and no part of the work will be finally accepted until it is properly completed and dressed off at the required grade.

CHAPTER IV.

TRESTLES.

158. Extent of use. Trestles constitute from 1 to 3% of the length of the average railroad. It was estimated in 1889 that there was then about 2400 miles of single-track railway trestle in the United States, divided among 150,000 structures and estimated to cost about $75,000,000. The annual charge for maintenance, estimated at $\frac{1}{8}$ of the cost, therefore amounted to about $9,500,000 and necessitated the annual use of perhaps 300,000,000 ft. B. M. of timber. The corresponding figures at the present time must be somewhat in excess of this. The magnitude of this use, which is causing the rapid disappearance of forests, has resulted in endeavors to limit the use of timber for this purpose. Trestles may be considered as justifiable under the following conditions:

a. Permanent trestles.

1. Those of *extreme* height — then called viaducts and frequently constructed of steel, as the Kinzua viaduct, 302 feet high.

2. Those across wide shallow waterways—*e.g.*, that across Lake Pontchartrain, near New Orleans, 22 miles long.

3. Those across swamps of soft deep mud, or across a river-bottom, liable to occasional overflow.

b. Temporary trestles.

1. To open the road for traffic as quickly as possible—often a reason of great financial importance.

2. To quickly replace a more elaborate structure, destroyed by accident, on a road already in operation, so that the interruption to traffic shall be a minimum.

3. To form an earth embankment with earth brought from a distant point by the train-load, when such a measure would cost less than to borrow earth in the immediate neighborhood.

4. To bridge an opening temporarily and thus allow time to learn the regimen of a stream in order to better proportion the

size of the waterway and also to facilitate bringing *suitable* stone for masonry from a distance. In a new country there is always the double danger of either building a culvert too small, requiring expensive reconstruction, perhaps after a disastrous washout, or else wasting money by constructing the culvert unnecessarily large. Much masonry has been built of a very poor quality of stone because it could be conveniently obtained and because good stone was unobtainable except at a prohibitive cost for transportation. Opening the road for traffic by the use of temporary trestles obviates both of these difficulties.

159. Trestles vs. embankments. Low embankments are very much cheaper than low trestles both in first cost and maintenance. Very high embankments are very expensive to construct, but cost comparatively little to maintain. A trestle of equal height may cost much less to construct, but will be expensive to maintain—perhaps $\frac{1}{8}$ of its cost per year. To determine the height beyond which it will be cheaper to maintain a trestle rather than build an embankment, it will be necessary to allow for the cost of maintenance. The height will also depend on the relative cost of timber, labor, and earthwork. At the present average values, it will be found that for less heights than 25 feet the *first cost* of an embankment will *generally* be less than that of a trestle; this implies that a permanent trestle should never be constructed with a height less than 25 feet except for the reasons given in § 158. The height at which a permanent trestle is certainly cheaper than earthwork is more uncertain. A high grade line joining two hills will invariably imply at least a culvert if an embankment is used. If the culvert is built of masonry, the cost of the embankment will be so increased that the height at which a trestle becomes economical will be materially reduced. The cost of an embankment increases much more rapidly than the height—with very high embankments more nearly as the square of the height—while the cost of trestles does not increase as rapidly as the height. Although local circumstances may modify the application of any set rules, it is probably seldom that it will be cheaper to build an embankment 40 or 50 feet high than to permanently maintain a wooden trestle of that height. A steel viaduct would probably be the best solution of such a case. These are frequently used for permanent structures, especially when very high. The cost of maintenance is much less than that of wood, which makes the use of steel preferable for permanent trestles unless wood is abnormally cheap. Neither the cost nor the construction of steel trestles will be considered in this chapter.

160. Two principal types. There are two principal types of wooden trestles—pile trestles and framed trestles. The great objection to pile trestles is the rapid rotting of the portion of the pile which is underground, and the difficulty of renewal. The maximum height of pile trestles is about 30 feet, and even this height is seldom reached. Framed trestles have been constructed to a height of considerably over 100 feet They are frequently built in such a manner that any injured piece may be readily taken out and renewed without interfering with traffic. Trestles consist of two parts—the supports called "bents," and the stringers and floor system. As the stringers and floor system are the same for both pile and framed trestles, the "bents" are all that need be considered separately.

PILE TRESTLES.

161. Pile bents. A pile bent consists generally of four piles driven into the ground deep enough to afford not only sufficient vertical resistance but also lateral resistance. On top of these piles is placed a horizontal "cap." The caps are fastened to the tops of the piles by methods illustrated in Fig. 68. The method of fastening shown in each case should not be considered as applicable only to the particular type of pile bent used to illustrate it. Fig. 68 (*a* and *d*) illustrates a mortise-joint with a hard-wood pin about $1\frac{1}{4}''$ in diameter. The hole for the pin should be bored separately through the cap and the mortise, and the hole through the cap should be at a slightly higher level than that through the mortise, so that the cap will be drawn down tight when the pin is driven. Occasionally iron dowels (an iron pin about $1\frac{1}{2}''$ in diameter and about 8″ long) are inserted partly in the cap and partly in the pile. The use of drift-bolts, shown in Fig. 68 (*b*), is cheaper in first cost, but renders repairs and renewals very troublesome and expensive. "Split caps," shown in Fig. 68 (*c*), are formed by bolting two half-size strips on each side of a tenon on top of the pile. Repairs are very easily and cheaply made without interference with the traffic and without injuring other pieces of the bent. The smaller pieces are more easily obtainable in a sound condition; the decay of one does not affect the other, and the first cost is but little if any greater than the method of using a single piece. For further discussion, see § 170.

For very light traffic and for a height of about 5 feet three vertical piles will suffice, as shown in Fig. 68 (*a*). Up to a height

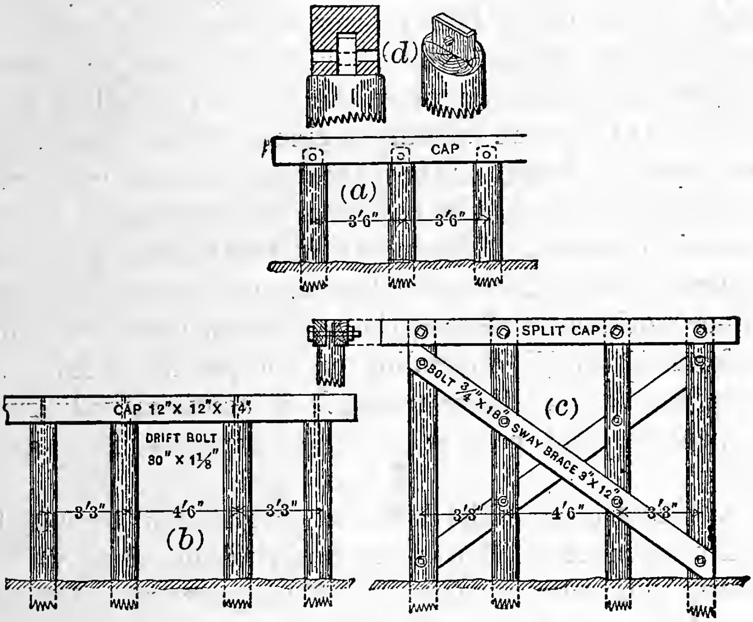


FIG. 68.

of 8 or 10 feet four piles may be used without sway-bracing, as in Fig. 68 (*b*), if the piles have a good bearing. For heights greater than 10 feet sway-bracing is generally necessary. The outside piles are frequently driven with a batter varying from 1 : 12 to 1 : 4.

Piles are made, if possible, from timber obtained in the vicinity of the work. Durability is the great requisite rather than strength, for almost any timber is strong enough (except as noted below) and will be suitable if it will resist rapid decay. The following list is quoted as being in the order of preference on account of durability:

1. Red cedar	5. White pine	9. White oak	12. Black oak
2. Red cypress	6. Redwood	10. Post-oak	13. Hemlock
3. Pitch-pine	7. Elm	11. Red oak	14. Tamarac
4. Yellow pine	8. Spruce		

Red-cedar piles are said to have an average life of 27 years with a possible maximum of 50 years, but the timber is rather weak, and if exposed in a river to flowing ice or driftwood is apt to be injured. Under these circumstances oak is preferable, although its life may be only 13 to 18 years.

162. Methods of driving piles. The following are the principal methods of driving piles:

a. A hammer weighing 2000 to 3000 lbs. or more, sliding in guides, is drawn up by horse-power or a portable engine, and the "nippers" or "tongs," which hold the hammer, are released by a light trip-rope, which permits the hammer to fall *freely*.

b. The drum of a steam hoisting engine is gripped and released by some form of clutch. When the hammer has been raised and the clutch released, the hammer falls, dragging the rope and turning the drum. The energy of the blow is thus somewhat reduced, falsely increasing the apparent resistance. But the hammer works much faster, the number of blows per minute varying from 12 to 25, depending on the height of fall. The mechanism for both of these methods is comparatively simple and inexpensive, and can be easily transported into a new country.

c. Steam pile-drivers. The hammer weighs 3000 to 5000 lbs., and has a movement of 36 to 40 inches, striking 60 to 80 blows per minute. The ram is raised by steam pressure. The older types are single-acting the ram falling by gravity. Some later types are double-acting, the ram being forced down by steam pressure, which increases both the force and the rapidity of the blows. Very rapid blows, which do not allow time for the soil to settle around the pile between consecutive blows, are more effective and encounter less resistance. The destructive impact of a weight of 5000 lbs. falling only 3 feet is but a small part of that of 3000 lbs. falling 20 feet and there is less danger of overdriving and rupturing the pile.

d. Water jet. Whenever a sufficient supply of water is available, and especially when the soil is sandy, pile driving is facilitated by forcing water through a pipe driven into the ground near the desired location of the pile. Two or even three pipes per pile may be used. The former practice was to attach the pipes to the pile, but the pipes were often broken when withdrawn, and present practice keeps the jet independent of the pile, churning it up and down near the pile point by means of a rope running through a block on the driver leads and leading to a hand-winch or to a nigger-head on the engine. When the soil is very soft, piles may be sunk, using the jet only, or with the aid of weights loaded on the pile, but a hammer is essential for harder ground, especially for driving the last few blows, the penetration of which will give a measure of the resisting power of the pile—see § 163. Although the jet has been employed using a hand-pump, effective work requires the use of a power pump, with a 2″ pipe for the jet, a pressure up to a maximum of about 200 lbs per square inch. and a flow of 250 to 500 gallons per minute. Many other details regarding pile driving are given in § 167.

Excessive driving frequently fractures the pile below the surface and thereby greatly weakens its bearing power. To prevent excessive "brooming" of the top of the pile, owing to the action of the hammer, the top should be protected by an iron ring fitted to the top of the pile. The "brooming" not only renders the driving ineffective and hence uneconomical, but vitiates the value of any test of the bearing power of the pile by noting the sinking due to a given weight falling a given distance. If the pile is so soft that brooming is unavoidable, the top should be adzed off frequently, and especially should it be done just before the final blows which are to test its bearing-power.

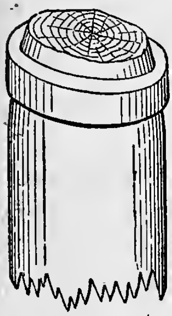


FIG. 69.

In a new country judgment and experience will be required to decide intelligently whether to employ a simple drop-hammer machine, operated by horse-power and easily transported but uneconomical in operation, or a more complicated machine working cheaply and effectively after being transported at greater expense.

163. Pile-driving formulæ. If R = the resistance of a pile, and s the set of the pile during the last blow, w the weight of the pile-hammer, and h the fall during the last blow, then we may state the approximate relation that $Rs = wh$, or $R = \frac{wh}{s}$. This is the basic principle of all rational formulæ, but the maximum weight which a pile will sustain after it has been driven some time is by no means the same as the resistance of the pile during the last blow. There are also many other modifying elements which have been variously allowed for in the many proposed formulæ. The formulæ range from the extreme of empirical simplicity to very complicated attempts to allow properly for all modifying causes. As the simplest rule, the A. R. E. A. specifications require that the piles shall be driven until the pile will not sink more than $2\frac{1}{2}$ inches under five consecutive blows of a 3000-lb hammer falling 15 feet. The "*Engineering News* formula" * gives the safe load as $\frac{2wh}{s+1}$, in which w = weight of hammer, h = fall in *feet*, s = set of pile in *inches* under the last blow. This formula is derived from the above basic formula by calling the safe load $\frac{1}{6}$ of the final resistance, and by adding (arbitrarily) 1 to the final set (s) as a compensation for the extra resistance caused by the settling of earth around the pile between each blow. This formula is used only for ordinary hammer-driving. When the piles are driven by a steam pile-driver the formula becomes safe load $=\frac{2wh}{s+0.1}$. In the last formula the constant in the denominator is changed from $s+1$ to $s+0.1$. The constant (1.0 or 0.1) is supposed to allow, as before stated, for the effect of the extra resistance caused by the earth settling around the pile between each blow. The more rapid the blows the less the opportunity to settle and the less the proper value of the constant.

The above formulae have been given on account of their simplicity and their practical agreement with experience. Many other formulae have been proposed, the majority of which are more complicated and attempt to take into account the weight of the pile, resistance of the guides, etc. While these elements, as well as many others, have their influence, their effect is so overshadowed by the indeterminable effect of other elements—as, for example, the effect of the settlement of earth around the pile between blows—that it is useless to attempt to employ anything but a purely empirical formula.

For the most careful work, dependence is placed on the actual load which may be carried, without yielding, by test piles, driven on the site of the work. In § 167, par. 16–20, some Am. Rwy. Eng. Assoc. rules are quoted regarding the use of test piles.

Examples. 1. A pile was driven with an ordinary hammer weighing 2500 pounds until the sinking under five consecutive blows was $15\frac{1}{2}$ inches. The fall of the hammer during the last

---

* *Engineering News*, Nov. 17, 1892.

blows was 24 feet. What was the safe bearing power of the pile?

$$\frac{2wh}{s+1}=\frac{2\times2500\times24}{(\frac{1}{5}\times15.5)+1}=\frac{120000}{4.1}=29300 \text{ pounds.}$$

2. Piles are being driven into a firm soil with a steam pile-driver until they show a *safe* bearing power of 20 tons. The hammer weighs 5500 pounds and its fall is 40 inches. What should be the sinking under the final blow?

$$40000=\frac{2wh}{s+0.1}=\frac{2\times5500\times3.33}{s+0.1},$$

$$s=\frac{36667}{40000}-0.1=.81 \text{ inch.}$$

164. Pile-points and pile-shoes. Piles are generally sharpened to a blunt point. If the pile is liable to strike boulders, sunken logs, or other obstructions which are liable to turn the point, it is necessary to protect the point by some form of shoe. Several forms in cast iron have been used, also a wrought-iron shoe, having four "straps" radiating from the apex, the straps being nailed on to the pile, as shown in Fig. 70 (*b*). The cast-iron form shown in Fig. 70 (*a*) has a base cast around a drift-bolt. The recess on the top of the base receives the bottom of the pile and prevents a tendency to split the bottom of the pile or to force the shoe off laterally. See § 167, par. 23.

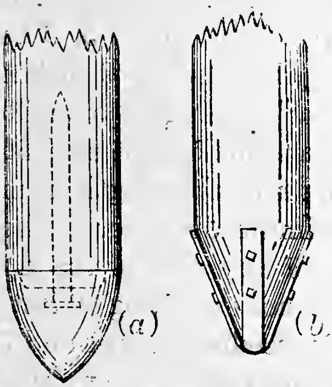


FIG. 70.

165. Details of design. No theoretical calculations of the strength of pile bents need be attempted on account of the extreme complication of the theoretical strains, the uncertainty as to the real strength of the timber used, the variability of that strength with time, and the insignificance of the economy that would be possible even if exact sizes could be computed. The caps are generally 14 feet long (for single track) with a cross-section 12″×12″ or 12″×14″. "Split caps" would consist of two pieces 6″×12″. The sway-braces, never used for less heights than 6′, are made of 3″×12″ timber, and are spiked on with $\frac{3}{8}$″ spikes 8″ long. The floor system will be the same as that described later for framed trestles.

166. Specifications for timber piles (Adopted 1909 by Amer. Rwy. Eng. Assoc.). 1. This grade [railroad heart grade] includes white, burr, and post oak; longleaf pine, Douglas fir, tamarack, Eastern white and red cedar, chestnut, Western cedar, redwood and cypress. 2. Piles shall be cut from sound trees; shall be close-grained and solid, free from defects, such as injurious ring shakes, large and unsound or loose knots, decay or other defects, which may materially impair their strength or durability. In Eastern red or white cedar a small amount of heart rot at the butt, which does not materially injure the strength of the pile, will be allowed. 3. Piles must be butt cut above the ground swell and have a uniform taper from butt to tip. Short bends will not be allowed. A line drawn from the center of the butt to the center of the tip shall lie within the body of the pile. 4. Unless otherwise allowed, piles must be cut when sap is down. Piles must be peeled soon after cutting. All knots shall be trimmed close to the body of the pile. 5. The minimum diameter at the tips of round piles shall be 9 inches for lengths not exceeding 30 feet; 8 inches for lengths over 30 feet but not exceeding 50 feet, and 7 inches for lengths over 50 feet The minimum diameter at one-quarter of the length from the butt shall be 12 inches and the maximum diameter at the butt 20 inches. 6. The minimum width of any side of the tip of a square pile shall be 9 inches for lengths not exceeding 30 feet; 8 inches for lengths over 30 feet but not exceeding 50 feet and 7 inches for lengths over 50 feet. The minimum width of any side at one-quarter of the length from the butt shall be 12 inches. 7. Square piles shall show at least 80% heart on each side at any cross-section of the stick, and all round piles shall show at least $10\frac{1}{2}$ inches diameter of heart at the butt.

The second grade ("Railroad falsework grade") includes other woods which "will stand driving" and which cannot pass the specification for proportion of heart; also, they are usually not peeled.

167. Pile driving—principles of practice. As adopted by the Amer. Rwy. Eng. Assoc. 1911 and revised 1915.

1. A thorough exploration of the soil by borings, or preliminary

test piles, is the most important prerequisite to the design and construction of pile foundations.

2. Soil consisting wholly or chiefly of sand is most favorable to the use of the water-jet.

3. In harder soils containing gravel the use of the jet may be advantageous, if sufficient volume and pressure be provided.

4. In clay it may be economical to bore several holes in the soil with the aid of the jet before driving the pile, thus securing the accurate location of the pile, and its lubrication while being driven.

5. In general, the water-jet should not be attached to the pile, but handled separately.

6. Two jets will often succeed where one fails. In special cases a third jet extending a part of the depth aids materially in keeping loose the material around the pile.

7. Where the material is of such a porous character that the water from the jets may be dissipated and fail to come up in the immediate vicinity of the pile, the utility of the jet is uncertain, except for a part of the penetration.

8. A steam or drop hammer should be used in connection with the water-jet, and used to test the final rate of penetration.

9. The use of the water jet is one of the most effective means of avoiding injury to piles by overdriving.

10. There is danger from overdriving when the hammer begins to bounce. Overdriving is also indicated by the bending, kicking or staggering of the pile.

11. The brooming of the head of the pile dissipates a part, and in some cases all, of the energy due to the fall of the hammer.

12. The steam hammer is usually more effective than the drop hammer in securing the penetration of a wooden pile without injury, because of the shorter interval between blows.

13. Where shock to surrounding material is apt to prove detrimental to the structure, the steam hammer should always be used instead of the drop hammer. This is especially true in the case of sheet piling which is intended to prevent the passage of water. In some cases also the jet should not be used.

14. In general, the resistance of piles, penetrating soft material, depending solely upon skin friction, is materially increased after a period of rest. This period may be as short as fifteen minutes, and rarely exceeds twelve hours.

15. Where a pile penetrates muck or a soft yielding material and bears upon a hard stratum at its foot, its strength should be determined as a column or beam; omitting the resistance, if any, due to skin friction.

16. Unless the record of previous experience at the same site is available, the approximate bearing power may be obtained by loading test piles. The results of loading test piles should be used with caution, unless their condition is fairly comparable with that of the piles in the proposed foundation.

17. In case the piles in a foundation are expected to act as columns, the results of loading test piles should not be depended upon unless they are sufficient in number to insure their action in a similar manner; and unless they are stayed against lateral motion.

18. Before testing the penetration of a pile in a soft material where its bearing power depends principally, or wholly, upon skin friction, the pile should be allowed to rest for 24 hours after driving.

19. Where the resistance of piles depends mainly upon skin friction it is possible to diminish the combined strength, or bearing capacity, of a group of piles, by driving additional piles within the same area.

20. Where piles will foot in a hard stratum, investigation should be made to determine that this stratum is of sufficient depth and strength to carry the load.

21. Timber piles may be advantageously pointed, in some cases, to a 4-inch or 6-inch square at the end.

22. Piles should not be pointed when driven into soft material.

23. Shoes should be provided for piles when the driving is very hard, especially in riprap or shale. These shoes should be so constructed as to form an integral part of the pile.

24. The use of a cap is advantageous in distributing the impact of the hammer more uniformly over the head of the pile, as well as in holding it in position during driving.

168. Cost of pile trestles. The cost, per linear foot, of piling depends on the method of driving, the scarcity of suitable timber, the price of labor, the length of the piles, and the amount of shifting of the pile-driver required. The cost of soft-wood piles varies from 8 to 15 cents per lineal foot, and the cost of oak piles varies from 10 to 30 cents per foot, according to the length, the longer piles costing more per foot. The total cost of putting the piles in place is so dependent on other items than the cost of driving, such as the cost of shifting the driver, getting the piles into the leaders, straightening and bracing them, leveling and nailing guide strips for sawing them off, and then the actual sawing, that there is a wide variation in the figures that are obtainable for the cost of such work. Of course the cost per pile of driving is also dependent on the total number of piles in the job. The cost per pile of placing a dozen piles for a single foundation would be far greater than the cost per pile for several hundred piles in one job. Among a large number of obtainable figures the average figure of $1.54 per pile for driving 1267 piles in 46 days is typical. Another quoted figure is $2.88 each, for driving 391 piles in 32 working days. On another job it cost $150 to drive thirty 30-foot piles, or an average of $5 each. In this case the piles cost $1.50 each or only 5 cents per lineal foot. The above cost figures are taken from Gillette's "Handbook of Cost Data" to which the student is referred for numerous examples of the cost of piles and pile-driving, as well as innumerable other cost analyses.

Specifications generally say that the piling will be paid for per lineal foot of piling *left in the work.* The wastage of the tops of piles sawed off is always something, and is frequently very large. Sometimes a small amount per foot of piling sawed off is allowed the contractor as compensation for his loss. This reduces the contractor's risk and possibly reduces his bid by an equal or greater amount than the extra amount actually paid him.

FRAMED TRESTLES

169. Typical design. A typical design for a framed trestle bent is given in Fig. 71. This represents, with slight variations of detail, the plan according to which a large part of the framed trestle bents of the country have been built—i.e., of those less than 20 or 30 feet in height, not requiring multiple story construction.

170. Joints. (a) **The mortise-and-tenon joint** is illustrated in

Fig. 71 and also in Fig. 68 (*a*). The tenon should be about

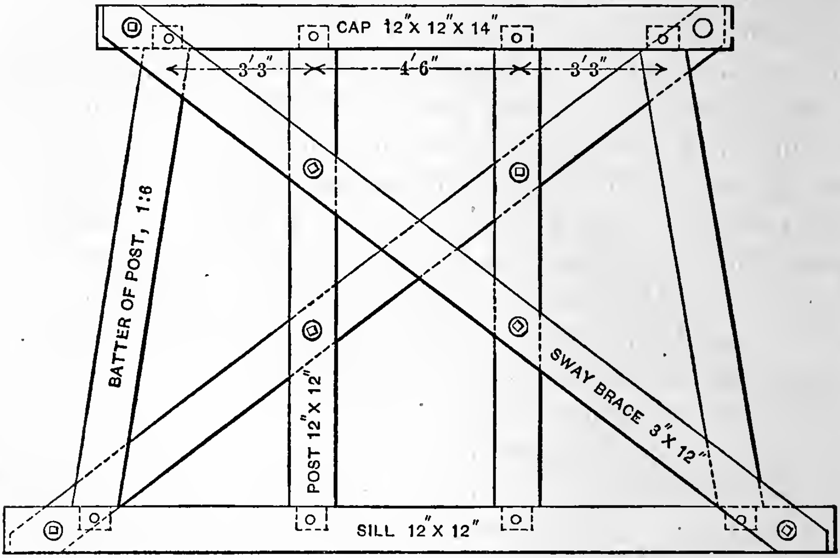


FIG. 71.

3″ thick, 8″ wide, and 5½″ long. The mortise should be cut a little deeper than the tenon. "Drip-holes" from the mortise to the outside will assist in draining off water that may accumulate in the joint and thus prevent the rapid decay that would otherwise ensue. These joints are very troublesome if a single post decays and requires renewal. It is generally required that the mortise and tenon should be thoroughly daubed with paint before putting them together. This will tend to make the joint water-tight and prevent decay from the accumulation and retention of water in the joint.

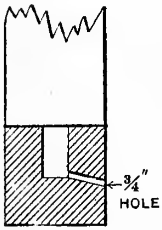


FIG. 72.

(b) The plaster joint. This joint is made by bolting and spiking a 3″×12″ plank on both sides of the joint. The cap and sill should be notched to receive the posts. Repairs are greatly facilitated by the use of these joints. This method has been used by the Delaware and Hudson Canal Co. [R. R.].

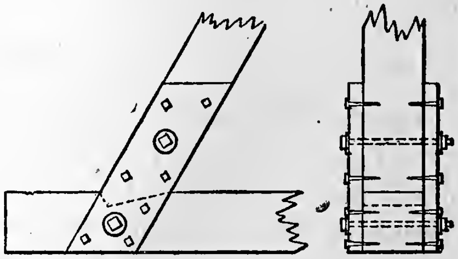


FIG. 73.

(c) Iron plates. An iron plate of the form shown in Fig. 74

(*b*) is bent and used as shown in Fig. 74 (*a*). Bolts passing through the bolt-holes shown secure the plates to the timbers and make a strong joint which may be readily loosened for repairs. By slight modifications in the design the method may be used for inclined posts and complicated joints.

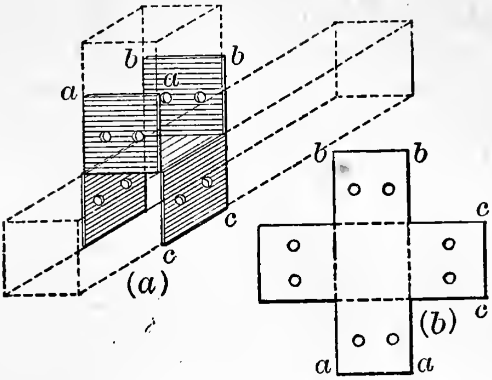


FIG. 74.—JOINT PLATES.

(d) Split caps and sills. These are described in § 161. Their advantages apply with even greater force to framed trestles.

(e) Dowels and drift-bolts. These joints facilitate cheap and rapid construction, but renewals and repairs are very difficult, it being almost impossible to extract a drift-bolt, which has been driven its full length, without splitting open the pieces containing it. Notwithstanding this objection they are extensively used, especially for temporary work which is not expected to be used long enough to need repairs.

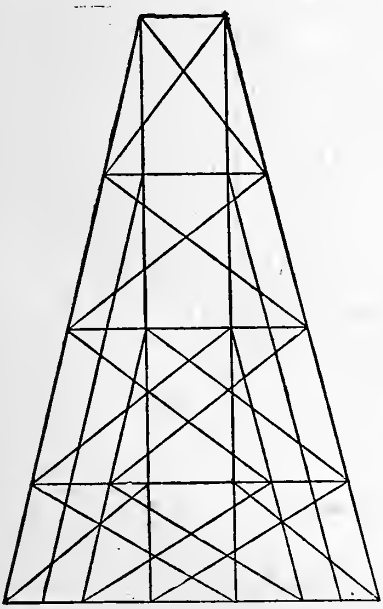


FIG. 75.

171. Multiple-story construction. Single-story framed trestle bents are used for heights up to 18 or 20 feet and exceptionally up to 30 feet. For greater heights some such construction as is illustrated in a skeleton design in Fig. 75 is used. By using split sills between each story and separate vertical and batter posts in each story, any piece may readily be removed and renewed if necessary. The height of these stories varies, in different designs, from 15 to 25 and even 30 feet. In some designs the structure of each story is independent of the stories above and below. This greatly facilitates both the original construction and subsequent repairs.

In other designs the verticals and batter-posts are made continuous through two consecutive stories. The structure is somewhat stiffer, but is much more difficult to repair.

Since the bents of any trestle are usually of variable height and those heights are not always an even multiple of the uniform height desired for the stories, it becomes necessary to make the

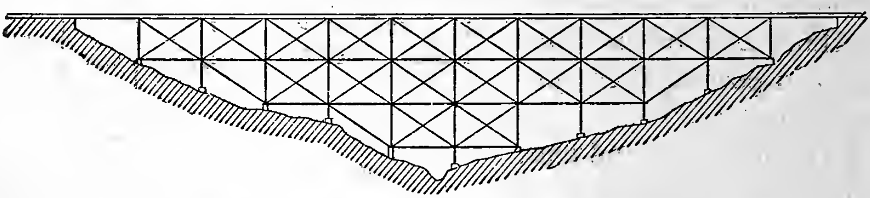


FIG. 76.—SKELETON ELEVATION OF TRESTLE.

upper stories of uniform height and let the odd amount go to the lowest story, as shown in Figs. 75 and 76.

172. Span. The shorter the span the greater the number of trestle bents; the longer the span the greater the required strength of the stringers supporting the floor. Economy demands the adoption of a span that shall make the sum of these require-

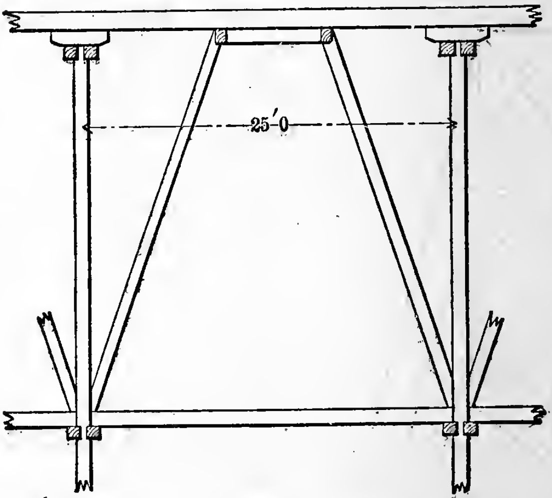


FIG. 77.—KNEE-BRACES FOR LONG-SPAN STRINGERS.

ments a minimum. The higher the trestle the greater the cost of each bent, and the greater the span that would be justifiable. Nearly all trestles have bents of variable height, but the advantage of employing uniform standard sizes is so great that many roads use the same span and sizes of timber not only for the panels of any given trestle, but also for all trestles regardless of height. The spans generally used vary from 10 to 16 feet. The Norfolk and Western R. R. uses a span of 12′ 6″ for all single-story trestles, and a span of 25′ for all multiple-story trestles. The stringers are the same in both cases, but when the span is 25 feet, knee-braces are run from the sill of the first story below to near the middle of each set of stringers. These knee-braces are connected at the top by a "straining-beam" on which the stringers rest, thus supporting the stringer in the center and virtually reducing the span about one-half.

173. Foundations. (a) **Piles.** Piles are frequently used as a foundation, as in Fig. 78, particularly in soft ground, and also for temporary structures. These foundations are cheap, quickly constructed, and are particularly valuable when it is financially necessary to open the road for traffic as soon as possible and with the least expenditure of money; but there is the disadvantage of inevitable decay within a few years unless the piles are chemically treated, as will be discussed later. Chemical treatment, however, increases the cost so that such a foundation would often cost more than a foundation of stone. A pile should be driven under each post as shown in Fig. 78.

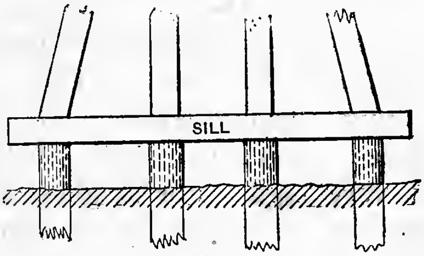


FIG. 78.—PILE FOUNDATION.

(b) **Mud-sills.** Fig. 79 illustrates the use of mud-sills as built by the Louisville and Nashville R. R. Eight blocks 12″×12″×6′ are used under each bent. When the ground is very soft, two additional timbers (12″×12″×length of bent-sill), as shown by the dotted lines, are placed underneath. The number required evidently depends on the nature of the ground.

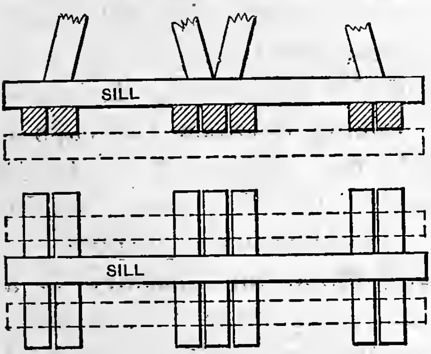


FIG. 79.—MUD-SILL FOUNDATION.

(c) **Stone foundations.** Stone foundations are the best and the most expensive. For very high trestles the Norfolk and

Western R. R. employs foundations as shown in Fig. 80, the walls being 4 feet thick. When the height of the trestle is 72 feet or less (the plans requiring for 72′ in height a foundation-wall 39′ 6″ long) the foundation is made continuous. The sill

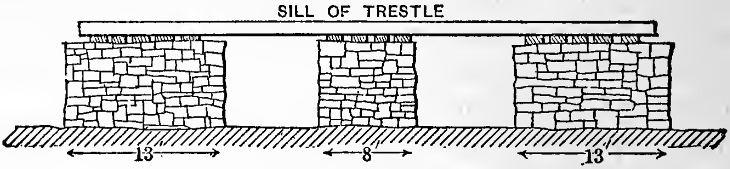


Fig. 80.—Masonry Trestle Foundation.

of the trestle should rest on several short lengths of 3″×12″ plank laid transverse to the sill on top of the wall.

174. Longitudinal bracing. This is required to give the structure longitudinal stiffness and also to reduce the columnar length of the posts. This bracing generally consists of horizontal "waling-strips" and diagonal braces. Sometimes the braces are placed wholly on the outside posts unless the trestle is very high. For single-story trestles the P. R. R. employs the "laced" system, i.e., a line of posts joining the cap of one bent with the sill of the next, and the sill of that bent with the cap of the next. Some plans employ braces forming an × in alternate panels. Connecting these braces in the center more than doubles their columnar strength. Diagonal braces, when bolted to posts, should be fastened to them as near the ends of the posts as possible. The sizes employed vary largely, depending on the clear length and on whether they are expected to act by tension or compression. 3″×12″ planks are often used when the design would require tensile strength only, and 8″×8″ posts are often used when compression may be expected.

175. Lateral bracing. Several of the more recent designs of trestles employ diagonal lateral bracing between the caps of adjacent bents. It adds greatly to the stiffness of the trestle and better maintains its alignment. 6″×6″ posts, forming an × and connected at the center, will answer the purpose.

176. Abutments. When suitable stone for masonry is at hand and a suitable subsoil for a foundation is obtainable without too much excavation, a masonry abutment will be the best. Such an abutment would probably be used when masonry footings for trestle bents were employed (§ 173, *c*).

Another method is to construct a "crib" of 10″×12″ timber, laid horizontally, drift-bolted together, securely braced and embedded into the ground. Except for temporary construction such a method is generally objectionable on account of rapid decay.

Another method, used most commonly for pile trestles, and for framed trestles having pile foundations (§ 173, *a*), is to use a pile bent at such a place that the natural surface on the *up-hill* side is not far below the cap, and the thrust of the material, filled in to bring the surface to grade, is insignificant. 3″×12″ planks are placed behind the piles, cap, and stringers to retain the filled material.

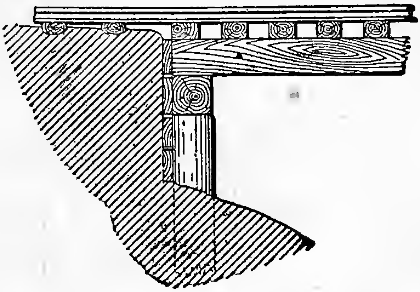


FIG. 81.—ABUTMENT PILE BENT.

FLOOR SYSTEMS.

177. Stringers. The general practice is to use two, three, and even four stringers under each rail. Sometimes a stringer is placed under each guard-rail. Generally the stringers are made of two panel lengths and laid so that the joints alternate. A few roads use stringers of only one panel length, but this practice is strongly condemned by many engineers. The stringers should be separated to allow a circulation of air around them and prevent the decay which would occur if they were placed close together. This is sometimes done by means of 2″ planks, 6′ to 8′ long, which are placed over each trestle bent. Several bolts, passing through all the stringers forming a group and through the separators, bind them all into one solid construction. Cast-iron "spools" or washers, varying from 4″ to $\frac{3}{4}$″ in length (or thickness), are sometimes strung on each bolt so as to separate the stringers. Sometimes washers are used between the separating planks and the stringers, the object of the separating planks then being to bind the stringers, especially abutting stringers, and increase their stiffness.

The most common size for stringers is 8″×16″. The Pennsylvania Railroad varies the width, depth, and number of stringers under each rail according to the clear span. It may be noticed that, assuming a uniform load per running foot, both the pressure per square inch at the ends of the stringers (the caps having a width of 12″) and also the stress due to transverse strain are kept *approximately* constant for the variable gross load on these varying spans.

Span c. to c. of bents.	Y. P. stringers under each rail.	
	For H6b and E3d engines [Max. mom. about 200,000 ft.-lbs.].	For heavier than H6b and E3d engines.
10 ft.	2 pcs. 10″×16″	2 pcs. 10″×16″
12	3 " 8″×16″	3 " 10″×16″
14	3 " 10″×16″	Steel stringers

178. Corbels. A corbel (in trestle-work) is a stick of timber (perhaps two placed side by side), about 3′ to 6′ long, placed underneath and along the stringers and resting on the cap. There are strong prejudices for and against their use, and a corresponding diversity in practice. They are bolted to the stringers and thus stiffen the joint. They certainly reduce the objectionable crushing of the fibers at each end of the stringer, but if the corbel is no wider than the stringers, as is generally the case, the area of pressure between the corbels and the cap is

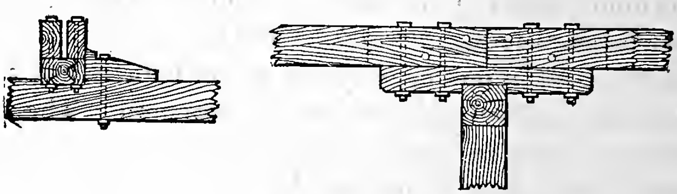


FIG. 82.—CORBEL.

no greater and the pressure per square inch on the cap is no less than the pressure on the cap if no corbels were used. If the corbels and cap are made of hard wood, as is recommended by some, the danger of crushing is lessened, but the extra cost and the frequent scarcity of hard wood, and also the extra cost and labor of using corbels, may often neutralize the advantages obtained by their use.

179. Guard-rails. These are frequently made of 6″×8″ stuff, notched 1″ for each tie. The sizes vary up to 8″×8″, and the depth of notch from $\frac{3}{4}$″ to $1\frac{1}{2}$″. They are generally bolted to every third or fourth tie. It is frequently specified that they shall be made of oak, white pine, or yellow pine. The joints are made over a tie, by halving each piece, as illustrated in Fig. 83. The joints on opposite sides of the trestle should be "staggered." Some roads fasten every tie to the guard-rail, using a bolt, a spike, or a lag-screw.

Guard-rails were originally used with the idea of preventing the wheels of a derailed truck from running off the ends of the ties. But it has been found that an outer guard-rail alone (without an inner guard-rail) becomes an actual element of danger, since it has frequently happened that a derailed wheel has caught on the outer guard-rail, thus causing the truck to slew around

FIG. 83.—GUARD TIMBER.

and so produce a dangerous accident. The true function of the *outside* guard-rail is thus changed to that of a tie-spacer, which keeps the ties from spreading when a derailment occurs. The inside guard-rail generally consists of an ordinary steel rail spiked about 10 inches inside of the running rail. These inner guard-rails should be bent inward to a point in the center of the track about 50 feet beyond the end of the bridge or trestle. If the inner guard-rails are placed with a clear space of 10 inches inside the running rail, the outer guard-rails should be *at least* 6′ 10″ apart. They are generally much farther apart than this.

180. Ties on trestles. If a car is derailed on a bridge or trestle, the heavily loaded wheels are apt to force their way between the ties by displacing them unless the ties are closely spaced and fastened. The clear space between ties is generally equal to or less than their width. Occasionally it is a little more than their width. 6″×8″ ties, spaced 14″ to 16″ from center to center, are most frequently used. The length varies from 9′ to 12′ for single track. They are generally notched ½″ deep on the under side where they rest on the stringers. Oak ties are generally required even when cheaper ties are used on the other sections of the road. Usually every third or fourth tie is bolted to the stringers. When stringers are placed underneath the guard-rails, bolts are run from the top of the guard-rail to the under side of the stringer. The guard-rails thus hold down the whole system of ties, and no direct fastening of the ties to the stringers is needed.

181. Superelevation of the outer rail on curves. The location of curves on trestles should be avoided if possible, especially when the trestle is high. Serious additional strains are introduced especially when the curvature is sharp or the speed high. Since such curves are sometimes practically unavoidable, it is necessary to design the trestle accordingly. If a train is stopped on a curved trestle, the action of the train on the trestle is evidently vertical. If the train is moving with a considerable velocity, the resultant of the weight and the centrifugal action is a force somewhat inclined from the vertical. Both of these conditions may be expected to exist at times. If the *axis* of the system of posts is vertical (as illustrated in methods *a*, *b*, *c*, *d*, and *e*), any lateral force, such as would be produced by a moving train, will tend to rack the trestle bent. If the stringers are set vertically, a centrifugal force likewise tends to tip them sidewise. If the axis of the system of posts (or of the stringers) is inclined so as to coincide with the pressure of the train on the trestle when the train is moving at its normal velocity, there is no tendency to rack the trestle when the train is moving at that velocity, but there will be a tendency to rack the trestle or twist the stringers when the train is stationary. Since a moving train is usually the normal condition of affairs, as well as the condition which produces the maximum stress, an inclined axis is evidently preferable from a theoretical standpoint; but whatever design is adopted, the trestle should evidently be sufficiently cross-braced for either a moving or a stationary load, and any proposed design must be studied as to the effect of *both* of these conditions. Some of the various methods of securing the requisite superelevation may be described as follows:

(a) Framing the outer posts longer than the inner posts, so that the cap is inclined at the proper angle; axis of posts vertical. (Fig. 84.) The method requires more work in framing the trestle, but simplifies subsequent track-laying and maintenance, unless it should be found that the superelevation adopted is unsuitable, in which case it could be corrected by one of the other methods given below. The stringers tend to twist when the train is stationary.

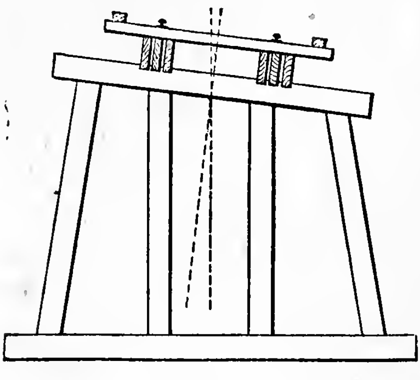


FIG. 84.

(b) Notching the cap so that the stringers are at a different

elevation. (Fig. 85.) This weakens the cap and requires that all ties shall be notched to a bevelled surface to fit the stringers, which also weakens the ties. A centrifugal force will tend to twist the stringers and rack the trestle.

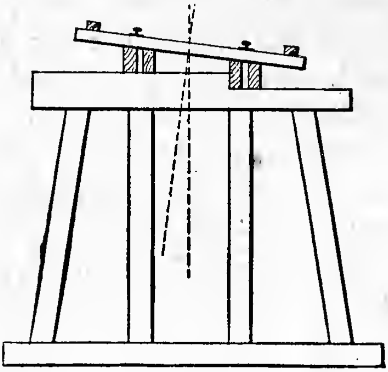


FIG. 85.

(c) Placing wedges underneath the ties at each stringer. These wedges are fastened with two bolts. Two or more wedges will be required for each tie. The additional number of pieces required for a long curve will be immense, and the work of inspection and keeping the nuts tight will greatly increase the cost of maintenance.

(d) Placing a wedge under the outer rail at each tie. This requires but one extra piece per tie. There is no need of a wedge under the inner tie in order to make 'he rail normal to the tread. The resulting inward inclination is substantially that produced by some forms of rail-chairs or tie-plates. The spikes (a little longer than usual) are driven through the wedge into the tie. Sometimes "lag-screws" are used instead of spikes. If experience proves that the superelevation is too much or too little, it may be changed by this method with less work than by any other.

(e) Corbels of different heights. When corbels are used (see § 178) the required inclination of the floor system may be obtained by varying the depth of the corbels.

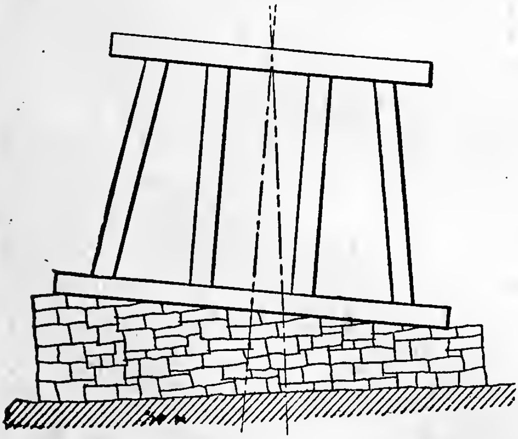


FIG. 86.

(f) Tipping the whole trestle. This is done by placing the trestle on an inclined foundation. If very much inclined, the trestle bent must be secured against the possibility of slipping sidewise, for the slope would be considerable with a sharp curve, and the vibration of a moving train would reduce the coefficient of friction to a comparatively small quantity.

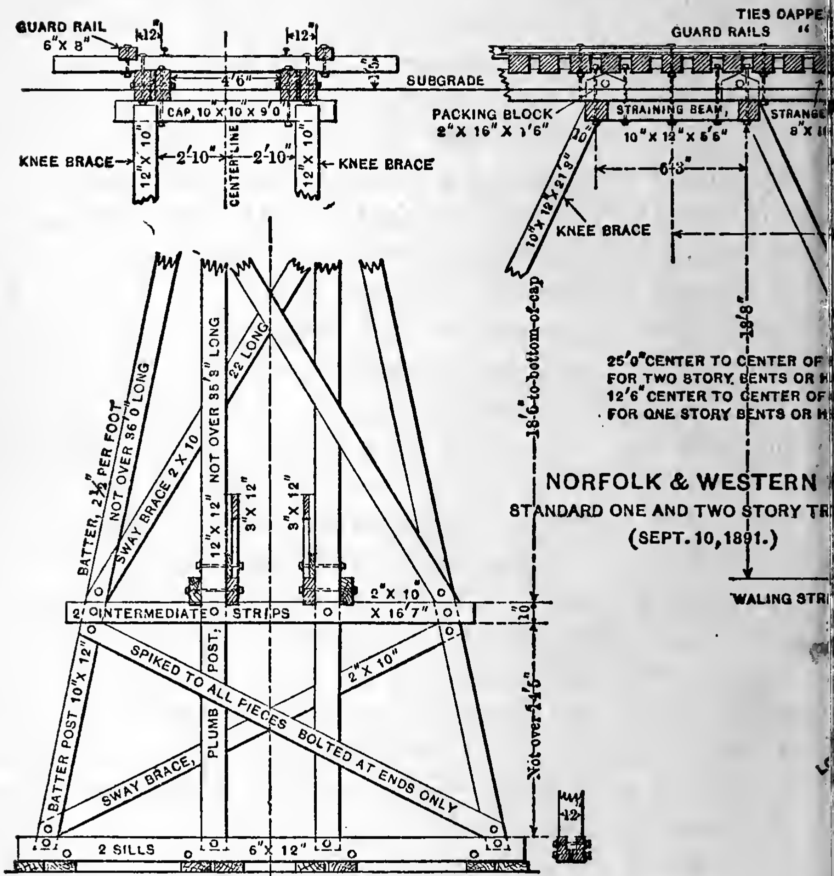
(g) **Framing the outer posts longer.** This case is identical with case (*a*) except that the axis of the system of posts is inclined, as in case (*f*), but the sill is horizontal.

The above-described plans will suggest a great variety of methods which are possible and which differ from the above only in minor details.

182. Protection from fire. Trestles are peculiarly subject to fire, from passing locomotives, which may not only destroy the trestle, but perhaps cause a terrible disaster. This danger is sometimes reduced by placing a strip of galvanized iron along the top of each set of stringers and also along the tops of the caps. Still greater protection was given on a long trestle on the Louisville and Nashville R. R. by making a solid flooring of timber, covered with a layer of ballast on which the ties and rails were laid as usual.

Barrels of water should be provided and kept near all trestles, and on very long trestles barrels of water should be placed every two or three hundred feet along its length. A place for the barrels may be provided by using a few ties which have an extra length of about four feet, thus forming a small platform, which should be surrounded by a railing. The track-walker should be held accountable for the maintenance of a supply of water in these barrels, renewals being frequently necessary on account of evaporation. Such platforms should also be provided as REFUGE-BAYS for track-walkers and trackmen working on the trestle. On very long trestles such a platform is sometimes provided with sufficient capacity for a hand-car.

183. Timber. Any strong durable timber may be used when the choice is limited, but oak, pine, or cypress are preferred when obtainable. When all of these are readily obtainable, the various parts of the trestle will be constructed of different kinds of wood—the stringers of long-leaf pine, the posts and braces of pine or red cypress, and the caps, sills, and corbels (if used) of white oak. The use of oak (or a similar hard wood) for caps, sills, and corbels is desirable because of its greater strength in resisting crushing across the grain, which is the critical test for these parts. There is no physiological basis to the objection, sometimes made, that different species of timber, in contact with each other, will rot quicker than if only one



ONE STORY BENT

(H ÷ 2.4) + 1'7" = LENGTH OF SILL.

H — 1'11" = LENGTH OF 12" X 12" TIMBER REQUIRED FOR PLUMB POSTS, SINGLE BENTS.

H — 21'11" = " " " " " " " " IN LOWER STORY, DOUBLE "

H — 3'5" = " " PLUMB POSTS BETWEEN SHOULDERS, SINGLE "

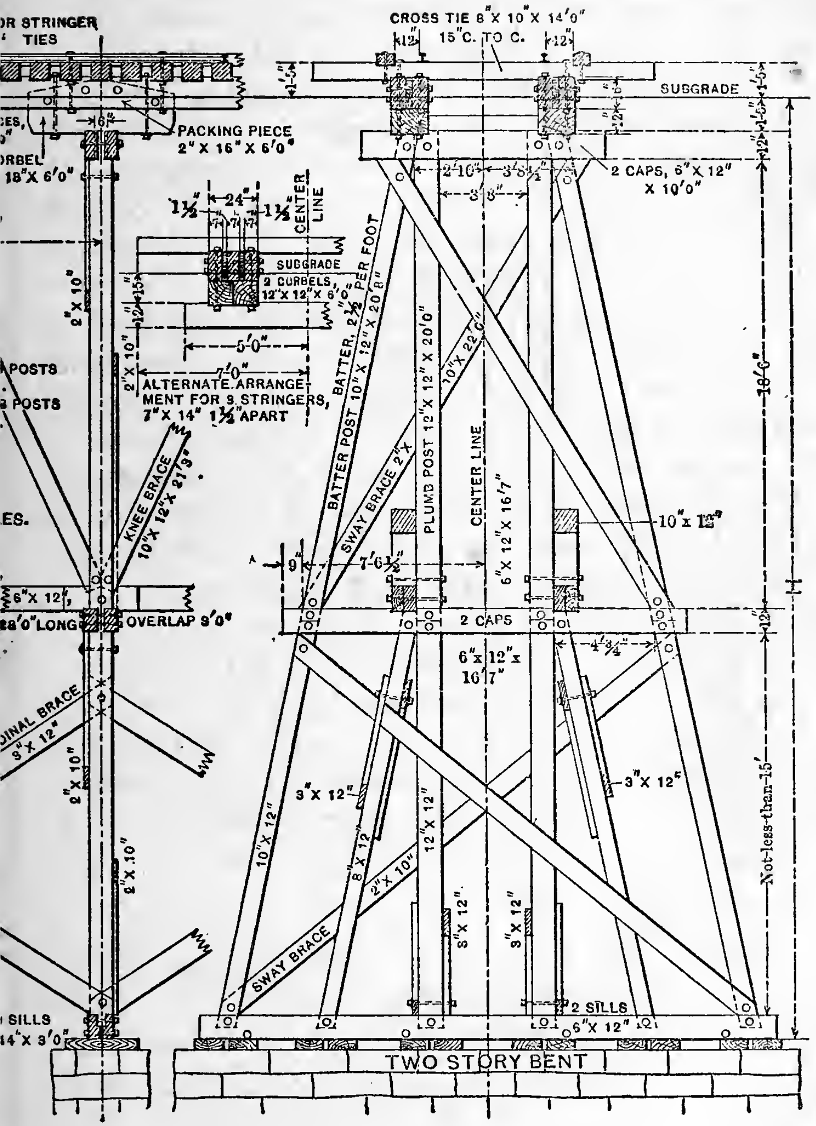
H — 22'11" = " " " " " " " " " DOUBLE "

(LENGTH OF PLUMB POST X 1.021) + 3" = LENGTH OF BATTER POST, EXCEPT IN 8" X 12" INTERMEDIATE BATTER POSTS WHERE ADD 9" INSTEAD OF 3"

WITH ALTERNATIVE ARRANGEMENT OF STRINGERS, ADD 2" TO LENGTHS GIVEN BY ABOVE FORMULAS.

(To face page 216.)

PLATE II.


CROSS TIE 8"X 10"X 14'0"
15"C. TO C.
SUBGRADE
PACKING PIECE 2" X 16" X 6'0"
2 CAPS, 6"X 12" X 10'0"
CENTER LINE
SUBGRADE
2 CORBELS, 12"X 12"X 6'0"
ALTERNATE ARRANGEMENT FOR 9 STRINGERS, 7"X 14" 1½"APART
BATTER, 2½" PER FOOT
BATTER POST 10"X 12"X 20'8"
SWAY BRACE 2"X 10"X 22'6"
PLUMB POST 12"X 12"X 20'0"
CENTER LINE
6"X 12"X 16'7"
KNEE BRACE 10"X 12"X 21'3"
OVERLAP 3'0"
2 CAPS
6"x 12"x 16'7"
10"x 12"
3"X 12"
SWAY BRACE
2 SILLS 6"X 12"
18'6"
Not-less-than-15'
TWO STORY BENT

kind of timber is used. When a very extensive trestle is to be built at a place where suitable growing timber is at hand but there is no convenient sawmill, it will pay to transport a portable sawmill and engine and cut up the timber as desired.

184. Cost of framed timber trestles. The cost varies widely on account of the great variation in the cost of timber. When a railroad is first penetrating a new and undeveloped region, the cost of timber is frequently small, and when it is obtainable from the company's right-of-way the only expense is felling and sawing. The work per M, B. M., is small, considering that a single stick 12″×12″×25′ contains 300 feet, B. M., and that sometimes two hours' work, worth perhaps $1, will finish all the work required on it. Smaller pieces will of course require more work per foot, B. M. Long-leaf pine can be purchased from the mills at from $27 to $45 per M feet, B. M., according to the dimensions. To this must be added the freight and labor of erection. The cartage from the nearest railroad to the trestle may often be a considerable item. Wrought iron will cost about 3 cents per pound and cast iron 2 cents, although the prices are often lower than these. The amount of iron used depends on the detailed design, but, as an average, will amount to $1.50 to $2 per 1000 feet, B. M., of timber. A large part of the trestling of the country has been built at a contract price of about $30 per 1000 feet, B. M., erected. While the cost will frequently rise to $50 and even $60 when timber is scarce, it will drop to $13 (cost quoted) when timber is cheap.

DESIGN OF WOODEN TRESTLES.

185. Common practice. A great deal of trestling has been constructed without any rational design except that custom and experience have shown that certain sizes and designs are *probably* safe. This method has resulted occasionally in failures but more frequently in a very large waste of timber. Many railroads employ a uniform size for all posts, caps, and sills, and a uniform size for stringers, all regardless of the height or span of the trestle. For repair work there are practical reasons favoring this. "To attempt to run a large lot of sizes would be more wasteful in the end than to maintain a few stock sizes only. Lumber can be bought more cheaply by giving a general order for 'the run of the mill for the season,' or 'a cargo lot,' specify ing approximate percentages of standard stringer size, of 12×12-inch stuff, 10×10-inch stuff, etc., and a liberal proportion of 3- or 4-inch plank, all lengths thrown in. The 12×12-inch stuff, etc., is ordered all lengths, from a certain specified length up. In case of a wreck, washout, burn-out, or sudden call for a trestle to be completed in a stated time, it is much more economical and practical to order a certain number of carloads of 'trestle stuff' to the ground and there to select piece after piece as fast as needed, dependent only upon the length of stick required. When there is time to make the necessary surveys of the ground and calculations of strength, and to wait for a special bill of timber to be cut and delivered, the use of different sizes for posts in a structure would be warranted to a certain extent." * For new construction, when there is generally sufficient time to design and order the proper sizes, such wastefulness is less excusable, and under any conditions it is both safer and more economical to prepare *standard designs* which can be made applicable to varying conditions and which will at the same time utilize as much of the strength of the timber as can be depended on. In the following sections will be given the elements of the preparation of such standard designs, which will utilize uniform sizes with as little waste of timber as possible. It is *not* to be understood that special designs should be made for each individual trestle.

186. Required elements of strength. The *stringers* of trestles are subject to transverse strains, to crushing across the grain at the ends, and to shearing along the neutral axis. The strength of the timber must therefore be computed for all these kinds of stress. *Caps* and *sills* will fail, if at all, by crushing across the grain; although subject to other forms of stress, these could hardly cause failure in the sizes usually employed. There is an apparent exception to this: if piles are improperly driven and an uneven settlement subsequently occurs, it may have the effect of transferring practically all of the weight to two or three piles, while the *cap* is subjected to a severe transverse strain which may cause its failure. Since such action is caused generally by avoidable errors of construction it may be considered as abnormal, and since such a failure will generally occur by a *gradual* settlement, all danger may be avoided by reasonable

* From "Economical Designing of Timber Trestle Bridges."

care in inspection. *Posts* must be tested for their columnar strength. These parts form the bulk of the trestle and are the parts which can be definitely designed from known stresses. The stresses in the bracing are more indefinite, depending on indeterminate forces, since the inclined posts take up an unknown proportion of the lateral stresses, and the design of the bracing may be left to what experience has shown to be safe, without involving any large waste of timber.

187. Strength of timber. Until recently tests of the strength of timber have generally been made by testing small, selected, well-seasoned sticks of "clear stuff," free from knots or imperfections. Such tests would give results so much higher than the vaguely known strength of large unseasoned "commercial" timber that very large factors of safety were recommended—factors so large as to detract from any confidence in the whole theoretical design. Recently the U. S. Government has been making a thoroughly scientific test of the strength of full-size timber under various conditions as to seasoning, etc. The work has been so extensive and thorough as to render possible the economical designing of timber structures.

One important result of the investigation is the determination of the great influence of the moisture in the timber and the law of its effect on the strength. It has been also shown that timber soaked with water has substantially the same strength as green timber, even though the timber had once been thoroughly seasoned. Since trestles are exposed to the weather they should be designed on the basis of using green timber. It has been shown that the strength of green timber is very regularly about 55 to 60% of the strength of timber in which the moisture is 12% of the dry weight, 12% being the proportion of moisture usually found in timber that is protected from the weather but not heated, as, *e.g.*, the timber in a barn. Since the moduli of rupture have all been reduced to this standard of moisture (12%), if we take *one-eighth* of the rupture values, it still allows a factor of safety of about five, even on green timber. In Table XX there are quoted the values taken from the U. S. Government reports on the strength of timber, the tests probably being the most thorough and reliable that were ever made.

In Table XXI are given the "working unit stresses for structural timber, expressed in pounds per square inch," as recommended by the committee on "Wooden Bridges and Trestles," of the American Railway Engineering Association. The report was presented at their tenth annual convention, held in Chicago, in March, 1909.

TABLE XX. MODULI OF RUPTURE FOR VARIOUS TIMBERS.
[12% moisture.]
(Condensed from U. S. Forestry Circular, No. 15.)

No.	Species.	Weight per cubic foot.	Cross-bending. Ultimate Strength.	Cross-bending. Modulus of Elasticity.	Crushing endwise.	Crushing across the grain.	Shearing along the grain.
1	Long-leaf pine....	38	12 600	2 070 000	8000	1180	700
2	Cuban "	39	13 600	2 370 000	8700	1220	700
3	Short-leaf "	32	10 100	1 680 000	6500	960	700
4	Loblolly "	33	11 300	2 050 000	7400	1150	700
5	White "	24	7 900	1 390 000	5400	700	400
6	Red "	31	9 100	1 620 000	6700	1000	500
7	Spruce "	39	10 000	1 640 000	7300	1200	800
8	Bald cypress......	29	7 900	1 290 000	6000	800	500
9	White cedar.......	23	6 300	910 000	5200	700	400
10	Douglas spruce....	32	7 900	1 680 000	5700	800	500
11	White oak.......	50	13 100	2 090 000	8500	2200	1000
12	Overcup "	46	11 300	1 620 000	7300	1900	1000
13	Post "	50	12 300	2 030 000	7100	3000	1100
14	Cow "	46	11 500	1 610 000	7400	1900	900
15	Red "	45	11 400	1 970 000	7200	2300	1100
16	Texan "	46	13 100	1 860 000	8100	2000	900
19	Willow "	45	10 400	1 750 000	7200	1600	900
20	Spanish "	46	12 000	1 930 000	7700	1800	900
21	Shagbark hickory..	51	16 000	2 390 000	9500	2700	1100
27	Pignut " ..	56	18 700	2 730 000	10900	3200	1200
28	White elm........	34	10 300	1 540 000	6500	1200	800
29	Cedar "	46	13 500	1 700 000	8000	2100	1300
30	White ash........	39	10 800	1 640 000	7200	1900	1100

188. Loading. As shown in § 172, the span of trestles is always small, is generally 14 feet, and is never greater than 18 feet except when supported by knee-braces. The greatest load that will ever come on any one span will be the concentrated loading of the drivers of a very heavy locomotive. With spans of 14 feet or less it is impossible for even the four pairs of drivers to be on the same span at once. The weight of the rails, ties, and guard-rails should be added to obtain the total load on the stringers, and the weight of these, plus the weight of the stringers, should be added to obtain the pressure on the caps or corbels.

TABLE XXI. WORKING UNIT STRESSES FOR STRUCTURAL TIMBER EXPRESSED IN LBS. PER SQ. IN. RECOMMENDED BY THE COMMITTEE ON WOODEN BRIDGES AND TRESTLES AMER. RWY. ENG. ASSOC.. 1909.

Kind of Timber.	Bending.			Shearing.				Compression.						Ratio of length of stringer to depth.
	Extreme fiber stress.		Modulus of elasticity.	Parallel to grain.		Longitudinal shear in beams		Perpendicular to grain.		Parallel to grain.		For colmns under 15 diams. safe stress.	Formulas for working stress in long column over 15 diams.	
	Aver. ultimate.	W'rking stress	Average.	Aver. ultimate.	W'rking stress	Aver. ultimate.	Working stress.	Elastic limit.	Working stress.	Aver. ultimate.	Working stress.			
Douglas fir	6100	1200	1,510,000	690	170	270	110	630	310	3600	1200	900	$1200\left(1-\frac{L}{60D}\right)$	10
Long-leaf pine	6500	1300	1,610,000	720	180	300	120	520	260	3800	1300	980	$1300\left(1-\frac{L}{60D}\right)$	10
Short-leaf pine	5600	1100	1,480,000	710	170	330	130	340	170	3400	1100	830	$1100\left(1-\frac{L}{60D}\right)$	10
White pine	4400	900	1,130,000	400	100	180	70	290	150	3000	1000	750	$1000\left(1-\frac{L}{60D}\right)$	10
Spruce	4800	1000	1,310,000	600	150	170	70	370	180	3200	1100	830	$1100\left(1-\frac{L}{60D}\right)$	......
Norway pine	4200	800	1,190,000	590	130	250	100	......	150	2600*	800	600	$800\left(1-\frac{L}{60D}\right)$	......
Tamarack	4600	900	1,220,000	670	170	260	100	......	220	3200*	1000	750	$1000\left(1-\frac{L}{60D}\right)$	......
Western hemlock	5800	1100	1,480,000	630	160	270*	100	440	220	3500	1200	900	$1200\left(1-\frac{L}{60D}\right)$	......
Redwood	5000	900	800,000	300	80	......	......	400	150	3300	900	680	$900\left(1-\frac{L}{60D}\right)$	......
Bald cypress	4800	900	1,150,000	500	120	......	......	340	170	3900	1100	830	$1100\left(1-\frac{L}{60D}\right)$	......
Red cedar	4200	800	860,000	......	......	......	......	470	230	2800	900	680	$900\left(1-\frac{L}{60D}\right)$	......
White oak	5700	1100	1,150,000	840	210	270	110	920	450	3500	1300	980	$1300\left(1-\frac{L}{60D}\right)$	12

Note.—These unit stresses are for a green condition of timber and are to be used without increasing the live load stresses for impact. * Partially air-dry.

L = length in inches. D = least side in ins.

These working stresses are for railroad bridges and trestles. For highway bridges and trestles increase the figures by 25 per cent. For buildings, etc., when protected from weather and free from impact, increase them 50 per cent. To compute deflection, under long-continued loading, use 50 per cent of modulus of elasticity.

This dead load is almost insignificant compared with the live load and may be included with it. The weight of rails, ties, etc., may be estimated at 240 pounds per foot. To obtain the weight on the caps the weight of the stringers must be added, which depends on the design and on the weight per cubic foot of the wood employed. But as the weight of the stringers is comparatively small, a considerable percentage of variation in weight will have but an insignificant effect on the result. Disregarding all refinements as to actual dimensions, the ordinary maximum loading for standard-gauge railroads may be taken as that due to four driving-axles, spaced 5′ 0″ apart and giving a pressure of 40000 pounds per axle. This should be increased to 54000 pounds per axle (same spacing) for the heaviest traffic. On the basis of 40000 pounds per axle or 20000 pounds per wheel the following results have been computed: This loading is assumed to allow for impact.

STRESSES ON VARIOUS SPANS DUE TO MOVING LOADS OF 20000 POUNDS, SPACED 5′ 0″ APART, WITH 120 POUNDS PER FOOT OF DEAD LOAD.

Span in feet.	Max. moment, ft. lbs.	Max. shear.	Max. load on one cap under one rail.
10	51 500	30 600	41 200
12	82 160	35 720	49 440
14	112 940	39 410	57 680
16	123 840	43 460	65 920
18	164 860	47 747	75 160

Although the dead load does not vary in proportion to the live load, yet, considering the very small influence of the dead load, there will be no appreciable error in assuming the corresponding values, for a load of 54000 lbs. per axle, to be $\frac{54}{40}$ of those given in the above tabulation.

189. Factors of safety. The most valuable result of the government tests is the knowledge that under given moisture conditions the strength of various species of sound timber is not the variable uncertain quantity it was once supposed to be, but that its strength can be relied on to a comparatively close percentage. This confidence in values permits the employment of lower factors of safety than have heretofore been permissible. Stresses, which when excessive would result in immediate destruction, such as cross-breaking and columnar stresses, should be allowed a higher factor of safety—say 6 or 8 for green timber. Other stresses, such as crushing across the grain and shearing along the neutral axis, which will be apparent to inspection before it is dangerous, may be allowed lower factors—say 3 to 5.

190. Design of stringers. The strength of rectangular beams of equal width varies as the square of the depth; therefore deep beams are the strongest. On the other hand, when any cross-sectional dimension of timber much exceeds 12″ the cost is much higher per M, B. M., and it is correspondingly difficult to obtain thoroughly sound sticks, free from wind-shakes, etc. Wind-shakes especially affect the shearing strength. Also, if the required transverse strength is obtained by using high narrow stringers, the area of pressure between the stringers and the cap may become so small as to induce crushing across the grain. This is a very common defect in trestle design. As already indicated in § 172, the span should vary roughly with the average height of the trestle, the longer spans being employed when the trestle bents are very high, although it is usual to employ the same span throughout any one trestle.

To illustrate, if we select a span of 14 feet, the load on one cap will be 57680 lbs. If the stringers and cap are made of long-leaf yellow pine, the allowable value, according to Table XXI, for "compression across the grain" is 260 pounds per square inch; this will require 222 square inches of surface. If the cap is 12″ wide, this will require a width of 18.5 inches, or say 2 stringers under each rail, each 9 inches wide. For rectangular beams.

$$\text{Moment} = \tfrac{1}{6}R'bh^2.$$

Using for R' the safe value 1300 lbs. per square inch, we have

$$112940 \times 12 = \tfrac{1}{6} \times 1300 \times 18 \times h^2,$$

from which $h = 18''.7$. If desired, the width may be increased to 10″ and the depth correspondingly reduced, which will give similarly $h = 17''.7$ or say 18″. This shows that two beams, 10″×18″, under each rail will stand the transverse bending and have more than enough area for crushing.

The shear per square inch will equal

$$\frac{3}{2}\frac{\text{total shear}}{\text{cross-section}} = \frac{3}{2}\frac{39410}{2 \times 10 \times 18} = 164 \text{ lbs. per sq. inch.}$$

This is higher than the recommended working value. The combination suggested in § 177, viz., 3 beams 10″×16″ for 14 feet span, gives a far safer value. Considering that wooden beams, tested to destruction, usually fail by shearing, the three-beam combination is safer.

The deflection should be computed to see if it exceeds the somewhat arbitrary standard of $\frac{1}{200}$ of the span. The deflection for *uniform loading* is

$$\Delta = \frac{5Wl^3}{32bh^3E},$$

in which l = length in inches;

W = total load, assumed as uniform = 57680;
E = modulus of elasticity, given as 1610000 lbs.

per sq. in. for long-leaf pine, according to Table XXI. Then

$$\Delta = \frac{5 \times 57680 \times 168^3}{32 \times 30 \times 16^3 \times 1610000} = 0''.216$$

$$\frac{1}{200} \times 168'' = 0''.84,$$

so that the calculated deflection is well within the limit. Of course the loading is not strictly uniform, but even with a liberal allowance the deflection is still safe.

For the heaviest practice (65000 lbs. per axle) these stringer dimensions must be correspondingly increased.

191. Design of posts. Four posts are generally used for single-track work. The inner posts are usually braced by the cross-braces, so that their columnar strength is largely increased; but as they are apt to get more than their share of work, the advantage is compensated and they should be treated as unsupported columns for the total distance between cap and sill in simple bents, or for the height of stories in multiple-story construction. The caps and sills are assumed to have a width of 12″. It facilitates the application of bracing to have the columns of the same width and vary the other dimension as required.

Unfortunately the experimental work of the U. S. Government on timber testing has not yet progressed far enough to establish unquestionably a general relation between the strength of long columns and the crushing strength of short blocks. The following formula has been suggested, but it cannot be considered as established:

$$f = F \times \frac{700 + 15c}{700 + 15c + c^2}, \quad \text{in which}$$

f = allowable working stress per sq. in for long columns;
F = " " " " " " " short blocks;
$c = \frac{l}{d}$;
l = length of column in inches;
d = least cross-sectional dimensions in inches.

The formula recommended by the A. R. E. A. is found in Table XXI. For all columns of which the length is less than 15 times the least diameter, a uniform unit stress is recommended. For longer columns, a unit stress is multiplied by the factor $(1 - l \div 60d)$, which is always less than unity. For the above case, $l = 240$ and $d = 12$, and the factor = .667, which, multiplied by 1300, gives a unit stress of 867 lbs. per square inch for a long-leaf yellow pine column of these dimensions.

$867 \times 144 = 124848$ lbs., the *working load* for *each* post. This is more than the total load on one trestle bent and illustrates the usual great waste of timber. Making the post $8'' \times 12''$ and calculating similarly, we have $f = 650$, and the working load per column is $650 \times 96 = 62400$ lbs. As considerable must be allowed for "weathering," which destroys the strength of the outer layers of the wood, and also for the dynamic effect of the live load, $8'' \times 12''$ may not be too great, but it is certainly a safe dimension, considered as a column. One method of allowing for weathering is to disregard the outer half-inch on all sides of the post, i.e., to calculate the strength of a post one inch smaller in each dimension than the post actually employed. On this basis an $8'' \times 12'' \times 20'$ post, computed as a $7'' \times 11''$ post, would have a *safe* columnar strength of 556 lbs. per square inch. With an area of 77 square inches, this gives a working load of 42812 lbs. for *each post*, or 171248 lbs. for the four posts. Considering that 115360 lbs. is the maximum load on one cap (14 feet span), the great excess of strength is apparent.

192. Design of caps and sills. The stresses in caps and sills are very indefinite, except as to crushing across the grain. As the stringers are placed almost directly over the inner posts, and as the sills are supported just under the posts, the transverse stresses are almost insignificant. In the above case four posts have an area of $4 \times 12'' \times 8'' = 384$ sq. in. The total load 115360 lbs. will then give a pressure of 300 pounds per square inch, which is more than the allowable limit. This one feature will require the use of $12'' \times 12''$ (or at least $10'' \times 12''$) posts rather than $8'' \times 12''$ posts, for the smaller posts, although probably strong enough as posts, would produce an objectionably high pressure.

193. Bracing. Although some idea of the stresses in the bracing could be found from certain assumptions as to wind-pressure, etc., yet it would probably not be found wise to decrease, for the sake of economy, the dimensions which practice has shown to be sufficient for the work. The economy that would be possible would be too insignificant to justify any risk. Therefore the usual dimensions, given in §§ 174 and 175, should be employed.

CHAPTER V.

TUNNELS.

SURVEYING.

194. Surface surveys. As tunnels are always dug from each end and frequently from one or more intermediate shafts, it is necessary that an accurate surface survey should be made between the two ends. As the natural surface in a locality where a tunnel is necessary is almost invariably very steep and rough, it requires the employment of unusually refined methods of work to avoid inaccuracies. It is usual to run a line on the surface that will be at every point vertically over the center line of the tunnel. Tunnels are generally made straight unless curves are absolutely necessary, as curves add greatly to the cost. Fig. 87 represents roughly a longitudinal section of the

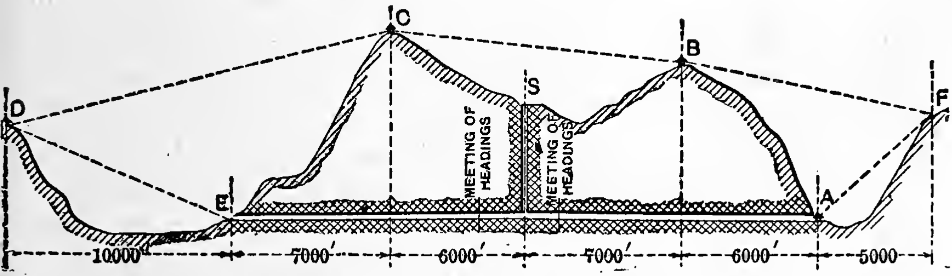


FIG. 87.—SKETCH OF SECTION OF THE HOOSAC TUNNEL.

Hoosac Tunnel. Permanent stations were located at *A*, *B*, *C*, *D*, *E*, and *F*, and stone houses were built at *A*, *B*, *C*, and *D*. These were located with ordinary field transits at first, and then all the points were placed as nearly as possible in one vertical plane by repeated trials and minute corrections, using a very large specially constructed transit. The stations *D* and *F* were necessary because *E* and *A* were invisible from *C* and *B*. The alinement at *A* and *E* having been determined with great accuracy, the true alinement was easily carried into the tunnel.

The relative elevations of *A* and *E* were determined with great accuracy. Steep slopes render necessary many settings of the level per unit of horizontal distance and require that the work be unusually accurate to obtain even fair accuracy per unit of distance. The levels are usually re-run many times until the probable error is a very small quantity

The exact horizontal distance between the two ends of the tunnel must also be known, especially if the tunnel is on a grade. The usual steep slopes and rough topography likewise render accurate horizontal measurements very difficult. Frequently when the slope is steep the measurement is best obtained by measuring along the slope and allowing for grade. This may be very accurately done by employing two tripods (level or transit tripods serve the purpose very well), setting them up slightly less than one tape-length apart and measuring between horizontal needles set in wooden blocks inserted in the top of each tripod. The elevation of each needle is also observed. The true horizontal distance between two successive positions of the needles then equals the square root of the difference of the squares of the inclined distance and the difference of elevation. Such measurements will probably be more accurate than those made by attempting to hold the tape horizontal and plumbing down with plumb-bobs, because (1) it is practically difficult to hold both ends of the tape truly horizontal; (2) on steep slopes it is impossible to hold the down-hill end of a 100-foot tape (or even a 25-foot length) on a level with the other end, and the great increase in the number of applications of the unit of measurement very greatly increases the probable error of the whole measurement; (3) the vibrations of a plumb-bob introduce a large probability of error in transferring the measurement from the elevated end of the tape to the ground, and the increased number of such applications of the unit of measurement still further increases the probable error.

195. Surveying down a shaft. If a shaft is sunk, as at *S*, Fig. 87, and it is desired to dig out the tunnel in both directions from the foot of the shaft so as to meet the headings from the outside, it is necessary to know, when at the bottom of the shaft, the elevation, alinement, and horizontal distance from each end of the tunnel.

The elevation is generally carried down a shaft by means of a steel tape. This method involves the least number of applications of the unit of measurement and greatly increases the accuracy of the final result.

The *horizontal distance from each end* may be easily transferred down the shaft by means of a plumb-bob, using some of the precautions described in the next paragraph.

To transfer the *alinement* from the surface to the bottom of a shaft requires the highest skill because the shaft is always small, and to produce a line perhaps several thousand feet long in a direction given by two points 6 or 8 feet apart requires that the two points must be determined with extreme accuracy. The eminently successful method adopted in the Hoosac Tunnel will be briefly described: Two beams were securely fastened across the top of the shaft (1030 feet deep), the beams being placed transversely to the direction of the tunnel and as far apart as possible and yet allow plumb-lines, hung from the intersection of each beam with the tunnel center line, to swing freely at the bottom of the shaft. These intersections of the beams with the center line were determined by averaging the results of a large number of careful observations for alinement. Two fine parallel wires, spaced about $\frac{1}{16}''$ apart, were then stretched between the beams so that the center line of the tunnel bisected at all points the space between the wires. Plumb-bobs, weighing 15 pounds, were suspended by fine wires beside each cross-beam, the wires passing between the two parallel alinement wires and bisecting the space. The plumb-bobs were allowed to swing in pails of water at the bottom. Drafts of air up the shaft required the construction of boxes surrounding the wires. Even these precautions did not suffice to absolutely prevent vibration of the wire at the bottom through a very small arc. The mean point of these vibrations in each case was then located on a rigid cross-beam suitably placed at the bottom of the shaft and at about the level of the roof of the tunnel. Short plumb-lines were then suspended from these points whenever desired; a transit was set (by trial) so that its line of collimation passed through both plumb-lines and the line at the bottom could thus be prolonged.

Some recent experience in the "Tamarack" shaft, 4250 feet deep, shows that the accuracy of the results may be affected by air-currents to an unsuspected extent. Two 50-lb. cast-iron plumb-bobs were suspended with No. 24 piano-wire in this shaft. The carefully measured distances between the wires at top and bottom were 16.32 and 16.43 feet respectively. After considerable experimenting to determine the cause of the variation, it was finally concluded that air-currents were alone responsible. The variation of the bobs from a true vertical plane passing through the wires at the top was of course an unknown quantity, but since the variation in *one* direction amounted to 0.11 foot, the accuracy in other directions was very questionable. This shows that a careful comparative measurement between the wires at top and bottom should always be made as a test of their parallelism.

196. Underground surveys. Survey marks are frequently placed on the timbering, but they are apt to prove unreliable on account of the shifting of the timbering due to settlement of the surrounding material. They should never be placed at the bottom of the tunnel on account of the danger of being disturbed or covered up. Frequently holes are drilled in the roof and filled with wooden plugs in which a hook is screwed exactly on line Although this is probably the safest method, even these plugs are not always undisturbed, as the material, unless very hard, will often settle slightly as the excavation proceeds. When a tunnel is perfectly straight and not too long, alinement-points may be given as frequently as desired from permanent stations located *outside* the tunnel where they are not liable to disturbance. This has been accomplished by running the alinement through the upper part of the cross-section, at one side of the center, where it is out of the way of the piles of masonry material, débris, etc., which are so apt to choke up the lower part of the cross-section. The position of this line relative to the cross-section being fixed, the alignment of any required point of the cross-section is readily found by means of a light frame or template with a fixed target located where this line would intersect the frame when properly placed. A level-bubble on the frame will assist in setting the frame in its proper position.

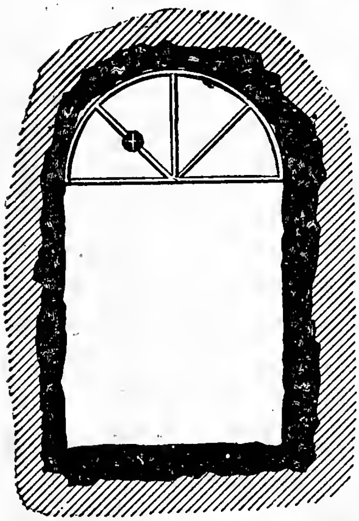


FIG. 88.

In all tunnel surveying the cross-wires must be illuminated by a lantern, and the object sighted at must also be illuminated. A powerful dark-lantern with the opening covered with *ground glass* has been found useful. This may be used to illuminate a plumb-bob string or a very fine rod, or to place behind a brass plate having a narrow slit in it, the axis of the slit and plate being coincident with the plumb-bob string by which it is hung.

On account of the interference to the surveying caused by the work of construction and also by the smoke and dust in the air resulting from the blasting, it is generally necessary to make the surveys at times when construction is temporarily suspended.

197. Accuracy of tunnel surveying. Apart from the very natural desire to do surveying which shall check well, there is an important financial side to accurate tunnel surveying. If the survey lines do not meet as desired when the headings come together, it may be found necessary, if the error is of appreciable size, to introduce a slight curve, perhaps even a reversed curve, into the alinement, and it is even conceivable that the tunnel section would need to be enlarged somewhat to allow for these curves. The cost of these changes and the perpetual annoyance due to an enforced and undesirable alteration of the original design will justify a considerable increase in the expenses of the survey. Considering that the cost of surveys is usually but a small fraction of the total cost of the work, an increase of 10 or even 20% in the cost of the surveys will mean an insignificant addition to the total cost and frequent'y, if not generally, it will result in a saving of many times the increased cost. The accuracy actually attained in two noted American tunnels is given as follows: The Musconetcong tunnel is about 5000 feet long, bored through a mountain 400 feet high. The error of alinement at the meeting of the headings was 0'.04, error of levels 0'.015, error of distance 0'.52. The Hoosac tunnel is over 25000 feet long. The heading from the east end met the heading from the central shaft at a point 11274 feet from the east end and 1563 feet from the shaft. The error in alinement was $\frac{5}{16}$ of an inch, that of levels "a few hundredths," error of distance "trifling." The alinement, corrected at the shaft, was carried on through and met the heading from the west end at a point 10138 feet from the west end and 2056 feet from the shaft. Here the error of alinement was $\frac{9}{16}''$ and that of levels 0.134 foot.

DESIGN

198. Cross-section. Nearly all tunnels have cross-sections peculiar to themselves—all varying at least in the details. The general form of a great many tunnels is that of a rectangle surmounted by a semi-circle or semi-ellipse. In very soft material an inverted arch is necessary along the bottom. In such cases the sides will generally be arched instead of vertical. The sides are frequently battered. In very long tunnels, several forms of cross-section will often be used in the same tunnel, owing to differences in the material encountered. In solid rock, which will not disintegrate upon exposure, no lining is required, and the cross-section will be the irregular section left by the blasting, the only requirement being that no rock shall be left within the required cross-sectional figure. Farther on, in the same tunnel, when passing through some very soft treacherous material, it may be necessary to put in a full arch lining—top, sides, and bottom—which will be nearly circular in cross-section. For an illustration of this see Figs. 89 and 90.

The cross-section recommended by the A. R. E. A. for single track is a rectangle 16 feet wide by 16 feet 6 inches high, surmounted by a semi-circle with a radius of 8 feet. The top of the tie is to be 2 feet above the bottom which is at sub-grade. If the surrounding material is yielding and exerts great pressure, the sides should be battered inward 1 foot at the bottom. For a double track tunnel the design is similar, except that the width is increased by the standard spacing between double tracks and the top is a compound curve made up of two 8-foot-radius curves at the sides which compound into a curve over the center which will give a clear height of 22 feet 6 inches over the center of each tie. The base of the roof curve is 13 feet 6 inches above the top of the ties. The bottom slopes to a central gutter which is 6 inches below the side corners, which are at sub-grade. Six-inch cast-iron pipes should be spaced as needed and run from each side to the central gutter. The width of both single and double track tunnels should be increased, if the tunnel is on a curve, and the track centers should also be displaced, so that the clearance on each side is as great as on a tangent. Figs. 89, 90 and 91,* show some typical cross-sections.

199. Grade. A grade of at least 0.2% is needed for drainage. If the tunnel is at the summit of two grades, the tunnel grade

* Drinker's "Tunneling."

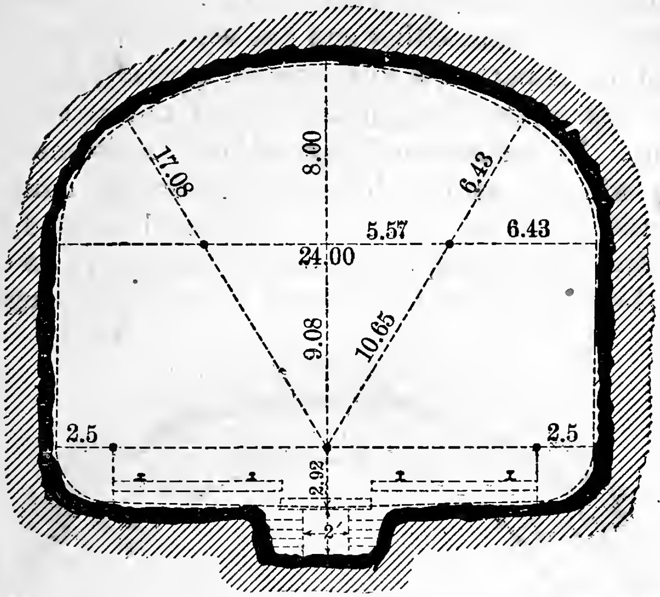


FIG. 89.—HOOSAC TUNNEL. SECTION THROUGH SOLID ROCK.

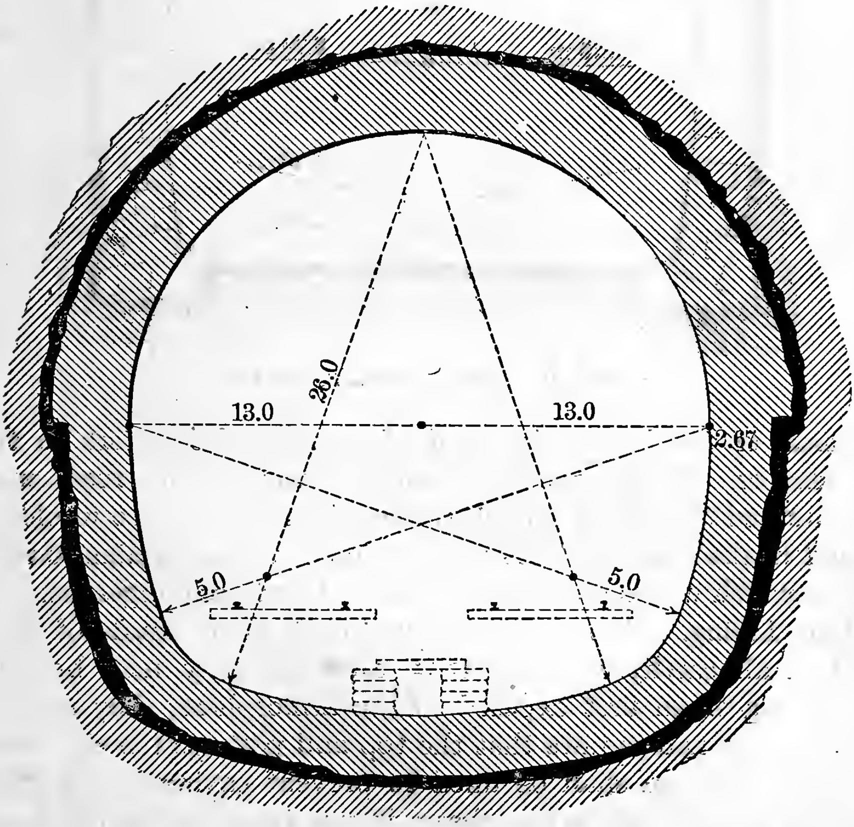


FIG. 90.—HOOSAC TUNNEL. SECTION THROUGH SOFT GROUND.

should be practically level, with an allowance for drainage, the actual summit being at either end but *not* in the center. When the tunnel forms part of a long ascending grade, it is advisable to reduce the grade through the tunnel unless the tunnel is very short. The additional atmospheric resistance and the decreased adhesion of the driver wheels on the damp rails in a tunnel will cause an engine to work very hard and still more rapidly vitiate the atmosphere until the accumulation of poisonous gases becomes a source of actual danger to the engineer and

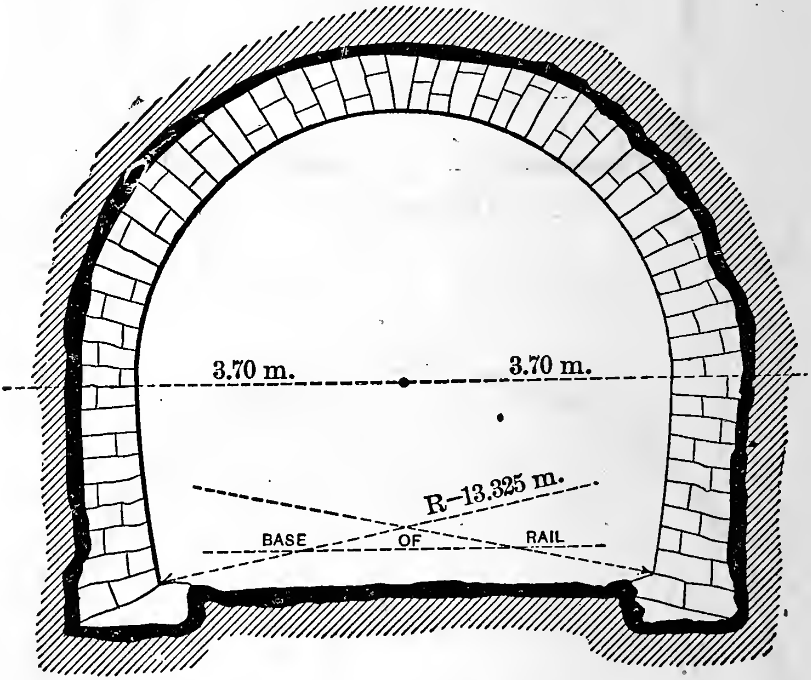


FIG. 91. —ST. CLOUD TUNNEL.

fireman of the locomotive and of extreme discomfort to the passengers. If the nominal ruling grade of the road were maintained through a tunnel, the maximum resistance would be found in the tunnel. This would probably cause trains to stall there, which would be objectionable and perhaps dangerous.

200. Lining. It is a characteristic of many kinds of rock and of all earthy material that, although they may be self-sustaining when first exposed to the atmosphere, they rapidly disintegrate and require that the top and perhaps the sides and even the bottom shall be lined to prevent caving in. In this country, when timber was cheap, it was formerly framed as an arch and used as the *permanent* lining (see Fig. 92), but in any such case the cross-section should be made extra large so that a masonry lining may subsequently be placed inside the wooden lining and thus postpone a large expense until the road is better able to pay for the work. In very soft unstable material, like quicksand, an arch of cut stone voussoirs may be necessary to withstand the pressure. A good quality of brick is occasionally used for lining, as they are easily handled and make good masonry if the pressure is not excessive. Only the best of cement mortar should be used, economy in this feature being the worst of folly. Of course the excavation must include the outside line of the lining. Any excavation which is made outside of this line (by the fall of earth or loose rock or by excessive blasting) must be refilled with stone well packed in. Occasionally it is necessary to fill these spaces with concrete. Of course it is not necessary that the lining be uniform throughout the tunnel.

201. Shafts. Shafts are variously made with square, rectangular, elliptical, and circular cross-sections. The rectangular

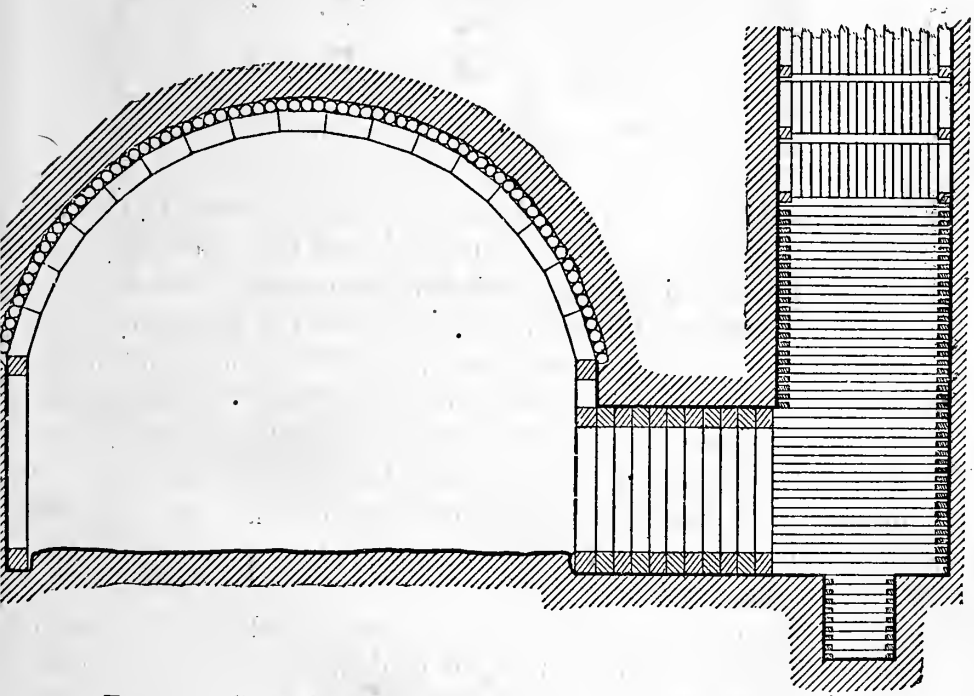


FIG. 92.—CONNECTION WITH SHAFT, CHURCH HILL TUNNEL.

cross-section, with the longer axis parallel with the tunnel, is most usually employed. Generally the shaft is directly over the center of the tunnel, but that always implies a complicated connection between the linings of the tunnel and shaft, provided such linings are necessary. It is easier to sink a shaft near to one side of the tunnel and make an opening through the nearly vertical side of the tunnel. Such a method was employed in the Church Hill Tunnel, illustrated in Fig. 92.* Fig. 93 † shows a cross-section for a large main shaft. Many shafts have been built with the idea of being left open permanently for ventilation and have therefore been elaborately lined with masonry.

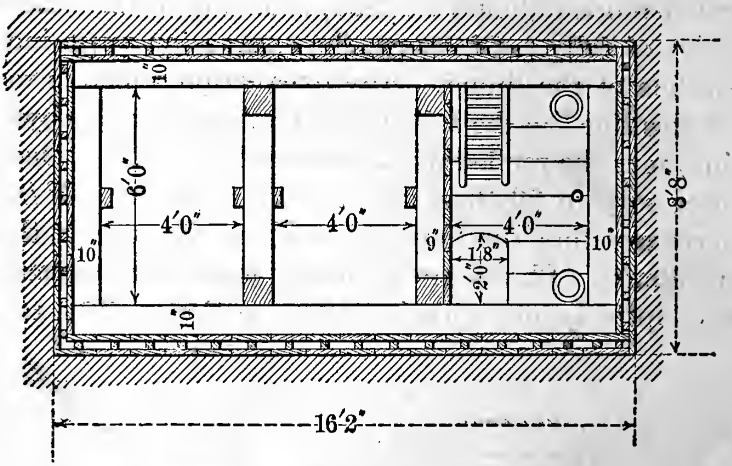


FIG. 93.—CROSS-SECTION. LARGE MAIN SHAFT.

The general consensus of opinion now appears to be that shafts are worse than useless for ventilation; that the quick passage of a train through the tunnel is the most effective ventilator; and that shafts only tend to produce cross-currents and are ineffective to clear the air. In consequence, many of these elaborately lined shafts have been permanently closed, and the more recent practice is to close up a shaft as soon as the tunnel is completed. Shafts always form drainage-wells for the material they pass through, and sometimes to such an extent that it is a serious matter to dispose of the water that collects at the bottom, requiring the construction of large and expensive drains.

202. Drains. A tunnel will almost invariably strike veins of water which will promptly begin to drain into the tunnel and not only cause considerable trouble and expense during construction, but necessitate the provision of permanent drains for its perpetual disposal. These drains must frequently be so large as

* Drinker's "Tunneling."
† Rziha, "Lehrbuch der Gesammten Tunnelbaukunst."

to appreciably increase the required cross-section of the tunnel. Generally a small open gutter on each side will suffice for this purpose, but in double-track tunnels a large covered drain is often built between the tracks. It is sometimes necessary to thoroughly grout the outside of the lining so that water will not force its way through the masonry and perhaps injure it, but may freely drain down the sides and pass through openings in the side walls near their base into the gutters.

CONSTRUCTION.

203. Headings. The methods of all tunnel excavation depend on the general principle that all earthy material, except the softest of liquid mud and quicksand, will be self-sustaining over a greater or less area and for a greater or less time after excavation is made, and the work consists in excavating some material and immediately propping up the exposed surface by timbering and poling-boards. The excavation of the cross-section begins with cutting out a "heading," which is a small horizontal drift whose breast is constantly kept 15 feet or more in advance of the full cross-sectional excavation. In solid self-sustaining rock, which will not decompose upon exposure to air, it becomes simply a matter of excavating the rock with the least possible expenditure of time and energy. In soft ground the heading must be heavily timbered, and as the heading is gradually enlarged the timbering must be gradually extended and perhaps replaced, according to some regular system, so that when the full cross-section has been excavated it is supported by such timbering as is intended for it. The heading is sometimes made on the center line near the top; with other plans, on the center line near the bottom; and sometimes two simultaneous headings are run in the two lower corners. Headings near the bottom serve the purpose of draining the material above it and facilitating the excavation. The simplest case of heading timbering is that shown in Fig. 94, in which cross-timbers are placed at intervals just under the roof, set in notches cut in the side walls and supporting poling-boards which sus-

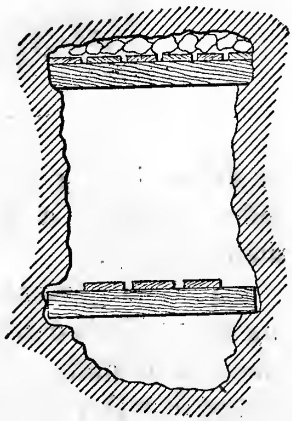


FIG. 94.

tain whatever pressure may come on them. Cross-timbers near the bottom support a flooring on which vehicles for transporting material may be run and under which the drainage may freely escape. As the necessity for timbering becomes greater, side timbers and even bottom timbers must be added, these timbers supporting poling-boards, and even the breast of the heading must be protected by boards suitably braced,

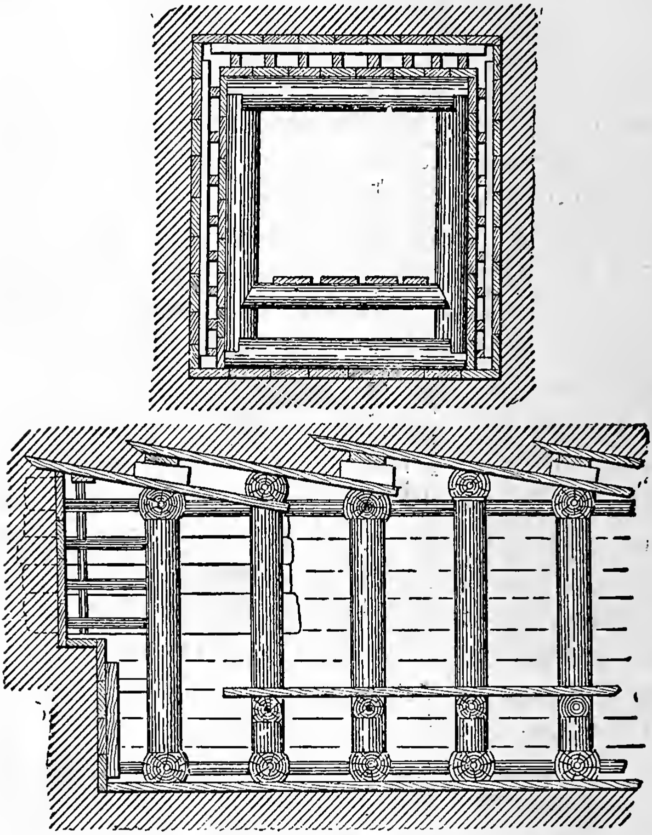


FIG. 95.—TIMBERING FOR TUNNEL HEADING.

as shown in Fig. 95. The supporting timbers are framed into collars in such a manner that added pressure only increases their rigidity.

204. Enlargement. Enlargement is accomplished by removing the poling-boards, one at a time, excavating a greater or less amount of material, and immediately supporting the exposed material with poling-boards suitably braced. (See Figs. 95 and 96.) This work being systematically done, space is thereby obtained in which the framing for the full cross-section may be gradually introduced. The framing is constructed with a cross-section so large that the masonry lining may be constructed within it.

205. Distinctive features of various methods of construction. There are six general systems, known as the English, German, Belgian, French, Austrian, and American. They are so named

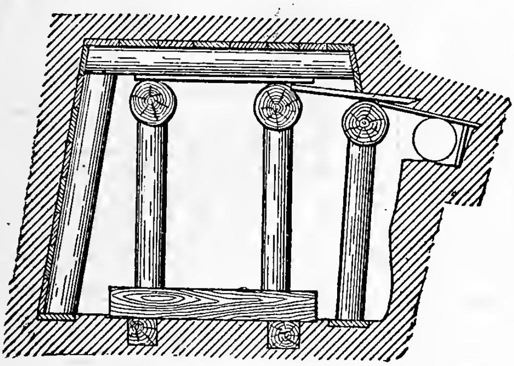


Fig. 96.

from the origin of the methods, although their use is not confined to the countries named. Fig. 97 shows by numbers (1 to 5) the order of the excavation within the cross-sections. The English, Austrian, and American systems are alike in excavating the entire cross-section before beginning the construction of the masonry lining. The German method leaves a solid core (5) until practically the whole of the lining is complete. This has the disadvantage of extremely cramped quarters for work, poor ventilation, etc. The Belgian and French methods agree in excavating the upper part of the section, building the arch at once, and supporting it temporarily until the side walls are built. The Belgian method then takes out the core (3), removes very short sections of the sides (4) immediately underpinning the arch with short sections of the side walls and thus gradually constructing the whole side wall. The French method digs out the sides (3), supporting the arch temporarily with timbers and then replacing the timbers with masonry; the core (4) is taken out last. The French method has the same disadvantage as the German—working in a cramped space. The Belgian and French systems have the disadvantage that the arch, supported temporarily on timber, is very apt to be strained and cracked by the slight settlement that so frequently occurs in soft material. The English, Austrian, and American methods differ mainly in the design of the timbering. The English support the roof by lines of very heavy *longitudinal* timbers which are supported at comparatively wide intervals by a heavy framework occupying the

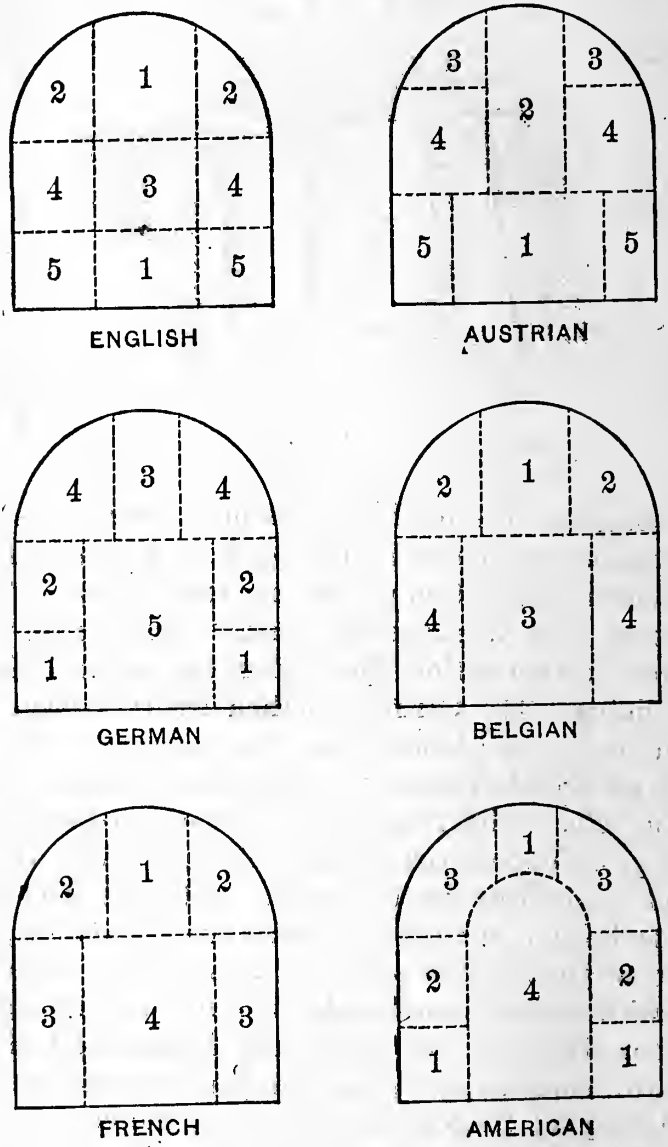


FIG. 97.—ORDER OF WORKING BY THE VARIOUS SYSTEMS.

whole cross-section. The Austrian system uses such frequent cross-frames of timber-work that poling-boards will suffice to support the material between the frames. The American system agrees with the Austrian in using frequent cross-frames supporting poling-boards, but differs from it in that the "cross frames" consist simply of arches of 3 to 15 wooden voussoirs, the voussoirs being blocks of 12″×12″ timber about 2 to 8 feet long and cut with joints normal to the arch. These arches are put together on a centering which is removed as soon as the arch is keyed up and thus immediately opens up the full cross-section, so that the center core (4) may be immediately dug out and the masonry constructed in a large open space. The American system has been used successfully in very soft ground, but its advantages are greater in loose rock, when it is much cheaper than the other methods which employ more timber. Fig. 92 and Plate III illustrate the use of the American system. Fig. 92 shows the wooden arch in place. The masonry arch may be placed when convenient, since it is *possible* to lay the track and commence traffic as soon as the wooden arch is in place. The student is referred to Drinker's "Tunneling" and to Rziha's "Lehrbuch der Gesammten Tunnelbaukunst" for numerous illustrations of European methods of tunnel timbering.

206. Ventilation during construction. Tunnels of any great length must be artificially ventilated during construction. If the excavated material is rock so that blasting is necessary, the need for ventilation becomes still more imperative. Fresh air is forced *into* the tunnel at or near the heading ("plenum process") and the foul air is thereby crowded out, or the foul air is sucked out ("vacuum process") and fresh air rushes into the tunnel at the entrance. "Compressed air wasted from power drills is so contaminated with oil from the cylinders that it cannot be taken into consideration as ventilation." The draft of air up a shaft will occasionally modify, and perhaps assist, the work of ventilation, but, in general, the work must be done by means of power fans.

207. Excavation for the portals. Under normal conditions there is always a greater or less amount of open cut preceding and following a tunnel. Since all tunnel methods depend (to some slight degree at least) on the capacity of the exposed material to act as an arch, there is implied a considerable thickness of material above the tunnel. This thickness is reduced to nearly zero over the tunnel portals and therefore requires special treatment, particularly when the material is very soft. Fig. 98 *

* Rziha, "Lehrbuch der Gesammten Tunnelbaukunst."

illustrates one method of breaking into the ground at a portal. The loose stones are piled on the framing to give stability to the framing by their weight and also to retain the earth on the

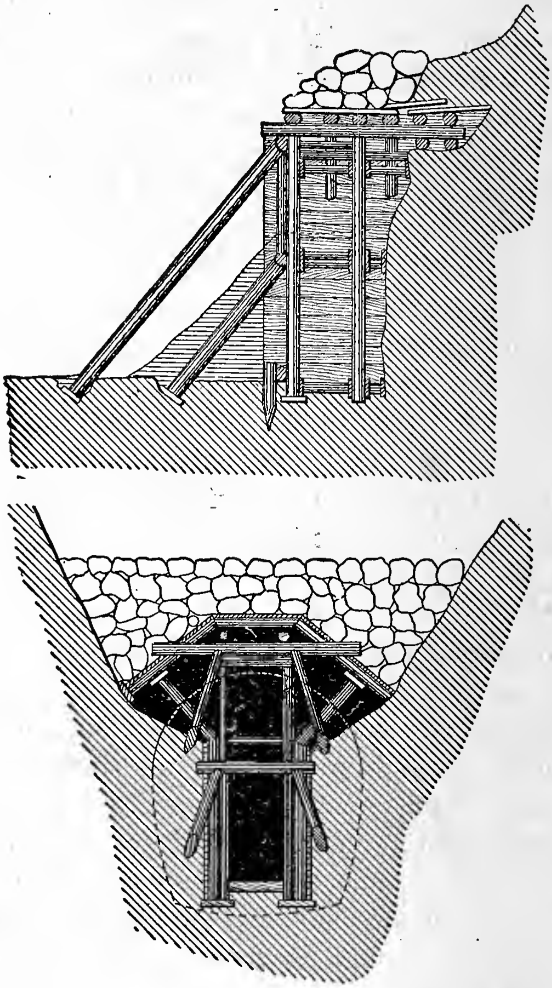
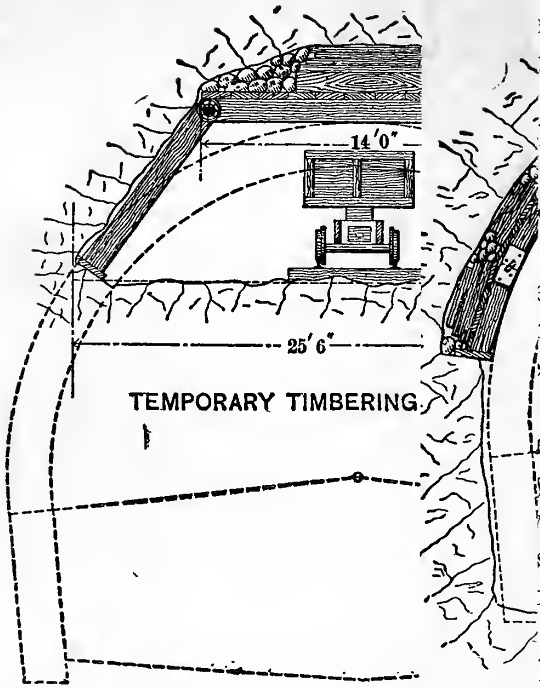
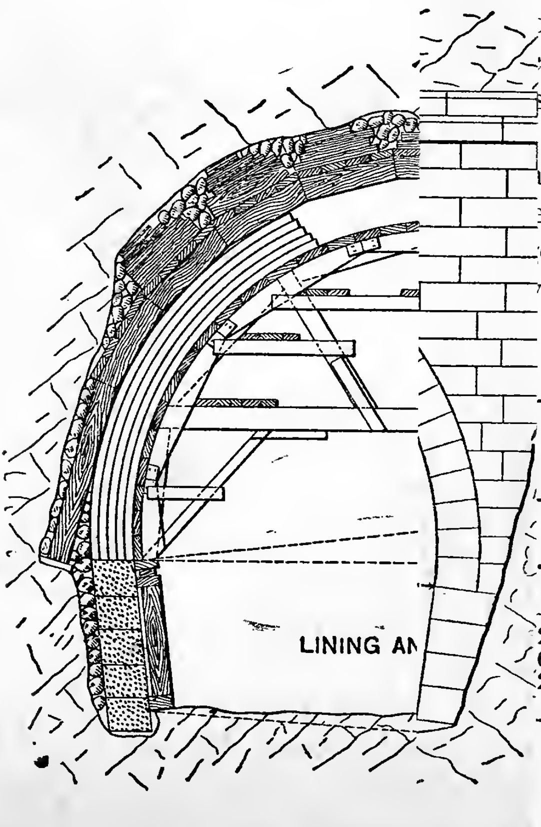


FIG. 98.—TIMBERING FOR TUNNEL PORTAL.

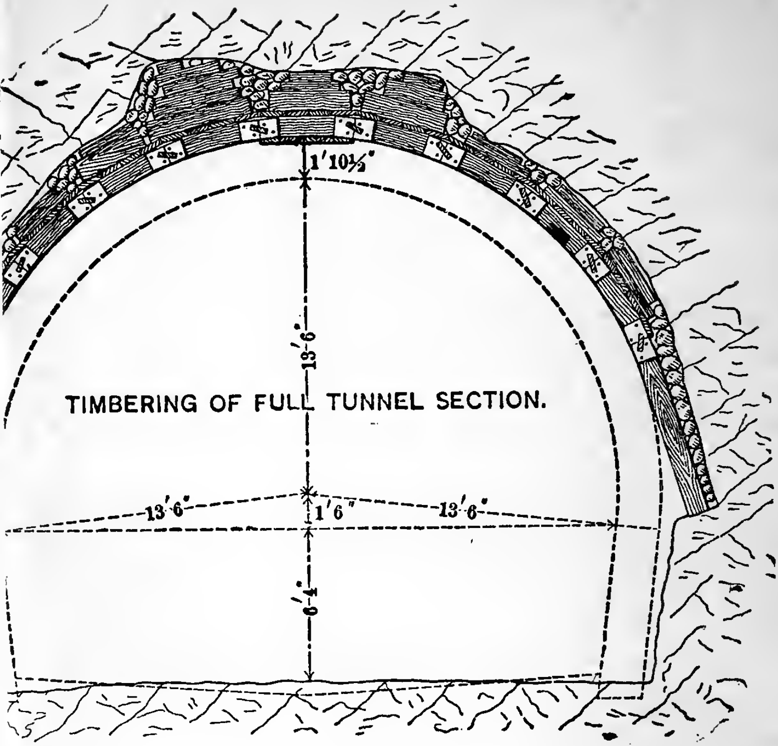
slope above. Another method is to sink a temporary shaft to the tunnel near the portal; immediately enlarge to the full size and build the masonry lining; then work back to the portal. This method is more costly, but is preferable in very treacherous ground, it being less liable to cause landslides of the surface material.

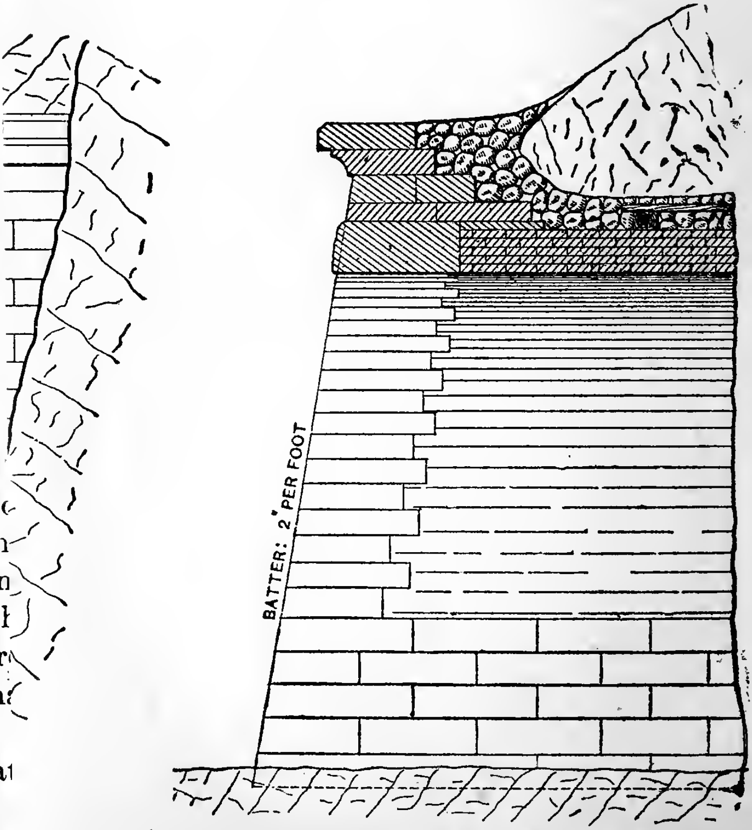
208. Tunnels vs. open cuts. In cases in which an open cut rather than a tunnel is a possibility the ultimate consideration is generally that of first cost combined with other financial con-





(*To face page* 243.)





LONGITUDINAL SECTION OF PORTAL.

siderations and annual maintenance charges directly or indirectly connected with it. Even when an open cut may be constructed at the same cost as a tunnel (or perhaps a little cheaper) the tunnel may be preferable under the following conditions:

1. When the soil indicates that the open cut would be liable to landslides.

2. When the open cut would be subject to excessive snow-drifts or avalanches.

3. When land is especially costly or it is desired to run under existing costly or valuable buildings or monuments. When running through cities, tunnels are sometimes constructed as open cuts and then arched over.

These cases apply to tunnels *vs.* open cuts when the alinement is fixed by other considerations than the mere topography. The broader question of excavating tunnels to avoid excessive grades or to save distance or curvature, and similar problems, are hardly susceptible of general analysis except as questions of railway economics and must be treated individually.

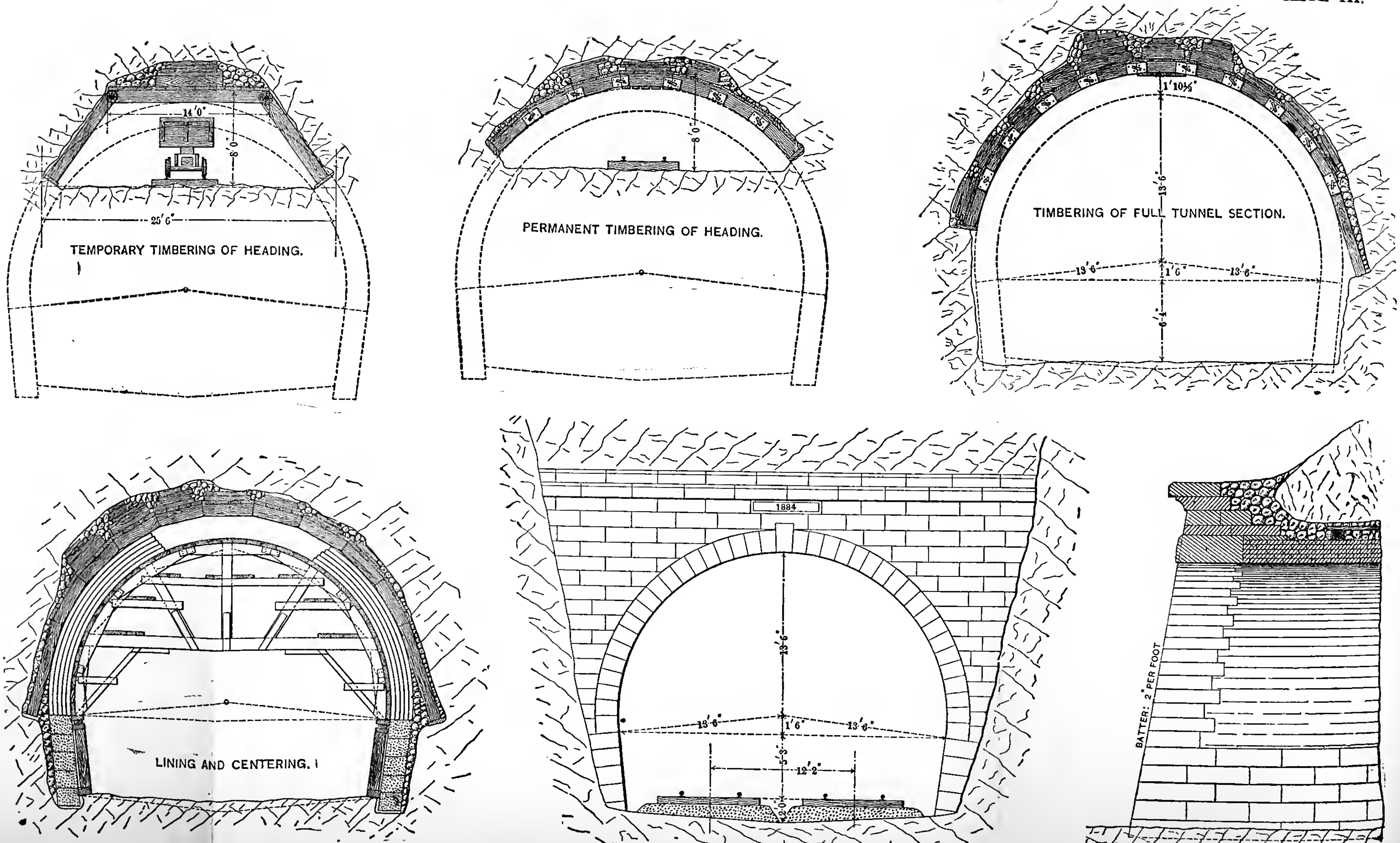
209. Cost of tunneling. The cost of any construction which involves such uncertainties as tunneling is very variable. It depends on the material encountered, the amount and kind of timbering required, on the size of the cross-section, on the price of labor, and especially on the *reconstruction* that *may* be necessary on account of mishaps.

Headings generally cost $4 to $5 per cubic yard for excavation, while the remainder of the cross-section in the same tunnel may cost about half as much. The average cost of a large number of tunnels in this country may be seen from the following table:*

Material.	Cost per cubic yard.				Cost per lineal foot.	
	Excavation.		Masonry.			
	Single.	Double.	Single.	Double.	Single.	Double.
Hard rock.....	$5.89	$5.45	$12.00	$8.25	$69.76	$142.82
Loose rock.....	3.12	3.48	9.07	10.41	80.61	119.26
Soft ground....	3.62	4.64	15.00	10.50	135.31	174.42

* Figures derived from Drinker's "Tunneling."

PLATE III.



(To face page 243.)

Elevation of Portal.
Phœnixville Tunnel. P. S. V. R. R.

Longitudinal Section of Portal.

The above figures are averages for tunnels constructed between 1831 and 1877. The prices paid for labor varied from $1.00 to $2.75 per day for "miners" and 0.75 to $2.00 for unskilled labor. The lower figures were usually paid during the earlier years. As an approximate average, the figures of $2.00 per day for miners and $1.50 per day for unskilled labor may be said to correspond to the average costs given in the tabular form. On the basis that all other expenses (explosives, cost of equipment, etc.) vary proportionately to wages, the tabular figures can even now be utilized by increasing them according to the present scale for labor. The figures are also instructive since they show the relative cost of tunneling through hard rock, loose rock and soft ground.

CHAPTER VI.

CULVERTS AND MINOR BRIDGES.

210. Definition and object. Although a variable percentage of the rain falling on any section of country soaks into the ground and does not immediately reappear, yet a very large percentage flows over the surface, always seeking and following the lowest channels. The roadbed of a railroad is constantly intersecting these channels, which frequently are normally dry. In order to prevent injury to railroad embankments by the impounding of such rainfall, it is necessary to construct waterways through the embankment through which such rainflow may freely pass. Such waterways, called culverts, are also applicable for the bridging of very small although perennial streams, and therefore in this work the term culvert will be applied to all water-channels passing through a railroad embankment which are not of sufficient magnitude to require a special structural design, such as is necessary for a large masonry arch or a truss bridge.

211. Elements of the design. A well-designed culvert must afford such free passage to the water that it will not "back up" over the adjoining land nor cause any injury to the embankment or culvert. The ability of the culvert to discharge freely all the water that comes to it evidently depends chiefly on the area of the waterway, but also on the form, length, slope, and materials of construction of the culvert and the nature of the approach and outfall. When the embankment is very low and the amount of water to be discharged very great, it sometimes becomes necessary to allow the water to discharge "under a head," i e., with the surface of the water above the top of the culvert. Safety then requires a much stronger construction than would otherwise be necessary to avoid injury to the culvert or embankment by washing. The necessity for such construction should be avoided if possible.

AREA OF THE WATERWAY.

212. Elements involved. The determination of the required area of the waterway involves such a multiplicity of indeterminate elements that any close determination of its value from purely theoretical considerations is a practical impossibility. The principal elements involved are:

a. Rainfall. The real test of the culvert is its capacity to discharge without injury the flow resulting from the extraordinary rainfalls and "cloud bursts" that may occur once in many years. Therefore, while a knowledge of the average annual rainfall is of very little value, a record of the maximum rainfall during heavy storms for a long term of years may give a relative idea of the maximum demand on the culvert.

b. Area of watershed. This signifies the total area of country draining into the channel considered. When the drainage area is very small it is sometimes included within the area surveyed by the preliminary survey. When larger it is frequently possible to obtain its area from other maps with a percentage of accuracy sufficient for the purpose. Sometimes a special survey for the purpose is considered justifiable.

c. Character of soil and vegetation. This has a large influence on the rapidity with which the rainflow from a given area will reach the culvert. If the soil is hard and impermeable and the vegetation scant, a heavy rain will run off suddenly, taxing the capacity of the culvert for a short time, while a spongy soil and dense vegetation will retard the flow, making it more nearly uniform and the maximum flow at any one time much less.

d. Shape and slope of watershed. If the watershed is very long and narrow (other things being equal), the water from the remoter parts will require so much longer time to reach the culvert that the flow will be comparatively uniform, especially when the slope of the whole watershed is very low. When the slope of the remoter portions is quite steep it may result in the nearly simultaneous arrival of a storm-flow from all parts of the watershed, thus taxing the capacity of the culvert.

e. Effect of design of culvert. The principles of hydraulics show that the slope of the culvert, its length, the form of the cross-section, the nature of the surface, and the form of the approach and discharge all have a considerable influence on the area of cross-section required to discharge a given volume of water in a given time, but unfortunately the combined hydraulic effect of these various details is still a very uncertain quantity.

213. Methods of computation of area. There are three possible methods of computation.

(a) **Theoretical.** As shown above it is a practical impossibility to estimate correctly the combined effect of the great multiplicity of elements which influence the final result. The nearest approach to it is to estimate by the use of empirical formulæ the amount of water which will be presented at the upper end of the culvert in a given time and then to compute, from the principles of hydraulics, the rate of flow through a culvert of given construction, but (as shown in § 212, *e*) such methods are still very unreliable, owing to lack of experimental knowledge. This method has *apparently* greater scientific accuracy than other methods, but a little study will show that the elements of uncertainty are as great and the final result no more reliable. The method is most reliable for streams of uniform flow, but it is under these conditions that method (*c*) is most useful. The theoretical method will not therefore be considered further.

(b) **Empirical.** As illustrated in § 214, some formulæ make the area of waterway a function of the drainage area, the formula being affected by a coefficient the value of which is estimated between limits according to the judgment. Assuming that the formulæ are sound, their use only narrows the limits of error, the final determination depending on experience and judgment in the choice of the proper coefficient.

(c) **From observation.** This method, considered by far the best for permanent work, consists in observing the high-water marks on contracted channel-openings which are on the same stream and as near as possible to the proposed culvert. If the country is new and there are no such openings, the wisest plan is to bridge the opening by a temporary structure in wood which has an ample waterway (see § 158, *b*, 4) and carefully observe all high-water marks on that opening during the 6 to 10 years which is ordinarily the minimum life of such a structure. As shown later, such observations may be utilized for a close computation of the required waterway. Method (*b*) may be utilized for an approximate calculation for the required area for the temporary structure, using a value which is intentionally excessive, so that a permanent structure of sufficient capacity may subsequently be constructed *within* the temporary structure.

214. Empirical formulæ. Two of the best known empirical formulæ for area of the waterway are the following:

(a) **Myer's formula:**

Area of waterway in square feet $= C \times \sqrt{\text{drainage area in acres}}$, where C is a coefficient varying from 1 for flat country to 4 for mountainous country and rocky ground. As an illustration, if the drainage area is 100 acres, the waterway area should be from 10 to 40 square feet, according to the value of the coefficient chosen. It should be noted that this formula does not regard the great variations in rainfall in various parts of the world nor the design of the culvert, and also that the final result depends largely on the choice of the coefficient.

(b) **Talbot's formula:**

Area of waterway in square feet $= C \times \sqrt[4]{(\text{drainage area in acres})^3}$. "For steep and rocky ground C varies from $\frac{2}{3}$ to 1. For rolling agricultural country subject to floods at times of melting snow, and with the length of the valley three or four times its width, C is about $\frac{1}{3}$; and if the stream is longer in proportion to the area, decrease C. In districts not affected by accumulated snow, and where the length of the valley is several times the width, $\frac{1}{5}$ or ^{1}, or even less, may be used. C should be increased for steep side slopes, especially if the upper part of the valley has a much greater fall than the channel at the culvert." * As an illustration, if the drainage area is 100 acres the area of waterway should be $C \times 31.6$. The area should then vary from 5 to 31 square feet, according to the character of the country. Like the previous estimate, the result depends on the choice of a coefficient and disregards local variations in rainfall, except as they may be arbitrarily allowed for in choosing the coefficient.

215. Value of empirical formulæ. The fact that these formulæ, as well as many others of similar nature that have been suggested, depend so largely upon the choice of the coefficient shows that they are valuable "more as a guide to the judgment than as a working rule," as Prof. Talbot explicitly declares in

* Prof. A. N. Talbot, "Selected Papers of the Civil Engineers' Club of the Univ. of Illinois."

commenting on his own formula. In short, they are chiefly valuable in indicating a probable maximum and minimum between which the true result probably lies.

216. Results based on observation. As already indicated in § 213, observation of the stream in question gives the most reliable results. If the country is new and no records of the flow of the stream during heavy storms has been taken, even the life of a temporary wooden structure may not be long enough to include one of the unusually severe storms which must be allowed for, but there will usually be some high-water mark which will indicate how much opening will be required. The following quotation illustrates this: "A tidal estuary may generally be safely narrowed considerably from the extreme water lines if stone revetments are used to protect the bank from wash. Above the true estuary, where the stream cuts through the marsh, we generally find nearly vertical banks, and we are safe if the faces of abutments are placed even with the banks. In level sections of the country, where the current is sluggish, it is usually safe to encroach somewhat on the general width of the stream, but in rapid streams among the hills the width that the stream has cut for itself through the soil should not be lessened, and in ravines carrying mountain torrents the openings must be left very much larger than the ordinary appearance of the banks of the stream would seem to make necessary." *

As an illustration of an observation of a storm-flow through a temporary trestle, the following is quoted: "Having the flood height and velocity, it is an easy matter to determine the volume of water to be taken care of. I have one ten-bent pile trestle 135 feet long and 24 feet high over a spring branch that ordinarily runs about six cubic inches per second. Last summer during one of our heavy rainstorms (four inches in less than three hours) I visited this place and found by float observations the surface velocity at the highest stage to be 1.9 feet per second. I made a high-water mark, and after the flood-water receded found the width of stream to be 12 feet and an average depth of $2\frac{3}{4}$ feet. This, with a surface velocity of 1.9 feet per second, would give approximately a discharge of 50

* J. P. Snow, Boston & Maine Railway. From Report to Association of Railway Superintendents of Bridges and Buildings. 1897.

cubic feet, or 375 gallons, per second. Having this information it is easy to determine size of opening required." *

217. Degree of accuracy required. The advantages resulting from the use of standard designs for culverts (as well as other structures) have led to the adoption of a comparatively small number of designs. The practical use made of a computation of required waterway area is to determine which one of several standard designs will most nearly fulfill the requirements. For example, if a 24-inch iron pipe, having an area of 3.14 square feet, is considered to be a little small, the next size (30-inch) would be adopted; but a 30-inch pipe has an area of 4.92 square feet, which is 56% larger. A similar result, except that the percentage of difference might not be quite so marked, will be found by comparing the areas of consecutive standard designs for stone box culverts.

The advisability of designing a culvert to withstand any storm-flow that may *ever* occur is considered doubtful. Several years ago a record-breaking storm in New England carried away a very large number of bridges, etc., hitherto supposed to be safe. It was not afterward considered that the design of those bridges was faulty, because the extra cost of constructing bridges capable of withstanding such a flood, added to interest for a long period of years, would be enormously greater than the cost of repairing the damages of such a storm once or twice in a century. Of course the element of danger has some weight, but not enough to justify a great additional expenditure, for common prudence would prompt unusual precautions during or immediately after such an extraordinary storm.

PIPE CULVERTS.

218. Advantages. Pipe culverts, made of cast iron or earthenware, are very durable, readily constructed, moderately cheap, will pass a larger volume of water in proportion to the area than many other designs on account of the smoothness of the surface, and (when using iron pipe) may be used very close to the track when a low opening of large capacity is required. Another advantage lies in the ease with which they may be inserted through a somewhat larger opening that has been

* A. J. Kelley, Kansas City Belt Railway. From Report to Association of Railway Superintendents of Bridges and Buildings. 1897.

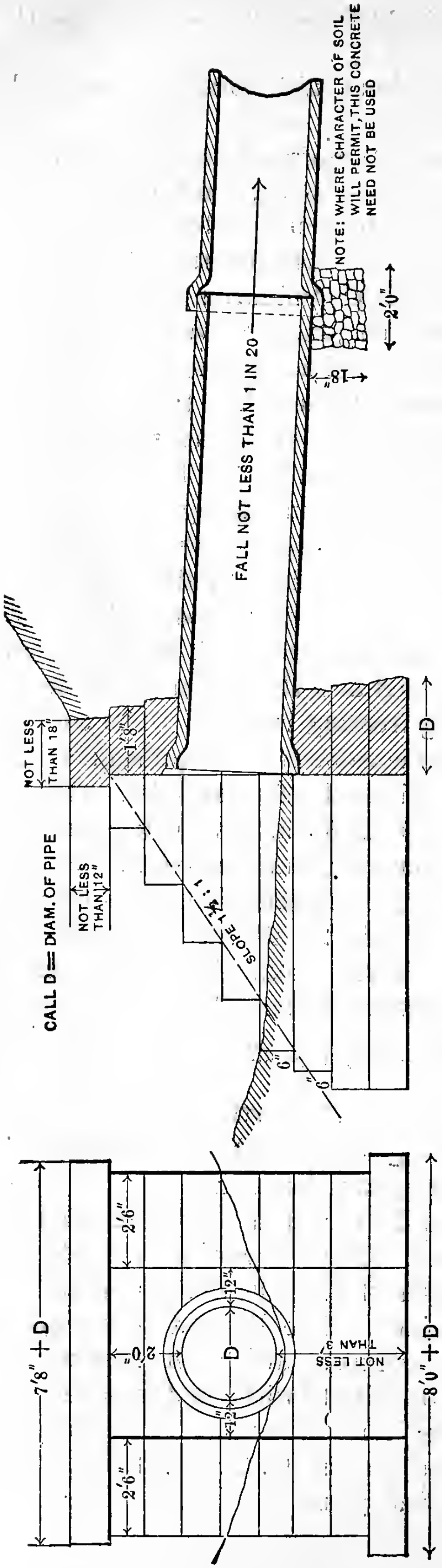
temporarily lined with wood, without disturbing the roadbed or track

219. Construction. Permanency requires that the foundation shall be firm and secure against being washed out. To accomplish this, the soil of the trench should be hollowed out to fit the lower half of the pipe, making suitable recesses for the bells. In very soft treacherous soil a foundation-block of concrete is sometimes placed under each joint, or even throughout the whole length. When pipes are laid through a slightly larger timber culvert great care should be taken that the pipes are properly supported, so that there will be no settling nor development of unusual strains when the timber finally decays and gives way. To prevent the washing away of material around the pipe the ends should be protected by a bulkhead. This is best constructed of masonry (see Fig. 99), although wood is sometimes used for cheap and minor constructions. The joints should be calked, especially when the culvert is liable to run full or when the outflow is impeded and the culvert is liable to be partly or wholly filled during freezing weather. The cost of a calking of clay or even hydraulic cement is insignificant compared with the value of the additional safety afforded. When the grade of the pipe is perfectly uniform, a very low rate of grade will suffice to drain a pipe culvert, but since some unevenness of grade is inevitable through uneven settlement or imperfect construction, a grade of 1 in 20 should preferably be required, although much less is often used. The length of a pipe culvert is approximately determined as follows:

$$\textit{Length} = 2s\ (\textit{depth of embankment}) + (\textit{width of roadbed}),$$

in which s is the slope ratio (horizontal to vertical) of the banks. In practice an even number of lengths should be used which will equal or exceed the length given by this formula.

220. Iron-pipe culverts. Simple cast-iron pipes are used in sizes from 12″ to 48″ diameter. These are usually made in lengths of 12 feet with a few lengths of 6 feet, so that any required length may be more nearly obtained. The lightest pipes made are sufficiently strong for the purpose, and even those which would be rejected because of incapacity to withstand considerable internal pressure may be utilized for this work. In Fig. 99 are shown the standard plans used on the C. C. C. & St. L. Ry., which may be considered as typical plans.



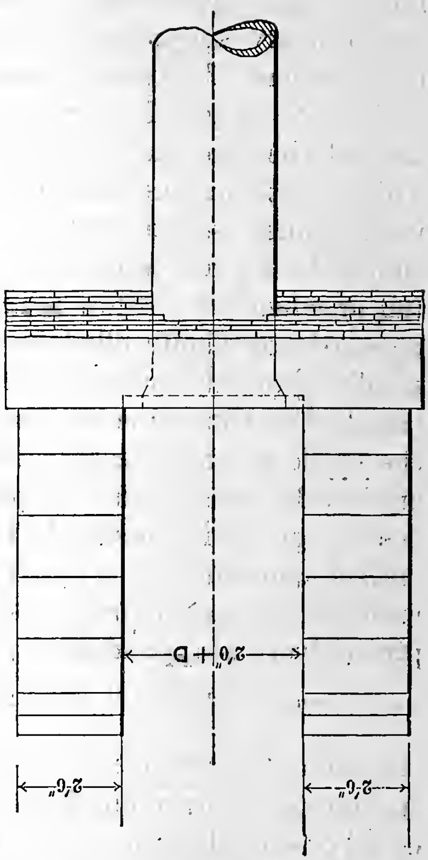


Fig. 99.—Standard Cast-iron Pipe Culvert. C. C. C. & St. L. Ry. (May 1893.)

Pipes formed of cast-iron segments have been used up to 12 feet diameter. The shell is then made comparatively thin, but is stiffened by ribs and flanges on the outside. The segments break joints and are bolted together through the flanges. The joints are made tight by the use of a tarred rope, together with neat cement.

221. Tile-pipe culverts. The pipes used for this purpose vary from 12″ to 30″ in diameter. When a larger capacity is required two or more pipes may be laid side by side, but in such a case another design might be preferable. It is frequently specified that "double-strength" or "extra-heavy" pipe shall be used.

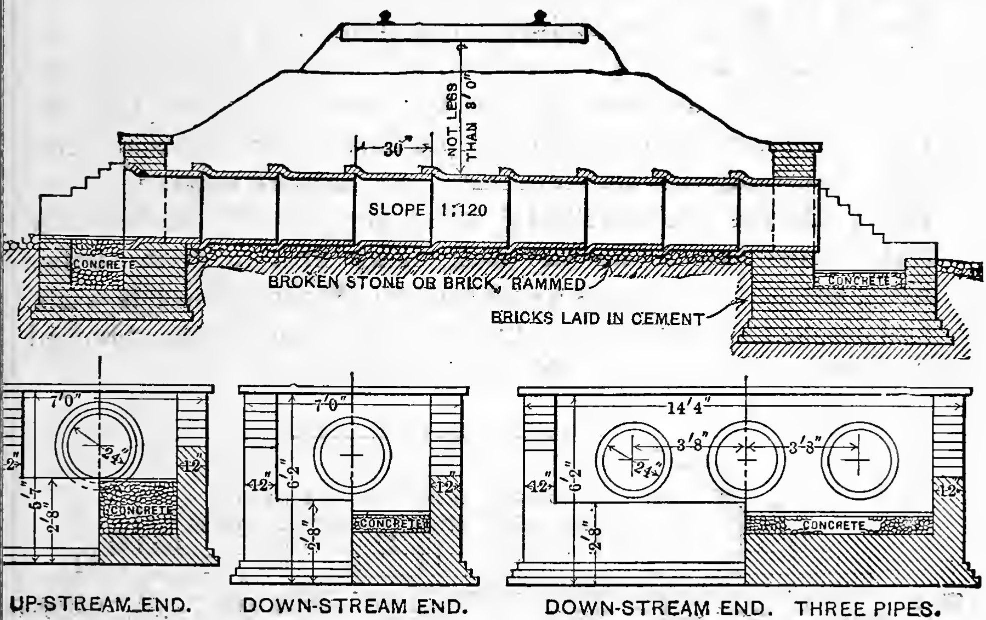


FIG. 100.—STANDARD VITRIFIED-PIPE CULVERT. PLANT SYSTEM. (1891.)

The author's personal experience is that tile pipe are very unreliable as culvert pipe, especially if there is any subsidence of the original soil which supports the embankment. See § 127–8. When a tile pipe is laid in a sewer, the soil on which it is laid is usually compact and there is no subsequent settlement. But when a culvert pipe is laid on soft meadow soil and a high embankment is formed over it, there is almost inevitably a settlement, which is probably *not* uniform and the culvert settles out of line, even if it does not break up and collapse. If the bed of the stream is rocky (precluding future settlement) and the pipes are bedded in concrete, there is less chance of failure. In Fig. 100 are shown the standard plans for vitrified-pipe culverts as used on the "Plant system." Tile pipe is much cheaper than iron pipe, but is made in much shorter lengths and requires much more work in laying and especially to obtain a uniform grade.

Concrete pipes, factory made, both plain and with metal reinforcement, 12″ to 48″ in diameter, have come into use in recent years. They are stronger and more dependable than tile and there is no deterioration.

BOX CULVERTS.

222. Wooden box culverts. This form serves the purpose of a cheap temporary construction which allows the use of a ballasted roadbed. As in all temporary constructions, the area should be made considerably larger than the calculated area (§§ 213–216), not only for safety but also in order that, if the smaller area is demonstrated to be sufficiently large, the permanent construction (probably pipe) may be placed inside without disturbing the embankment. All designs agree in using heavy timbers (12″×12″, 10″×12″, or 8″×12″) for the side walls, cross-timbers for the roof, every fifth or sixth timber being notched down so as to take up the thrust of the side walls, and planks for the flooring. Fig. 101 shows some of the standard designs as used by the C., M. & St. P. Ry.

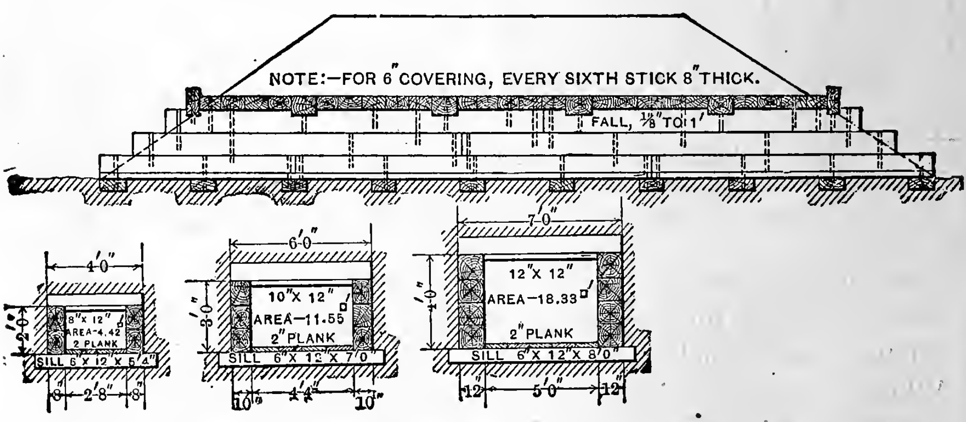


FIG. 101.—STANDARD TIMBER BOX CULVERT. C., M. & ST. P. RY. (Feb. 1889.)

223. Stone box culverts. In localities where a good quality of stone is cheap, stone box culverts are the cheapest form of permanent construction for culverts of medium capacity, but their use is decreasing owing to the frequent difficulty in obtaining really suitable stone within a reasonable distance of the culvert. The clear span of the cover-stones varies from 2 to 4 feet. The required thickness of the cover-stones is sometimes calculated by the theory of transverse strains on the basis of certain assumptions of loading—as a function of the height of the embankment and the unit strength of the stone used. Such a method is simply another illustration of a class of calculations which look very precise and beautiful, but which are worse than useless (because misleading) on account of the hopeless uncer-

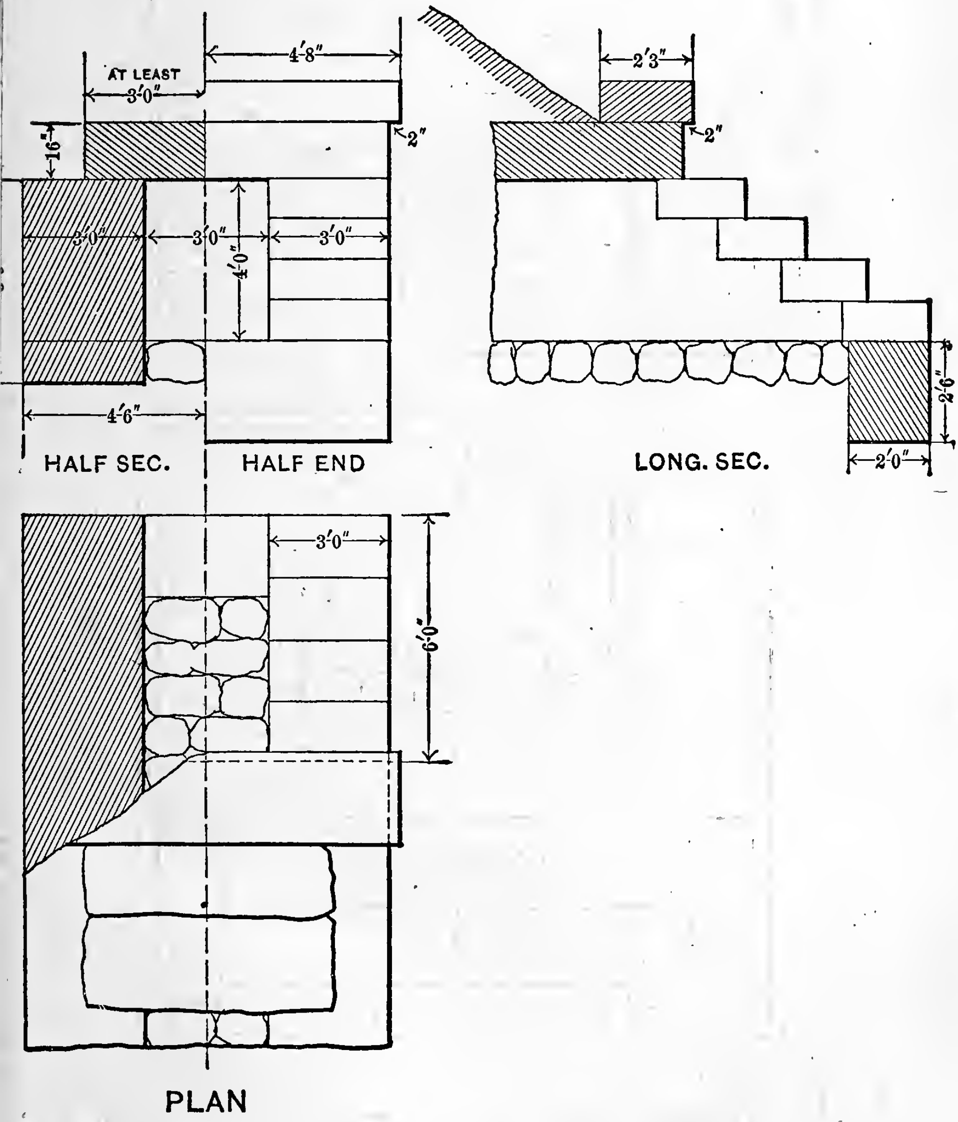


Fig. 102.—Standard Single Stone Culvert (3'×4'). N. & W. R.R. (1890.)

tainty as to the true value of certain quantities which must be used in the computations In the first place the true value of the unit tensile strength of stone is such an uncertain and variable quantity that calculations based on any assumed value for it are of small reliability. In the second place the weight of the prism of earth lying directly above the stone, plus an allowance for live load, is by no means a measure of the load on the stone nor of the forces that tend to fracture it. All earthwork will tend to

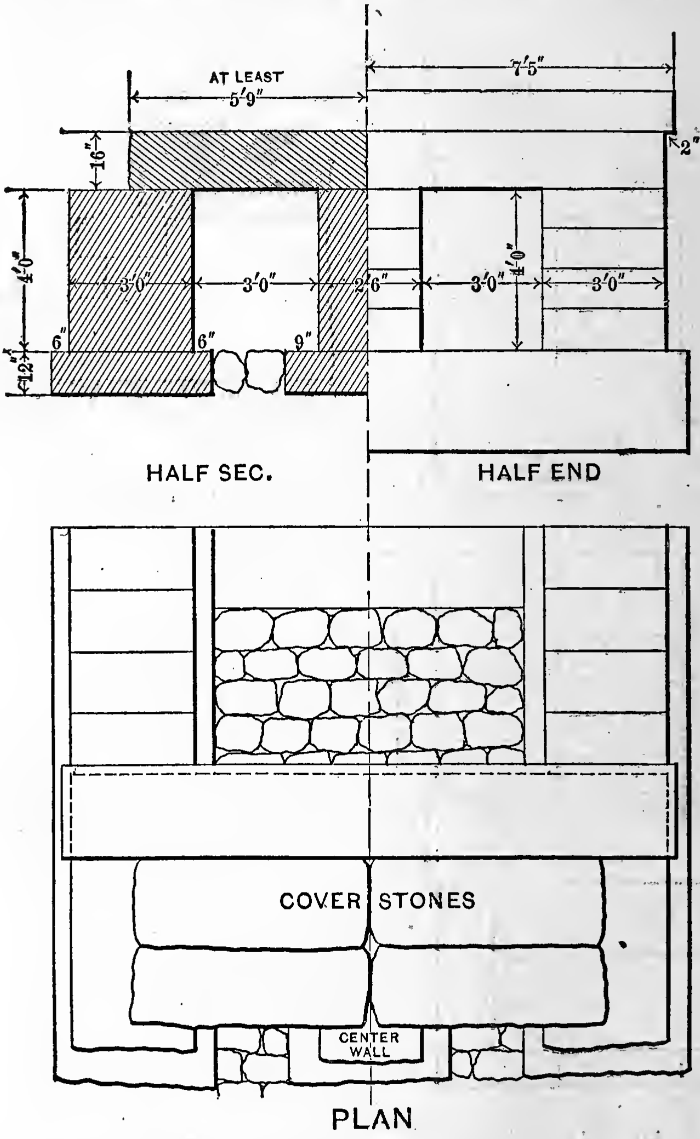


Fig. 103.—Standard Double Stone Culvert (3'×4'). N. & W. R. R. (1890.)

form an arch above any cavity and thus relieve an uncertain and probably variable proportion of the pressure that might otherwise exist. The higher the embankment the *less* the *pro-*

portionate loading, until at some uncertain height an increase in height will not increase the load on the cover-stones. The effect of frost is likewise large, but uncertain and not computable. The usual practice is therefore to make the thickness such as experience has shown to be safe with a good quality of stone, i.e., about 10 or 12 inches for 2 feet span and up to 16 or 18 inches for 4 feet span. The side walls should be carried down deep enough to prevent their being undermined by scour or heaved by frost. The use of cement mortar is also an important feature of first-class work, especially when there is a rapid scouring current or a liability that the culvert will run under a head. In Figs. 102 and 103 are shown standard plans for single and double stone box culverts as used on the Norfolk & Western R.R.

224. Old-rail culverts. It sometimes happens (although very rarely) that it is necessary to bring the grade line within 3 or 4 feet of the bottom of a stream and yet allow an area of 10 or 12 square feet. A single large pipe of sufficient area could not be used in this case. The use of several smaller pipes side by side would be both expensive and inefficient. For similar reasons neither wooden nor stone box culverts could be used. In such cases, as well as in many others where the head-room is not so limited, the plan illustrated in Fig. 104 is a very satisfactory

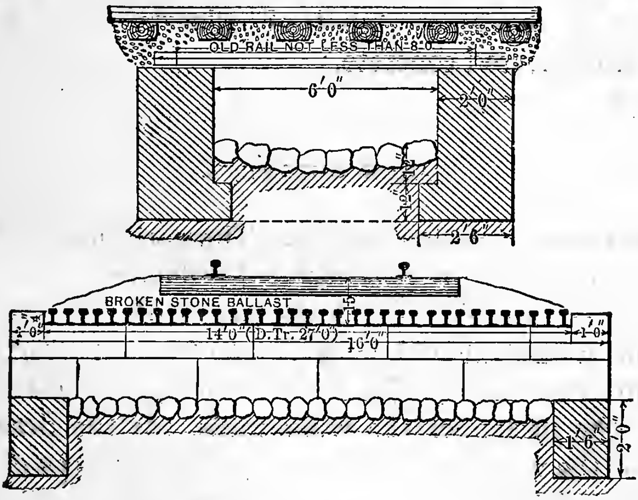


FIG. 104.—STANDARD OLD-RAIL CULVERT. N. & W. R.R. (1895.)

solution of the problem. The old rails, having a length of 8 or 9 feet, are laid close together across a 6-foot opening. Sometimes the rails are held together by long bolts passing through the webs of the rails. In the plan shown the rails are confined by low end walls on each abutment. This plan requires only 15 inches between the base of the rail and the top of the culvert channel. It also gives a continuous ballasted roadbed.

225. Reinforced Concrete Culverts. The development of reinforced concrete as a structural material is illustrated in its extensive adoption for arches and also for culverts. One of the special types which has been adopted is that of a box culvert which has a concrete bottom. Since this bottom can be made so that it will withstand an upward transverse stress, it furnishes a broad foundation for the whole culvert, and thus entirely eliminates the necessity for extensive footing to the side walls of the culvert, such as are necessary in soft ground with an ordinary stone culvert. Another advantage is that the inside of the culvert may be made perfectly smooth and thus offer less resistance to the passage of water through it. As may be noticed from Fig. 105, such a culvert is provided with flaring head walls, and sunken end walls, so that the water may not scour underneath the culvert, and other features common to other types. No attempt will here be made to discuss the design of reinforced concrete, except to say that all four sides of such a box culvert are designed to withstand a computed bursting pressure which tends to crush the flat sides inward. In Fig. 105 is shown one illustration of the many types of culverts which have been designed of reinforced concrete.

ARCH CULVERTS.

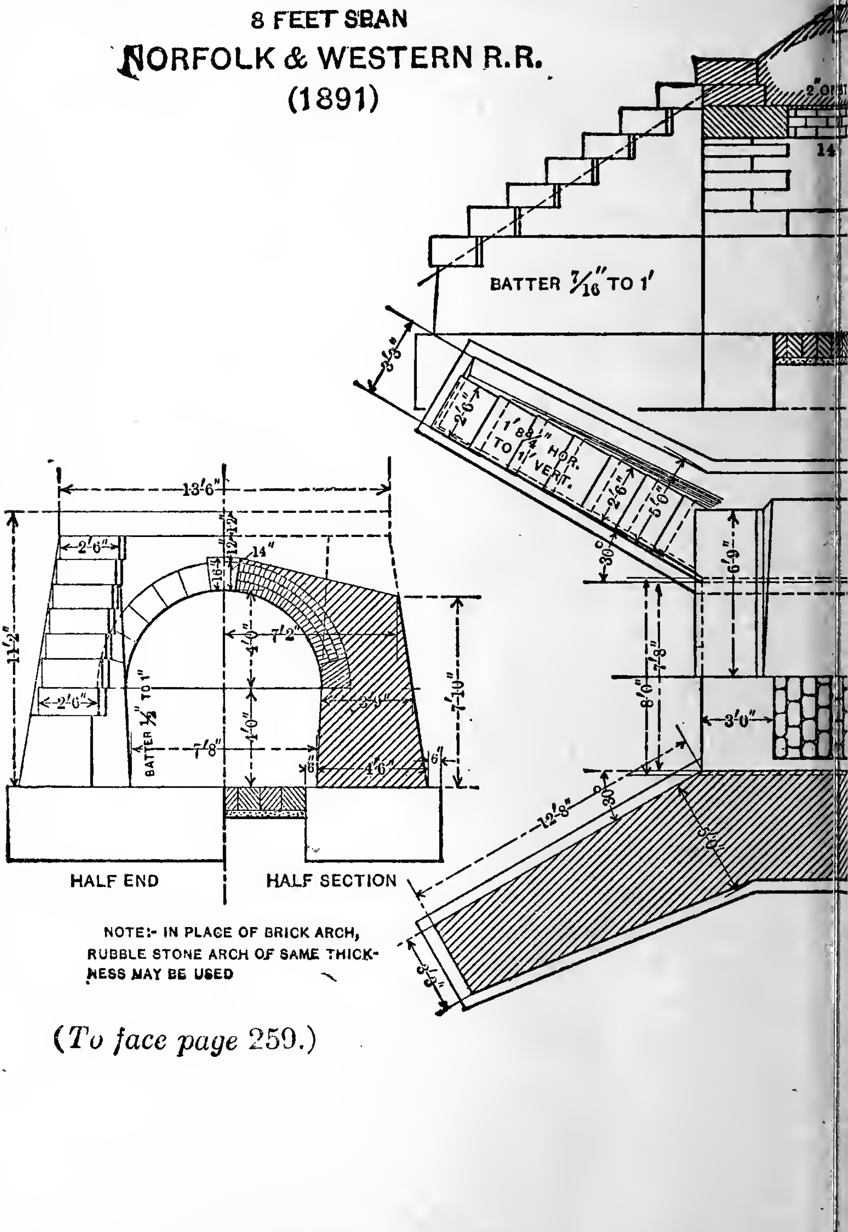
226. Influence of design on flow. The variations in the design of arch culverts have a very marked influence on the cost and efficiency. To combine the least cost with the greatest efficiency, due weight should be given to the following elements: (*a*) amount of masonry. (*b*) the simplicity of the constructive work, (*c*) the design of the wing walls, (*d*) the design of the junction of the wing walls with the barrel and faces of the arch, and (*e*) the safety and permanency of the construction. These elements are more or less antagonistic to each other, and the defects of most designs are due to a lack of proper proportion in the design of these opposing interests. The simplest construction (satisfying elements *b* and *e*) is the straight barrel arch

STANDARD ARCH CULVERT

8 FEET SPAN

NORFOLK & WESTERN R.R.

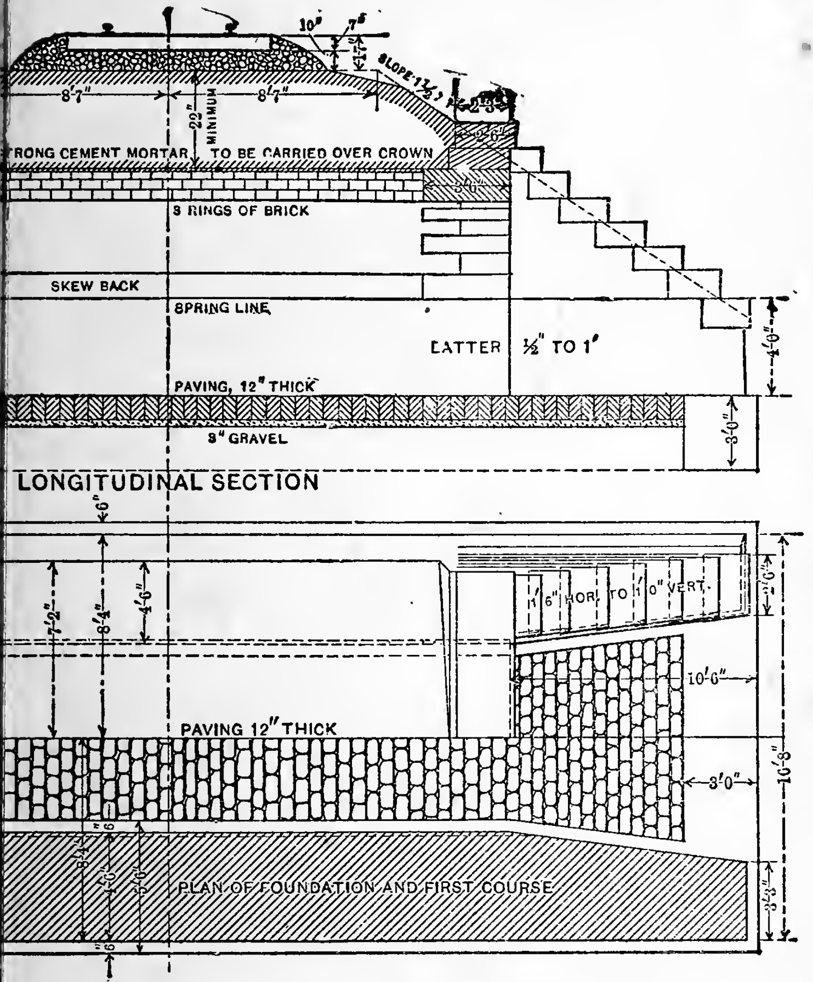
(1891)



NOTE:- IN PLACE OF BRICK ARCH, RUBBLE STONE ARCH OF SAME THICKNESS MAY BE USED

(*To face page* 259.)

PLATE IV



PLAN

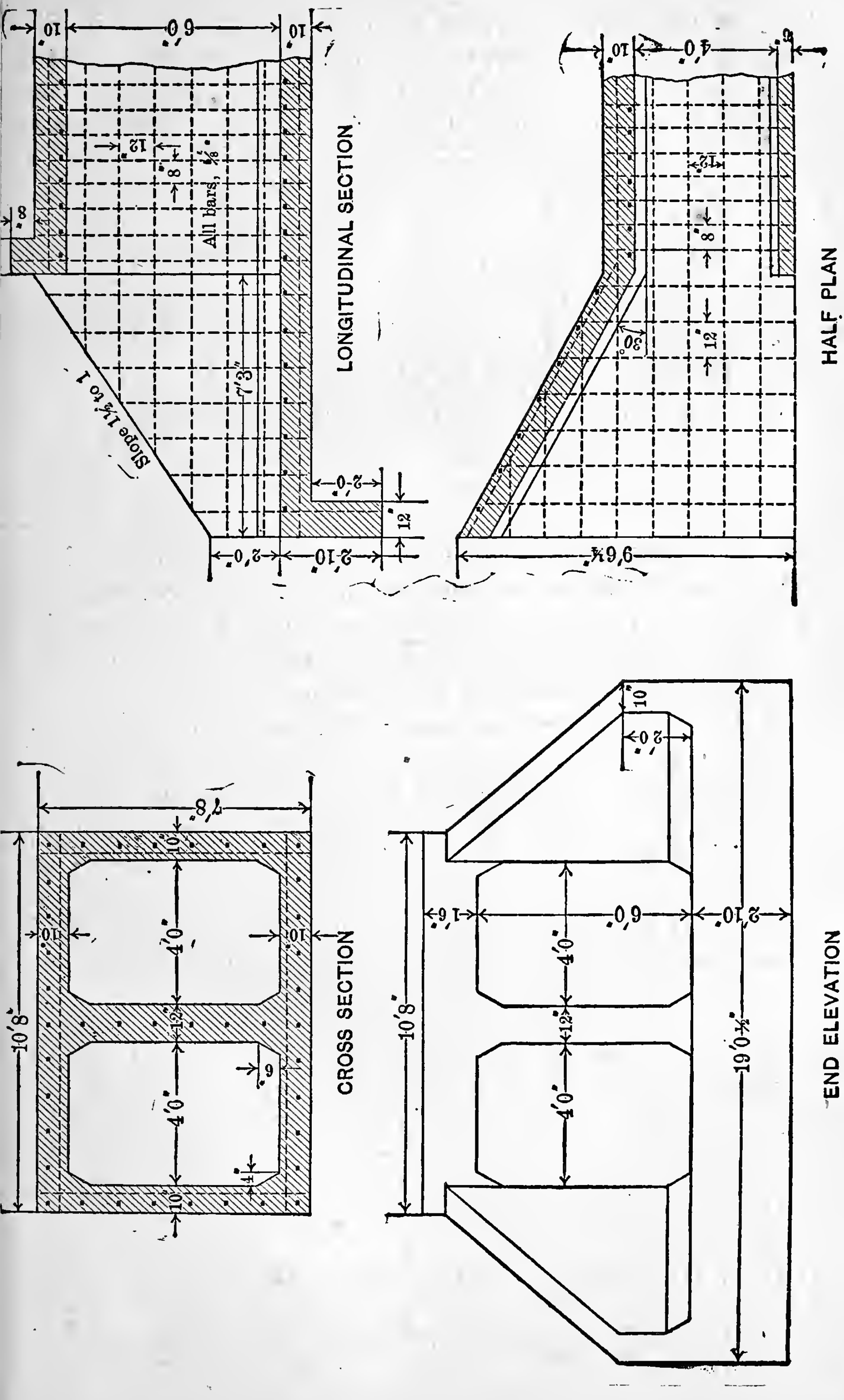


Fig. 105.—Reinforced Concrete Box Culvert.

between two parallel vertical head walls, as sketched in Fig. 106, *a*. From a hydraulic standpoint the design is poor, as the water eddies around the corners, causing a great resistance which decreases the flow. Fig. 106, *b*, shows a much better

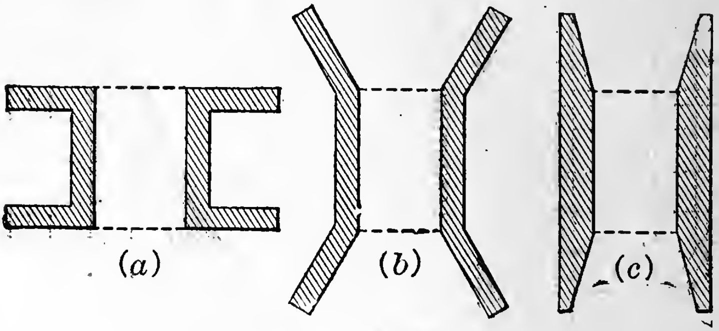


FIG. 106.—TYPES OF CULVERTS.

design in many respects, but much depends on the details of the design as indicated in elements (*b*) and (*d*). As a general thing a good hydraulic design requires complicated and expensive masonry construction, i.e., elements (*b*) and (*d*) are opposed. Design 106, *c*, is sometimes inapplicable because the water is liable to work in behind the masonry during floods and perhaps cause scour. This design uses less masonry than (*a*) or (*b*).

227. Example of arch culvert design. In Plate IV is shown the design for an 8-foot arch culvert according to the standard of the Norfolk and Western R. R. Note that the plan uses the flaring wing walls (Fig. 106, *b*) on the up-stream side (thus protecting the abutments from scour) and straight wing walls (similar to Fig. 106, *c*) on the down-stream end. This economizes masonry and also simplifies the constructive work. Note also the simplicity of the junction of the wing walls with the barrel of the arch, there being no re-entrant angles below the springing line of the arch. The design here shown is but one of a set of designs for arches varying in span from 6′ to 30′.

MINOR OPENINGS.

228. Cattle-guards. (a) Pit guards. Cattle-guards will be considered under the head of minor openings, since the old-fashioned plan of pit guards, which are even now defended and preferred by some railroad men, requires a break in the continuity of the roadbed. A pit about three feet deep, five feet

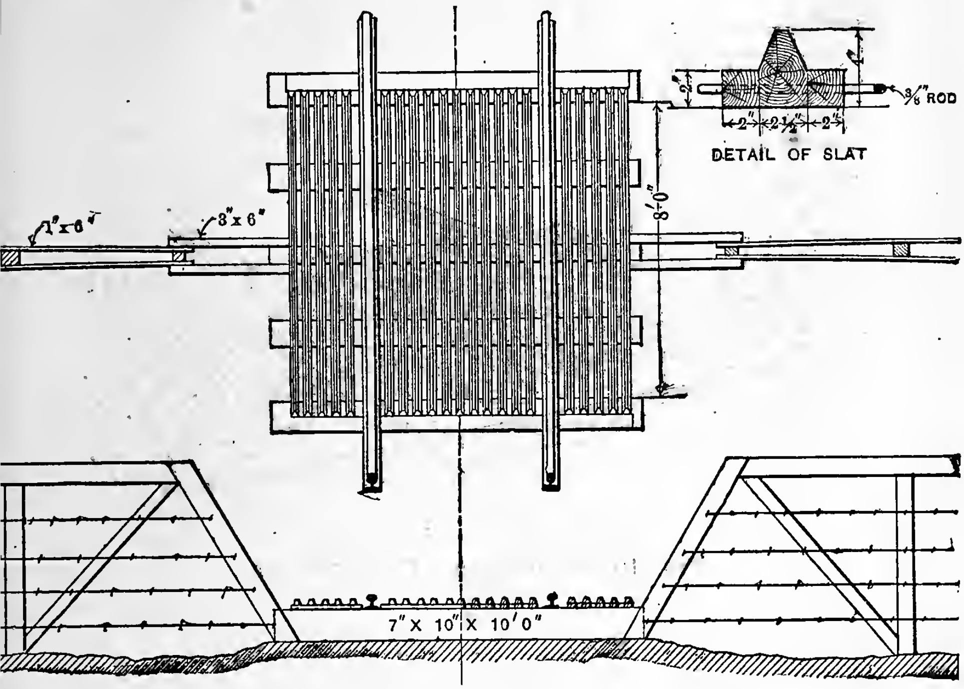


FIG. 107.—CATTLE-GUARD WITH WOODEN SLATS.

long, and as wide as the width of the roadbed, is walled up with stone (sometimes with wood), and the rails are supported on heavy timbers laid longitudinally with the rails. The break in the continuity of the roadbed produces a disturbance in the elastic wave running through the rails, the effect of which is noticeable at high velocities. The greatest objection, however, lies in the dangerous consequences of a derailment or a failure of the timbers owing to unobserved decay or destruction by fire—caused perhaps by sparks and cinders from passing locomotives. The very insignificance of the structure often leads to careless inspection. But if a single pair of wheels gets off the rails and drops into the pit, a costly wreck is inevitable.

(b) **Surface cattle-guards.** These are fastened on top of the ties; the continuity of the roadbed is absolutely unbroken and thus is avoided much of the danger of a bad wreck owing to a possible derailment. The device consists essentially of overlaying the ties (both inside and outside the rails) with a surface on which cattle will not walk. The multitudinous designs for such a surface are variously effective in this respect. An objection,

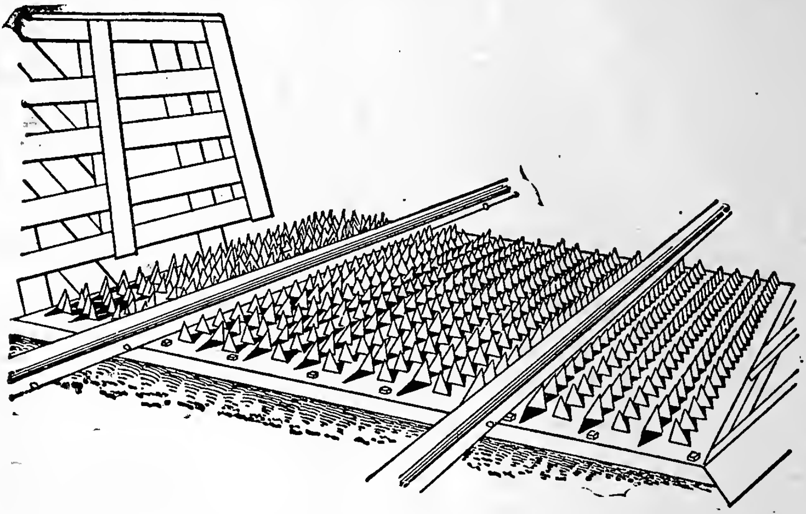


FIG. 108.—SHEFFIELD CATTLE-GUARD.

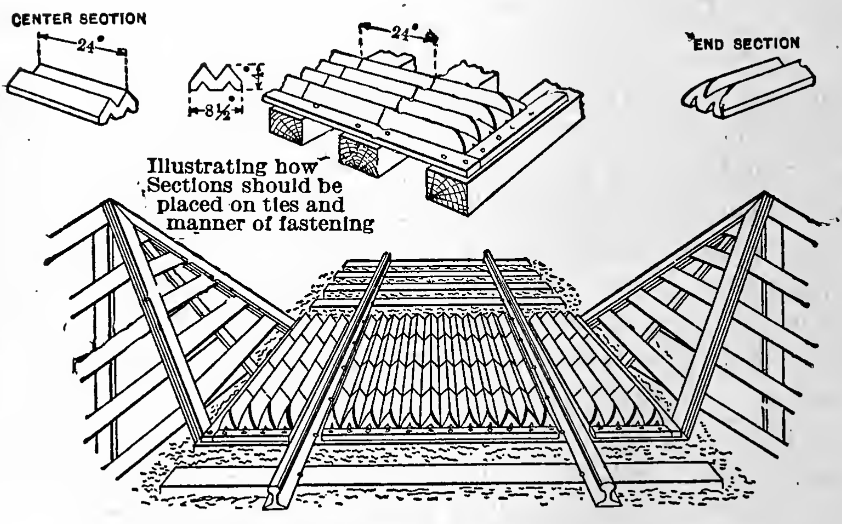
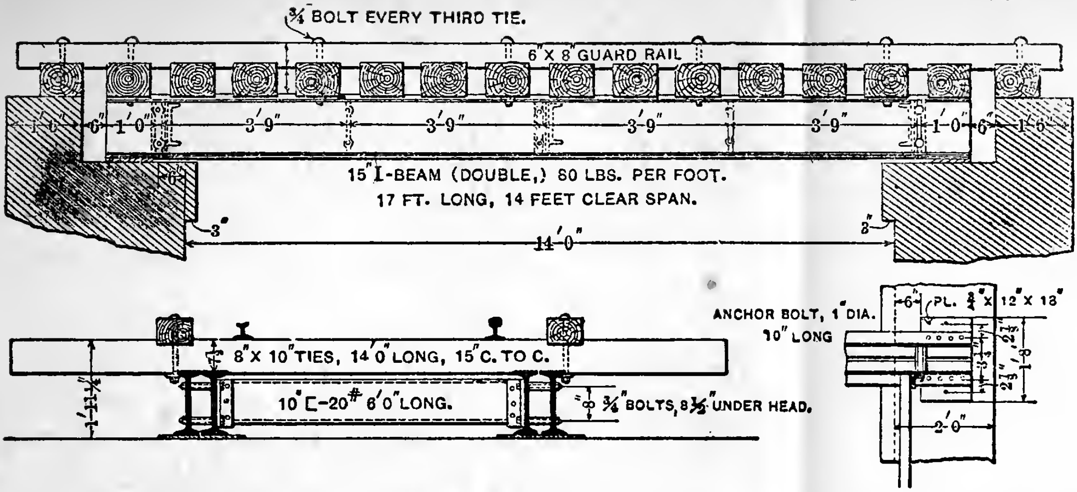


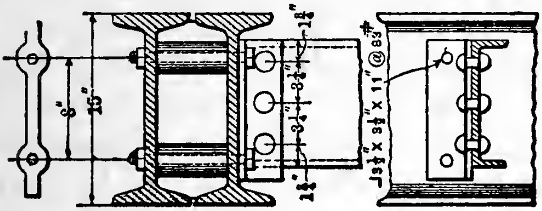
FIG. 109.—CLIMAX CATTLE-GUARD (TILE).

which is often urged indiscriminately against all such designs, is the liability that a brake-chain which may happen to be dragging *may* catch in the rough bars which are used. The bars are sometimes "home-made," of wood, as shown in Fig. 107. Steel guards may be made as shown in Fig. 108. The general construction is the same as for the wooden bars. The metal bars have far greater durability, and it is claimed that they are more effective in discouraging cattle from attempting to cross.

229. Cattle-passes. Frequently when a railroad crosses a farm on an embankment, cutting the farm into two parts, the railroad company is obliged to agree to make a passageway through the embankment sufficient for the passage of cattle and perhaps even farm-wagons. If the embankment is high enough so that a stone arch is practicable, the initial cost is the only great objection to such a construction; but if an open wooden structure is necessary, all the objections against the old-fashioned cattle-guards apply with equal force here. The avoidance of a grade crossing which would otherwise be necessary is one of the great compensations for the expense of the construction and maintenance of these structures. The construction is sometimes made by placing two pile trestle bents about 6 to 8 feet apart, supporting the rails by stringers in the usual way, the special feature of this construction being that the embankments are filled in behind the trestle bents, and the thrust of the embankments is mutually taken up through the stringers, which are notched at the ends or otherwise constructed so that they may take up such a thrust. The designs for old-rail culverts and arch culverts are also utilized for cattle-passes when suitable and convenient, as well as the designs illustrated in the following section, and the reinforced concrete design of § 225.

230. Standard stringer and I-beam bridges. The advantages of standard designs apply even to the covering of short spans with wooden stringers or with I beams—especially since the methods do not require much vertical space between the rails and the upper side of the clear opening, a feature which is often of prime importance. These designs are chiefly used for culverts or cattle-passes and for crossing *over* highways—providing such a narrow opening would be tolerated. The plans all imply stone abutments, or at least abutments of sufficient stability to withstand all thrust of the embankments. Some of the designs are illustrated in Plate V. The preparation of these standard designs should be attacked by the same general methods as already illustrated in § 190. When computing the required transverse strength, due allowance should be made for lateral bracing, which should be amply provided for. Note particularly the methods of bracing illustrated in Plate V. The designs calling for iron (or steel) stringers may be classed as permanent constructions, which are cheap, safe, easily inspected and maintained, and therefore a desirable method of construction.

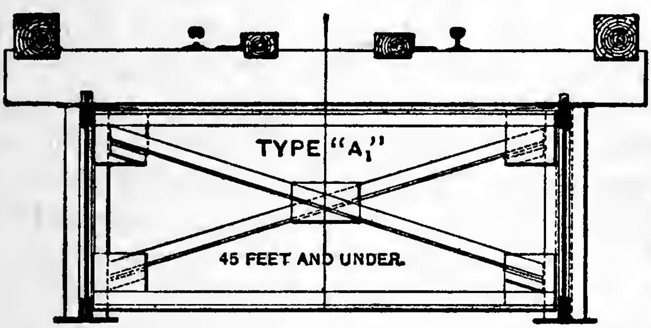


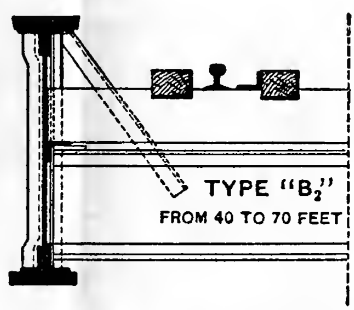


STANDARD I-BRIDGES—14-FT. SPAN.

NORFOLK AND WESTERN R.R.

(1891.)

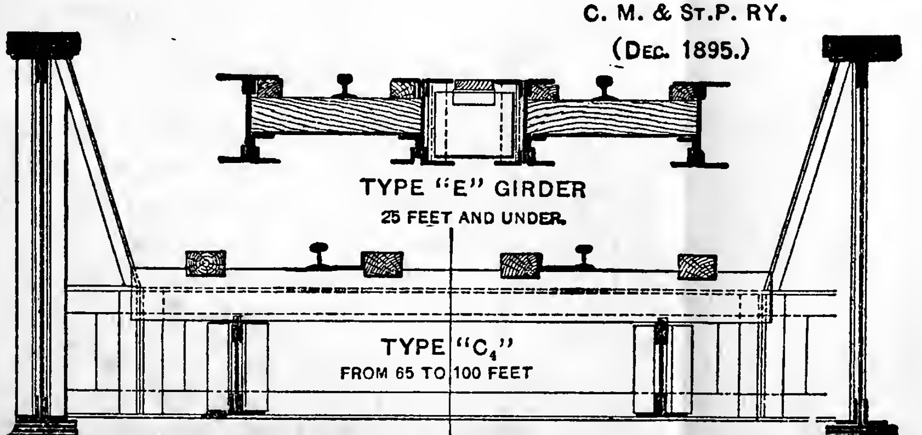




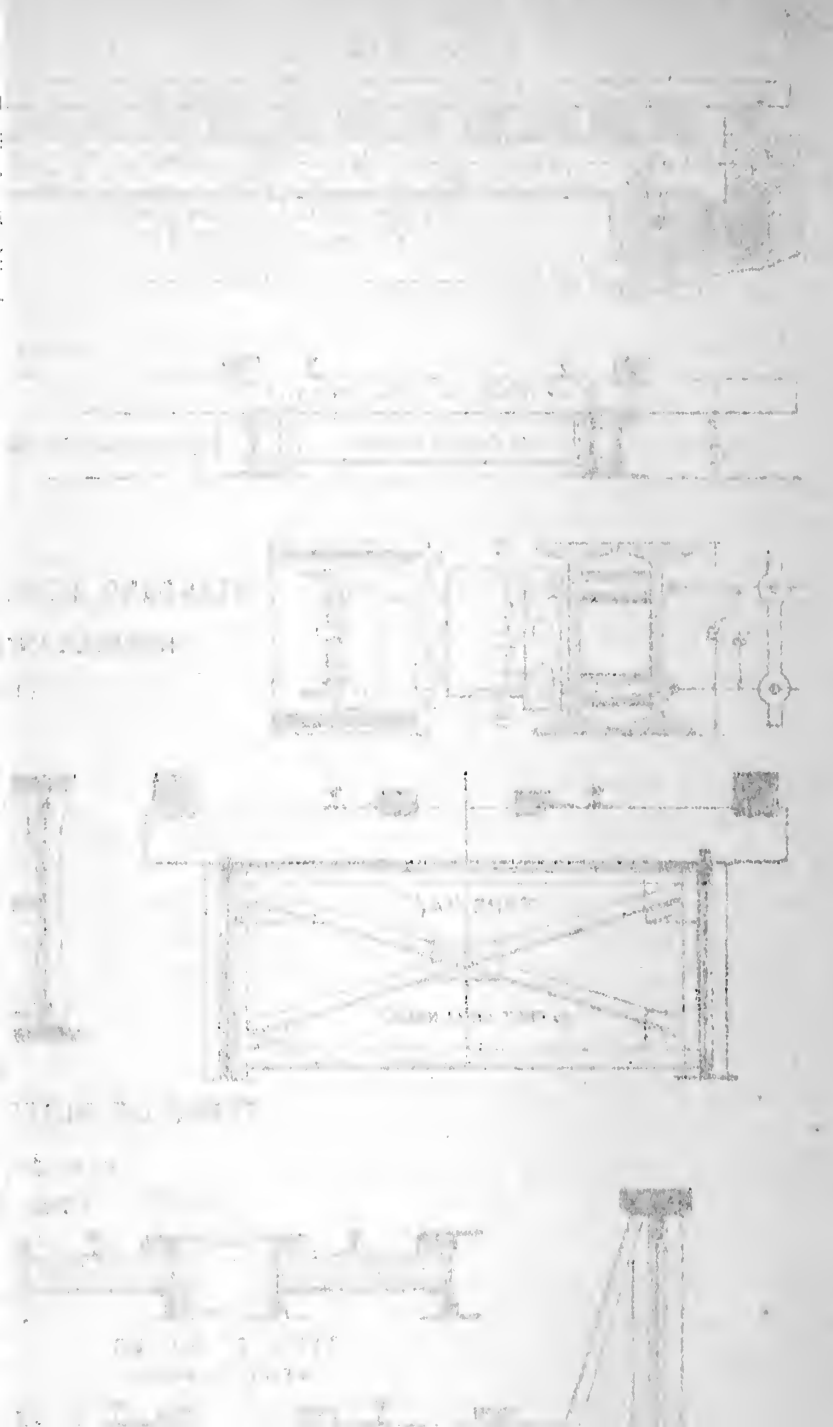
TYPES OF PLATE GIRDER BRIDGES.

C. M. & St.P. RY.

(Dec. 1895.)



(To face page 264.)



CHAPTER VII.

BALLAST.

231. Purpose and requirements. "The object of the ballast is to transfer the applied load over a large surface; to hold the timber work in place horizontally; to carry off the rain-water from the superstructure and to prevent freezing up in winter; to afford means of keeping the ties truly up to the grade line; and to give elasticity to the roadbed." This extremely condensed statement is a description of an ideally perfect ballast. The value of any given kind of ballast is proportional to the extent to which it fulfills these requirements. The ideally perfect ballast is not necessarily the most economical ballast for all roads. Light traffic generally justifies something cheaper, but a very common error is to use a very cheap ballast when a small additional expenditure would procure a much better ballast, which would be much more economical in the long run.

232. Materials. The materials most commonly employed are gravel and broken stone. In many sections of the country other materials which more or less perfectly fulfill the requirements as given above, are used. The various materials including some of these special types have been defined by the American Railway Engineering Association as follows:

DEFINITIONS.

Ballast. Selected material placed on the roadbed for the purpose of holding the track in line and surface.

Sub-ballast. Any material of a character superior to that in the adjacent cuts, which is spread on the finished sub-grade of the roadbed and below the top ballast, to provide better drainage, prevent upheaval by frost, and better distribute the load over the roadbed.

Top-ballast. Any material of a superior character spread over a sub-ballast to support the track structure, distribute the load to the sub-ballast, and provide good initial drainage.

Stone ballast. Stone broken by artificial means into small fragments of specified sizes.

Burnt clay. A clay or gumbo which has been burned into material for ballast.

Chats. Tailings from mills in which zinc, lead, silver and other ores are separated from the rocks in which they occur.

Chert. An impure flint or hornstone occurring in natural deposits.

Cinders. The residue from the coal used in locomotives and other furnaces.

Gravel. Worn fragments of rock, occurring in natural deposits, that will pass through a $2\frac{1}{2}$-inch ring and be retained upon a No. 10 screen.

Gumbo. A term commonly used for a peculiarly tenacious clay, containing no sand.

Sand. Any hard, granular, comminuted rock which will pass through a No. 10 screen and be retained upon a No. 50 screen.

Slag. The waste product, in a more or less vitrified form, of furnaces for reduction of ore. Usually the product of a blast-furnace.

There is still another classification which may or may not be considered as ballast. It is perhaps hardly correct to speak of the natural soils as ballast, yet many miles of cheap railways are "ballasted" with the natural soil, which is then called Mud ballast.

Broken or crushed stone. Rock ballast is specified to be that which will all pass in any position through a $2\frac{1}{2}$-inch ring, but which cannot pass through a $\frac{3}{4}$-inch mesh. It is most easily handled with forks. This method also has the advantage that when it is being rehandled the fine chips which would interfere with effectual drainage will be screened out. Rock ballast is more expensive in first cost and is also more troublesome to handle, but in heavy traffic especially, the track will be kept in better surface and will require less work for maintenance after the ties have become thoroughly bedded.

Burnt clay. This material has been used in many sections of the country where broken stone or gravel are unobtainable except at a prohibitive cost, and where a suitable quality of clay is readily obtained. This clay should be of "gumbo" variety and contain no gravel. It is sometimes burnt in a kiln, or it is sometimes burnt by piling the clay in long heaps over a mass of fuel, the pile being formed in such a way that a temporary but effectual kiln is made. It is necessary that a clear, clean fuel shall be used and that the firing shall be done by a man who is experienced in maintaining such a fire until the burning is completed. Such ballast may be burned very hard and it will last from four to six years. The cost of burning varies from 30 to 60 cents per cubic yard, according to the circumstances.

Chats. This is a form of ballast which is peculiar to Southwestern Missouri and Southeastern Kansas. When this material was first used it was obtained from the refuse piles of the mills which treated the zinc and lead ores mined in those regions. With the processes then employed the material was obtained in lumps as large as broken stone, and they were considered to be as valuable as broken stone for ballast. Improvements in the processes of treating the ores have resulted in making this by-product very much smaller grained and of less value as ballast, although it is still considered a desirable form of ballast where it may readily be obtained. It should be noted that it is classed with gravel and cinders in the forms of cross-section shown later.

Chert. This is a form of flint or hornstone which occurs in nodules of a size that is suitable for ballast, and is a very good type of ballast wherever it is found, but its occurrence is comparatively infrequent. It is classed with cemented gravel in the design of cross-sections of ballast.

Cinders. This is one of the most universal forms of ballast, since it is a by-product of every road which uses coal as fuel. The advantages consist in the fairly good drainage, the ease of handling and the cheapness—after the road is in operation. One of the greatest disadvantages is the fact that the cinders are readily reduced to dust, which in dry weather becomes very objectionable. Cinders are usually considered preferable to gravel in yards.

Gravel. This is one of the most common forms of good ballast. There are comparatively few railroads which cannot find, at some place along their line, a gravel pit which will afford a suitable supply of gravel for ballast. Sometimes it is used just as found in the pit, but for Class A and even Class B roads it is usually necessary to screen it. See § 238*a* for specifications.

Sand. Railroads which run along the coast are frequently ballasted merely with the sand obtained in the immediate neighborhood. One great advantage lies in the almost perfect drainage which is obtained.

Slag. When slag is readily obtainable it furnishes an excellent ballast which is free from dust and perfect in drainage qualities. Slag is classified with crushed rock in the cross-sections shown below, but it should be noted that this only applies to the best qualities of slag, since its quality is quite variable.

Mud ballast. When the natural soil is gravelly so that rain will drain through it quickly, it will make a fair roadbed for light traffic, but for heavy traffic, and for the greater part of the length of most roads, the natural soil is a very poor material for ballast; for, no matter how suitable the soil might be along limited sections of the road, it would practically never happen that the soil would be uniformly good throughout the whole length of the road. Considering that a heavy rain will in one day spoil the results of weeks of patient "surfacing" with mud ballast, it is seldom economical to use "mud" if there is a gravel-bed or other source of ballast anywhere on the line of the road.

233. **Cross-sections.** The required depth of the cross-section to the sub-soil depends largely on the weight of the rolling stock which is to pass over the track. A careful examination of a roadbed to determine the changes which take place under the ties and also an examination of the track and ties during the passage of a heavy train shows that the heavy loads which are now common on railroad tracks force the tie into the ballast with the passage of every wheel load. The effect on the ballast is a greater or less amount of crushing of the ballast. Even the very hardest grades of broken stone are more or less crushed by grinding against each other during the passage of a train. The softer and weaker forms of ballast are ground up much more quickly. One result is the formation of a fine dust which interferes with the proper drainage of water through the ballast. A second result is the compression of the ballast immediately under the tie into the sub-soil. In a comparatively short time a hole is formed under the tie which acts virtually like a pump. With every rise and fall of the tie under each wheel load, the tie actually pumps the water from the surrounding ballast and sub-soil into these various holes. When the

ballast is of such a character that the water does not drain through it easily, the water will settle in these holes long enough to seriously deteriorate the ties. When the track becomes so much out of line or level, or so loose that it needs to be tamped up, the process of tamping has practically the effect of deepening the amount of ballast immediately under the tie, while the sub-soil is forced up between the ties. A longitudinal section of the sub-soil of a track which has been frequently tamped generally has a saw-tooth appearance, and the sub-soil, instead of being a uniform line, has a high spot between each tie, while the ballast is considerably below its normal level immediately under the tie.

234. **Classification of Railroads.** The American Railway Engineering Association has divided railroads into three classes with respect to the standards of construction which should be adopted for ballasting, as well as other details of construction. The three classes are as follows (quoted from the Association Manual):

"Class 'A' shall include all districts of a railway having more than one main track, or those districts of a railway having a single main track with a traffic that equals or exceeds the following:

Freight-car mileage passing over districts per year per mile	150000
or,	
Passenger-car mileage per annum per mile of district	10000

with maximum speed of passenger-trains of 50 miles per hour.

"Class 'B' shall include all districts of a railway having a single main track with a traffic that is less than the minimum prescribed for Class 'A' and that equals or exceeds the following:

Freight-car mileage passing over districts per year per mile	50000
or,	
Passenger-car mileage per annum per mile of district	5000

with maximum speed of passenger-trains of 40 miles per hour.

"Class 'C' shall include all districts of a railway not meeting the traffic requirements of Classes 'A' or 'B.'"

The classification was adopted on the consideration that *quality* of traffic as well as mere tonnage should determine the classification of a railroad. For example, it is considered that a road which operates a train at a speed of 50 miles an hour should adopt the first class or Class "A" standards, even though there is but one train per day on that railroad. It likewise means that any road whose traffic makes necessary the construction of a regular double track should adopt the first class specifications.

235. Recommended sections for the several classifications. In Fig. 110 are shown a series of cross-sections which were

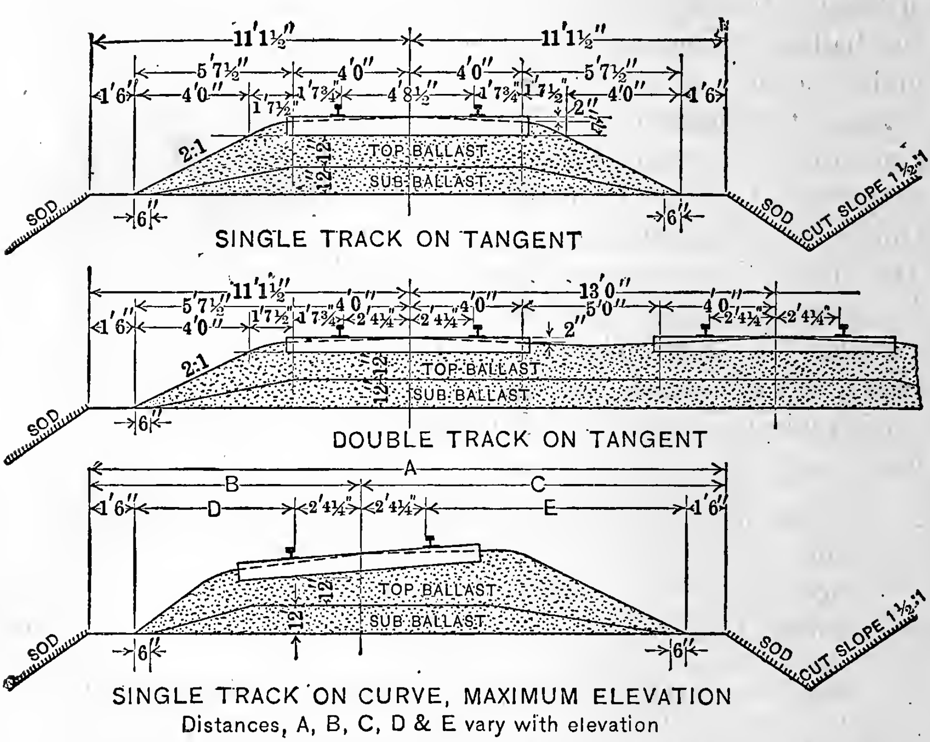


FIG. 110.—CROSS-SECTIONS OF BALLAST FOR CLASS "A" ROADS.

recommended by the A. R. E. A. for Class "A" traffic. It should be noticed that in each case the cross-section of the roadbed from shoulder to shoulder of the roadbed is 22′ 3″ plus the space between track centers for double track if any. The width of side ditches is merely added to that of the roadbed. The clear thickness of the ballast underneath the ties is made 24 inches. The slope of ½ inch to the foot from the center of the track to the end of the tie, which is common to all the cross-sections, is designed with the idea of allowing a clear space of 1 inch underneath the rail. The ballast is then rounded off on a curve of 4 feet radius and finally reaches the subsoil on a slope which is 2 : 1.

In Fig. 111 are shown a series of cross-sections for various classes of ballast for railroads that belong to Class "B." It

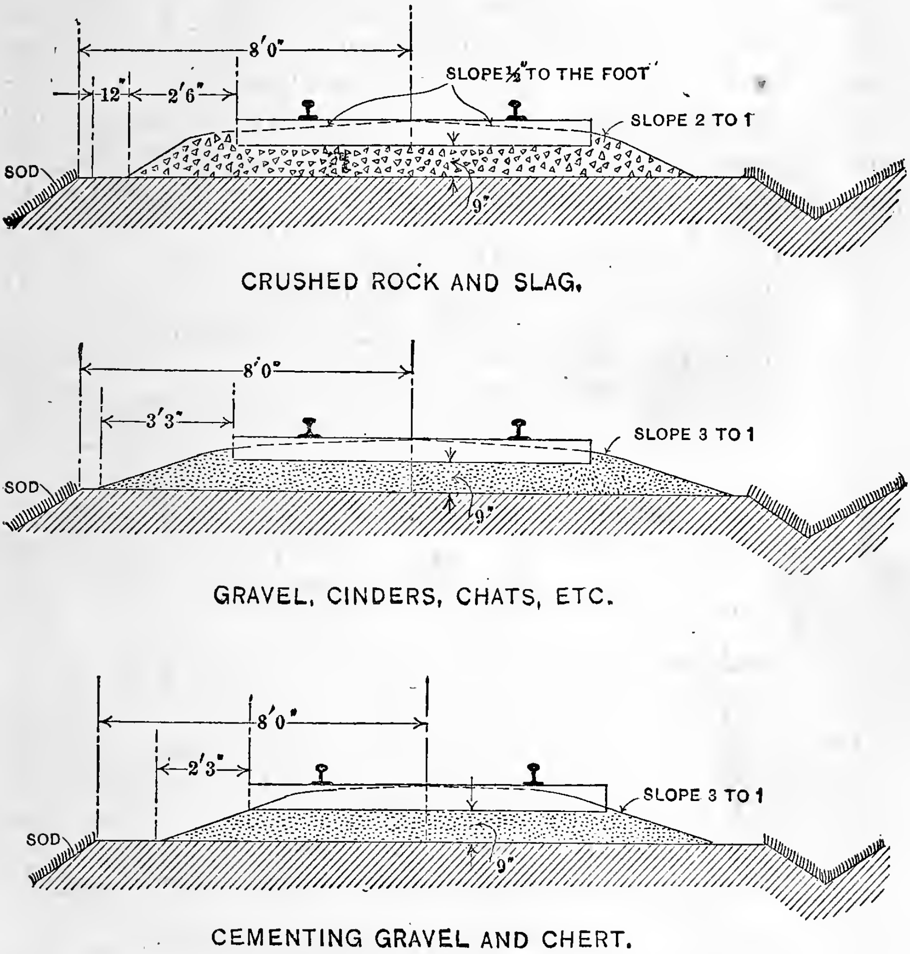
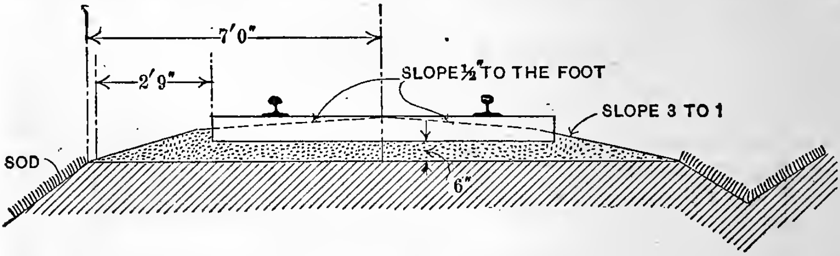


Fig. 111.—Cross-sections of Ballast for Class "B" Roads.

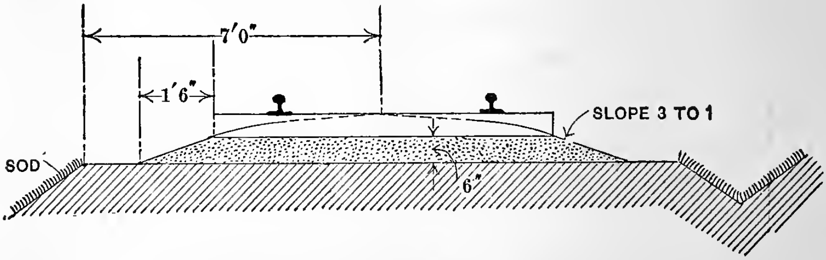
may be noted that the thickness of the ballast under the tie is 9 inches for this class. The width of roadbed between the shoulders, recommended for Class "B" is 16 feet. As before, the width of the ditches is supposed to be added to this width. It should be noted that when using cementing gravel and chert the slope of 3 : 1 is made to begin at the bottom of the tie instead of at a point about 2 inches below the top of the tie. This is done in order to prevent water from accumulating around the end of the tie in a material which is less permeable than the other forms of ballast.

In Fig. 112 are shown two cross-sections for ballast for roads belonging to Class "C." On roads of this class it is assumed that crushed rock will not be used for ballast. The width of roadbed between shoulders is 14 feet, while the depth of ballast underneath the tie is 6 inches.

It should be noticed that the above sections issued by the association do not include any cross-section which is recommended when no special ballast is used other than the natural soil. In such a case a cross-section very similar to the sections shown for cementing gravel and chert should be used. The



GRAVEL, CINDERS, CHATS, ETC.,



CEMENTING GRAVEL AND CHERT.

Fig. 112.—Cross-sections of Ballast for Class "C" Roads.

essential feature of such a section is that the soil, which is probably not readily permeable, should be kept away from the ends of the ties. Specifications for the placing of mud ballast, as well as other forms of ballast, have frequently specified that the ballast should be crowned about 1 inch above the level of the tops of the ties in the center of the track. This feature of any cross-section, although proposed, was rejected by the association, in spite of the fact that when a tie is so imbedded it certainly will have a somewhat greater holding power in the ballast.

236. Proper depth of ballast. The *depth of ballast* is officially defined by the A. R. E. A. as "the distance from the bottom of the tie to the top of the subgrade." In the recommended sections (Figs. 110 to 112) the depth shown varies from 6 inches to 24 inches. But the Ballast Committee reported in 1915 as a recommended conclusion that "From the data available, it is concluded that with ties 7 in. by 9 in. by $8\frac{1}{2}$ ft., spaced approximately 24 in. to 25.5 ins., center to center, a depth of 24 inches of stone ballast is necessary to produce uniform pressure on the subgrade, and a combination of a lower layer of gravel or cinder ballast, 18 inches to 14 inches, and an upper layer of stone ballast, 6 inches to 10 inches, approximately 24 inches deep in the aggregate, with the same spacing of the ties, will produce nearly the same results." New sections for Class "A" roads which would conform with the above were also recommended. The sections shown in Fig. 110, which are similar to those recommended in 1915, were adopted in 1921. The investigations of the Committee on Track Stresses (see Chap. XXV) have shown why deep ballast is necessary, but the economy of using a second-grade ballast as sub-ballast is possible. As previously stated, old track generally has a depth of ballast under the tie which is greater than the 2 feet recommended—often 3 or 4 feet.

237. Methods of laying ballast. The cheapest method of laying ballast on new roads is to lay ties and rails directly on the prepared subgrade and run a construction train over the track to distribute the ballast. Then the track is lifted up until sufficient ballast is worked under the ties and the track is properly surfaced. This method, although cheap, is apt to injure the rails by causing bends and kinks, due to the passage of loaded construction trains when the ties are very unevenly and roughly supported, and the method is therefore condemned and prohibited in some specifications. The best method is to draw in carts (or on a contractor's temporary track) the ballast that is required under the level of the *bottom* of the ties. Spread this ballast carefully to the required surface. Then lay the ties and rails, which will then have a very fair surface and uniform support. A construction train can then be run on the rails and distribute sufficient additional ballast to pack around and between the ties and make the required cross-section.

The necessity for constructing some lines at an absolute minimum of cost and of opening them for traffic as soon as possible has often led to the policy of starting traffic when there is little or no ballast—perhaps nothing more than a mere tamping of the natural soil under the ties. When this is done ballast may subsequently be drawn where required by the train-load on flat cars and unloaded at a minimum of cost by means of a "plough." The plough has the same width as the cars and is guided either by a ridge along the center of each car or by short posts set up at the sides of the cars. It is drawn from one end of the train to the other by means of a cable. The cable is sometimes operated by means of a small hoisting-engine carried on a car at one end of the train. Sometimes the locomotive is detached temporarily from the train and is run ahead with the cable attached to it.

238. Cost. The cost of ballast *in the track* is quite a variable item for different roads, since it depends (*a*) on the first cost of the material as it comes to the road, (*b*) on the distance from the source of supply to the place where it is used, and (*c*) on the method of handling. The first cost of cinder or slag is frequently insignificant. A gravel-pit may cost nothing except the price of a little additional land beyond the usual limits of the right of way. Broken stone will usually cost $1 or more per cubic yard. If suitable stone is obtainable on the company's land, the cost of blasting and breaking should be somewhat less than this. The cost of hauling will depend on the distance hauled, and also, to a considerable extent, on the limitations on the operation of the train due to the necessity of keeping out of the way of regular trains. There is often a needless waste in this way. The "mud train" is considered a pariah and entitled to no rights whatever, regardless of the large daily cost of such a train and of the necessary gang of men. "The cost of broken-stone ballast *in the track* is estimated at $1.25 per cubic yard. The cost of gravel ballast is estimated at 60 c. per cubic yard in the track. The cost of placing and tamping gravel ballast is estimated at 20 c. to 24 c. per cubic yard, for cinders 12 c. to 15 c. per cubic yard. The cost of loading gravel on cars, using a steam-shovel, is estimated at 6 c. to 10 c. per cubic yard."—Report Roadmasters' Association, 1885.

238a. Specifications. (Condensed from Am. Rwy. Eng. Assoc. Manual, 1915.) **Broken stone ballast.** To be selected on the basis of maximum (or minimum) figures for the following qualities: (*a*) weight per cubic foot, maximum; (*b*) water absorption in pounds per cubic foot, minimum; (*c*) per cent of wear, minimum; (*d*) hardness, maximum; (*e*) toughness, maximum; (*f*) cementing value, minimum; (*g*) compression test, maximum. **Gravel ballast.** For Class A railways: Bank gravel which contains more than two (2) per cent dust or forty (40) per cent sand should be washed or screened. Washed or screened gravel should contain not less than twenty-five (25) per cent nor more than thirty-five (35) per cent sand. For Class B railways: Bank gravel which contains more than three (3) per cent dust or sixty (60) per cent sand should be screened or washed. Washed or screened gravel should not contain less than twenty-five (25) per cent nor more than fifty (50) per cent sand. For Class C railways. Any material which makes better track than the natural roadbed may be economically used.

Testing gravel for ballast. Obtain five samples, each about one cubic foot, from various parts of the pit; mix thoroughly; make up a sample of about one cubic foot from the mixture. Sift through a screen, 10 meshes per linear inch, made of No. 24 B. & S. wire; the residue is the "gravel," G. Sift the remainder through a screen, 50 meshes per linear inch, made of No. 31 B. & S. wire; the residue is the "sand," S. That which passed through the screen is "dust," D. The percentage of sand, for example, equals $S \div (G+S+D)$.

CHAPTER VIII.

TIES,

AND OTHER FORMS OF RAIL SUPPORT.

239. Various methods of supporting rails. It is necessary that the rails shall be sufficiently supported and braced, so that the gauge shall be kept constant and that the rails shall not be subjected to excessive transverse stress. It is also preferable that the rail support shall be neither rigid (as if on solid rock) nor too yielding, but shall have a *uniform* elasticity throughout. These requirements are more or less fulfilled by the following methods.

(a) **Longitudinals.** The fundamental idea is to have continous support for the rail rather than to have it act as a continuous girder with numerous supporting points—the ties. In § 264 will be described a system of rails, used to some extent in Europe, having such broad bases that they are self-supporting on the ballast and are only connected by tie-rods to maintain the gauge.

(b) **Cast-iron "bowls" or "pots."** These are castings resembling large inverted bowls or pots, having suitable chairs on top for holding and supporting the rails, and tied together with tie-rods. They will be described more fully later (§ 263).

(c) **Cross-ties of metal or wood.** These will be discussed in the following sections.

240. Economics of ties. The true cost of ties depends on the relative total cost of maintenance for long periods of time. The first cost of the ties delivered to the road is but one item in the economics of the question. Cheap ties require frequent renewals, which cost for the *labor* of each renewal practically the same whether the tie is of oak or of hemlock. Cheap ties make a poor roadbed which will require more track labor to keep even in tolerable condition. The roadbed will require to be disturbed so frequently on account of renewals that the ties never get an opportunity to get settled and to form a smooth roadbed for any length of time. Irregularity in width, thickness, or length of ties is especially detrimental in causing the ballast to act and wear unevenly. The life of ties has thus a more or less direct influence on the life of the rails, on the wear of rolling stock, and on the speed of trains. These last items are not so readily reducible to dollars and cents, but when it can be shown that the total cost, for a long period of time, of several renewals of cheap ties, with all the extra track labor involved, is as great as or greater than that of a few renewals of durable ties, then there is no question as to the real economy. In the following discussions of the merits of untreated ties (either cheap or costly), chemically treated ties, or metal ties, the true question is therefore of the ultimate cost of maintaining any particular kind of ties for an indefinite period, the cost including the first cost of the ties, the labor of placing them and maintaining them to surface, and the somewhat uncertain (but not therefore non-existent) effect of frequent renewals on repairs of rolling stock, on possible speed, etc.

WOODEN TIES.

241. Choice of wood. This naturally depends, for any particular section of country, on the supply of wood which is most readily available. Table XXII shows the relative use of the chief varieties in the U. S. Two-thirds of the entire list is white oak, red oak and southern pine. Douglas fir, which grows only in the west, is being transported to the east in increasingly large quantities and is displacing other woods. The use of eastern tamarack, lodge pole pine, western larch, western yellow pine, and hemlock is almost confined to the "western region" — west of the Mississippi river. Redwood was formerly used quite extensively in the west, on account of cheapness and immunity from decay, but the wood is

TABLE XXII.—NUMBER AND KINDS OF CROSS TIES USED BY 78% OF TOTAL MILEAGE OF STEAM RAILROADS IN UNITED STATES IN 1915.

(Bull. 549, U. S. Dept. Agric.).

Kind of wood.	Number of ties.	Per cent.
White oak	30,160,316	34.1
Red oak	15,989,605	18.1
Southern pine	13,226,654	15.0
Douglas fir	6,308,685	7.1
Cypress	4,375,012	4.9
Cedar	4,121,570	4.7
Chestnut	2,666,402	3.0
Eastern tamarack	2,520,475	2.8
Lodge pole pine	1,254,420	1.4
Western larch	1,196,415	1.3
Western yellow pine	1,183,535	1.3
Beech	1,139,457	1.3
Maple	1,062,086	1.2
Hemlock	839,924	1.0
All other	2,454,099	2.8
Total	88,498,655	100.0

too soft. The use of cypress is nearly confined to the west and south, and on the other hand the use of chestnut is nearly confined to the "eastern region"—north of the Ohio and Potomac and east of Chicago.

On the basis of 88,498,655 ties for 78.46% of the mileage, the proportionate total is 112,974,615 ties. 100,000,000 to 125,000,000 ties per year is elsewhere stated to be the normal demand. This means an annual *average* of about 290 ties for each mile of track, including sidings.

242. Durability. The durability of ties depends on the climate; the drainage of the ballast; the volume, weight, and speed of the traffic; the curvature, if any; the use of tie-plates; the time of year of cutting the timber; the age of the timber and the degree of its seasoning before placing in the track; the nature of the soil in which the timber is grown; and, chiefly, for untreated ties, on the species of wood employed. The variability in these items will account for the discrepancies in the reports on the life of various woods used for ties. For example, six records of untreated white oak ties on six different roads gave figures varying from 3 to 14 years. Such a range of values is too wide for practical utilization.

The variability in the actual life of a "group" of ties of nominally the same quality and placed in the track at the same time

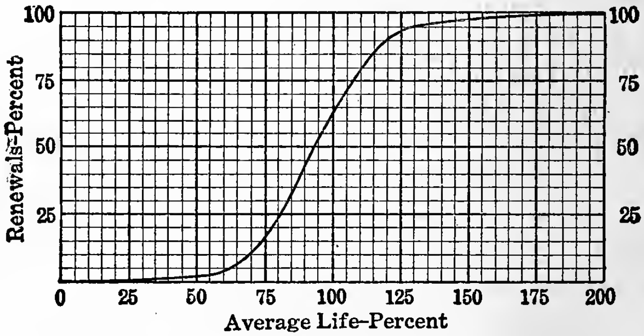


FIG. 112*a*.—RELATIVE ACTUAL LIFE OF TIES OF NOMINALLY UNIFORM QUALITY.

is shown in a study * made by the Forest Products Laboratory, U. S. Forest Service. Records show that there will be, in general,

* "Relation between average life of ties and percentage of renewals," by Mabel E. Thorne, Statistician.

no replacements until after about 30% of the average life of the whole group. Then the replacements will commence and grow more frequent until at the time of the *average* life of the whole group, about 60% will have been replaced. After a time equal to 120% of the average life, about 90% of the ties will have been replaced, but a few of the remainder may stay in the track until nearly or quite 200% of the average life. The law is based on the records of 43 groups of ties comprising 42936 ties, or an average of about 1000 ties per group. The law is substantially true whether applied to short-lived untreated ties or to long-lived treated ties. The law may even be considered as sufficiently established so that when 10% of a "group" of ties have been removed from a track, the time already elapsed may be considered as approximately 70% of the *average* life of the entire group, and the probable life of the remaining 90% of ties may be estimated accordingly.

Some of the softer woods used for ties, such as *cedar* and *redwood*, resist decay very well, but are so soft that they are badly cut by the rail-flanges and do not hold the spikes very well, necessitating frequent respiking. Since the spikes must be driven within certain very limited areas on the face of each tie, it does not require many spike holes to "spike-kill" the tie. On sharp curves, especially with heavy traffic, the wheel-flange pressure produces a side pressure on the rail tending to overturn it, which tendency is resisted by the spike, aided sometimes by rail-braces. Whenever the pressure becomes too great the spike will yield somewhat and will be slightly withdrawn. The resistance is then somewhat less and the spike is soon so loose that it must be redriven in a new hole. If this occurs very often, the tie may need to be replaced long before any decay has set in.

243. Dimensions. The usual dimensions for the best roads (standard gauge) are 8′ to 9′ long, 6″ to 7″ thick, and 8″ to 10″ wide on top and bottom if they are sawed. Hewed ties (with rounded sides) shall have the faces not less than 6 inches wide, but the cross sectional area must not be less than a sawed tie of the same class. Narrow gauge and very-light-traffic roads will reduce these dimensions as much as twenty per cent.

244. Spacing. The Penna. R. R. standard spacing (1921) called for 14, 16, 18 or 20 ties per 33-foot rail, according to the classification of track. The joints of the two lines of rails are placed "staggered" rather than "opposite" each other. The joints are "suspended" (see § 282) on two ties spaced 20″ c. c. There are for each rail length two spaces 20″ each and 12, 14, 16 or 18 spaces of $29\frac{2}{3}''$, $25\frac{3}{7}''$, $22\frac{1}{4}''$, or $19\frac{7}{9}''$ each.

245. Specifications. The specifications for ties are apt to include the items of size, kind of wood, and method of construction, besides other minor directions about time of cutting, seasoning, delivery, quality of timber, etc.

(a) **Size.** The particular size or sizes required will be somewhat as indicated in § 243.

(b) **Kind of wood.** When the kind or kinds of wood are specified, the most suitable kinds that are available in that section of country are usually required.

(c) **Method of construction.** It is generally specified that the ties shall be hewed on two sides; that the two faces thus made shall be parallel planes and that the bark shall be removed. It is sometimes required that the ends shall be sawed off square; that the timber shall be cut in the winter (when the sap is down); and that the ties shall be seasoned for six months These last specifications are not required or lived up to as much as their importance deserves. It is sometimes required that the ties shall be delivered on the right of way, neatly piled in rows, the alternate rows at right angles, piled if possible on ground not lower than the rails and at least ten feet away from the nearest rail, the lower row of ties resting on two ties which are themselves supported so as to be clear of the ground.

(d) **Quality of timber.** The usual specifications for sound timber are required, except that they are not so rigid as for a better class of timber work The ties must be sound, reasonably straight-grained, and not very crooked—one test being that a line joining the center of one end with the center of the middle shall not pass outside of the other end. Splits or shakes, especially if severe, should cause rejection.

Specifications sometimes require that the ties shall be cut from small trees, making what is known as "pole ties" and definitely condemning those which are cut or split from larger trunks, giving two "slab

FIG. 113.—METHODS OF CUTTING TIES.

ties" or four "quarter ties" for each cross-section, as is illustrated in Fig. 113. Even if pole ties are better, their exclusive use means the rapid destruction of forests of young trees.

246. Regulations for laying and renewing ties.—The regulations issued by railroad companies to their track foremen will generally include the following, in addition to directions regarding dimensions, spacing, and specifications given in §§ 242–245. When hewn ties of somewhat variable size are used, as is frequently the case, the largest and best are to be selected for use as joint ties. If the upper surface of a tie is found to be warped (contrary to the usual specifications) so that one or both rails do not get a full bearing across the whole width of the tie, it must be adzed to a true surface along its whole length and not merely notched for a rail-seat. When respiking is necessary and spikes have been pulled out, the holes should be immediately plugged with "wooden spikes," which are supplied to the foreman for that express purpose, so as to fill up the holes and prevent the decay which would otherwise take place when the hole becomes filled with rain-water. Ties should always be laid at right angles to the rails and never obliquely Minute regulations to prevent premature rejection and renewal of ties are frequently made. It is generally required that the requisitions for renewals shall be made by the actual count of the individual ties to be renewed instead of by any wholesale estimates. It is unwise to have ties of widely variable size, hardness, or durability adjacent to each other in the track, for the uniform elasticity, so necessary for smooth riding, will be unobtainable under those circumstances.

After a considerable discussion of the two policies of tie renewals over long continuous stretches of track or of single tie renewals where individually needed, the A. R. E. A. has decided in favor of single tie renewals, as being most economical and producing least track disturbance.

247. Dating nails. These are made of iron or steel, galvanized with zinc. They should be $2\frac{1}{2}$ inches long, $\frac{1}{4}$ inch in diameter, with $\frac{5}{8}$-inch head, which has two figures $\frac{3}{16}$ inch high, denoting the year, which are stamped, by depression, into the head. They should be driven into the upper side of all treated ties, 10 inches inside the rail, on the line side of the track. The use of such dates gives definite knowledge of the life of the tie when it is renewed and a means of studying the effectiveness of the tie treatment.

248. Cost of ties. When railroads can obtain ties cut by farmers from woodlands in the immediate neighorhood, they sometimes advertise a schedule of prices which they will pay, the prices being considerably lower than the prices demanded by dealers. Prices as low as 35 c. were formerly paid directly to tie cutters in tie growing sections, but increasing scarcity has raised the price. A great railway paid $610,713 for 453,000 ties in 1920, an average of $1.31 each. These were of higher grade than the average. The following schedule shows proportionate prices: white oak, $1.39; heart pine, $1.66; chestnut, $1.37; red oak, $1.34; sap pine, $1.19; maple, beech and birch, $1.27.

PRESERVATIVE PROCESSES FOR WOODEN TIES.

249. General principles. Wood has a fibrous cellular structure, the cells being filled with sap or air. The woody fiber is but little subject to decay unless the sap undergoes fermentation. Preservative processes generally aim at removing as much of the water and sap as possible and filling up the pores of the wood with an antiseptic compound. The most common methods all agree in this general process and only differ in the method employed to get rid of the sap and in the antiseptic chemical with which the fibers are filled. One valuable feature of these processes lies in the fact that the softer cheaper woods are more readily treated than are the harder woods and from them a tie can be made which will be as durable as the best (from the standpoint of decay), and, if protected from mechanical wear by tie-plates, will have a very long life. The following woods may be used without preservative treatment: White oak family, long-leaf strict heart yellow pine, cypress, excepting the white cypress, redwood, white cedar, chestnut, catalpa, locust, except the honey locust, walnut and black cherry. The following woods should preferably not be used without preservative treatment: Red oak family, beech, elm, maple, gum, loblolly, short-leaf, Western yellow pine, Norway, North Carolina pine and other sap pines, red fir, spruce, hemlock, and tamarack. It is better to use an excess of chemical rather than not enough. Ties should be grouped before treatment; for example, green ties should not be mixed with seasoned ties, since the treatment should be different. Ties should be air-seasoned before being treated. When there is time to air-season them at the plant before treatment, they should be piled in groups having the same degree of seasoning, so that they rest on seasoned stringers, the lowest ties at least 6 inches from the ground, which should be thoroughly drained and cleared from weeds, high grass and decaying matter. The ties should not be allowed to over-season or deteriorate. Ties which show signs of checking should be secured with S-irons or bolts to prevent further checking. When ties are to be adzed or bored for the use of tie-plates or screw spikes, the adzing or boring should be done before chemical treatment. Steam seasoning, if excessive, weakens the wood. It should therefore be limited, unless it is imperative to treat green ties because air-seasoned ties are not obtainable.

To do the work, long cylinders, which may be opened at the ends, are necessary. Usually the timbers are run in and out on iron carriages running on rails fastened to braces on the inside of the cylinder. When the load has been run in, the ends of the cylinder are fastened on. The water and air in the pores of the wood are drawn out by subjecting the wood alternately to steam-pressure and to the action of a vacuum-pump. Live steam should be admitted so that a pressure of 20 lbs. is produced within 30 to 50 minutes. This pressure may be maintained from 1 to 5 hours, depending on the condition of the wood, but the pressure should never exceed 20 lbs. A vent should be provided to allow the escape of air and condensed water. After steaming, a vacuum of not less than 24 inches of mercury at sea-level (or correspondingly less for higher altitudes), shall be produced and maintained for half an hour. Then, without breaking the vacuum, the chemical shall be admitted.

250. Creosoting. This process consists in impregnating the wood with creosote oil, a product obtained from coal-gas tar or coke oven tar which shall be free from any tar, including coal-gas tar, oil or residue obtained from petroleum or any other source. The pure creosote oil is strongly recommended by the A.R. E. A., but they recognize that the practice of using other coal tar distillates, when the available supply of creosote is inadequate, is firmly established, and have made specifications accordingly.

It would require about 35 to 50 lbs. of creosote to completely fill the pores of a cubic foot of wood. But it would be impossible to force such an amount into the wood, nor is it necessary or desirable. After one of the vacuum periods, the cylinder is filled with creosote oil having a temperature of not less than 160° F. The cylinders should be provided with steam coils in order to maintain that temperature during injection. The pressure should immediately be raised to 75 lbs. per square inch, and then by a gradual increase to a maximum of 175 or 200 lbs. or until about 6 to 10 lbs. per cubic foot, or about 21 to 35 lbs. per tie, is absorbed, this amount being indicated by calculations based on gauge readings of the oil in the oil reservoir, taken before and after the introduction and withdrawal of the oil from the cylinder. Owing to variations in the volume of the creosote due to change of temperature during treatment, also to variations in the capacity volume of the cylinder due to change in temperature of the metal, and several other causes, the determination of the volume of the oil actually absorbed by the ties is not simple. Each cylinder must be calibrated by a series of tests, since these causes may easily produce an error of 25% in the nominal results. As a check, the ties on a cylinder tram-car should occasionally be weighed before and after treatment. Even this check will not be conclusive if the ties have been steam seasoned, since steam seasoning usually increases the weight and this increase would be credited as absorption of chemical.

251. Burnettizing (chloride-of-zinc process). This process is very similar to the creosoting process except that the chemical is chloride of zinc. The chemical is heated to 140° F. before using. The preliminary treatment of the wood to alternate vacuum and pressure is not continued for quite so long a period as in the creosoting process. Care must be taken, in using this process, that the ties are of as uniform quality as possible, for seasoned ties will absorb much more zinc-chloride than unseasoned (in the same time), and the product will lack uniformity unless the seasoning is uniform. The amount of solution injected shall be equivalent to $\frac{1}{2}$ lb. of dry soluble zinc-chloride per cubic foot of timber. The solution shall be as weak as can be used and still obtain the desired absorption of zinc-chloride, and shall not be stronger than 5%. If the cylinders are provided with steam coils, steam pressure shall be maintained in these coils during treatment. One great objection to burnettized ties is the fact that the chemical is somewhat easily washed out, when the wood again becomes subject to decay. Another objection is the fact that when the solution of zinc-chloride is made strong (over 3%)

the timber is made very brittle and its strength is reduced. The reduction in strength has been shown by tests to amount to $\frac{1}{4}$ to $\frac{1}{10}$ of the ultimate strength, and that the elastic limit has been reduced by about $\frac{1}{7}$.

252. **Kyanizing (bichloride-of-mercury or corrosive-sublimate process).** This process has been much used, but it is so objectionable, on account of the chemical being such a virulent poison that workmen are sickened by fumes arising from the tanks, that it is no longer included as one of the standard methods.

253. **Zinc-tannin process.** The last two methods described (as well as some others employing similar chemicals) are open to the objection that since the wood is impregnated with an aqueous solution, it is liable to be washed out very rapidly if the wood is placed under water, and will even disappear, although more slowly, under the action of moisture and rain. Several processes have been proposed or patented to prevent this. By one of these processes the timber is successively subjected to the action of chemicals, each individually soluble in water, and hence readily impregnating the timber, but the chemicals when brought in contact form insoluble compounds which cannot be washed out of the wood-cells. After injecting the zinc-chloride, as before described, the solution is run off and the ties drained for 15 minutes. Then a 2% solution of tannic acid, made from $6\frac{2}{3}$ lbs. of 30% extract of tannin and 100 lbs. of water is run in and maintained at 100 lbs. pressure for one-half hour. Then a solution of glue made by dissolving 2.1 lbs. of glue containing 50% gelatine in 100 lbs. of water is run in and maintained at 100 lbs. pressure for one-half hour. The glue and tannin combine to form an insoluble leathery compound in the cells, which will prevent the zinc-chloride from being washed out.

254. **Zinc-creosote emulsion process.** The chemical is an emulsion which will leave in the wood an equivalent of 0.4 lb. of dry, soluble zinc-chloride and from 1.25 to 1.5 lbs. of creosote per cubic foot. The zinc-chloride must not be stronger than 3.5%. The emulsion must be effectively mixed in a storage tank and heated to at least 140° F. before it enters the cylinder, where the pressure is raised to 100 lbs. per square inch and maintained there until the required amount of chemical has been absorbed by the wood.

255. **Two-injection zinc-creosote process.** The zinc-chloride and creosote are injected separately. The zinc-chloride must be as weak as possible (not more than 5%), and yet strong enough

so that the equivalent of 0.3 lb. can be injected per cubic foot. After impregnation, the remaining zinc-chloride is run out and the creosote is forced in and maintained at 100 lbs. pressure until the wood has absorbed about 3 lbs. of oil per cubic foot.

256. Cost of treating. The cost of treating ties by the various methods has been estimated as follows.* The total cost is divided into (1) seasoning; (2) labor; (3) fuel; (4) maintenance and (5) chemicals.

Seasoning. The labor required for air-seasoning, the usual practice, is estimated at from 0.75 c. to 1.5 c. per tie, or is averaged at 1.0 c. per tie. **Labor.** The labor involved in all other handling of the ties is averaged at 6.0 c. per tie. **Fuel** may cost 0.5 c. per tie when natural gas or oil is obtainable and up to 2.0 c. per tie for other scarcer fuels; it is averaged at 1.0 c. per tie. **Maintenance** of the plant is estimated at 1.25 c. to 2.0 c. per tie; as an average it is placed at 1.5 c. for creosoting plants and 1.6 c. for plants using zinc-chloride, since it is more corrosive. **Chemicals.** On the basis of a $7'' \times 9'' \times 8'$ tie, having a volume of 3.5 cubic feet, and $\frac{1}{2}$ lb. of zinc-chloride per cubic foot, the amount of $ZnCl_2$ is 1.75 lbs. per tie; at 4c. per pound this would cost 7 c. per tie. Using 10 lbs. of creosote per cubic foot or 35 lbs. per tie, 4.08 gallons (8.58 lbs. per gallon) of creosote would be used per tie. A price of 6 to 10 cents per gallon is quoted for large quantities of creosote. Apparently 6.84 c. per gallon was used in the calculation, since the cost of the creosote was put at 27.9 c. per tie. Summarizing, the cost by the several methods was as given below.

Chemical used.	Quantity per cubic foot.	Seasoning, labor, fuel.	Maintenance of plant.	Chemical cost.	Total.
Creosote	10 lbs.	8.0 c.	1.5 c.	27.9 c.	37.5 c.
"	6 "	8.0 "	1.5 "	16.8 "	26.3 "
{ Creosote	3 "	} 8.0 "	1.6 "	15.4 "	25.0 "
{ $ZnCl_2$	$\frac{1}{2}$ "				
Zinc chloride	$\frac{1}{2}$ "	8.0 "	1.6 "	7.0 "	16.6 "

Of course the above figures are merely illustrative. Variations in the cost of labor and materials will probably change all these figures. Nothing is included for interest, depreciation, superintendence or profit.

* Bull. No. 118, U. S. Dept. of Agric., Div. of Forestry. Nov., 1912.

257. Economics of treated ties. The fact that treated ties are not universally adopted is due to the argument that the added life of the tie is not worth the extra cost. If ties can be bought for 25 c., and cost 25 c. for treatment, and the treatment only doubles their life, there is apparently but little gained except the work of placing the extra tie in the track, which is more or less offset by the interest on 25 c. for the life of the untreated tie, and the larger initial outlay makes a stronger impression on the mind than the computed ultimate economy. But when (utilizing some statistics from the Pittsburg, Ft. Wayne & Chicago Railroad) it is found that white oak ties laid in rock ballast had a life of 10.17 years, and that hemlock ties treated with the zinc-tannin process and laid in the same kind of ballast lasted 10.71 years, then the economy is far more apparent. Unfortunately no figures were given for the cost of these ties nor for the cost of the treatment; but if we assume that the white oak ties cost 75 c. and the hemlock ties 35 c. plus 20 c. for treatment, there is not only a saving of 20 c. on each tie, but also the advantage of the slightly longer life of the treated tie. In the above case the total life of the two kinds of ties is so nearly the same that we may make an approximation of their relative worth by merely comparing the initial cost; but usually it is necessary to compare the value of two ties one of which may cost more than the other, but will last considerably longer. The mathematical comparison of the real value of two ties under such conditions may be developed as follows: The real cost of a tie, or any other similar item of constructive work, is measured by the cost of perpetually maintaining that item in proper condition in the structure. It will be here assumed that the annual cost of the trackwork, which is assignable to the tie, is the same for all kinds of ties, although the difference probably lies in favor of the more expensive and most durable ties. By assuming this expense as constant, the remaining expense may be considered as that due to the cost of the new ties whenever necessary, plus the cost of placing them in the track. We also may combine these two items in one, and consider that the cost of placing a tie in the track, which we will assume at the constant value of 20 c. per tie, regardless of the kind of tie, is merely an item of 20 c. in the total cost of the tie. We will assume that T_1 is the present cost of a tie, the cost including the preservative treatment if any, and the cost of placing in the track. The tie is assumed to last n years. At the end of n years another tie is placed in the track, and, for lack of more precise knowledge, we will assume that this cost T_2 equals T_1. The "present worth" of T_2 is the sum which, placed at compound interest, would equal T_2 at the end of n years, and is expressed by the quantity $\frac{T_2}{(1+r)^n}$, in which r equals the rate of interest. Similarly at the end of $2n$ years we must expend a sum T_3 to put in the third tie, and the present worth of the cost of that third tie is expressed by the fraction $\frac{T_3}{(1+r)^{2n}}$. We may similarly express the present worths of the cost of ties for that particular spot for an indefinite period. The sum of all these present worths is given by the sum of a converging series and equals (assuming that all the T's are equal) $\frac{T \times (1+r)^n}{(1+r)^n - 1}$. But instead of laying aside a sum of money which will maintain a tie in that particular place in perpetuity, we may compute the annual sum which must be paid at the end of each year, which would be the equivalent. We will call that annual payment A, and then the present worths of all these items are as follows:

For the first payment .... $\frac{A}{(1+r)}$,

For the second payment................ $\frac{A}{(1+r)^2}$;

For the third payment .... $\frac{A}{(1+r)^3}$,

For the nth payment .... $\frac{A}{(1+r)^n}$.

After the next tie is put in place we have the present worths of the annual payments on the second tie, of which the first one would be

For the $(n+1)$ payment .... $\frac{A}{(1+r)^{(n+1)}}$.

Similarly after x ties have been put in place the last payment for the x tie would have a present worth $\frac{A}{(1+r)^{nx}}$. The sum of all these present worths is represented by the sum of a converging series and equals the very simple expression $\frac{A}{r}$. But since the sum of the present worths of these annual payments must equal the sum of the present worths of the payments made at intervals of n years, we may place these two summations equal to each other, and say that

$$A=\frac{r\times T\times(1+r)^n}{(1+r)^n-1}.$$

Values of A for various costs of a tie T on the basis that r equals 5% have been computed and placed in Table XVIII. To illustrate the use of this table, assume that we are comparing the relative values of two ties, both untreated, one of them a white oak tie which will cost, say 75 c., and will last twelve years, the other a yellow pine tie which will cost, say 35 c., and will last six years. Assuming a charge for each case of 20 c. for placing the tie in the track, we have as the annual charge against the white oak tie, which costs 95 c. in the track, 10.72 c. The pine tie, costing 55 c. in the track and lasting six years, will be charged with an annual cost of 10.48 c., which shows that the costs are practically equal. It is probably true that the track work for maintaining the white oak would be less than that for the pine tie, but since the initial cost of the pine tie is less than that of the oak tie, it would probably be preferred in this case, especially if money was difficult to obtain. It may be interesting to note that if a comparison is made from a similar table which is computed on the basis of compounding the money at 4% instead of 5%, the annual charges would be 10.13 and 10.49 c. for the oak and pine ties respectively, thus showing that when money is "easier" the higher priced tie has the greater advantage.

Example 2. Considering again the comparison previously made of a white oak untreated tie which was assumed to cost 75 c., and a hemlock treated tie, which cost 35 c. for the tie and 20 c. for the treatment, the total costs of these ties laid in the track would therefore be 95 c. and 75 c. respectively. These ties had practically the same life (10.17 and 10.71 years), but in order to use the table, we will call it ten years for each tie. The annual charge against the oak tie would therefore be 12.30 c., while that against the hemlock tie would be 9.72 c. This gives an advantage in the use of the treated tie of 2.58 c. per year, which capitalized at 5% would have a capitalized value of 51.6 c.

The Atchison, Topeka and Santa Fé R. R. has compiled a record of treated pine ties removed in 1897, '98, '99, and 1900, showing that the *average* life of the ties removed had been about 11 years. On the Chicago, Rock Island and Pacific R. R., the average life of a very large number of treated hemlock and tamarack ties was found to be 10.57 years. Of one lot of 21,850 ties, 12% still remained in the track after 15 years' exposure.

It has been demonstrated that much depends on the minor details of the process—whatever it may be. As an illustration, an examination of a batch of ties, treated by the zinc-creosote process, showed 84% in service after 13 years' exposure; another batch, treated by another contractor by the same process (nominally), showed 50% worthless after a service of six years.

METAL TIES.

258. Extent of use. In 1894 * there were nearly 35000 miles of "metal track" in various parts of the world. Of this total, there were 3645 miles of "longitudinals" (see § 264), found exclusively in Europe, nearly all of it being in Germany. There were over 12000 miles of "bowls and plates" (see § 263), found almost entirely in British India and in the Argentine Republic. The remainder, over 18000 miles, was laid with metal cross-ties of various designs. There were over 8000 miles of metal cross-ties in Germany alone, about 1500 miles in the rest of Europe, over 6000 miles in British India, nearly 1000 miles in the rest of Asia, and about 1500 miles more in various other parts of the world. Several railroads in this country have tried various designs of these ties, but their use has never passed the experimental stage. These 35000 miles represent about 9% of the total railroad mileage of the world—nearly 400000 miles. They represent about 17.6% of the total railroad mileage, exclusive of the United States and Canada, where they are used but little, except experimentally. In the four years from 1890 to 1894 the use of metal track increased from less than 25000 miles to nearly

* Bulletin No. 9, U. S. Dept. of Agriculture, Div. of Forestry.

35000 miles. This increase was practically equal to the total increase in railroad mileage during that time, exclusive of the increase in the United States and Canada. This indicates a large growth in the percentage of metal track to total mileage, and therefore an increased appreciation of the advantages to be derived from their use.

The above figures were true in 1894. Since then there has been considerable development. In 1915, over one million of the "Carnegie" steel ties, M21 section, had been laid on the Bessemer and Lake Erie R. R. It is now the standard on that road. On several other roads these ties are used extensively and "are not in the nature of test installations." The National Railways of Mexico have adopted as standard a pressed steel tie. The scarcity of tie timber in Mexico, the comparatively light weight of rolling stock and comparatively low speed, combine to favor this form of tie, which is very similar to a tie tried as an experiment by the N. Y. C. & H. R. R. R. in 1892, but which was found unsuitable for their requirements.

259. Forms and dimensions of some metal ties. As shown on Plate VI, the tics have approximately the same external dimensions as wooden ties. Stability in the ballast requires that they shall be heavy, at least as heavy as a wooden tie, and that the shape shall be such that, when surrounded by ballast, they shall be anchored against horizontal or vertical motion. The broad lower flange of the Carnegie tie apparently fulfils the latter requirement. The "Champion" tie, shown on Plate VI, is essentially an inverted T, of $\frac{5}{16}''$ metal, with a base 10″ wide, and a flange 5″ high. Two pairs of white oak blocks, easily renewable, and into which cut spikes or screw spikes may be driven, are higher than the flange and there is therefore no trouble about the insulation of track circuits. The "System Couillet," used in Europe, has some of the same principles, but is much lighter and only serviceable for lighter rolling stock.

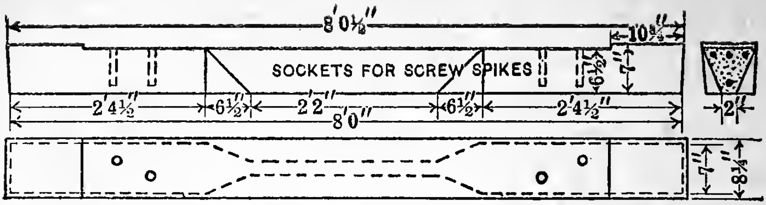
260. Durability. Many metal ties have failed because of breakage, which generally begins at some opening, perhaps a bolt hole, or a place where the metal has been sheared on three sides and bent down on the fourth side to form a lug; the break invariably begins at some *corner*, if the opening has sharp corners. Some metal ties have crushed down immediately under the rail, showing that the design was too light and that there was too little metal there for the traffic it had to carry.

Metal ties are subject to rust, especially when in damp localities, such as tunnels; but on the other hand it is in such confined localities, where renewals are troublesome, that it is especially desirable to employ the best and longest-lived ties. Paint, tar, etc., have been tried as a protection against rust, but such protection is quickly scraped off and the conditions prevent any renewal of the protection, such as may be done by repainting a bridge, for example. Thirty Carnegie ties, which weighed originally 5213 pounds, were taken from the track after six years' service; after the dirt and rust had been removed, they were found to weigh 4912 pounds, a loss of 301 pounds, or an average loss of less than 1% per year. A metal tie could perhaps lose 35% of its weight by rusting before this cause alone would require its removal.

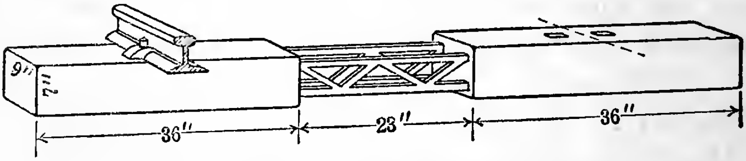
Virtual failures, necessitating removal, are frequently due to defects in the device for fastening the rails to the ties. Some of the designs include a lug, fitting over the base of the rail and held in place by a bolt and nut. These are often jarred loose, unless the nuts are held by nutlocks.

Many ties, both steel and concrete, which have abundant strength to support the mere weight of the traffic, are immediately broken when a derailment causes car wheels or engine drivers to strike them directly. They do not have the toughness and resiliency of wooden ties to withstand such shocks.

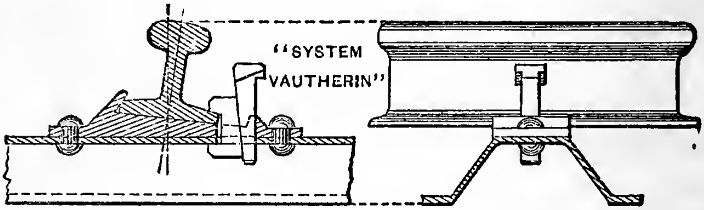
The Carnegie tie is the only steel tie which has been used in sufficient quantities and for such a length of time that any rational estimate of its life may be made—except those experimental types of ties whose life has been so short that they are evidently failures. 22400 Carnegie ties were laid on the Duluth, Missabe & Northern Rwy. in 1908. In 1916 one tie was removed under special circumstances. In 1919, 30 had failed by crushing under the rail seat. By 1920, a total of about 100 had failed. This is a little over 0.4% after a period of twelve years. This ratio is too small to apply to the curve shown in Fig. 112*a*, § 242, but it indicates a very long average life. Another far less favorable case is that of 384 ties placed in the Erie R. R. in 1909. Ten were removed in 1916, eighteen more in 1918, and fourteen more in June, 1919. A later report states that the last of them were removed by August, 1919, after an average of over nine years' service. "The majority of them were crushed under the rail seat," which indicates that they were too light for the

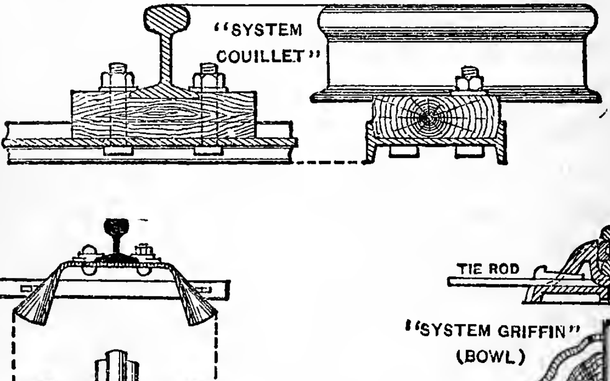


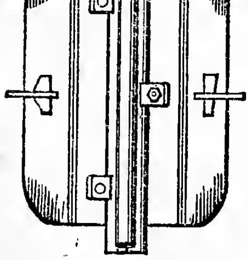
PERCIVAL REINFORCED CONCRETE TIE (1910)



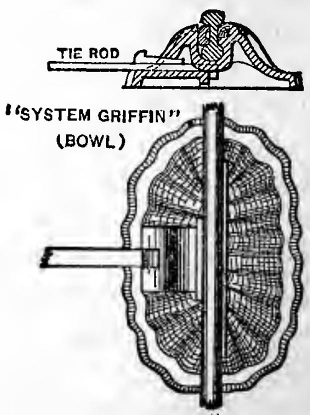
BATES REINFORCED CONCRETE TIE (1912)

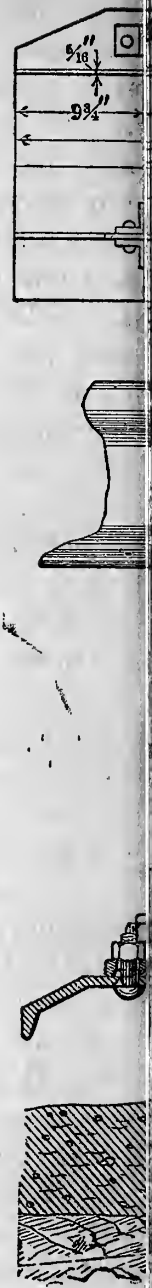


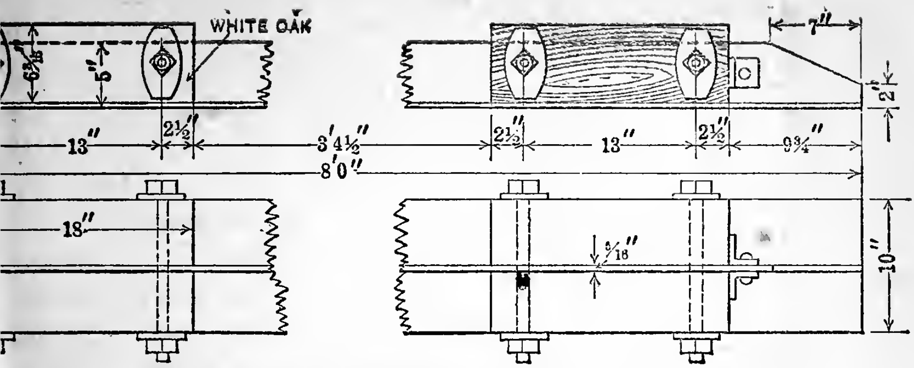




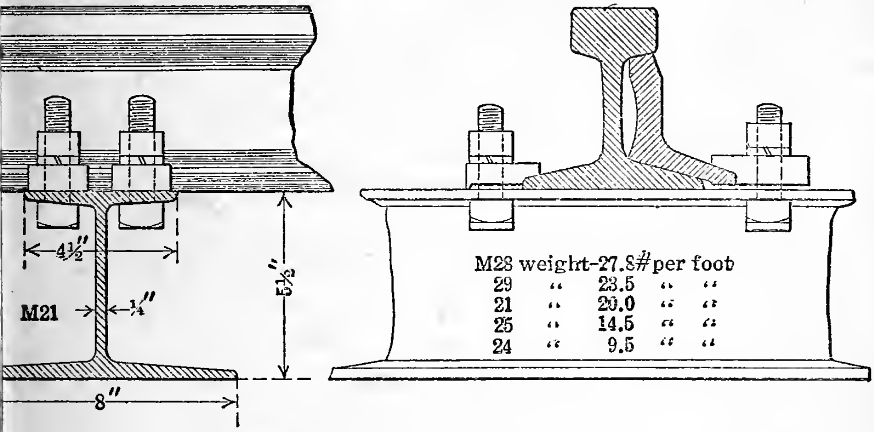
LIVESEY BOWL. (1864)



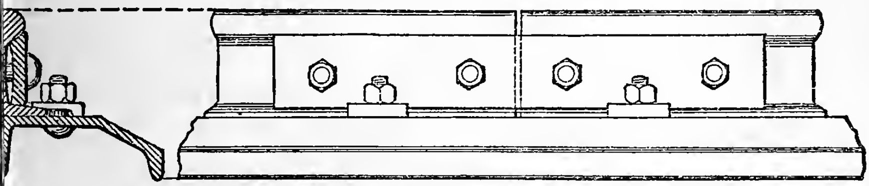




CHAMPION STEEL (1920)



CARNEGIE STEEL TIE (1916)



"SYSTEM KÖSTLIN U. BATTIG"—LONGITUDINAL.

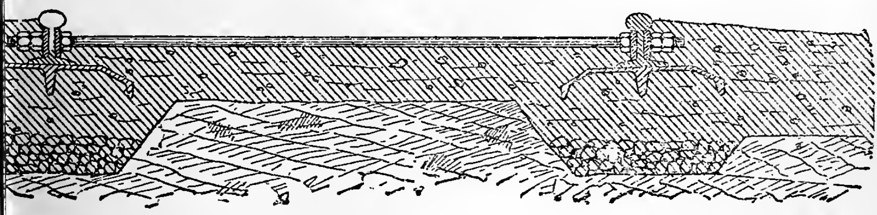


PLATE VI.—SOME FORMS OF METAL TIES.

(Between pp. 292 and 293.)

work they had to do. Several other roads have made similar reports—a few experimental ties have crushed under the head after a few years' service, evidently because the type chosen (there are five weights) was too light for the weight of the rolling stock.

261. Economics of steel ties. Perhaps the most potent reason for the slow adoption of a substitute for the wooden tie is the plain matter of cost. In spite of the fact that the available supplies of tie timber are being used up at a rate which is several times the rate of renewal of such supplies by growth, the relative cost of steel and wooden ties is such that the steel tie must show a great superiority in order to justify its extra cost. Present prices (1921) are abonormal but are perhaps relatively nearly the same. Assume that a white oak tie costs $1.40 and that it costs $1.12 more for spikes and tie plates, and 30 c. more to place it in the track; assume that this tie will last 8 years under a certain class of traffic. Then, by Table XVIII, the annual charge for an initial cost of $2.82 is $2.82 \times 15.47 = 43.63$ c. The present quoted price for a Carnegie M21 tie, *including fastenings*, is $5.00; adding 30 c. for placing in track, we have a total of $5.30. $43.63 \div 5.30 = 8.23$, the *annual* charge in *cents* for each *dollar* of initial expenditure. By interpolation in Table XVIII between 8.27 for 19 years and 8.02 for 20 years, it is seen that the metal tie must have an *average* life of 19 yrs. 2 mo. to equal the economy of the oak tie. The above comparison assumes the substantial equality of cost of track labor and the maintenance of the track fastenings with the two kinds of ties.

---

263. Bowls or plates. As mentioned before, over 12000 miles of railway, chiefly in British India and in the Argentine Republic, are laid with this form of track. It consists essentially of large cast-iron inverted "bowls" laid at intervals under each rail and opposite each other, the opposite bowls being tied together with tie-rods. A suitable chair is riveted or bolted on to the top of each bowl so as to properly hold the rail. Being made of cast iron, they are not so subject to corrosion as steel or wrought iron. They have the advantage that when old and worn out their scrap value is from 60% to 80% of their initial cost, while the scrap value of a steel or wrought-iron tie is practically nothing. Failure generally occurs from breakage, the failures from this cause in India being about 0.4% per annum. They weigh about 250 lbs. apiece and are therefore quite expensive in first cost and transportation charges. There are miles of them in India which have already lasted 25 years and are still in a serviceable condition. Some illustrations of this form of tie are shown in Plate VI.

264. Longitudinals. Although the discussion of longitudinals might be considered to belong more properly to the subject of Rails, yet the essential idea of all designs must necessarily be the *support* of a rail-head on which the rolling stock may run, and therefore this form, unused in this country, will be briefly described here. This form, the use of which is confined almost exclusively to Germany, is being gradually replaced on many lines by metal cross-ties. The system generally consists of a compound rail of several parts, the upper bearing rail being very light and supported throughout its length by other rails, which are suitably tied together with tie-rods so as to maintain the proper gauge, and which have a sufficiently broad base to be properly supported in the ballast. One great objection to this method of construction is the difficulty of obtaining proper drainage especially on grades, the drainage having a tendency to follow along the lines of the rails. The construction is much more complicated on sharp curves and at frogs and switches. Another fundamentally different form of longitudinal is the Haarman compound "self-bearing rail," having a base 12″ wide and a height of 8″, the alternate sections breaking joints so as to form a practically continuous rail.

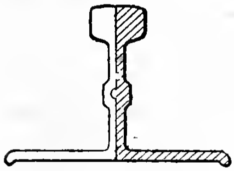


FIG. 114.

Some of the other forms of longitudinals are illustrated in Plate VI.

For a very complete discussion of the subject of metal ties, see the "Report on the Substitution of Metal for Wood in Railroad Ties" by E. E. Russell Tratman, it being Bulletin No. 4, Forestry Division of the U. S. Dept. of Agriculture.

265. Reinforced concrete ties. The wide application of reinforced concrete to various structural purposes, combined with its freedom from decay, has led to its attempted adoption for ties. For several years a standing committee of the Amer. Rwy. Eng. Assoc. has systematically followed the experimental tests on several railroads of numerous substitutes for wooden ties. Many of these ties are made of metal and have been previously referred to. Others are made of concrete, reinforced with steel. The concrete is not subject to decay but it is so brittle that, when struck by a derailed car or locomotive, it will almost inevitably crack, and after that, its disintegration is a matter of a very short time. The Percival tie, shown on Plate VI, has been tested for several years on some roads having comparatively light traffic. The reports from these roads are encouraging, if not conclusive. The "Bates" tie consists of two concrete blocks, one under each rail, which are connected by a pair of trussed structures of steel. In the center space of of about two feet between the two blocks, the steel is exposed to rust. A report on these ties said that, after seven years service, the exposed trusses were "rusted to a maximum depth of possibly $\frac{1}{16}''$ but not to such an extent as to seriously weaken the trusses." It is a common belief that it is essentially impossible to design a concrete tie, even when reinforced with steel, which will have sufficient resiliency to withstand the shocks of rail traffic. Innumerable concrete ties have ignominiously failed after a very short service.

CHAPTER IX.

RAILS.

266. Early forms. The first rails ever laid were wooden stringers which were used on very short tram-roads around coal-mines. As the necessity for a more durable rail increased, owing chiefly to the invention of the locomotive as a motive power, there were invented successively the cast-iron "fish-belly" rail and various forms of wrought-iron strap rails which finally developed into the T rail used in this country and the double-headed rail, supported by chairs, used so extensively in England. The cast-iron rails were cast in lengths of about 3 feet and were supported in iron chairs which were sometimes set upon stone piers. A great deal of the first railroad track of this country was laid with longitudinal stringers of wood placed upon cross-ties, the inner edge of the stringers being protected by wrought-iron straps. The "bridge" rails were first rolled in this country in 1844. The "pear" section was an approach to the present form, but was very defective on account of the difficulty of designing a good form of joint. The "Stevens" section was designed in 1830 by Col. Robert L. Stevens, Chief Engineer of the Camden and Amboy Railroad; although quite defective in its proportions, according to the present knowledge of the requirements, it is essentially the present form. In 1836, Charles Vignoles invented essentially the same form in England; this form is therefore known throughout England and Europe as the Vignoles rail.

267. Present standard forms. The larger part of modern railroad track is laid with rails which are either "T" rails or the double-headed or "bull-headed" rails which are carried in chairs. The double-headed rail was designed with a symmetrical form with the idea that after one head had been worn out by traffic the rail could be reversed, and that its life would be practically doubled. Experience has shown that the wear of the rail in the chairs is very great; so much so that when one head has been worn out by traffic the whole rail is generally useless.

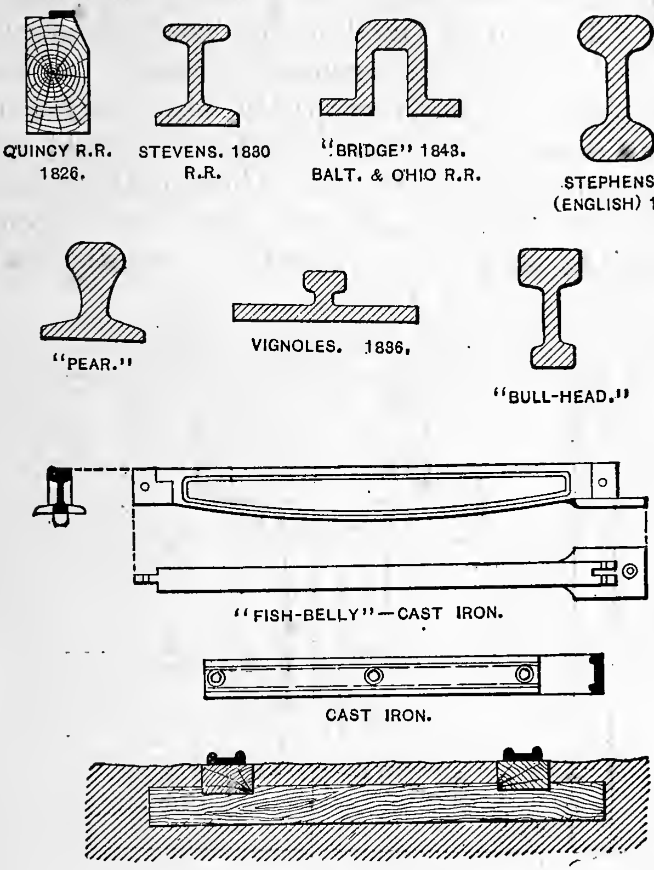


FIG. 115.—EARLY FORMS OF RAILS.

If the rail is turned over, the worn places, caused by the chairs, make a rough track and the rail appears to be more brittle and subject to fracture, possibly due to the crystallization that may have occurred during the previous usage and to the reversal of stresses in the fibers. Whatever the explanation, experience has demonstrated the *fact*. The "bull-headed" rail has the lower head only large enough to properly hold the wooden keys with which the rail is secured to the chairs (see Fig. 116) and furnish the necessary strength. The use of these rails requires the use of two cast-iron chairs for each tie. It is claimed that such track is better for heavy and fast traffic, but it is more

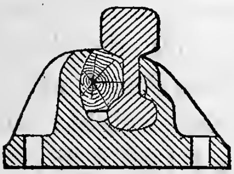


FIG. 116. — BULL-HEADED RAIL AND CHAIR.

expensive to build and maintain. It is the standard form of track in England and some parts of Europe.

Until after 1893 there was a very great multiplicity in the designs of "T" rails as used in this country, nearly every prominent railroad having its own special design, which perhaps differed from that of some other road by only a very minute and insignificant detail, but which nevertheless would require a complete new set of rolls for rolling. This had a very appreciable effect on the cost of rails. In 1893, the American Society of Civil Engineers, after a very exhaustive investigation of the

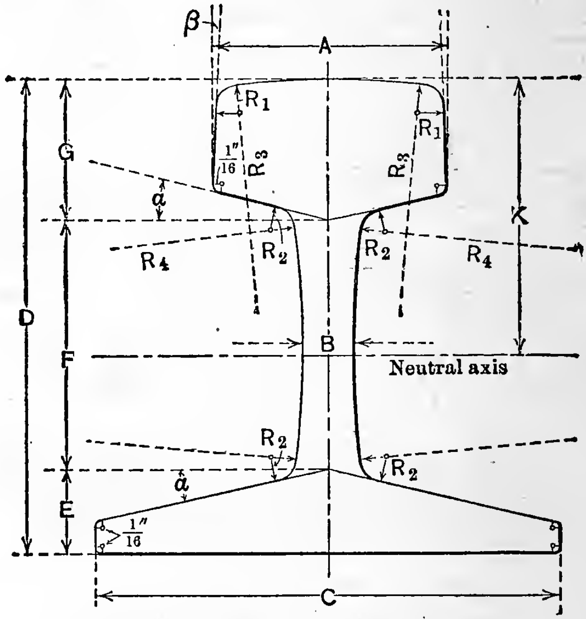


FIG. 117.—STANDARD RAIL SECTIONS.

subject, extending over several years, having obtained the opinions of the best experts of the country, adopted a series of sections which have been very extensively adopted by the railroads of this country.

In 1909 the American Railway Association and the American Railway Engineering Association, by combined action, developed a series of sections. Fig. 117 shows diagrammatically all of these sections and their variations with different weights and systems are shown by the tabular values for the lettered dimensions. It may be noted that the radii of the upper and lower corners of the flanges and of the lower corners of the head are constant ($\frac{1}{16}''$) for all weights of rail and for all systems.

TABLE XXIII.—ANGLES AND DIMENSIONS OF STANDARD DESIGNS FOR RAILS.

System.	Branding symbol.	Radii, inches. Upper corner of head. R_1	Radii, inches. Fillet corners. R_2	Radii, inches. Top of head. R_3	Radii, inches. Side of web. R_4	Angles. Bottom of head and top of flange. α	Angles. Side of head. β	Weight of rail, lbs. per yard.	Dimensions, inches. A	B	C	D	E	F	G	K
American Society of Civil Engineers	A.S.C.E.	$\frac{5}{16}$	$\frac{1}{4}$	12	12	13°	Vert.	60	$2\frac{3}{8}$	$\frac{31}{64}$	$4\frac{1}{4}$	$4\frac{1}{4}$	$\frac{49}{64}$	$2\frac{17}{64}$	$1\frac{7}{32}$	2.20
								70	$2\frac{7}{16}$	$\frac{33}{64}$	$4\frac{5}{8}$	$4\frac{5}{8}$	$\frac{13}{16}$	$2\frac{15}{32}$	$1\frac{11}{32}$	2.40
								80	$2\frac{1}{2}$	$\frac{35}{64}$	5	5	$\frac{7}{8}$	$2\frac{5}{8}$	$1\frac{1}{2}$	2.62
								90	$2\frac{5}{8}$	$\frac{9}{16}$	$5\frac{3}{8}$	$5\frac{3}{8}$	$\frac{59}{64}$	$2\frac{55}{64}$	$1\frac{19}{32}$	2.82
								100	$2\frac{3}{4}$	$\frac{9}{16}$	$5\frac{3}{4}$	$5\frac{3}{4}$	$\frac{31}{32}$	$3\frac{5}{64}$	$1\frac{45}{64}$	3.02
American Railway Association	R.A.-A.	$\frac{3}{8}$	$\frac{3}{8}$	14	14	4:1 14° 02′	1:16 3° 35′	60	$2\frac{1}{4}$	$\frac{15}{32}$	4	$4\frac{1}{2}$	$\frac{13}{16}$	$2\frac{29}{64}$	$1\frac{16}{64}$	2.37
								70	$2\frac{3}{8}$	$\frac{1}{2}$	$4\frac{1}{4}$	$4\frac{3}{4}$	$\frac{29}{32}$	$2\frac{1}{2}$	$1\frac{11}{32}$	2.55
								80	$2\frac{1}{2}$	$\frac{33}{64}$	$4\frac{5}{8}$	$5\frac{1}{8}$	$\frac{31}{32}$	$2\frac{23}{32}$	$1\frac{7}{16}$	2.81
and								90	$2\frac{9}{16}$	$\frac{9}{16}$	$5\frac{1}{8}$	$5\frac{5}{8}$	1	$3\frac{6}{32}$	$1\frac{15}{32}$	3.09
								100	$2\frac{3}{4}$	$\frac{9}{16}$	$5\frac{1}{2}$	6	$1\frac{1}{16}$	$3\frac{3}{8}$	$1\frac{9}{16}$	3.25
American Railway Engineering Association	R. A.-B.	$\frac{3}{8}$	$\frac{5}{16}$	12	12	13°	3°	60	$2\frac{1}{8}$	$\frac{31}{64}$	$3\frac{11}{16}$	$4\frac{3}{16}$	$\frac{7}{8}$	$2\frac{1}{16}$	$1\frac{1}{4}$	$2\frac{15}{64}$
								70	$2\frac{3}{8}$	$\frac{33}{64}$	$4\frac{3}{64}$	$4\frac{35}{64}$	$\frac{59}{64}$	$2\frac{17}{64}$	$1\frac{23}{64}$	$2\frac{25}{64}$
								80	$2\frac{7}{16}$	$\frac{35}{64}$	$4\frac{7}{16}$	$4\frac{15}{16}$	1	$2\frac{15}{32}$	$1\frac{15}{32}$	$2\frac{85}{128}$
								90	$2\frac{9}{16}$	$\frac{9}{16}$	$4\frac{49}{64}$	$5\frac{17}{64}$	$1\frac{1}{32}$	$2\frac{5}{8}$	$1\frac{39}{64}$	$2\frac{105}{128}$
								100	$2\frac{21}{32}$	$\frac{9}{16}$	$5\frac{9}{64}$	$5\frac{41}{64}$	$1\frac{5}{64}$	$2\frac{55}{64}$	$1\frac{45}{64}$	$3\frac{1}{64}$
Amer. Rwy. Eng. Assoc. (adopted in 1915)	R.E.	$\frac{3}{8}$	* $\frac{3}{8}$ † $\frac{5}{8}$	14	14	4:1 14° 02′	1:16	100	$2\frac{11}{16}$	$\frac{9}{16}$	$5\frac{3}{8}$	6	$1\frac{1}{16}$	$3\frac{9}{32}$	$1\frac{21}{32}$	$3\frac{1}{4}$
								110	$2\frac{25}{32}$	$\frac{19}{32}$	$5\frac{1}{2}$	$6\frac{1}{4}$	$1\frac{1}{8}$	$3\frac{13}{32}$	$1\frac{23}{32}$	$3\frac{27}{64}$
								120	$2\frac{7}{8}$	$\frac{5}{8}$	$5\frac{3}{4}$	$6\frac{1}{2}$	$1\frac{3}{16}$	$3\frac{17}{32}$	$1\frac{25}{32}$	$3\frac{37}{64}$
Amer. Rwy. Eng. Assoc. (adopted in 1920)	R.E.	$\frac{3}{8}$	$\frac{1}{2}$ $\frac{3}{4}$	14	14	4:1 14° 02′	1:16	130	$2\frac{15}{16}$	$\frac{21}{32}$	6	$6\frac{3}{4}$	$1\frac{7}{32}$	$3\frac{11}{16}$	$1\frac{27}{32}$	$3\frac{23}{32}$
								140	3	$\frac{11}{16}$	$6\frac{1}{4}$	7	$1\frac{1}{4}$	$3\frac{27}{32}$	$1\frac{29}{32}$	$3\frac{55}{64}$

* Fillet radius under head. † Fillet radius above base.

The chief features of disagreement among railroad men relate to the radius of the upper corner of the head and the slope of the side of the head. The radius ($\frac{5}{16}''$) adopted by the A. S. C. E. for the upper corner (constant for all weights) is a little more than is advocated by those in favor of "sharp corners" who prefer a radius of $\frac{1}{4}''$. On the other hand it is much less than is advocated by those who consider that it should be nearly equal to (or even greater than) the larger radius universally adopted for the corner of the wheel-flange. The discussion turns on the relative rapidity of rail wear and the wear of the wheel-flanges as affected by the relation of the form of the wheel-tread to that of the rail. It is argued that sharp rail corners wear the wheel-flanges so as to produce sharp flanges, which are liable to cause derailment at switches and also to require that the tires of engine-drivers must be more frequently turned down to their true form. On the other hand it is generally believed that rail wear is much less rapid when the area of contact between the rail and wheel-flange is small, and that when the rail has worn down, as it invariably does, to nearly the same form as the wheel-flange, the rail wears away very quickly. The A. R. E. A. system uses $\frac{3}{8}''$ radius for all rail weights. The "B" sections were proposed to satisfy those that desired that the head should be narrower and deeper than as found in the "A" sections. The A. R. E. A. Manual (1915), suggests that if a section is found to be inadequate because of lack of depth of head, the next heavier section will be found more desirable and economical.

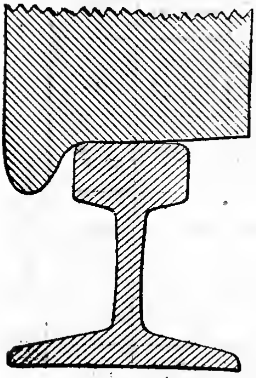


FIG. 118.—RELATION OF RAIL TO WHEEL-TREAD.

268. Weight for various kinds of traffic. The heaviest rails in use weigh 120 to 140 lbs. per yard, and even these are only used on some of the heaviest traffic sections of such roads as the N. Y. Central, the Pennsylvania, the N. Y., N. H. & H., and a few others. Probably the larger part of the mileage of the country is laid with 80- to 90-lb. rails—considering the fact that "the larger part of the mileage" consists of comparatively light-traffic roads and may exclude all the heavy trunk lines. Very light-traffic roads are sometimes laid with 70-lb. rails. Roads with fairly heavy traffic generally use 90- to 100-lb. rails, especially when grades are heavy and there is much and sharp curvature. The tendency on all roads is toward an increase in the weight, rendered necessary on account of the increase in the weight and capacity of rolling stock, and due also to the fact that accumulated operating experience has shown that it is both better and cheaper to obtain a more solid and durable track by increasing the weight of the rail rather than by attempting to support a weak rail by an excessive number of ties or by excessive track labor in tamping. It should be remembered that in buying rails the mere weight is, in one sense, of no importance. The important thing to consider is the STRENGTH and the STIFFNESS. If we assume that all weights of rails have *similar* cross-sections (which is nearly although not exactly true), then, since for beams of similar cross-sections the *strength* varies as the *cube* of the homologous dimensions and the *stiffness* as the *fourth power*, while the area (and therefore the weight per unit of length) only varies as the *square*, it follows that the stiffness varies as the square of the weight, and the strength as the $\frac{3}{2}$ power of the weight. Since for ordinary variations of weight the price per ton is the same, adding (say) 10% to the weight (and cost) adds 21% to the stiffness and over 15% to the strength. As another illustration, using an 80-lb. rail instead of a 75-lb. rail adds only $6\frac{2}{3}$% to the cost, but adds about 14% to the stiffness and nearly 11% to the strength. This shows why heavier rails are more economical and are being adopted even when they are not absolutely needed on account of heavier rolling stock. The stiffness, strength, and consequent durability are increased in a much greater ratio than the cost.

The relation between weight of rail and the weight on the drivers of the locomotives which are to run on it has been briefly expressed by the Baldwin Locomotive Works as "300 pounds of wheel per pound of rail per yard." * This rule may be utilized by making a diagram as shown in Fig. 119. For example, if it is desired to use a type of locomotive with 170,000 lbs. on the drivers and also 75-lb. rails, four pairs of drivers will be needed and such a type of locomotive should be used. By using 95-lb. rails the same weight on the drivers could be placed on three axles. As another example, a Pacific-type locomotive, with 150,000 lbs. on its six drivers, should have a rail with a minimum weight of 83 lbs., or say an 85-lb. rail. Whatever elements are given, the corresponding proper value for the other element may be derived.

---

* See § 447 (*c*) for expansion of this rule.

269. Effect of stiffness on traction. A very important but generally unconsidered feature of a stiff rail is its effect on tractive force. An extreme illustration of this principle is seen when a vehicle is drawn over a soft sandy road. The constant compression of the sand in front of the wheel has virtually the same effect on traction as drawing the wheel up a grade whose

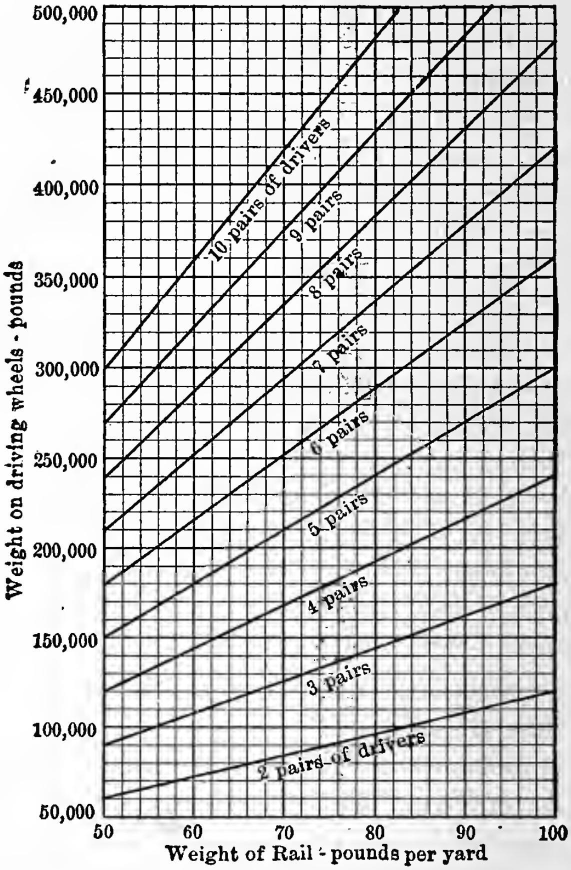


Fig. 113.—Curves for Finding the Number of Drivers Needed for Given Weight on Driving Wheels and Weight of Rails.

steepness depends on the radius of the wheel and the depth of the rut. On the other hand, if a wheel, made of perfectly elastic material, is rolled over a surface which, while supported with absolute rigidity, is also perfectly elastic, there would be a forward component, caused by the expanding of the compressed metal just behind the center of contact, which would just balance the backward component. If the rail was supported throughout its length by an absolutely rigid support, the high elasticity of the wheel-tires and rails would reduce this form of resistance to an insignificant quantity, but the ballast and even the ties are comparatively inelastic. When a weak rail yields, the ballast is more or less compressed or displaced, and even though the elasticity of the rail brings it back to nearly its former place, the work done in compressing an inelastic material is wholly lost. The effect of this on the fuel account is certainly very considerable and yet is frequently entirely overlooked. It is practically impossible to compute the saving in tractive power, and therefore in cost of fuel, resulting from a given increase in the weight and stiffness of the rail, since the yielding of the rail is so dependent on the spacing of the ties, the tamping, etc. But it is not difficult to perceive in a general way that such an economy is possible and that it should not be neglected in considering the value of stiffness in rails.

270. Length of rails. The recommended standard length of rails is 33 feet. Several years ago, many roads experimented with 45-foot and even 60-foot rails. The argument in favor of longer rails is chiefly that of the reduction in track-joints, which are costly to construct and to maintain and are a fruitful source of accidents. Mr. Morrison of the Lehigh Valley R. R.* declared that, as a result of extensive experience with 45-foot rails on that road, he found that they are much less expensive to handle, and that, being so long, they can be laid around sharp curves without being curved in a machine, as is necessary with the shorter rails. The great objection to longer rails lies in the difficulty in allowing for the expansion, which will require, in the coldest weather, an opening at the joint of nearly $\frac{3}{4}''$ for a 60-foot rail. The Pennsylvania R. R. and the Norfolk and Western R. R. each laid a considerable mileage with 60-foot rails. The net result is the fixed standard of 33 feet.

271. Expansion of rails. Steel expands at the rate of .0000065 of its length per degree Fahrenheit. The extreme range of temperature to which any rail will be subjected will be about 160°, or say from $-20°$ F. to $+140°$ F. With the above coefficient and a rail length of 60 feet the expansion would be 0.0624 foot, or about $\frac{3}{4}$ inch. But it is doubtful whether there would ever be such a range of motion even if there were such a range of temperature. Mr. A. Torrey, chief engineer of the Mich. Cent. R. R., experimented with a section over 500 feet long, which,

* Report, Roadmasters Association, 1895.

although not a single rail, was made "continuous" by rigid splicing, and he found that there was no appreciable additional contraction of the rail at any temperature below +20° F. The reason is not clear, but the *fact* is undeniable.

The heavy girder rails, used by the street railroads of the country, are bonded together with perfectly tight rigid joints which do not permit expansion. If the rails are laid at a temperature of 60° F. and the temperature sinks to 0°, the rails have a *tendency* to contract .00039 of their length. If this tendency is resisted by the friction of the pavement in which the rails are buried, it only results in a tension amounting to .00039 of the modulus of elasticity, or say 10920 pounds per square inch, assuming 28 000 000 as the modulus of elasticity. This stress is not dangerous and may be permitted. If the temperature rises to 120° F., a tendency to expansion and buckling will take place, which will be resisted as before by the pavement, and a compression of 10920 pounds per square inch will be induced, which will likewise be harmless. The range of temperature of rails which are buried in pavement is much less than when they are entirely above the ground and will probably never reach the above extremes. Rails supported on ties which are only held in place by ballast must be allowed to expand and contract almost freely, as the ballast cannot be depended on to resist the distortion induced by any considerable range of temperature, especially on curves.

272. Rules for allowing for temperature. Track regulations generally require that the track foremen shall use iron (*not* wooden) shims for placing between the ends of the rails while splicing them. The thickness of these shims should vary with the temperature. Some roads use such approximate rules as the following: "The proper thickness for coldest weather is $\frac{5}{16}$ of an inch; during spring and fall use $\frac{1}{8}$ of an inch, and in the very hottest weather $\frac{1}{16}$ of an inch should be allowed." This is on the basis of a 30-foot rail. When a more accurate adjustment than this is desired, it may be done by assuming some very high temperature (100° to 125° F.) as a maximum, when the joints should be *tight;* then compute in tabular form the spacing for each temperature, varying by 25°, allowing 0''.0643 (very nearly $\frac{1}{16}''$) for each 25° change. Such a tabular form would be about as follows (rail length 33 feet):

Temperature..	Over 100°	100°–75°	75°–50°	50°–25°	25°–0°	Below 0°
Rail opening..	Close	$\frac{1}{16}''$	$\frac{1}{8}''$	$\frac{3}{16}''$	$\frac{1}{4}''$	$\frac{5}{16}''$

One practical difficulty in the way of great refinement in this work is the determination of the real temperature of the rail when it is laid. A rail lying in the hot sun has a very much higher temperature than the air. The temperature of the rail cannot be obtained even by exposing a thermometer directly to the sun, although such a result might be the best that is easily obtainable. On a cloudy or rainy day the rail has practically the same temperature as the air; therefore on such days there need be no such trouble.

273. Standard specifications. Specifications are constantly varying. They are always a compromise between the wishes of railroad engineers and the interests of rail manufacturers. At present (1921) rail prices are high, the railroads are relatively in a low financial condition, and the specifications are much less rigid than those mutually accepted in 1910. Therefore, instead of quoting verbatim, in this edition, the specifications now current, the general features have been discussed, many of which will probably be modified in future specifications. When buying rails for any road, the latest issue of standard Am. Rwy. Eng. Assoc. specifications should be obtained for reference.

273a. Chemical composition. More than 98% of the composition of steel rails is iron, but the value of the rail, as a rail, is almost wholly dependent upon the large number of other chemical elements which are, or may be, present in very small amounts.

Carbon. Many years ago, when rails were comparatively light and the maximum wheel loads were correspondingly light, the carbon in rails ranged from 0.20% to 0.50%. But the great increase in wheel loads produces a concentrated pressure on the rails which causes the steel to " flow " if the steel is comparatively soft. An increase of a few hundredths of a percent of carbon makes the steel harder but an excess of carbon makes it too brittle. Since heavier wheel loads require heavier rails, more carbon is used in the heavier sections. Since it is safer to use more carbon in open-hearth rails than in Bessemer rails, a higher percentage is so used. The limits at present (1921) are as follows:

Chemical elements.	Bessemer process. Weight, pounds per yard.		Open-hearth process. Weight, pounds per yard.		
	70 to 84	85 and over	70 to 84	85 to 110	111 and over
Carbon.......	0.40 to 0.50	0.45 to 0.55	0.53 to 0.68	0.62 to 0.77	0.67 to 0.82
Phosphorus, not to exceed	0.10	0.10	0.04	0.04	0.04
Manganese...	0.80 to 1.10	0.80 to 1.10	0.60 to 0.90	0.60 to 0.90	0.60 to 0.90
Silicon, not less than.......	0.10	0.10	0.10	0.10	0.10

Sulphur. Former specifications required that sulphur should not exceed 0.075% in Bessemer rails and 0.06% in open-hearth rails. Manufacturers now demand an excess price if a definite limitation is made but say that it is to their own interests, for other reasons, to have the sulphur within safe limits. As a compromise, no definite limitation is now made. This concession, now allowed by the railroads, illustrates forcibly how the railroads are compelled by financial considerations to relax from the former rigidity of specifications.

When a railroad buys a large order of rails directly from a rail mill, the railroad usually sends an inspector, who is furnished by the manufacturer with chemical analyses of the steel, one for each day and night turn for Bessemer rails or one for each heat of open-hearth rails. Sometimes samples are furnished the inspector, if he is a chemist, and he is given facilities at the mill to make his own check analyses.

273b. Physical requirements. These are increasingly depended on to determine (*a*) ductility or toughness as opposed to brittleness and (*b*) soundness, or its homogeneity and freedom from seams, laminations, cavities, or interposed foreign matter. The ductility is tested by dropping a tup weighing 2000 pounds, which has a striking face with a radius of 5 inches, on a test rail about 5 to 6 feet long, which is supported on two pedestals, also having bearing surfaces with radii of 5 inches, the pedestals being adjustable to spans varying from 3 feet to 4 feet 6 inches. The pedestals are spaced 3 feet for rails weighing 110 pounds per yard or less, and are spaced 4 feet for rails weighing 111 to 140 pounds per yard. The pedestals are firmly secured to an anvil weighing 20,000 pounds which is supported on 20 very heavy springs. Gauge marks, one inch apart for three inches each side of the center, are marked in the center of the top of the rail. The rails are usually tested with the head in tension, or with the rail inverted. The tup falls from a height of 16 feet on 70- to 79-pound rails, 17 feet on 80- to 90-pound rails, 18 feet on 91- to 110-pound rails and 20 feet on 111- to 140-pound rails. Under such impacts the elongation on one inch of the six-inch scale, marked as above, shall be at least 8%. The permanent set, on a 3-foot chord, is noted for each blow. The test pieces, which do not break under ordinary blows, are nicked and broken so that the interior may be examined for "soundness," or for such flaws as fissures, laminations, cavities, etc. Fissures which are really indicative of structural defects in a rail are sometimes microscopic, even when a specimen is carefully cut from the rail and the surface polished. The defects may be deepened and accentuated by etching the surface with hot concentrated hydrochloric acid.

By agreement between a railroad and a rail manufacturer, the physical test may be made by a **quick-bend machine** instead of a falling weight. Such a machine is essentially a hydraulic press of not less than 350 tons capacity. The bearing supports of the tested rail are flat surfaces, with vertical faces 48 inches apart, of which the inner edges are rounded to a $\frac{1}{8}$-inch radius. The head of the ram has a bearing surface with a radius of five inches. The percentage of elongation before failure may be observed as before.

273c. **Classification.** Rails are classified as No. 1 and No. 2. No. 1 rails are those with no injurious defects or flaws. No. 2 rails are those which arrive at the straightening presses more crooked than is allowed for No. 1 rails but which, in the judgment of the inspector, may be accepted in spite of this or other minor defects which do not impair their soundness and strength. No. 2 rails must not exceed 5 per cent of the whole order. They must have their ends painted white and have two prick-punch marks on the side of the web near the heat number, near the end of the rail, so placed as not to be covered by the joint bars.

273d. **Branding.** The name of the manufacturer, the month and year of manufacture, and the weight and type of section of rail shall be rolled in raised letters and figures on one side of the web, where it will not be covered by joint bars. The markings shall be done so effectively that the marks may be read as long as the rails are in service. The type of section is indicated by

A. S. C. E., R. A.–A., R. A.–B., or R. E., to indicate one of the various types elaborated in Table XXIII. Open-hearth rails are branded or stamped O. H., in addition to the other marks.

273e. Dimensions and drilling. The standard length is 33 feet at a temperature of 60° F. Ten per cent of the entire order will be accepted in shorter lengths, varying by one foot from 32 to 25 feet. A variation of $\frac{1}{4}''$ from specified lengths is allowed, except that 15% of the order may vary $\frac{3}{8}''$ from specified lengths. Drill holes may vary $\frac{1}{32}''$ in size and location from the drawings furnished by the railroad company. The recommended position (vertically) in the web is "midway between the intersections of the vertical center line of the rail with the planes of the fishing surfaces of the head and base." The hole centers should be $5\frac{1}{2}''$ apart, the first hole center being $2\frac{11}{16}''$ from the end of the rail, which allows $\frac{1}{8}$-inch clearance when the rails are bolted together in normal position.

273f. Finishing. Rails must be smooth at the heads, straight in line and surface, and without twists, waves or kinks. The limiting allowable camber in a 33-foot rail is "4 inches for thick base sections and 5 inches for thin base sections." They shall be sawed square at the ends, a variation of not more than $\frac{1}{32}''$ being allowed. Burrs must be carefully removed. When a finished rail shows defects at either end or in any drilled hole, the entire rail shall be rejected.

274. Life of rails. There has been a great development since 1900 in the science of manufacturing rails. This is indicated by the decrease in rail "failures." If there is a defect in a rail it will usually break or "fail" before it is worn down. If the defect is serious it will break in a few weeks or months. Minor defects require much longer time to develop. The accompanying tabular form shows the number of rail failures per 100 track miles, after one to five years' service, reported by several railroads of the United States. To appreciate the figures, note that there are 32000 rails 33 feet long in 100 miles of track. The record for rails rolled in 1913 showed that after five years' service, a total of 246.5 per 100 miles, or an average of 0.77%, had failed. Note that the increase of failures per year, after the first year, is regular, as it should be. Note also that there has been a steady improvement in the figures for 3, 4 and 5 years' service, but that since 1914 or 1915 the failures have increased somewhat,

AVERAGE RAIL FAILURES PER 100 TRACK MILES

Year rolled.	Years of service.					
	0	1	2	3	4	5
1908	.....	.....	.....	.....	.....	398.1
1909	.....	.....	.....	.....	224.1	277.8
1910	.....	.....	.....	124.0	152.7	198.5
1911	.....	.....	77.0	104.4	133.3	176.3
1912	.....	28.9	32.1	49.3	78.9	107.1
1913	2.0	12.5	25.8	44.8	69.5	91.9
1914	1.2	8.2	19.8	32.9	50.9	74.0
1915	0.7	8.9	19.0	34.2	53.0	82.4
1916	1.6	11.8	29.2	47.7	70.6	
1917	5.3	21.6	38.9	66.0		
1918	1.6	8.9	27.6			
1919	2.0	14.8				
1920	3.9					

indicating perhaps that war conditions had lowered the quality of the rails. The reports also show that failures are more common using Bessemer than open-hearth rails, and, considering that Bessemer are used in general for lighter service, the ratio against Bessemer would probably be greater for the same service. Bessemer rails cost less than open hearth, and this fact is perhaps the only reason for their use. The percentage of Bessemer rails to the total in 1913 was about 9.1%; in 1918 the percentage was reduced to 2.7%. These figures are based on reports made to the A. R. E. A. Presumably complete statistics (unobtainable) would show a somewhat larger percentage of Bessemer rails, used on small roads which did not make reports, but the above figures show that open-hearth rails are considered to be superior in spite of the higher price.

275. Intensity of pressure on rails. A special committee of the A. R. E. A. made an investigation to determine the intensities of pressure produced by varying wheel loads on the head of a rail and also the amount of permanent deformation or "flow" of the metal. The testing mechanism made it possible to increase the "wheel load" up to 580,000 lbs., a figure about 30 times as great as the greatest working wheel load. The unit intensity of pressure increased with an increase of the wheel load from zero up to about 30,000 lbs. At that figure, which corresponds to an axle load of 60,000 lbs., or nearly the maximum of present practice, the unit intensity of pressure reached its maximum and remained substantially constant while the wheel load was increased from 30,000 to 580,000 lbs. In other words, the area of contact increased as fast as the pressure increased. This maximum *average* unit pressure varied considerably with the different rails tested, although it was nearly constant for any one rail. The unit values varied from 105,000 to 160,000 lbs. per square inch.

275a. Flow of metal. The permanent deformation of the metal was measured by noting the reduction in the horizontal and vertical diameters of very small tapering holes drilled into the head of the tested rail slightly below the bearing surface. The testing wheel was caused to roll over the tested rail several hundred thousand times. In one test the initial load was 15,000 lbs., increasing by steps up to 30,000 lbs. Up to a load of 20,000 lbs. no permanent deformation of the holes was observable. With a load of 25,000 lbs. a slight set was observable which grew more rapid when the load was increased to 30,000 lbs. But even then the deformation was not as great as it was in another test when the initial loading was 30,000 lbs. This indicates that the effect on a rail of continued rolling pressure of less than 20,000 lbs., or 40,000 lbs. per axle, is to harden the surface metal and make it better able to withstand wear. This seems to be corroborated by, and also explains, the remarkable wearing qualities of many old rails which were surfaced-hardened by comparatively light loads and which subsequently carried much heavier loads with less wear than new rails.

276. Rail wear on tangents. The weight carried by a single engine driver is often from 24,000 to 30,000 lbs. Each of the eight wheels of a 140,000-lb. capacity coal car, when loaded, carries nearly 25,000 lbs. Such loads will certainly cause a flow of metal, as shown by the laboratory test above described, but a four-weeks' *service* test on the *same* test rails (referred to above) showed a flow of metal as indicated in Fig. 120, the flow being considerably greater than that produced in the laboratory tests with the same weight and number of rollings. The average wheel load in the service test was much less than the maximum in the laboratory tests, but the greater effect was probably due to the great variety of wheel treads making different forms of contact between rail and tread, with occasional great concentration of pressure. But Fig. 120 shows the typical normal wear of a rail on a tangent, the wear being all on the top. The center of pressure is usually about one-half inch inside from the center of the rail and is inclined outward. The wear is approximately symmetrical with this axis. Fig. 120 also shows the *flow* of metal outside of the original contour, which all occurred on the gauge side. Very soft badly worn rails may show a fin on the outside.

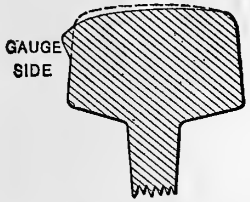


FIG. 120.—RAIL WEAR ON A TANGENT.

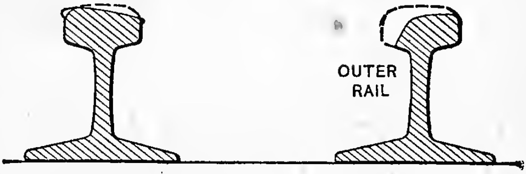


FIG. 121.—RAIL WEAR ON CURVES.

276a. Rail wear on curves. The pressure and grinding action of the wheel flanges against the rails wears away the inner side of the head of the outer rail on curves. If the rail is left in the track and the wear is permitted to continue, the head may be worn to approximately the form shown in Fig. 121. On the other hand, the inner rail is not subjected to any such lateral grinding action, and the rail is worn to substantially the same form as on a tangent, but the wear is more rapid due to the longitudinal slipping—see § 395. If the rails are soft or the traffic very heavy, there will be a flow of metal and a fin will form on the inner edge and perhaps also on the outer edge.

277. Experimental determination of rail wear. Several years ago a series of tests for rail wear were made on the Northern Pacific R. R. by taking up, weighing, and replacing, each year, the several groups of rails under test. Some of these rails were on tangents, the others on curves of various curvature. Some of the rails of each group were made of Bessemer steel, the others of open-hearth steel. No tests were made to determine the loss of weight through mere oxidation. All of the rails were in service for five years and some lasted for six years or more, but the loss in weight during the sixth year was nearly always equal to, and in some cases twice as much as, the loss during the preceding five years. Some of the rails lost over 10% of their weight, or about one-fourth the weight of the head, before being removed. Although the tests were too few to establish any positive laws, some tendencies which may be observed will give at least an approximate idea of the laws of rail wear.

1. The average loss of weight during the first five years on

20 rails on tangents was 0.412 lb. per yard per 10,000,000 tons of traffic.

2. Ten of these same rails were kept in place at least one year longer and during the sixth year lost almost twice as much metal as during the previous five years; in other words, about two-thirds of the entire loss occurred during the sixth year.

3. The average loss of weight during the first five years from 20 rails on a tangent was 0.463 lb. per yard per 10,000 trains. The relation between mere tonnage and number of trains could not be even indicated by so few tests. There is reason to believe that engine drivers are more responsible for rail wear than mere car-wheel tonnage. This practically means that one effect of grade is to increase rail wear, since more (or heavier) engines are needed to haul a given car tonnage.

4. The wear of the outer rail of curves is, of course, far greater than that of the inner rail, but the figures obtained did not seem to follow any rational law, the ratio of outer to inner rail wear varying from 144 to 244%, with an average of 182%.

5. The average rail wear on curves, averaging inner and outer rails, per yard, per degree of curve, per 10,000,000 tons traffic, varied from 0.145 lb. for a 4° 04′ curve down to 0.102 lb. per degree for a 10° 13′ curve. Based on the four curves tested, the results seemed to point to the law that rail wear on curves does *not* increase as fast as the degree of the curve.

6. Although the tests were too few to establish any law, the increase of the mean rail wear on curves with increase in degree of curve was very regular and indicated that the average rail wear on a curve of about 6° 40′ is about twice as great as that on a tangent.

7. The wear on open-hearth rails was almost invariably less than that on Bessemer rails, under identical conditions.

278. Cost of rails. In 1873 the cost of steel rails was about $120 per ton, and the cost of iron rails about $70 per ton. Although the steel rails were at once recognized as superior to iron rails on account of more uniform wear, they were an expensive luxury. The manufacture of steel rails by the Bessemer process created a revolution in prices, and they steadily dropped in price until, many years ago, steel rails were manufactured and sold for $22 per ton. For several years since then the price was very uniform at $28 per ton at the mill. But now (1921) the advantages of open-hearth steel are better appreciated and a large proportion of rails are being rolled from open-hearth steel, which commands about $2 per ton more. At present (1921) the current prices at Pittsburgh mills run at about $38 per ton for Bessemer and $40 for open-hearth.

There is no longer any demand for iron rails, since the cost of manufacturing them is substantially the same as that of steel rails, while their durability is unquestionably inferior to that of steel rails. Rail quotations are generally on the basis of "long tons" of 2240 lbs.

The freight charge for transporting rails from the mill to the place where used is usually so large that it adds a very appreciable amount to the cost per ton. As an approximation, the freight may be estimated as 0.6 cent per ton-mile, or $3.00 per ton for a haul of 500 miles.

CHAPTER X.

RAIL-FASTENINGS.

RAIL-JOINTS

279. Theoretical requirements for a perfect joint. A perfect rail-joint is one that has the *same strength* and *stiffness*—no more and no less—as the rails which it joins, and which will not interfere with the regular and uniform spacing of ties. It should also be reasonably cheap both in first cost and in cost of maintenance. Since the action of heavy loads on an elastic rail is to cause a wave of translation in front of each wheel, any change in the stiffness or elasticity of the rail structure will cause more or less of a shock, which must be taken up and resisted by the joint. The greater the change in stiffness the greater the shock, and the greater the destructive action of the shock. The perfect rail-joint must keep both rail-ends truly in line both laterally and vertically, so that the flange or tread of the wheel need not jump or change its direction of motion suddenly in passing from one rail to the other. A consideration of all the above requirements will show that only a perfect welding of rail-ends would produce a joint of uniform strength and stiffness which would give a uniform elastic wave ahead of each wheel. As welding is impracticable for ordinary railroad work (see § 271), some other contrivance is necessary which will approach this ideal as closely as may be.

280. Efficiency of any type of rail-joint. Throughout the middle portion of a rail the rail acts as a continuous girder. If we consider for simplicity that the ties are unyielding, the deflection of such a continuous girder between the ties will be but one-fourth of the deflection that would be found if the rail were cut half-way between the ties and an equal concentrated load were divided equally between the two unconnected ends. The maximum stress for the continuous girder would be but one-half of that in the cantilevers. Joining these ends with rail-joints will give the ordinary "suspended" joint. In order to maintain uniform strength and stiffness the rail-joint must supply the deficiency. These theoretical relations are modified to an unkown extent by the uncertain and variable yielding of the ties. Since a theoretically perfect joint is unattainable, on account of the necessity for allowing for expansion, the nearest approach appears to be a joint which, when tested in comparison with a solid rail on an equal span (20 inches), will withstand an equal load before permanent set takes place. Some very thorough tests of several types of joints were made on this basis by the Pennsylvania R. R. at Altoona in 1915. The types tested were plain angle-bars, the "Continuous," the "Bonzano," the "100-per-cent," (see Plate VII) and also the "Duquesne," which is similar to the Bonzano and the 100-per-cent, except that the fin which projects below the rail between the ties has a different form. The "efficiency" of these joints was computed as the ratio of the load carried by the joint when it began to fail (or when permanent set commenced) to the load carried by the solid rail when it began to fail. The efficiencies for these joints, as ordinarily used, tested from 29% to 64%. Tests were also made of "heat-treated" joints (see § 285) which showed efficiencies from 60 to 150% higher than the untreated joints, the efficiencies being, in nearly every case, over 100%. The heat treatment costs about 0.2 c. per pound or say 16 c. for an 80-lb. pair. The added efficiency is so well worth the added cost that the use of heat treated splice bars is becoming more common and may soon become standard.

281. Effect of rail gap at joints. It has been found that the jar at a joint is due almost entirely to the *deflection* of the joint and scarcely at all to the small gap required for expansion. This gap causes a drop equal to the versed sine of the arc having a chord equal to the gap and a radius equal to the radius of the wheel. Taking the extreme case (for a 30-foot rail) of a $\frac{3}{8}''$ gap and a 33″ freight-car wheel, the drop is about $\frac{1}{1000}''$. In order to test how much the jarring at a joint is due to a gap between the rails, the experiment was tried of cutting shallow notches in the top of an otherwise solid rail and running a locomotive and an inspection car over them. The resulting jarring was practically imperceptible and not comparable to the jar produced at joints. Notwithstanding this fact, many plans have been tried for avoiding this gap. The most of these plans consist essentially of some form of compound rail, the sections breaking joints. (Of course the design of the compound rail has also several other objects in view.) In Fig. 122 are shown a few of the very many designs which have been proposed. These designs have invariably been abandoned after trial. Another plan, which has been extensively tried on the Lehigh Valley R. R., is the use of mitered joints. The advantages gained by their use are as yet doubtful, while the added expense is unquestionable. The "Roadmasters Association of America" in 1895

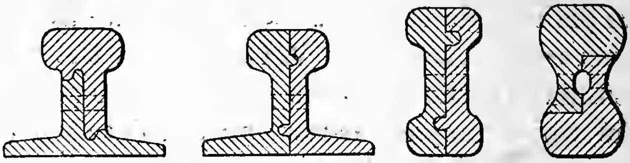


FIG. 122.—COMPOUND RAIL SECTIONS.

adopted a resolution recommending mitered joints for double track, but their use has been abandoned.

282. **"Supported," "suspended," and "bridge" joints.** A joint is "supported" when a tie is placed immediately under the middle of the joint. The localized traffic stress at the joint must be carried almost exclusively by that one tie and comparatively little is carried by the adjacent ties. A "suspended" joint is located symmetrically between two ties, which share equally the localized stress. Formerly there was a considerable proportion of railroad engineers who favored supported joints, but now the suspended joint is almost universally the standard.

"Bridge"-joints are similar to suspended joints in that the joint is supported on two ties, but there is the important difference that the bridge joint supports the rail from *underneath* and there is no transverse stress in the rail, whereas the suspended joint requires the combined transverse strength of both angle-bars and rail. The "Fisher" bridge joint, now seldom seen, is purely of this type, only two bolts being used to hold the rail ends together. But the principle of supporting the base of the rail is seen in the Wolhaupter, the Weber, the Continuous and the Atlas. See Plate VII. Although some of these forms are in extensive use, the angle-bar (see § 284) is the standard on a large proportion of the mileage of the country.

283. **Failures of rail-joints.** An instructive report was made in 1915 by an Engineer of Tests of the Pennsylvania R. R. on

an examination of 960 angle-bars, found in a scrap pile, to determine the various causes for their removal from the track. The various causes were classified under five headings, the typical failures being illustrated in Fig. 123. (1) Abrasion on the top fishing surface, the depth of wear varying from $\frac{1}{32}''$ to $\frac{1}{16}''$ and extending perhaps 8 inches each way from the center. On short 4-hole bars the wear is almost wholly in the center; on the longer 6-hole bars, wear is also found near the ends of the bar. Such wear demonstrates the amount of working and grinding which evidently takes place when a joint is depressed under

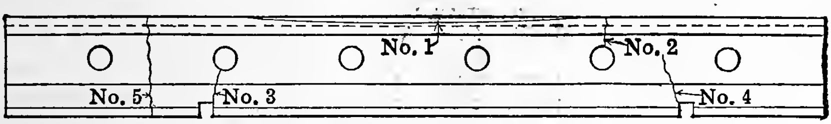


FIG. 123.—DIAGRAM OF TYPES OF BREAKS OF ANGLE-BARS.

traffic. This is the only form of actual *wear* which occurs. 24% of the 960 bars were removed for this cause. (2) When a joint bar is very long, the stresses in the bar may be reversed and there may be tension in the top and a break may start at the top and continue down, usually into a bolt hole. Less than 5% of the failures were of this class. (3) and (4). Usually a crack starts at the bottom and may or may not extend to a bolt hole. Usually the crack starts from a spike slot or from the re-entrant angle at either end of a depending flange. If the cracked bar is permitted to remain in the track, the crack of (2), (3) or (4) develops into a complete break (5). 44% of the 960 bars, or 59% of all but No. 1, were complete breaks.

284. Standard angle-bars. An angle-bar must be so made as to closely fit the rails. The great multiplicity in the designs of rails (referred to in Chapter IX) results in a corresponding variety in the detailed dimensions of the angle-bars. The absolutely essential features required for a fit are (1) the angles of the upper and lower surfaces of the bar where they fit against the rail, and (2) the height of the bar. The bolt-holes in the bar and rail must also correspond. The holes in the angle-bars are elongated or made oval, so that the track-bolts, which are made of corresponding shape immediately under the head, will not be turned by jarring or vibration. The holes in the rails are made of larger diameter (by about $\frac{3}{16}''$) than the bolts, so as to allow the rail to expand with temperature.

In Table XXIV and in Fig. 124 are shown the angles and dimensions for angle-bars to fit the standard rail sections shown in § 267. Note that the dimension a for the angle-bar corresponds with dimension F for the rail and that R_4 and the angle α are the same for both for each type of rail. These dimensions were copied from the 1916 Handbook of the Carnegie Steel Co. Although they correspond perfectly with the rail standards of the

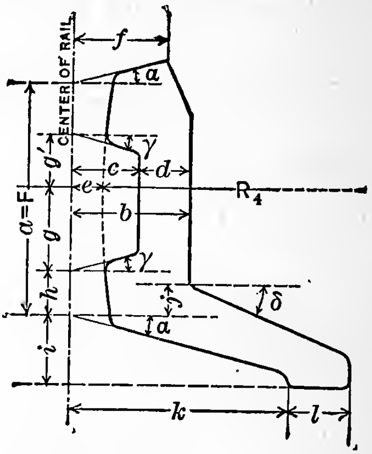


Fig. 124.—Standard Angle Bar.

A. R. E. A., that association has not yet adopted any such definite standard dimensions for a rail-joint.

The standard drilling for bolt-holes in angle-bar, as adopted by the A. R. E. A. in 1914, is as follows:

For 6-bolt splices, 5 spaces of $5\frac{1}{2}$ inches.
For 4-bolt splices, 3 spaces of $5\frac{1}{2}$ inches.

No definite recommendation was made by the Association as to the total length of angle-bars, but the committee recommended that, on the basis of the above spacing of holes, 24 inches is a satisfactory length for a 4-bolt splice and 32 inches for a 6-bolt splice, in both cases using suspended joints. On this basis, the spacing from the center of the last hole to the end of the bar would be $3\frac{3}{4}$ inches for the 4-bolt splice and $2\frac{1}{4}$ inches for the 6-bolt splice.

In Plate VII are shown some of the many designs which have been competing for favor and which have been more or less

TABLE XXIV.—ANGLES AND DIMENSIONS OF STANDARD DESIGNS FOR ANGLE-BARS.

System.		Weight of rail.	R_4-inches.	Angle or slope ratio.			Dimensions, inches.												
				α	δ	γ	a	b	c	d	e	f	g	g'	h	i	j	k	l
A. S. C. E.		60					2 17/64	1 19/64	43/64		25/64	1 3/16	7/16	7/16	89/128	43/64	21/128	2 5/16	3/8
		70					2 15/32	1 27/64	47/64	11/16	27/64	1 7/32	7/16	7/16	51/64	23/32	11/64	2 1/2	7/16
		80	12	13°	20°	—	2 5/8	1 17/32	25/32	3/4	29/64	1 1/4	7/16	7/16	7/8	3/4	3/16	2 3/4	7/16
		90					2 55/64	1 5/8	13/16	13/16	15/32	1 5/16	1/2	1/2	119/128	51/64	15/64	2 15/16	1/2
		100					3 5/64	1 23/32	27/32	7/8	15/32	1 3/8	1/2	1/2	1 5/128	27/32	9/32	3 1/8	1/2
Am. Rwy. Eng. Assoc. and Am. Rwy. Assoc.		60					2 29/64	1 21/64	45/64	5/8	25/64	1 1/8	1 7/128	65/128	51/128	3/4	45/128	2 7/16	5/8
		70		14° 02′	23°	14° 02′	2 1/2	1 27/64	51/64	5/8	13/32	1 3/16	1 7/64	33/64	25/64	27/32	23/64	2 9/16	11/16
	A	80	14				2 23/32	1 17/32	7/8	21/32	57/128	1 1/4	1 15/64	39/64	23/64	29/32	25/64	2 3/4	3/4
		90		4:1		4:1	3 5/32	1 21/32	15/16	23/32	15/32	1 9/32	1 11/32	19/32	9/16	15/16	7/16	3	13/16
		100					3 3/8	1 23/32	31/32	3/4	15/32	1 3/8	1 7/32	3/4	21/32	1	15/32	3 3/16	7/8
		60					2 1/16	1 3/8	11/16	11/16	51/128	1 1/16	55/64	3/4	11/64	3/4	7/32	2 9/32	23/32
		70		14° 02′	17°	14° 02′	2 17/64	1 9/16	13/16	3/4	53/128	1 3/16	55/64	3/4	35/128	51/64	35/128	2 59/128	3/4
	B	80	14				2 15/32	1 19/32	27/32	3/4	59/128	1 7/32	1 1/128	27/32	29/128	7/8	17/64	2 31/32	13/16
		90		4:1		4:1	2 5/8	1 23/32	29/32	13/16	15/32	1 9/32	1/32	29/32	9/32	29/32	17/64	2 105/128	27/64
		100					2 55/64	1 23/32	29/32	13/16	15/32	1 21/64	1 1/32	29/32	51/128	61/64	45/128	3 1/128	7/8

extensively tried out for both steam and electric railroad wor While many thousands in the aggregate have been placed various roads, no one design has succeeded in displacing t angle-bar. There are necessarily as many variations in t details of the angle-bars as there are variations in the sizes rails, beside other slight variations, but all cross-sections a similar to that shown in Fig. 124. This general design pro ably represents the majority of all the angle-bars in the country.

285. Specifications for steel angle-bars. Formerly these we made of either Bessemer or open-hearth steel. Now (1921), t specifications of the A. E. R. A. require open-hearth steel excl sively. Three grades are used: "high carbon steel," "quenche carbon," and "quenched alloy steel." The special requirement in addition to the usual requirements about accuracy of wor manship, branding, inspection, etc., are as follows: phosphor not to exceed 0.04%; quenched bars must have carbon betwe 0.42 and 0.55%, but 1.00% of nickel or 0.35% of chromium w be considered the equivalent of 0.07% of carbon. The physic requirements are:

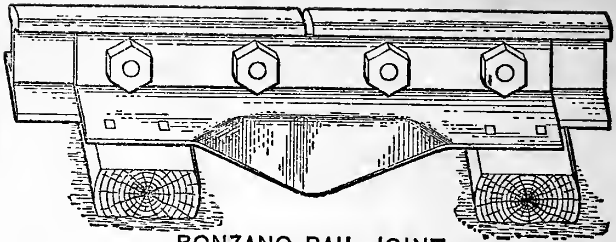
	High carbon steel.	Quenched carbon.	Quenche alloy steel.
Tensile strength, min., lbs. per sq. in...	85,000	100,000	110,000
Elastic limit, lbs. per sq. in............	......	70,000	85,000
Elongation, per cent in 2 inches, min...	16%	1,600,000 ÷ tens. str. min. 12%	

All grades: cold bending test, 90°, on arc with diameter three time thickness of tested piece.

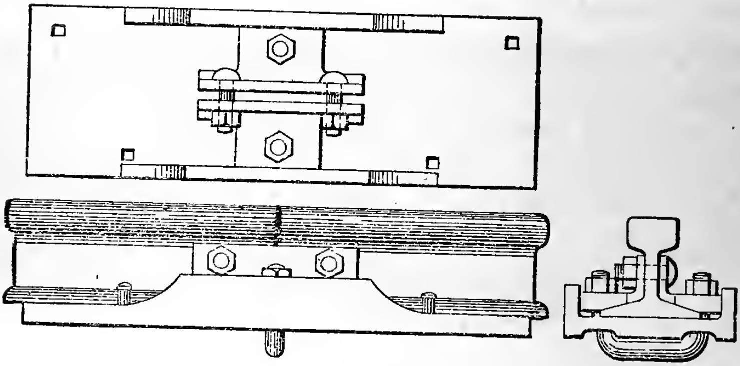
All punching, slotting and shaping is to be done at a temper ature not less than 800° C. or 1470° F. Quenching shall be don in a bath of oil (or water, if specified) having a temperature o 810° C. (1490° F.) and kept in the bath until cool enough t handle.

TIE-PLATES.

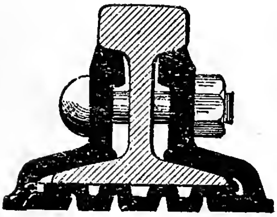
286. Advantages. (*a*) As already indicated in § 242, the lif of a soft-wood tie is very much reduced by "rail-cutting" an "spike-killing," such ties frequently requiring renewal lon before any serious decay has set in. It has been practicall demonstrated that the "rail-cutting" is not due to the mer



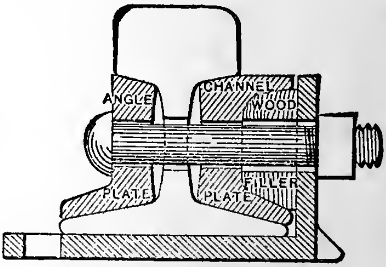
BONZANO RAIL JOINT.



FISHER BRIDGE JOINT.



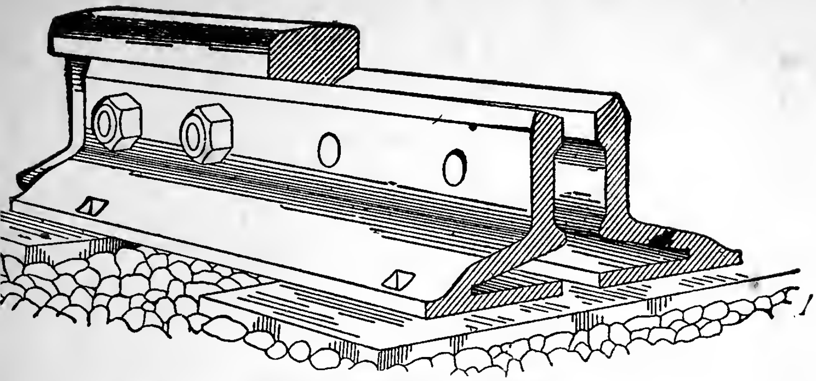
WOLHAUPTER JOINT



WEBER RAIL JOINT.

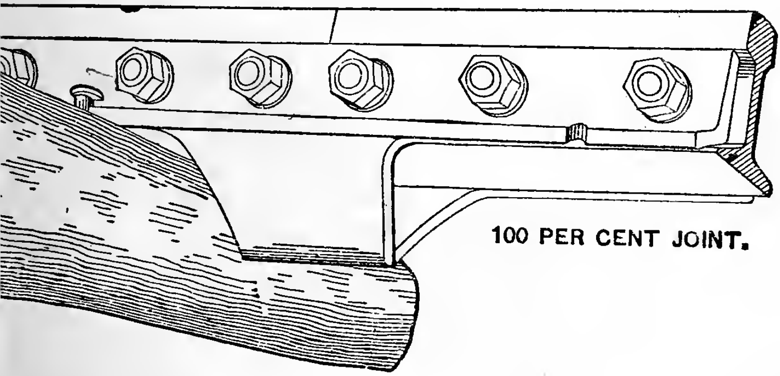
PLATE VII.—SOME FORMS OF RAIL JOINTS.

(Between pp. 320 and 321.)

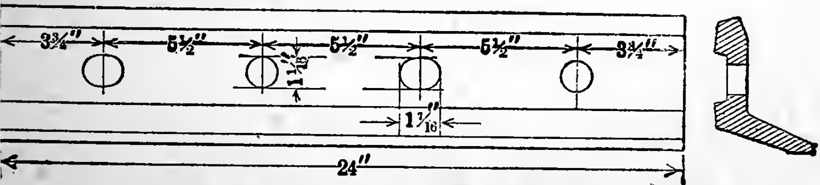


CONTINUOUS RAIL JOINT.

ATLAS SUSPENDED RAIL JOINT.



100 PER CENT JOINT.



TYPICAL 4-BOLT SPLICE BAR

pressure of the rail on the tie, even with a maximum load on the rail, but is due to the impact resulting from vibration and to the longitudinal working of the rail. It has been proved that this rail-cutting is practically prevented by the use of tie-plates. (b) On curves there is a tendency to overturn the outer rail due to the lateral pressure on the side of the head. This produces a concentrated pressure of the outer edge of the base on the tie which produces rail-cutting and also draws the inner spikes. Formerly the only method of guarding against this was by the use of "rail-braces," one pattern of which is shown in Fig. 125. But shoulder tie-plates serve the purpose even better and rail-braces are chiefly used for guard rails and stock rails at switches. (c) Driving spikes through holes in the plate enables the spikes on *each* side of the rail to mutually support each other, no matter in which (lateral) direction the rail may tend to move, and this probably accounts in large measure for the added stability obtained by the use of tie-plates. (d) The wear in spikes, called "necking," caused by the vertical vibration of the rail against them, is very greatly reduced. (e) The cost is very small compared with the value of the added life of the tie, the large reduction in the work of track maintenance, and the smoother running on the better track which is obtained. It has been estimated that by the use of tie-plates the life of hard-wood ties is increased from one to three years and the life of soft-wood ties is increased from three to six years. From the very nature of the case, the value of tie-plates is greater when they are used to protect soft ties.

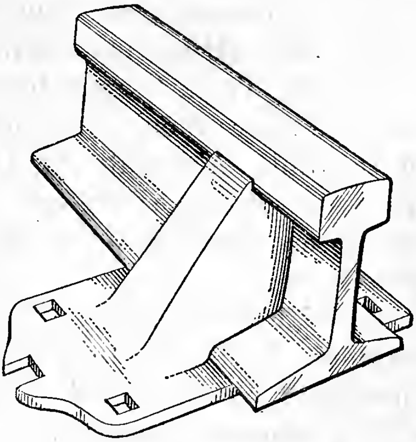


FIG. 125.—ATLAS BRACE K.

287. Elements of the design. The Am. Rwy. Eng. Assoc. has stated these principles in its Manual, as follows:

1. "Plates shall not be less than 6 inches in width, and as much wider as consistent with the class of ties to be used." The use of a wide tie presumes heavy traffic and heavy wheel loads and, therefore, a width as great as the face of the tie, up to at least eight inches, has been recommended.

2. "The length of the plates [parallel with the length of the tie] shall not be less than the safe-bearing area of the ties divided by the width of the plate, and, when made for screw spikes, shall be so shaped as to provide proper support for the screw spikes." 335 lbs. per square inch is declared to be, by test, the minimum safe-bearing load. Tie-plates sometimes sink quickly and deeply into the tie, thus proving that the area is inadequate for the wheel loads and traffic on them.

3. "The thickness of the plate shall be properly proportioned to the length." Tie-plates have been used as thin as $\frac{3}{16}$ inch, but it is now being realized that the real function of the plate is to be a *bearing* plate which shall distribute the load, rather than a mere surface plate which shall protect the tie from abrasion. The Track Committee of the A. R. E. A. recommended that the plates should be at least $\frac{5}{8}$ inch thick under either edge of the rail. Although the Association refused to concur, the discussion developed the fact that the thin plates formerly used have been found to be too thin and that thicker plates are more satisfactory.

4. Height of shoulder. The height of "at least $\frac{1}{2}$-inch" was recommended in the 1915 Manual. The Track Committee has since then recommended that the height should "not be less than $\frac{1}{4}''$ nor more than $\frac{3}{8}''$.

5. "Where treated ties are used or where plates are for screw spikes, a flat-bottom plate is preferable. Where ribs of any kind are used on base of plate, these shall be few in number and not to exceed $\frac{1}{4}$ inch in depth." This specification is in direct contrast to the older designs which had been corrugations and even "claws" which were forced deeply into the tie, in order to anchor the plate immovably to the tie. But experience has proved that these corrugations hasten deterioration. In spite of this, the type using claws (see Fig. 126) is still the standard on some roads.

6. "Punching must correspond to the slotting in the splice-bars and, where advisable, may be so arranged that the plates may be used for joints. Spike holes may be punched for varying widths of rail base where the slotting will permit such punching without the holes interfering with each other and when the plate is of such design that the additional holes will not impair the strength of the plate."

Tie-plates are variously made of steel, wrought iron and malleable iron. Tie-plates are peculiarly subject to rust, especially as an effect of brine drippings from refrigerator cars. The comparative immunity from rust of malleable iron explains its use for this purpose. The specifications for steel and wrought iron are similar to other physical tests for such a metal when toughness rather than high ultimate strength is desired. The malleable iron tie-plates have lugs cast on them for testing purposes. When this lug is broken off, it must not break easily, as cast iron, but must show toughness. The fracture must show a narrow band of white metal on the surface, the center portion

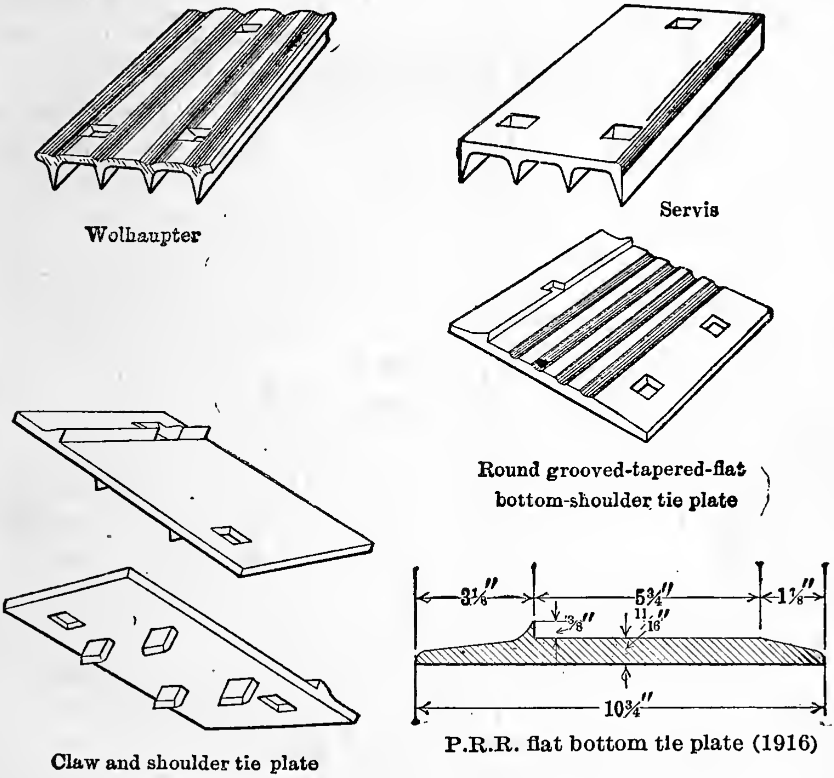


FIG. 126.—VARIOUS FORMS OF TIE-PLATES.

being dark and fiberless. The plates must, when tested, bend sufficiently to prove thorough annealing.

The holes in a tie-plate should be about $\frac{1}{16}''$ larger than the size of the intended spike. The length of the plate, perpendicular to the rail, should be $8\frac{1}{2}$ to 11 in., the extension on the outside of the rail base being $\frac{3}{4}''$ to $1\frac{1}{4}''$ more than that on the inside. For very heavy traffic the thickness should be $\frac{5}{8}''$ to $\frac{3}{4}''$; for lighter traffic they may be as thin as $\frac{3}{8}''$. Flat-bottom plates should be at least $\frac{1}{2}''$ thick; corrugated plates, being somewhat stiffer, may be thinner for the same service. The tie-plates over the joint ties must be somewhat longer than the intermediates, in order to allow for the extra length from out to out of the angle-plates.

288. Method of setting. A very important detail in the process of setting the tie-plates on the ties is that the plates should be rigidly attached to the ties in their intended position during the process of setting. If tie-plates with flat bottoms are used, the surface of the tie must be adzed, so that it is not only plane but level, so that there will be no danger that the plate will rock on the tie. When using tie-plates which are corrugated on the under surface, it is necessary to force them into the tie until the under side of the plate is flush with the surface of the tie. This requires a pressure of several thousand pounds. Sometimes trackmen have depended on the easy process of waiting for passing trains to force the corrugations into the tie until the plate is in its intended position. Until the plates are finally set the spikes cannot be driven home, and this apparently cheap and easy process generally results in loose spikes and rails. The best method for new work is to drive the plates into the tie before setting the tie in position. A tie-plate gauge holds both tie-plates in their proper relative position, and both plates may be driven by the use of heavy beetles. When it is necessary to place the plate under the rail and drive it in, it is somewhat difficult to drive it by striking the plate with a swage on each side of the rail alternately. When it is struck on one side, the other side flies up unless held down by a wedge driven between the plate and the rail on the other side of the rail. A straddler, which straddles the rail somewhat like an inverted U, is very useful for this purpose, since it makes it possible to strike the head of the straddler and force down both sides of the plate at once. The Southern Pacific Railroad Company has rigged up a small pile-driver on a hand-car, which is used in connection with a straddler to drive the tie-plates into position. Some western railroads have even adopted the process of rigging up a flat car with a machine which will press the tie-plates into place in the ties before the ties are placed in the track.

SPIKES.

289. Requirements. The rails must be held to the ties by a fastening which will not only give sufficient resistance, but which will retain its capacity for resistance. It must also be cheap and easily applied. The ordinary track-spike fulfills the last requirements, but has comparatively small resisting power, compared with screws or bolts. Worse than all, the tendency to

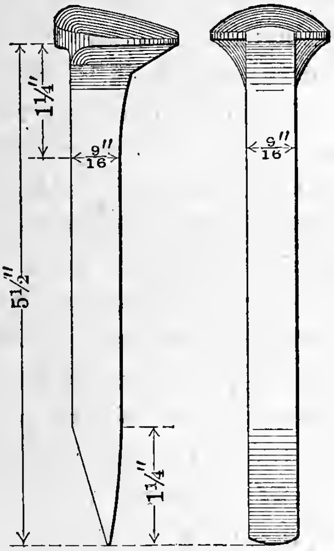


FIG. 127.

FIG. 128.

vertical vibration in the rail produces a series of upward pulls on the spike that soon loosens it. When motion has once begun the capacity for resistance is greatly reduced, and but little more vibration is required to pull the spike out so much that redriving is necessary. Driving the spike to place again in the same hole is of small value except as a very temporary expedient, as its holding power is then very small. Redriving the spikes in new holes very soon "spike-kills" the tie. Many plans have been devised to increase the holding power of spikes, such as making them jagged, twisting the spike, swelling the spike at about the center of its length, etc. But it has been easily demonstrated that the fibers of the wood are generally so crushed and torn by driving such spikes that their holding power is less than that of the plain spike, and the durability is greatly diminished.

The ordinary spike (see Fig. 127) is made with a square cross-section which is uniform through the middle of its length, the lower $1\frac{1}{4}$ in. tapering down to a chisel edge, the upper part swelling out to the head. The Goldie spike (see Fig. 128) aims to improve this form by reducing to a minimum the destruction of the fibers. To this end, the sides are made smooth, the edges are clean-cut, and the point, instead of being chisel-shaped, is ground down to a pyramidal form. Such fiber-cutting as occurs is thus accomplished without much crushing, and the fibers are thus pressed away from the spike and slightly downward. Any tendency to draw the spike will, therefore, cause the fibers to press still harder on the spike and thus increase the resistance.

A series of tests made by a committee of the A. R. E. A. and reported to the 1914 Convention, established some very valuable conclusions with respect to the use of the ordinary cut spike. Spikes with sharp pyramidal points and with various degrees of bluntness, and also the ordinary chisel-pointed spike, were driven into ties and other timbers and were withdrawn by a testing machine. Then the timbers were cut so as to expose the holes to their full length, so that the crushing of the fibers by the spike driving could be observed. A series of photographs illustrated this feature. In some cases the spikes were driven into $\frac{3}{8}$-in. bored holes, some of which were $2\frac{1}{2}$ ins. deep, but the most of them were 4 ins. deep. In other cases, the spikes were driven without previous boring. The following conclusions were unmistakable.

1. The spike with a pyramidal point about 1 in. long (virtually the "Goldie" design Fig. 128), has greater holding power, not only when it first begins to yield, but also afterward while the spike is being drawn out.

2. The long-pointed spikes crushed the fiber far less than any other type.

3. The chisel-pointed spike, virtually as shown in Fig. 127, and which is the type now in most common use, has the least holding power and is more destructive in crushing the fibers.

4. Spikes driven into $\frac{3}{8}$-in. bored holes have greater holding power than when driven without boring, and the crushing of the fiber is much less. This indicates the very real economy in boring holes where the life of the tie is an economical consideration.

290. Driving. The holding power of a spike depends largely on how it is driven. If the blows are eccentric and irregular in direction, the hole will be somewhat enlarged and the holding power largely decreased. The spikes on each side of the rail in any one tie should not be directly opposite, but should be staggered. Placing them directly opposite will tend to split the tie, or at least decrease the holding power of the spikes. The direction of staggering should be reversed in the two pairs of spikes in any one tie (see Fig. 129). This will tend to prevent any twisting of the tie in the ballast, which would otherwise loosen the rail from the tie.

291. Screw spikes. The D., L. & W. R. R. began the general use of screw spikes for all new work and for extensive track renewals in 1910. In five years they used over 12,000,000 screw spikes. The design is shown in Fig. 130. From a report made by Mr. G. J. Ray, Chief Engineer, to the A. R. E. A., the following facts and conclusions are deduced:

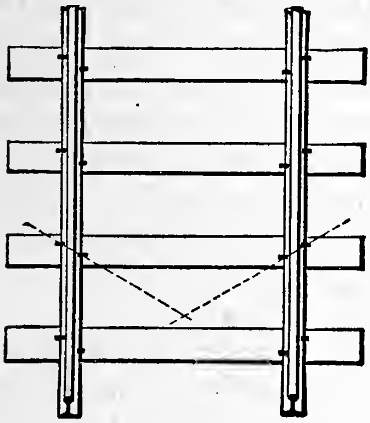


FIG. 129.—SPIKE-DRIVING.

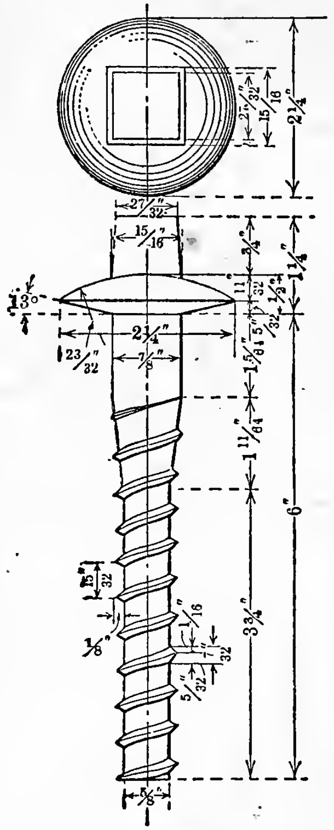


FIG. 130.—SCREW SPIKE, D. L. &. W. R. R.

1. The use of screw spikes, in conjunction with suitable tie-plates, is almost a necessity in order to fully utilize the durability of a treated tie. A treated tie is seldom removed on account of decay in the body of the tie. Its destruction is generally due to "spike-killing," rail cutting, or to the decay which comes immediately after mechanical injury to the wood under the rail. Screw spikes and tie-plates largely prevent this mechanical injury.

2. "As a rule, with woods which it will pay to treat, the poorer the quality of the timber the more elaborate and expensive the fastening must be if the mechanical life of the tie is made to approach the life of the treated timber."

3. "Tie-plates should be used on all ties where screw spikes are used."

4. "Four holes should be provided for screw spikes, so that two extra holes will be available if needed."

5. "The size of screw spikes and the design of the thread should be carefully considered before a screw spike is adopted. Thereafter no changes should be made; otherwise the new screw spikes cannot be used in old holes without damaging the wood fiber."

6. "The screw-spike head should have tapering sides to prevent turning in the wrench socket after the size of the head has been diminished by rust."

7. "When screw spikes are fully seated, no further strain should be put on them, as this will tend to destroy the threads in the wood or injure the spikes."

8. "All ties should be bored at the treating plant before treatment. This can be done while the ties are being adzed, and not only insures that the holes are bored sufficiently deep, but provides for good treatment of all wood adjacent to the spike holes."

9. "Where the ties are bored before treatment, the track must be to proper gauge before the ties can be placed."

10. "The holes for screw spikes should be of proper dimensions for the class of wood used, with due regard to the size of screw spike used."

11. "A limited number of holes can be bored with one bit, after which its size will diminish so as to make it unfit for a hole of a given size." [The paper nowhere makes any statement as to the size of the bored hole in comparison with the diameter of the screw. The bored hole should have *about* the same diameter as the diameter of the screw at the base of the screw thread, but the hardness of the wood requires some variation, since, if the hole is too small, it will be impossible to turn the screw. The exact diameter must be determined for each kind of wood and must be strictly maintained.]

12. "Holes should be bored somewhat deeper than the length of the screw spike. There is no serious objection to boring the holes clear through the ties."

13. "Not only is the lateral and vertical resistance of a screw spike greater than that of a cut spike when both are first applied, but the lateral and vertical resistance of a loose screw spike is considerably greater than the lateral and vertical resistance of a loose cut spike."

14. "When the threads in the tie are entirely destroyed, a screw lining (any one of several different varieties) may be used with good results."

15. "All ties should be bored and adzed before treatment. This insures good gauge, a perfect bearing for the tie-plates and good treatment under the rail seat and around the screw-spike holes."

16. "In placing screw spikes, they should be driven by hammer only sufficient to make the threads take hold. If rigid instructions are not carried out, laborers will continually overdrive spikes and thus destroy the wood fibers near the top of the holes."

17. "The best results with the screw spikes can be expected in new construction, and where the number of screw spikes in tie renewals predominate over cut spikes."

18. "The use of screw spikes for the past five years has not made it necessary to increase the number of sectionmen per mile of track."

19. "Whether or not it will pay to use screw spikes will depend upon the cost of ties, their probable life and the amount of traffic."

292. "Wooden spikes." Among the regulations for track-laying given in § 246, mention was made of wooden "spikes," or plugs, which are used to fill up the holes when spikes are withdrawn. The value of the policy of filling up these holes is unquestionable, since the expense is insignificant compared with the loss due to the quick and certain decay of the tie if these holes are allowed to fill with water and remain so. But the method of making these plugs is variable. On some roads they are "hand-made" by the trackmen out of otherwise useless scraps of lumber, the work being done at odd moments. This policy, while apparently cheap, is not necessarily so, for the hand-made plugs are irregular in size and therefore more or less inefficient. It is also quite probable that if the trackmen are required to make their own plugs, they would spend time on these very cheap articles which could be more profitably employed otherwise. Since the holes made by the spikes are larger at the top than they are near the bottom, the plugs should *not* be of uniform cross-section but should be slightly wedge-shaped. The "Goldie tie-plug" (see Fig. 131) has been designed to fill these requirements. Being machine-made, they are uniform in size; they are of a shape which will best fit the hole; they can be furnished of any desired wood, and at a cost which makes it a wasteful economy to attempt to cut them by hand.

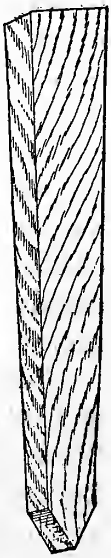


FIG. 131.

TRACK-BOLTS.

293. Essential requirements. The track-bolts must have sufficient strength and must be screwed up tight enough to hold the angle-plates against the rail with sufficient force to develop the full transverse strength of the angle-bars. On the other hand the bolts should not be screwed so tight that slipping may not take place when the rail expands or contracts with temperature. It would be impossible to screw the bolts tight enough to prevent slipping during the contraction due to a considerable fall of temperature on a straight track, but when the track is curved, or when expansion takes place, it is conceivable that the resistance of the ties in the ballast to lateral motion may be less than the resistance at the joint. A test to determine this resistance was made by Mr. A. Torrey, chief engineer of the Mich. Cent. R. R., using 80-lb. rails and ordinary angle-bars, the bolts being screwed up as usual. If required a force of about 31000 to 35000 lbs. to start the joint, which would be equivalent to the stress induced by a change of temperature of about 22°. But if the central angle of any given curve is small, a comparatively small lateral component will be sufficient to resist a compression of even 35000 lbs. in the rails. Therefore there will ordinarily be no trouble about having the joints screwed too tight. The vibration caused by the passage of a train reduces the resistance to slipping. This vibration also facilitates an objectionable feature, viz., loosening of the nuts of the track-bolts. The bolt is readily prevented from turning by giving it a form which is *not* circular immediately under the head and making corresponding holes in the angle-plate. See Fig. 132. Note also the elongated and the round bolt holes in the standard angle bar shown on Plate VII. Half the nuts are thus on either side of the rail and the danger that *all* the bolts of a joint might be simultaneously sheared off by a derailment is somewhat minimized.

"As a rule, as large track-bolts should be used as the rail and splice-bars will permit." [From 1915 Manual, A. R. E. A.] There is always some danger that a trackman may stretch a bolt beyond its elastic limit. A pull of 100 lbs. on a 33-inch track wrench will induce a stress of about 45000 lbs. per square inch in a $\frac{7}{8}$-inch track bolt. The same work on a 1-inch bolt would produce a stress of about 35000 lbs. per square inch. In order to obtain the necessary toughness, bolts must be made of low-carbon steel or of nickel-steel, untreated or heat-treated. When made of carbon steel, specifications require an elastic limit of at least 35,000 lbs. per square inch but at the same time an elongation of 25% in 2 inches and a reduction of area of at least 50%. A harder steel would have a higher elastic limit, but would not be sufficienlty ductile. Higher elastic limits, with sufficient ductility, may be obtained by using untreated nickel or other alloy steel (at least 45,000 lbs. per square inch), or heat-treated nickel or other alloy steel (at least 75,000 lbs. per square inch). The elastic limit shall not be less than 50% of the ultimate. Added strength can only be obtained by using larger bolts or a more expensive metal.

294. Design of track-bolts. In Fig. 132 is shown a common design of track-bolt. In its general form this represents the bolt used on nearly all roads, being used not only with the common angle-plates, but also with many of the improved designs of rail-joints. The variations are chiefly a general increase in size to correspond with the increased weight of rails, besides variations in detail dimensions which are frequently unimportant. The diameter is usually $\frac{3}{4}''$ to $\frac{7}{8}''$; 1″ bolts are used for 100-lb. rails. As to length, the bolt should not extend more than $\frac{1}{2}''$ outside of the nut when it is screwed up. If it extends farther than this it is liable to be broken off by a possible derailment at that point. The lengths used vary from $3\frac{1}{4}''$, which may be used with 60-lb. rails, to 5″, which is required with 100-lb. rails. The length required depends somewhat on the type of nut-lock used.

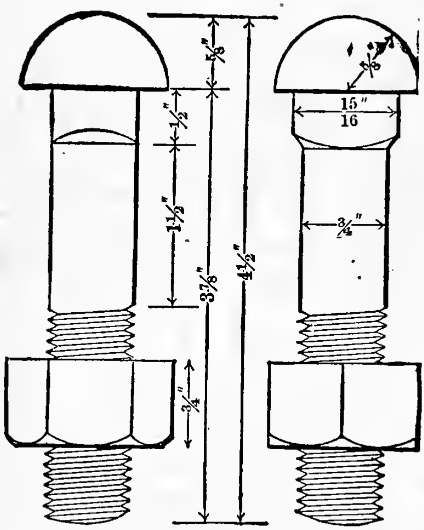


FIG. 132.—TRACK-BOLT.

NUT-LOCKS.

295. Design of nut-locks. The designs for nut-locks may be divided into three classes: (*a*) those depending entirely on an

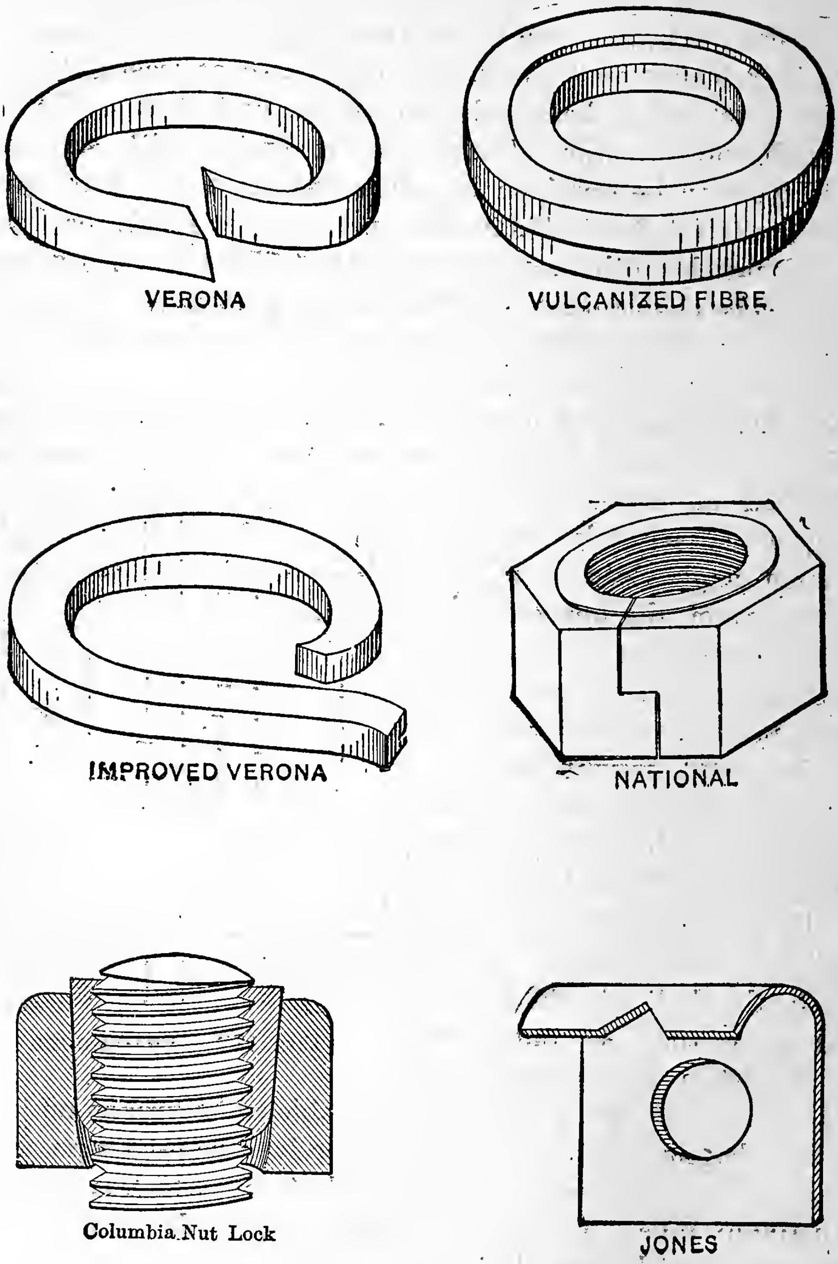


Fig. 133.—Types of Nut-locks.

elastic washer which absorbs the vibration which might otherwise induce turning; (*b*) those which jam the threads of the bolt and nut so that, when screwed up, the frictional resistance is too great to be overcome by vibration; (*c*) the "positive" nut-locks—those which mechanically hold the nut from turning. Some of the designs combine these principles to some extent. The "vulcanized fiber" nut-lock is an example of the first class. It consists essentially of a rubber washer which is protected by an iron ring. When first placed this lock is effective, but the rubber soon hardens and loses its elasticity and it is then ineffective and worthless. Another illustration of class (*a*) is the use of wooden blocks, generally 1″ to 2″ oak, which extend the entire length of the angle-bar, a single piece forming the washer for the four or six bolts of a joint. This form is cheap, but the wood soon shrinks, loses its elasticity, or decays so that it soon becomes worthless, and it requires constant adjustment to keep it in even tolerable condition. The "Verona" nut-lock is another illustration of class (*a*) which also combines some of the positive elements of class (*c*). It is made of tempered steel and, as shown in Fig. 133, is warped and has sharp edges or points. The warped form furnishes the element of elastic pressure when the nut is screwed up. The steel being harder than the iron of the angle-bar or of the nut, it bites into them, owing to the great pressure that must exist when the washer is squeezed nearly flat, and thus prevents any *backward* movement, although forward movement (or tightening the bolt) is not interfered with. The "National" nut-lock is a type of the second class (*b*), in which, like the "Harvey" nut-lock, the nut and lock are combined in one piece. With six-bolt angle-bars and 30-foot rails, this means a saving of 2112 pieces on each mile of single track. The "National" nuts are open on one side. The hole is drilled and the thread is cut slightly smaller than the bolt, so that when the nut is screwed up it is forced slightly open and therefore presses on the threads of the bolt with such force that vibration cannot jar it loose. Unlike the "National" nut, the "Harvey" nut is solid, but the form of the thread is progressively varied so that the thread pinches the thread of the bolt and the frictional resistance to turning is too great to be affected by vibration.

The "Columbia" nut-lock is a two-piece nut, both parts of which must turn simultaneously. As shown in the figure, one section wedges into the other. The greater the tension in the bolt, the greater the wedging action and the greater the friction to prevent turning.

The "Jones" nut-lock, belonging to class (*c*), is a type of a nut-lock that does not depend on elasticity or jamming of screw-threads. It is made of a thin flexible plate, the square part of which is so large that it will not turn after being placed on the bolt. After the nut is screwed up, the thin plate is bent over so that the re-entrant angle of the plate engages the corner of the nut and thus mechanically prevents any turning. The metal is supposed to be sufficiently tough to endure without fracture as many bendings of the plate as will ever be desired. Nut-locks of class (*c*) are not in common use.

The above types have been discussed in order to show the development of the various devices. With but few exceptions, the standard nut-lock is a steel spring ring of the same general class as the Verona. The A. R. E. A. have prepared specifications for such nut-locks which include the following:

"After the finished nut-lock has been subjected for one hour to pressure sufficient to compress it flat and has been released, its reaction shall be not less than two-thirds its height or thickness of section, provided thickness is less than width of section. If the section is square, the reaction must be not less than one-half its thickness. If height or thickness of section is more than width, the reaction shall be not less than the width of the section. The internal diameters naturally affect the percentage of reaction, and the above specifications apply to nut-locks of internal diameters from $\frac{13}{16}$ in. to 1 $\frac{5}{16}$ ins. Owing to the difficulty of establishing a common rate of percentage that shall be uniformly applicable to any internal diameter of any nut-lock of any section it has been sought to cover the matter as above. Amount and durability of reactionary power under constant pressure is the true test of any spiral spring nut-lock. The percentage of reaction increases proportionately with the increased internal diameter of any given section."

"With one end of the finished nut-lock secured in a vise, and the opposite end twisted to 45 degrees, there must be no sign of fracture. When further twisted until broken, the fracture must show a good quality of steel."

CHAPTER XI.

SWITCHES AND CROSSINGS.

SWITCH CONSTRUCTION.

296. Essential elements of a switch. Flanges of some sort are a necessity to prevent car-wheels from running off from the rails on which they may be moving. But the flanges, although a necessity, are also a source of complication in that they require some special mechanism which will, when desired, guide the wheels out from the controlling influence of the main-line rails. This must either be done by raising the wheels high enough so that the flanges may pass *over* the rails, or by breaking the continuity of the rails in such a way that channels or "flange spaces" are formed *through* the rails. An ordinary stub-switch breaks the continuity of the main-line rails in three places, two of them at the switch-block and one at the frog. The Wharton switch avoids two of these breaks by so placing inclined planes that the wheels, rolling on their flanges, will surmount these inclines until they are a little higher than the rails. Then the wheels on the side toward which the switch runs are guided over and across the main rail on that side This rise being accomplished in a short distance, it becomes impracticable to operate these switches except at slow speeds, as any sudden change in the path of the center of gravity of a car causes very destructive jars both to the switch and to the rolling stock. The other general method makes a break in one main rail (or both) at the switch-block. In both methods the wheels are led to one side by means of the "lead rails," and finally one line of wheels passes *through* the main rail on that side by means of a "frog." There are some designs by which even this break in the main rail is avoided, the wheels being led *over* the main rail by means of a short *movable* rail which is on occasion placed across the main rail, but such designs have not come into general use.

297. Frogs. Frogs are provided with two channel-ways or "flange spaces" through which the flanges of the wheels move.

Each channel cuts out a parallelogram from the tread area. Since the wheel-tread is always wider than the rail, the wing rails will support the wheel not only across the space cut out by the channel, but also until the tread has passed the point of the frog and can obtain a broad area of contact on the tongue of the frog. This is the theoretical idea, but it is very imperfectly

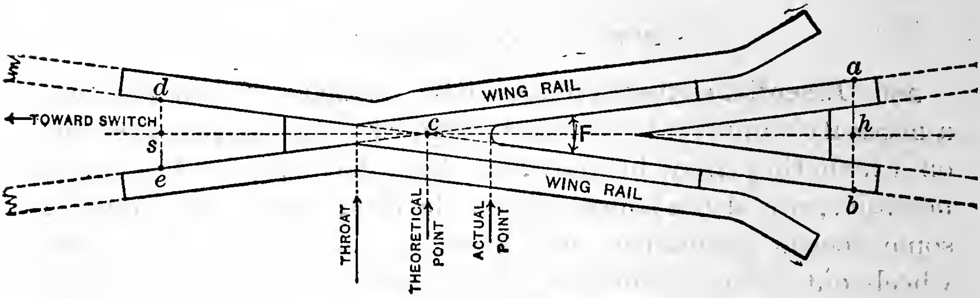
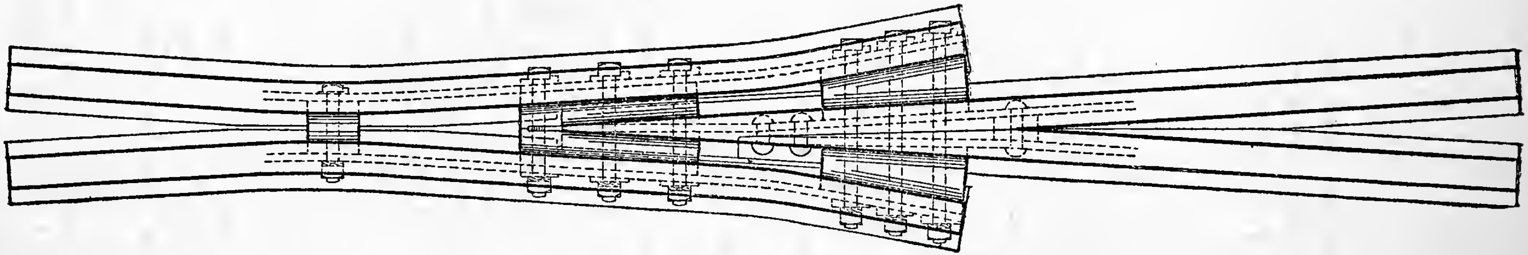
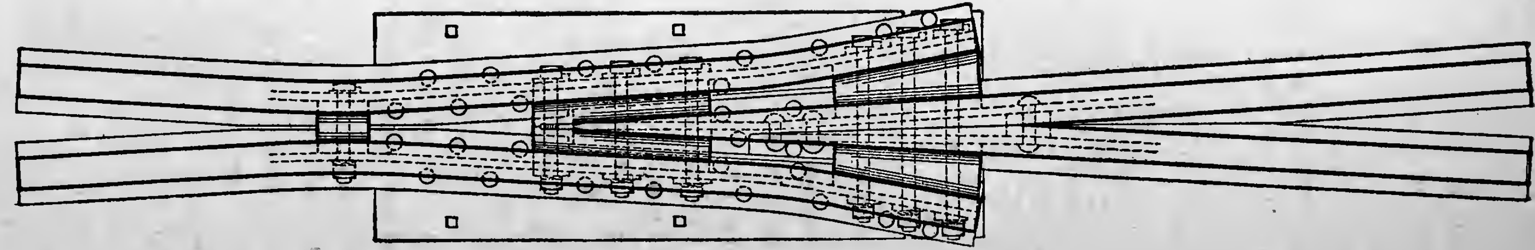


FIG. 134.—DIAGRAMMATIC DESIGN OF FROG.

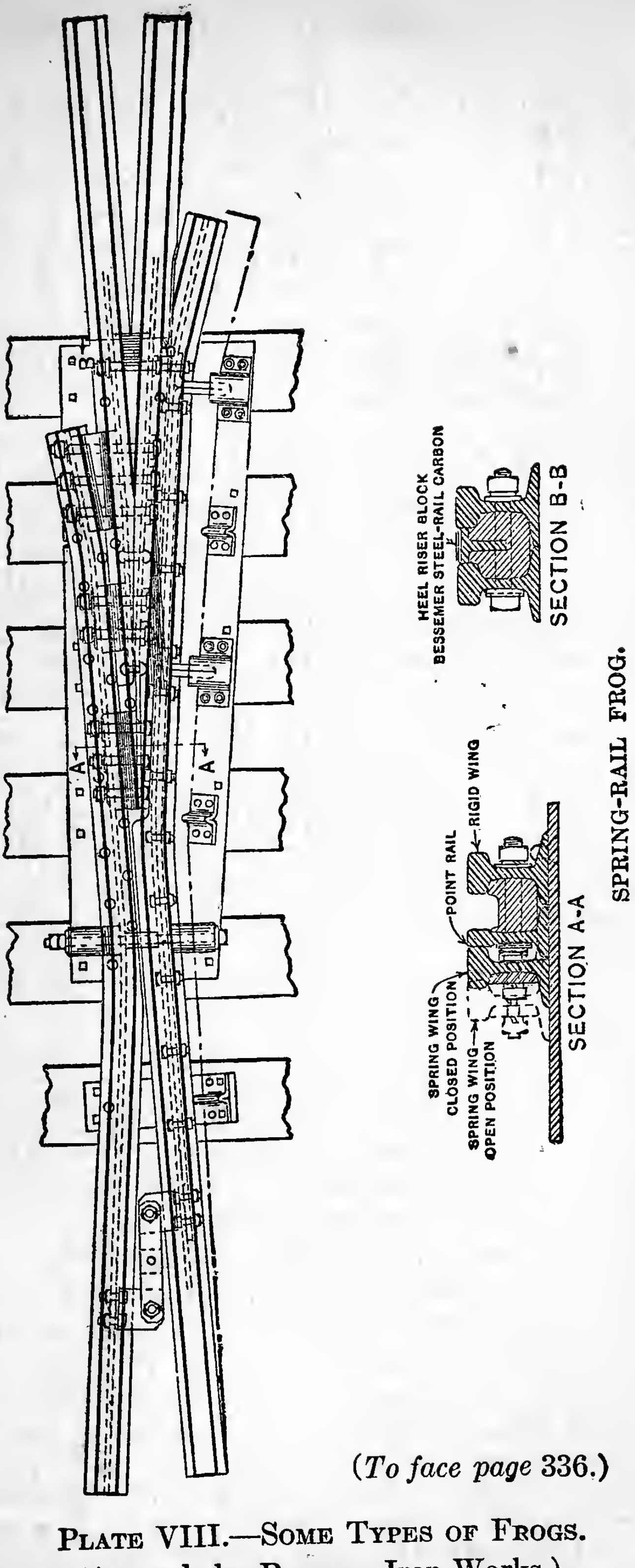
realized. The wing rails are sometimes subjected to excessive wear owing to "hollow treads" on the wheels—owing also to the frog being so flexible that the point "ducks" when the wheel approaches it. On the other hand the sharp point of the frog will sometimes cause destructive wear on the tread of the wheel. Therefore the tongue of the frog is not carried out to the sharp theoretical point, but is purposely somewhat blunted. But the break which these channels make in the continuity of the tread area becomes extremely objectionable at high speeds, being mutually destructive to the rolling stock and to the frog. The jarring has been materially reduced by the device of "spring frogs"—to be described later. Frogs were originally made of cast iron—then of cast iron with wearing parts of cast steel, which were fitted into suitable notches in the cast iron. This form proved extremely heavy and devoid of that elasticity of track which is necessary for the safety of rolling stock and track at high speeds. The present standard practice is to build the frog up of pieces of rails which are cut or bent as required. There are always four pieces for single-pointed frogs. Usually they are assembled by bolts running through the rail webs, which are properly separated by rolled steel filler blocks. Sometimes they are enclosed by clamps held in place by wedges. Sometimes the rails are bolted or riveted to a base plate. For the hardest service, the wearing parts are made of manganese



BOLTED FROG.



BOLTED FROG RIVETED TO BASE PLATE.



(*To face page* 336.)

Plate VIII.—Some Types of Frogs.
(As made by Ramapo Iron Works.)

steel. For details, study Plate VIII. The operation of a spring-rail frog is evident from the figure. Since a siding is usually operated at slow speed, while the main track may be operated at fast speed, a spring-rail frog will be so set that the tread is continuous for the main track and broken for the siding. This also means that the spring-rail will only be moved by trains moving at a (presumably) slow speed on to the siding. For the fast trains on the main line such a frog is substantially a "fixed" frog and has a tread which is practically continuous.

298. To find the frog number. The frog number (n) equals the ratio of the distance of any point on the tongue of the frog from the theoretical point of the frog divided by the width of the tongue at that point, i.e. $=hc \div ab$ (Fig. 134). This value may be directly measured by applying any convenient unit of measure (even a knife, a short pencil, etc.) to some point of the tongue where the width just equals the unit of measure, and then noting how many times the unit of measure is contained in the distance from that place to the theoretical point. But since c, the theoretical point, is not so readily determinable with exactitude, it being the imaginary intersection of the gauge lines, it may be more accurate to measure de, ab, and hs; then n, the frog number, $=hs \div (ab+de)$. If the frog angle be called F, then

$$n = hc \div ab = hs \div (ab+de) = \tfrac{1}{2}\cot\tfrac{1}{2}F;$$

i.e.,

$$\cot\tfrac{1}{2}F = 2n.$$

299. Stub switches. The use of these, although once nearly universal, has been practically abandoned as turnouts from *main track* except for the poorest and cheapest roads. In some States their use on main track is prohibited by law. They have the sole merit of cheapness with adaptability to the circumstances of very light traffic operated at slow speed when a considerable element of danger may be tolerated for the sake of economy. The rails from A to B (see Fig. 135*) are not fastened

* The student should at once appreciate that in Fig. 135, as well as in nearly all the remaining figures in this chapter, it becomes necessary to use excessively large frog angles, short radii, and a very wide gauge in order to illustrate the desired principles with figures which are sufficiently small for the page. In fact, the proportions used in the figures are such that serious mechanical difficulties would be encountered if they were used. These difficulties are here ignored because they can be neglected in the proportions used in practice.

to the ties; they are fastened to each other by tie-rods which keep them at the proper gauge; at and back of *B* they are securely spiked to the ties, and at *A* they are kept in place by

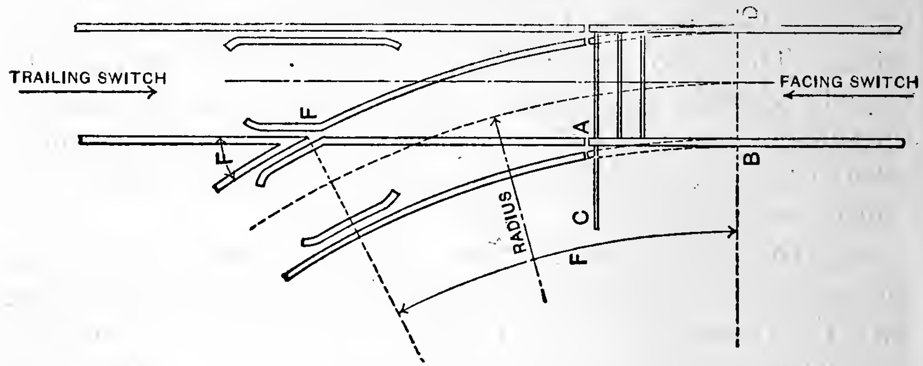


FIG. 135.—STUB SWITCH.

the connecting bar (*C*) fastened to the switch-stand. One great objection to the switch is that, in its usual form, when operated as a trailing switch, a derailment is inevitable if the switch is misplaced. The very least damage resulting from such a derailment must include the bending or breaking of the tie-rods of the switch-rail. Several devices have been invented to obviate this objection, some of which succeed very well mechanically, although their added cost precludes any economy in the total cost of the switch. Another objection to the switch is the looseness of construction which makes the switches objectionable at high speeds. The gap of the rails at the head-block is always considerable, and is sometimes as much as two inches. A driving-

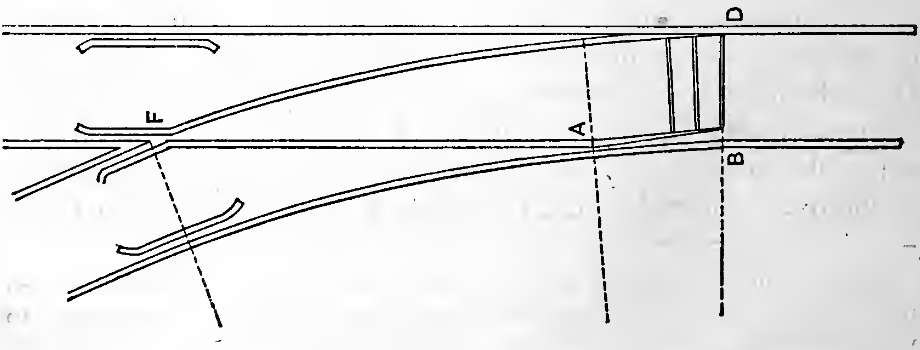


FIG. 136.—POINT SWITCH.

wheel with a load of 20000 to 30000 pounds, jumping this gap with any considerable velocity, will do immense damage to the farther rail end, besides producing such a stress in the construction that a breakage is rendered quite likely, and such a breakage might have very serious consequences.

300. Point switches. The essential principle of a point switch is illustrated in Fig. 136. As is shown, one main rail and also one of the switch-rails is unbroken and immovable. The other main rail (from *A* to *F*) and the corresponding portion of the other lead rail are substantially the same as in a stub switch. A portion of the main rail (*AB*) and an equal length of the opposite lead rail (usually 16.5 to 22 feet long) are fastened together by tie-rods. The end at *A* is jointed as usual and the other end is pointed, both sides being trimmed down so that the feather edge at *B* includes the web of the rail. In order to retain in it as much strength as possible, the point-rail is raised so that it rests on the base of the stock-rail, one side of the base of the point-rail being nearly cut away. As may be seen in Fig. 137, although the influence of the point of the rail in moving the wheel-flange away from the stock-rail is really zero at that point, yet the rail has all the strength of the web, more than one-half that of the base, and is also reinforced. The planing runs back in *straight* lines, until at about six or seven feet back from the point the full width of the head is obtained. The full width of the base will only be obtained at about 13 feet from the point. The A. R. E. A. standard switch rail is always cut on the basis that the distance between gauge lines at the heel of the switch (the distance *MN* in Fig. 143) is $6\frac{1}{4}$ inches and that the "point" is $\frac{1}{4}$ inch wide. Then, using four standard lengths, 11, $16\frac{1}{2}$, 22 and 30 feet, the angles vary from 2° 36′ 19″ to 0° 57′ 18″ as shown in Table III.

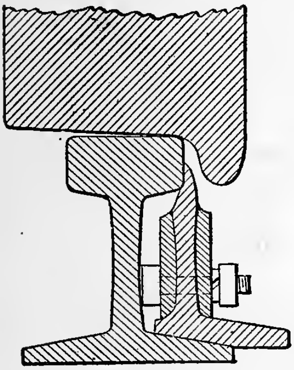


FIG. 137.

---

301. Switch-stands. The simplest and cheapest form is the "ground lever," which has no target. The radius of the circle described by the connecting-rod pin is precisely one-half the throw. From the nature of the motion the device is practically self-locking in either position, padlocks being only used to prevent malicious tampering.

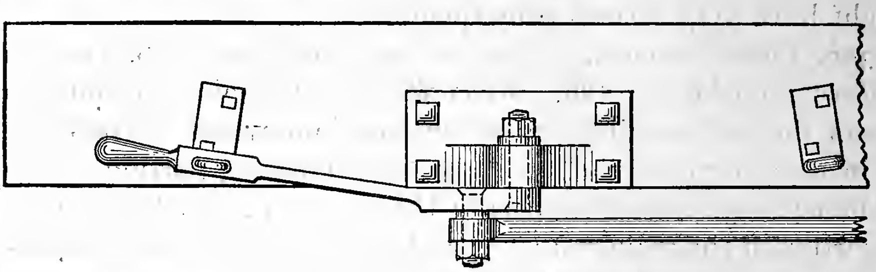


Fig. 138.—Ground Lever for Throwing a Switch.

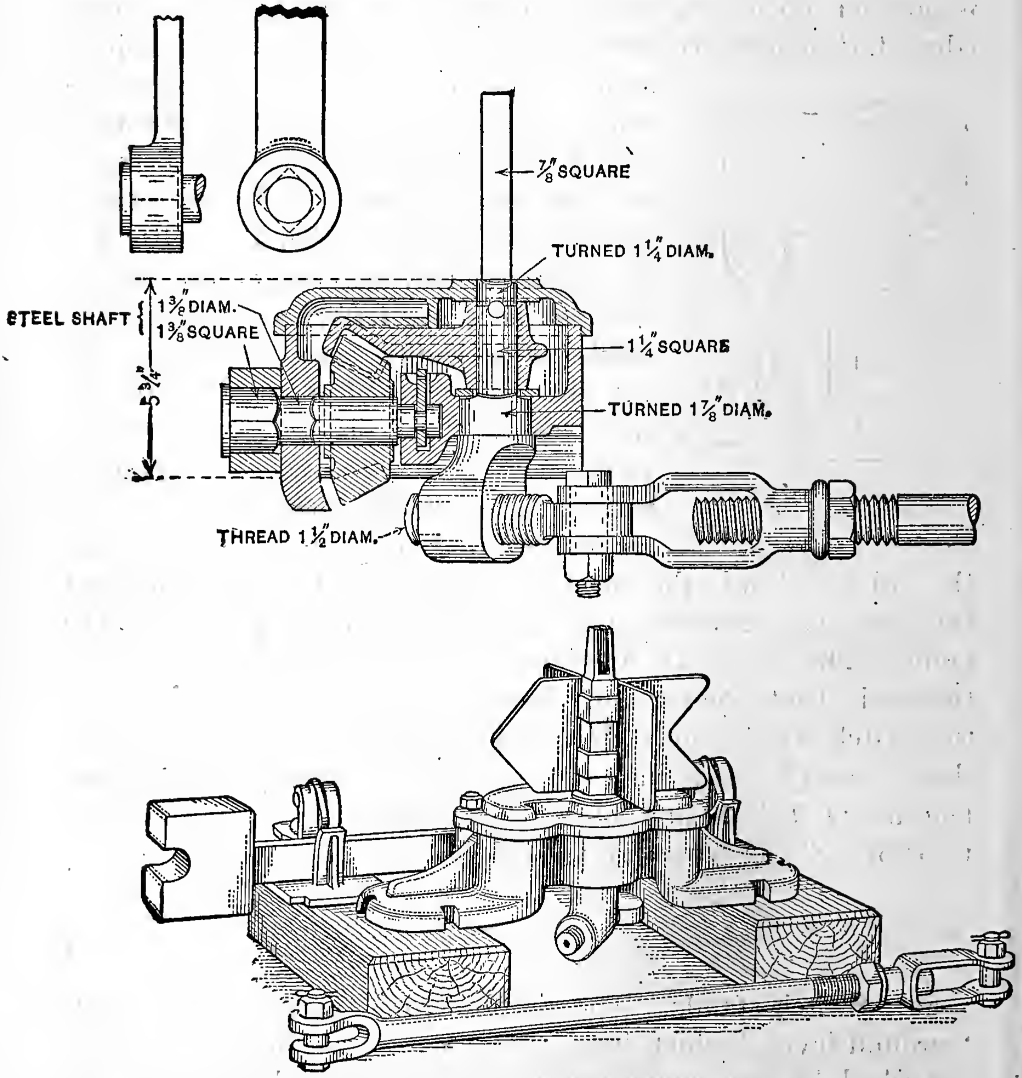


Fig. 139.—Ramapo Patent Switch Stand. Non-automatic.

In Fig. 139 is shown a design in which the arc of the throwing lever is parallel to the track, an important feature in quick switching work.

302. Tie-rods. These are fastened to the webs of the rails by means of lugs which are bolted on, there being usually a hinge-

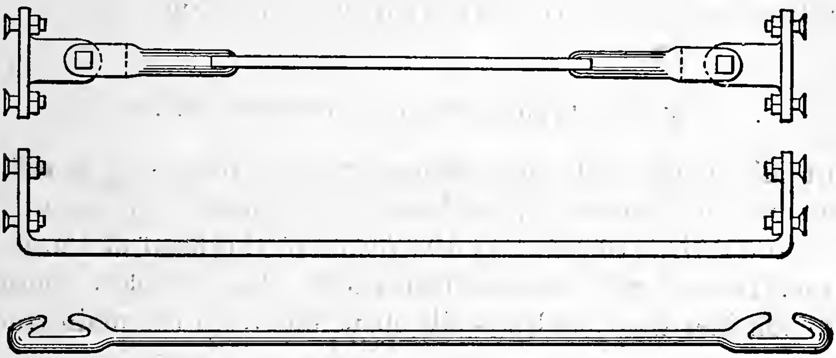


Fig. 140.—Forms of Tie-rods.

joint between the rod and the lug. Two such tie-rods (three for a 30-foot switch) are generally necessary. The first rod is sometimes made without hinges, which gives additional stiffness to the comparatively weak rail-points. The old-fashioned tie-rod, having jaws fitting the base of the rail, was almost universally used in the days of stub switches. One great inconvenience in their use lies in the fact that they must be slipped on, one by one, over the *free* ends of the switch-rails.

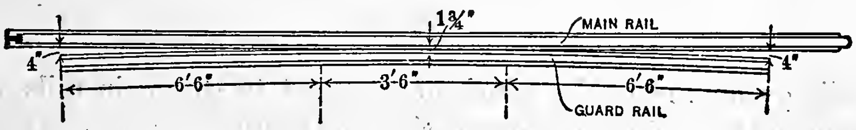


Fig. 141.—Standard Guard-rail.

303. Guard-rails. As shown in Figs. 135 and 136, guard-rails are used on both the main and switch tracks opposite the frog-point. Their function is not only to prevent the possibility of the wheel-flanges passing on the wrong side of the frog-point, but also to save the side of the frog-tongue from excessive wear. The flange-way space between the heads of the guard-rail and wheel-rail should equal $1\frac{3}{4}$ inches. Since this is less than the space between the heads of ordinary (say 80-pound) rails when placed base to base, to say nothing of the $\frac{3}{4}''$ required for spikes, it becomes necessary to cut the flange of the guard-rail. The length of the rail should be 16 feet 6 inches, the middle portion being straight for a length of 3 feet 6 inches, and the ends, each being 6 feet 6 inches long, curved out so that the side of the rail head at each end is 4 inches from the main rail head, when the flange-way at the center is $1\frac{3}{4}$ inches. See Fig. 141.

MATHEMATICAL DESIGN OF SWITCHES.

In all of the following demonstrations regarding switches, turnouts, and crossovers, the lines are assumed to represent the *gauge-lines*—i.e., the lines of the *inside* of the head of the rails.

304. Design with circular lead-rails. The simplest method is to consider that the lead-rails curve out from the main track-

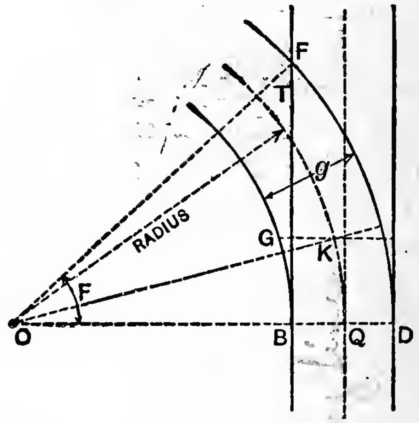


Fig. 142.

rails by arcs of circles which are tangent to the main rails and which extend to the frog-point F. The simple curve from D to F is of such radius that $(r+\frac{1}{2}g)$ vers $F=g$, in which F = the frog angle g = gauge, L = the "lead" (BF), and r = the radius of the *center* of the switch-rails.

$$\therefore r+\tfrac{1}{2}g=\frac{g}{\text{vers } F}. \quad \text{. . . . .} \quad (69)$$

Also, $BF \div BD=\cot \frac{1}{2}F$; $BD=g$; $BF=L$.

$$\therefore L=g \cot F. \quad \text{. . . . .} \quad (70)$$

Also, $$L=(r+\tfrac{1}{2}g)\sin F; \quad \text{(71)}$$

$$QT=2r\sin\tfrac{1}{2}F. \quad \text{(72)}$$

These formulæ involve the angle F. As shown in Table III, the angles (F) are always odd quantities, and their trigonometric functions are somewhat troublesome to obtain closely with ordinary tables. The formulæ may be simplified by substituting the frog-number n, from the relation that $n=\frac{1}{2}\cot\frac{1}{2}F$. Since

$$r-\tfrac{1}{2}g=L\cot F \quad \text{and} \quad r+\tfrac{1}{2}g=L\operatorname{cosec} F,$$

then
$$\begin{aligned} r&=\tfrac{1}{2}L(\cot F+\operatorname{cosec} F)\\ &=\tfrac{1}{2}g\cot\tfrac{1}{2}F(\cot F+\operatorname{cosec} F)\\ &=\tfrac{1}{2}g\cot^2\tfrac{1}{2}F, \text{ since } (\cot a+\operatorname{cosec} a)=\cot\tfrac{1}{2}a\\ &=2gn^2. \quad \text{(73)}\end{aligned}$$

Also, $$L=2gn, \quad \text{(74)}$$

from which $$r=n\times L. \quad \text{(75)}$$

These extremely simple relations may obviate altogether the necessity for tables, since they involve only the frog-number and the gauge. On account of the great simplicity of these rules, they are frequently used as they are, regardless of the fact that the curve is never a uniform simple curve from switch-block to frog. In the first place there is a considerable length of the gauge-line within the frog, which is straight unless it is purposely curved to the proper curve while being manufactured, which is seldom if ever done—except for the very large-angled frogs used for street-railway work, etc. It is also doubtful whether the switch-rails (BA, Fig. 135) are bent to the computed curve when the rails are set for the switch. The switch-rails of point switches are *straight*, thus introducing a stretch of straight track which is about one-fifth of the total length of the lead-rails. The effect of these modifications on the length and radius of the lead-rails will be developed and discussed in the following sections.

The throw (t) of a stub switch depends on the weight of the rail, or rather on the width of its base. The throw must be at least $\frac{3}{4}''$ more than that width. The head-block should therefore be placed at such a distance from the heel of the switch (B) that the versed sine of the arc equals the throw. These points *must* be opposite on the two rails, but the points on the two rails where these relations are exactly true will not be opposite. Therefore, instead of considering either of the two radii $(r+\frac{1}{2}g)$ and $(r-\frac{1}{2}g)$, the mean radius r is used. Then (see Fig. 142)

$$\text{vers } KOQ = t \div r,$$

and the length of the switch-rails is

$$QK = r \sin KOQ. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (76)$$

Stub-switches are generally used with large frog angles. For small frog angles (large frog-numbers) the values of QK are so great that the length of rail left unspiked is too great for a safe track. If this were obviated by spiking down a portion of the lead the theoretical accuracy of the switch would be lost.

The use of stub switches may now be considered obsolete. But the above demonstration has been retained in this edition for its educational value as an introduction to the more complicated method which is now the standard.

305. Standard design, using straight frog-rails and straight point-rails. It becomes necessary in this case to find a curve which shall be tangent to both the point-rail and the frog-rail. The curve therefore begins at M, its tangent making an angle of α (varying from 0° 52′ to 2° 36′) with the main rail, and runs to J. $FJ = W =$ the length of the " wing-rail " from the theoretical point of the frog (F) to the toe, J or J'. $FK = K =$ the length from the theoretical point to the heel of the frog. $MN = H =$ the " heel distance," or the distance of the gauge line of the switch-rail at the heel from the gauge line of the main track rail.

The central angle of the curve equals $(F-a)$. The angle of the chord JM with the main rails is therefore

$$\tfrac{1}{2}(F-a)+a = \tfrac{1}{2}(F+a);$$

$$JM = \frac{g - W \sin F - H}{\sin \frac{1}{2}(F+a)};$$

$$r+\tfrac{1}{2}g=\frac{JM}{2\sin\frac{1}{2}(F-a)}$$

$$=\frac{g-W\sin F-H}{2\sin\frac{1}{2}(F+a)\sin\frac{1}{2}(F-a)}$$

$$=\frac{g-W\sin F-H}{\cos a-\cos F}; \qquad (77)$$

$$DN=s\cos\alpha, \qquad (78)$$

in which S = length of switch-rail.

$$BF=L=JM\cos\tfrac{1}{2}(F+a)+W\cos F+S\cos\alpha$$

$$=(g-W\sin F-H)\cot\tfrac{1}{2}(F+a)+W\cos F+S\cos\alpha. \qquad (79)$$

It may be more simple, if $(r+\frac{1}{2}g)$ has already been computed, to write

$$L=2(r+\tfrac{1}{2}g)\sin\tfrac{1}{2}(F-a)\cos\tfrac{1}{2}(F+a)+W\cos F+S\cos\alpha$$

$$=(r+\tfrac{1}{2}g)(\sin F-\sin a)+W\cos F+S\cos\alpha. \qquad (80)$$

The above equations for L give the distance from the actual (blunt) point of the switch-rail to the *theoretical* point of the frog. The lead (L') given in Table III is the distance from the actual point of the switch-rail to the actual (blunt) point of the frog. The difference (L'—L) is the "frog bluntness," which in each case equals the width of the frog point ($\frac{1}{2}$ inch = .04166 foot) multiplied by the frog number. The values of the frog bluntness for the various frogs is given in the second column of Part B, Table III.

The value of $MN=H$ has been standardized by the A. R. E. A. as $6\frac{1}{4}$ inches for all lengths of switch-rail and for all values of α. The point of the switch-rail (at D) is invariably $\frac{1}{4}$-inch thick. When it is necessary to calculate MN for other standards of construction, it may be computed (calling S = length of switch-rail) to be

$$MN=S\sin\alpha+(\text{thickness of point of switch rail}).$$

The length to the blunt point of the frog ($W=FJ$) is given for each frog in the third column of Table III, Part B. The several values of F and α are also given in Table III. g is the gauge $=4$ feet $8\frac{1}{2}$ inches $=4.7083$ feet.

The solution of Eq. 77–80 for various frog angles will give a series of "theoretical leads," as given in Table III. Part B. The "closure rails," between the switch points and the frog, will invariably have such odd total lengths that there must be at least one rail cutting (and some wastage of rail) for each

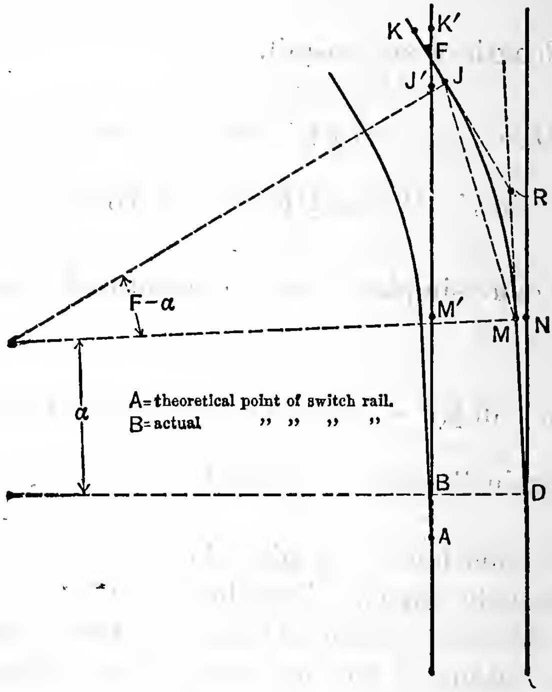


FIG. 143.

closure length. By shortening the radius of the connecting curve very slightly and inserting a very short length of tangent either between the curve and switch-rail at M, or between the curve and frog-rail at J, all of which will change very slightly the length of lead, the closure lengths can be made such that one rail cutting can be eliminated, and yet the combinations of curves and tangents are mathematically perfect. The detailed method of computing these combinations is tedious and will not be elaborated here, but a series of results developed by the A. R. E. A. is given under the heading of "practical leads" in Table III. Part C.

The above computations and tabular values assume that the two switch points (at B and D) are directly opposite. This would always mean that the straight rail (BF) is somewhat shorter than the curved rail from D to F. In the maximum case the difference is less than 4 inches. Therefore, assuming that rails are obtainable at even-foot lengths down to 27 feet, or 24 feet for a No. 4 frog switch, the system of practical leads never requires more than one rail cutting. But even this is sometimes avoided by using for the straight-rail closure the same number and lengths of uncut rails as are specified for the closure of the curved part. The chief effect of this is that the point of the switch-rail will be located a few inches below its normal position at B and that the gauge at the switch-point will be slightly widened when the switch is open. This effect is possibly an advantage rather than a disadvantage.

306. Design for a turnout from the OUTER side of a curved track. Fig. 144 is a diagram of what the construction would be

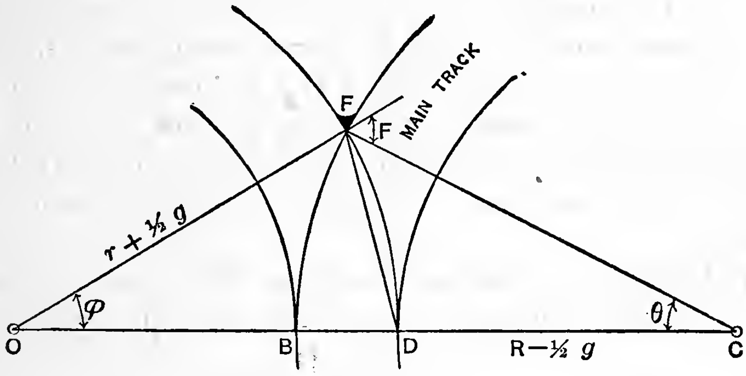


FIG. 144.

if the switch-rails were circular throughout. Before the invention of point switches and when stub switches were in universal use, the lead-rails were considered to be circular, both for straight and for curved main track. If Eqs. 70 and 75 and the corresponding Eqs. 77 to 80 are solved for any given frog, it is found that the lead, when using straight switch-rails and straight frog-rails, is considerably less than when using circular lead-rails throughout; also the curvature is considerably sharper. But stub-rail switches are obsolete and the mathematical solutions used for them cannot be utilized, even approximately, for point switches. If such a diagram as Fig. 144 is worked out in detail, as has been done in previous editions, it is found that (*a*) the lead (*BF*) is almost identical with that computed from Eq. 70 or 74, when the main line is straight.

(*b*) the degree of curve (*d*) of the circular switch-rails would be *very nearly* equal to the degree of curve (*d'*) of the circular switch-rails for a straight track minus the degree of curve (*D*) of the main track; or, $d = d' - D$.

These statements are more exactly true when the degree of curvature of the main track is small. Even for a 10° curve on the main track the errors are not large. It has been found to be a needless refinement to compute the precise mathematical properties of the switch-rails from a curved main track, any more than as given by the two principles stated above: Therefore

(*a*) the length of the lead is assumed to be the same as that for a straight track, using the same frog, and

(*b*) the degree of curve of the switch-rails is found as stated above—in principle (*b*). As the curvature of the main track sharpens, the curvature of the switch-rails becomes less until they become straight. For still sharper main track, the center of curvature is on the same side. This is illustrated in Fig. 145, if we consider the sharper curved track to be the main track and the easier curve the switch. The above rule is still applicable, the algebraic sign of the result showing the location of the center.

307. Design for a turnout from the INNER side of a curved track. As in the previous section, Fig. 145 illustrates the dia-

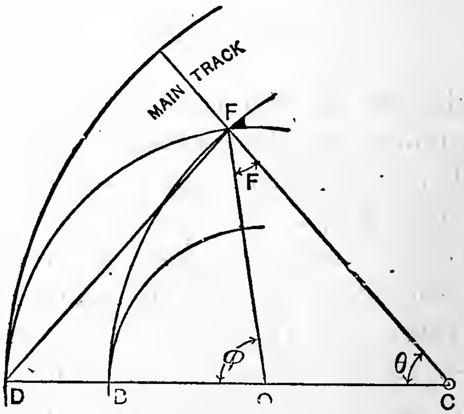


FIG. 145.

gram for circular lead rails. It may be shown that the degree of the turnout (*d*) is *nearly* the *sum* of the degree of the main track (D) and the degree (d') of a turnout from a straight track when the frog angle is the same. The discrepancy in this case is somewhat greater than in the other, especially when the curvature of the main track is sharp. If the frog angle is also large, the curvature of the turnout is excessively sharp. If the frog angle is very small, the liability to derailment is great. Turnouts to the inside of a curved track should therefore be avoided, unless the curvature of the main track is small.

308. Connecting curve from a straight track. The "connecting curve" is the track lying between the frog and the side

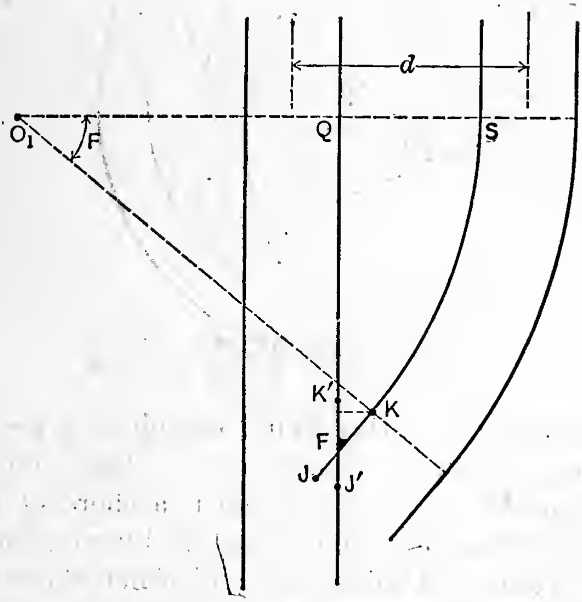


FIG. 146.

track where it becomes parallel to the main track (KS in Fig. 146 or 147). Call d the distance between track centers. The angle $KO_1S = F$ (see Fig. 146). Call r' the radius of the connecting curve. Then

$$(r' - \tfrac{1}{2}g) = \frac{d - g \; - K \sin f}{\text{vers } F}; \quad . \quad . \quad . \quad . \quad . \quad (81)$$

$$FQ = (r' - \tfrac{1}{2}g) \sin F + K \cos f \quad . \quad . \quad . \quad . \quad (82)$$

In these equations (and in several that follow) K is the distance from the theoretical point of the frog to the heel. The length, for each standard frog, is found in Table III, Part B.

309. Connecting curve from a curved track to the OUTSIDE. When the main track is curved, the required quantities are the radius of the connecting curve from K to S, Fig. 147, and its length or central angle.

The accuracy of all these computations on switches and frogs in curved main track is vitiated by the fact that the frog-rails are straight. The design might be mathematically more perfect if the main track curve were transformed into two curves on either side of the frog which had centers separated as far as the length of the frog, but this would introduce a very great and needless complication and is never done. The more simple solution is to consider that the frog-rail is a chord of the original curve, which (*a*) narrows the track gauge by an amount equal to the middle ordinate of that chord and which (*b*) is not tangent to the curve at either end. For all ordinary curvature neither of these theoretical defects is vitally objectionable or even appreciable. In Fig. 147 KC is practically perpendicular to one frog-rail and KO_1 is exactly perpendicular to the other frog-rail. Therefore, the angle CKO_1 equals the frog angle F. While the following calculations are amply precise for practical purposes, the discrepancy from strict mathematical accuracy should be noted and properly valued.

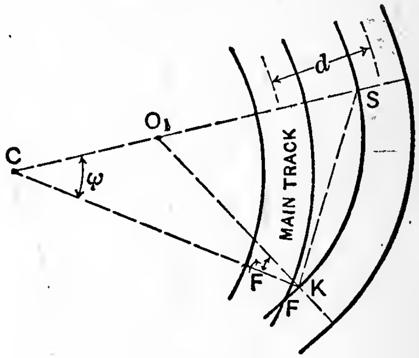


FIG. 147.

In the triangle CSK

$$CS+CK:CS-CK::\tan\tfrac{1}{2}(CKS+CSK):\tan\tfrac{1}{2}(CKS-CSK);$$

but $\frac{1}{2}(CKS+CSK)=90-\frac{1}{2}\psi$; and, since the triangle O_1SK is isosceles, $\frac{1}{2}(CKS-CSK)=\frac{1}{2}F$;

$$\therefore 2R+d+K \sin F : d-g-K \sin F :: \cot \tfrac{1}{2}\psi : \tan \tfrac{1}{2}F$$
$$:: \cot \tfrac{1}{2}F : \tan \tfrac{1}{2}\psi;$$

$$\therefore \tan \tfrac{1}{2}\psi = \frac{2n(d-g-K \sin F)}{2R+d+K \sin F}. \qquad (83)$$

From the triangle CO_1K we may derive

$$r-\tfrac{1}{2}g : R+\tfrac{1}{2}g+K \sin F :: \sin \psi : \sin (F+\psi);$$

$$r-\tfrac{1}{2}g = (R+\tfrac{1}{2}g+K \sin F)\frac{\sin \psi}{\sin (F+\psi)}. \qquad (84)$$

Also

$$KS = 2(r-\tfrac{1}{2}g) \sin \tfrac{1}{2}(F+\psi). \qquad (85)$$

310. Connecting curve from a curved track to the INSIDE. As above, it may readily be deduced from the triangle CKS (see Fig. 148) that

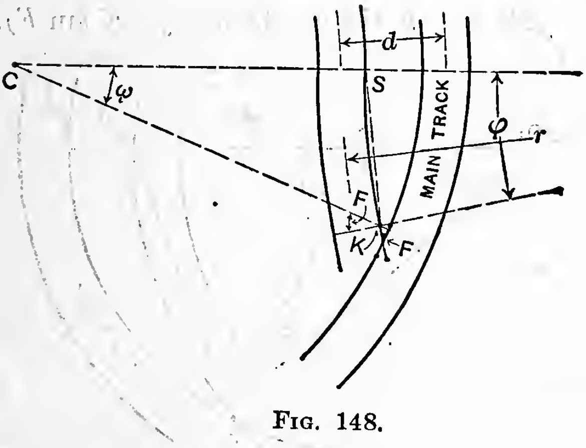


FIG. 148.

$$CK+CS : CK-CS :: \tan \tfrac{1}{2}(CSK+CKS) : \tan \tfrac{1}{2}(CSK-CKS);$$
$$(2R-d-K \sin F) : (d-g-K \sin F :: \cot \tfrac{1}{2}\psi : \tan \tfrac{1}{2}F;$$

$$\tan \tfrac{1}{2}\psi = \frac{2n(d-g-K \sin F)}{2R-d-K \sin F}. \qquad (86)$$

From triangle CO_1K,

$$O_1K : CK :: \sin \psi : \sin (F-\psi);$$
$$(r-\tfrac{1}{2}g) : (R-\tfrac{1}{2}g-K \sin F) :: \sin \psi : \sin (F-\psi);$$

$$(r-\tfrac{1}{2}g) = (R-\tfrac{1}{2}g-K \sin F)\frac{\sin \psi}{\sin (F-\psi)}. \qquad (87)$$

Also

$$KS=2(r-\tfrac{1}{2}g)\sin\tfrac{1}{2}(F-\psi). \quad . \quad . \quad . \quad . \quad (88)$$

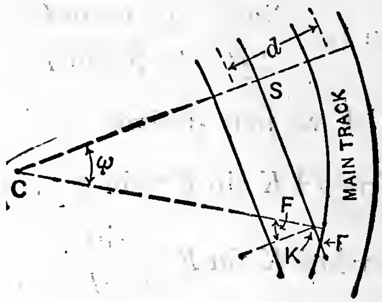


FIG. 149.

Two other cases are possible. (*a*) *r* may increase until it becomes infinite (see Fig. 149), then $F=\psi$. In such a case we may write, by substituting in Eq. 86,

$$2R-d-K\sin F=4n^2(d-g-K\sin F). \quad . \quad . \quad (89)$$

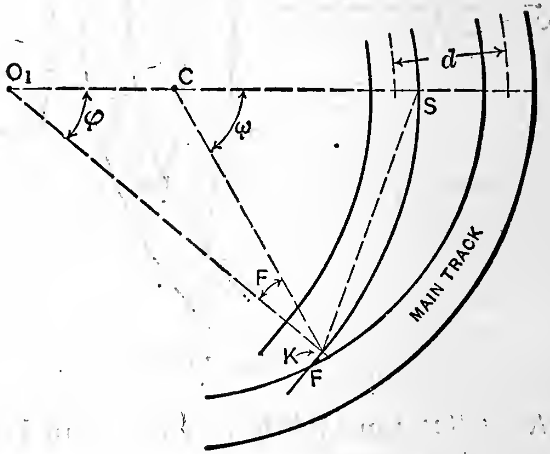


FIG. 150.

This equation shows the value of *R* which renders this case possible. (*b*) ψ may be greater than *F*. As before (see Fig. 150).

$$(2R-d-K\sin F) : (d-g-K\sin F) :: \cot\tfrac{1}{2}\psi : \tan\tfrac{1}{2}F;$$

$$\tan\tfrac{1}{2}\psi=\frac{2n(d-g-K\sin F)}{2R-d-K\sin F}$$

the same as Eq. 86, but

$$(r+\tfrac{1}{2}g=(R-\tfrac{1}{2}g-K\sin f)\frac{\sin\psi}{\sin(\psi-F)}. \quad . \quad . \quad (90)$$

Problem. To find the dimensions of a connecting curve running to the INSIDE of a curved main track; number 9 frog, 4° 30′ curve, $d=13'$, $g=4'\ 8\frac{1}{2}''$.

Solution.

[Eq. 86] $d=13.000$	$K=10'\ 0''$ $K \sin F=1.108$		$\log 2n=1.25527$
5.816	$g=4.708$		
7.184	5.816		
			$\log 7.184=0.85636$
$R=1273.6$	$2R-d-K\sin F=2533.1$		
$2R=2547.2$	$\log=3.40365$		
$(d+K\sin F)=14.108$	co-log $=6.59635$		
			co-log $=6.59635$
			$\log\tan\frac{1}{2}\psi=8.70799$
			$\frac{1}{2}\psi=2°\ 55'\ 20''$
			$\psi=5°\ 50'\ 40''$
			$F=6°\ 21'\ 35''$
			$F-\psi=0°\ 30'\ 55'$

Since $F>\psi$, we must use Eq. 87, rather than Eq. 90.

$\frac{1}{2}g=2.354$	$R-\frac{1}{2}g-K\sin F=1270.1$		$\log=3.10384$
$K\sin F=1.108$	$(F-\psi)=1855''$; $\log$	$=3.26834$	$\log\sin\psi=9.00787$
		4.68557	
sum $=3.462$			
		7.95391	
		co-log $=2.04608$	co-log $=2.04608$
		$r-\frac{1}{2}g=14381.2$	4.15779
		$r=14383.5$	
		$d=0°\ 24'$	

[Eq. 88].		2	0.30103
$\frac{1}{2}(F-\psi)=927.5''$; $\log=2.96731$			
4.68557		$r-\frac{1}{2}g$	4.15779
			7.65289
$\sin\frac{1}{2}(F-\psi)=7.65289$			
		$KS=129.33$	2.11171

311. Crossover between two parallel straight tracks. (See Fig. 151.) The turnouts are as usual. The cross-over track may be straight, or it may be a reversed curve. The reversed curve shortens the total length of track required, but is somewhat objectionable. The first method requires that both frogs must be equal. The second method permits unequal frogs, although equal frogs are preferable. The length of straight crossover track is F_1T.

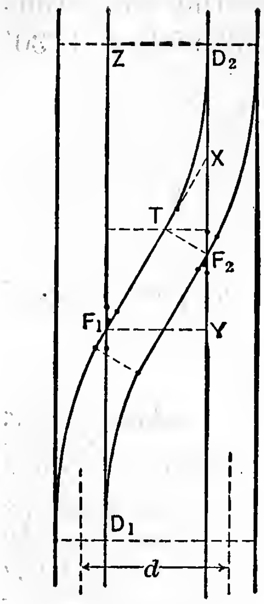


FIG. 151.

$$F_1T \sin F_1 + g \cos F_1 = d - g;$$

$$F_1T = \frac{d-g}{\sin F_1} - g \cot F_1. \quad . \quad . \quad (91)$$

The total distance along the track may be derived as follows:

$$DZ = D_1F_1 + D_2F_2 + F_2Y$$
$$= DF_1 + D_2F_2 + XY - XF_2;$$

$$XY = (d-g) \cot F_1;$$

$$XF_2 = g \div \sin F_2;$$

$$\therefore D_1Z = 2D_1F_1 + (d-g) \cot F_1 - \frac{g}{\sin F_2}. \quad (92)$$

312. Crossover between two parallel curved tracks. Using a straight connecting curve. This solution has limitations. If one frog (F_1) is chosen, F_2 must be determined, being a function of F_1. If F_1 is less than some limit, depending on the width (d) between the parallel tracks, this solution becomes impossible. In Fig. 152 assume F_1 as known. Then $K_1N = g \sec F_1$. In the triangle NOK_2 we have

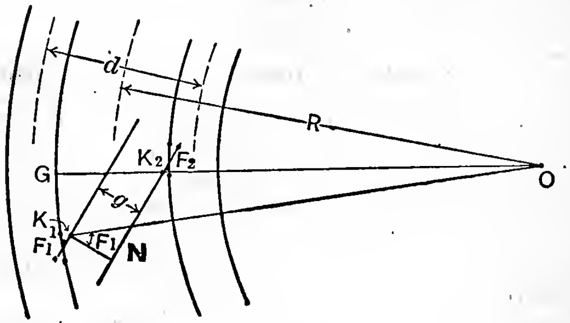


FIG. 152.

$$\sin NK_2O : \sin K_2NO :: NO : K_2O;$$
$$\sin K_2NO = \cos F_1; \quad NK_2O = 90° + F_2;$$
$$\therefore \sin NK_2O = \cos F_2.$$

$$NO = R + \tfrac{1}{2}d - \tfrac{1}{2}g - K_1 \sin F_1 - g \sec F_1; \quad K_2O = R - \tfrac{1}{2}d + \tfrac{1}{2}g + K_2 \sin F_2;$$

$$\therefore \cos F_2 = \cos F_1 \frac{R + \frac{1}{2}d - \frac{1}{2}g - K_1 \sin F_1 - g \sec F_1}{R - \frac{1}{2}d + \frac{1}{2}g + K_2 \sin F_2}. \quad . \quad . \quad (93)$$

The solution of this equation involves the frog angle F_2, which is the angle sought, but there is little error in considering in this solution that $K_2 \sin F_2$ is numerically equal to $K_1 \sin F_1$ and solving accordingly. If the computed value of F_2 is very different from F_1, it would be more precise to recompute Eq. 93 by substituting for $K_2 \sin F_2$ the more exact quantities obtainable from the first trial solution. The relative position of the frogs F_1 and F_2 may be determined as follows:

$$NO_2K = 180° - (90° - F_1) - (90° + F_2) = F_1 - F_2.$$

Then $$GF_1 = 2(R + \tfrac{1}{2}d - \tfrac{1}{2}g) \sin \tfrac{1}{2}(F_1 - F_2) + K_1 \cos F_1. \quad . \quad (94)$$

There is a theoretical, but practically inappreciable, inaccuracy in Eq. 94, since the chord GF_1 is really the sum of two chords of which one is the chord from the point G to the point where ON produced intersects the gauge line. After locating G, the point radially opposite, on the outer gauge line of the inner track, may be located, from which the frog-point F_2 is located at a distance of $K_2 \cos F_2$. Note that these frog-points referred to are the *theoretical* points. Due allowance must be made during location for the "frog bluntness."

In general, the value of F_2 computed from Eq. 93 is *not* the angle of any standard number-frog, and a strict compliance with theory would require that the frog should be made to order. This is needlessly expensive and the nearest size frog may generally be used without appreciable error.

Example. A crossover between parallel tracks on a 6° curve, the track spacing d being 13 feet. F_1 assumed a No. 9 frog.

[Eq. 93]

$R = 955.37$	$\tfrac{1}{2}g = 2.35$	$K_1 = 10$ ft.
$\tfrac{1}{2}d = \ \ 6.5$	$K_1 \sin F_1 = 1.11$	$\sin F_1 = .11077$
961.87	$g \sec F_1 = 4.74$	
$-\ \ 8.20$	8.20	

953.67 . . . . log = 2.97940

$R = 955.37$
$\tfrac{1}{2}g = \ \ 2.35$
$K_2 \sin F_2 = \ \ 1.11$ (assumed = to $K_1 \sin F_1$)
958.83
$-\tfrac{1}{2}d = -6.5$

952.33 . . . . log = 2.97879

0.00061

log cos F_1 . . 9.99732

$F_2 = 5° 35' 30''$ log cos 5° 35′ 30″ 9.99793

This angle is within 8 minutes of the angle of a No. 10 frog, which could be used without appreciable error. The point K_2 would be shifted laterally .023 foot, or about $\frac{1}{4}$ inch, but there would be no visible irregularity in alinement.

$$NOK_2 = F_1 - F_2 = 6° \, 21' \, 35'' - 5° \, 35' \, 30'' = 0° \, 46'.$$

[Eq. 94]	$R + \frac{1}{2}d = 961.87$		
	$-\frac{1}{2}g = -2.35$	2 . .	$\log = 0.30103$
	959.52	. . . .	$\log = 2.9820\bar{5}$
		$\sin \frac{1}{2} NOK_2 = \sin 0° \, 23' =$	7.82545
		12.84	$\log = 1.1085\bar{3}$
		$K_1 \cos F_1 = 9.94$	
		$GF_1 = 22.78$	

It is instructive to note that if the same crossover problem is worked out for a straight track, as in § 311, using No. 9 frogs on both tracks, the distance between frog points, measured parallel with the track, is nearly the same as in the above problem, especially when the distance 12.84, measured on the outer track, is reduced by bringing it in to the center line. This is analogous to the statement, previously made, that the lead of a switch on a curved track is nearly the same as that for a straight track.

It is theoretically possible to find two standard frog angles which may be so located that the connecting curve consists of straight lines and circular curves, which connect tangentially, making perfect alinement, but such methods are very complicated and the above method is sufficiently exact for practical purposes.

313. Practical rules for switch-laying. A consideration of the previous sections will show that the formulæ are comparatively simple when the lead-rails are assumed as circular; that they become complicated, even for turnouts from a straight main track, when the effect of straight frog and point rails is allowed for, and that they become hopelessly complicated when allowing for this effect on turnouts from a curved main track. It is also shown (§ 306) that the length of the lead is practically the same whether the main track is straight or is curved with such curves as are commonly used, and that the degree of curve of the lead-rails from a curved main track may be found with close approximation by mere addition or subtraction. From this it may be assumed that if the length of lead (L) and the radius of the lead-rails (r) are computed from Eq. 77 and 80 for various frog angles, the same leads may be used for curved main track; also, that the degree of curve of the lead-rails may be found by addition or subtraction, as indicated in § 306, and that the approximations involved will not be of practical detriment. In accordance with this plan Table III has been computed from Eq. 77, 78 and 80. The *leads* there given may be used for all main tracks, straight or curved. The table gives the degree of curve of the lead-rails for *straight* main track; for a turnout to the *inside, add* the degree of curve of the main track; for a turnout to the *outside, subtract* it.

But there are complications resulting from practical and economical switch construction. A committee of the A. R. E. A., in 1921, adopted certain standards in details, which, when applied to Eqs. 77 to 80 give the values for switch dimensions as quoted in the second section of Table III. They adopted four lengths of switch-rails. In each case the "point" is always $\frac{1}{4}''$ thick. The gauge line at the other end is always to be placed $6\frac{1}{4}''$ from the gauge line of the main rail, and the planing is so done that when in this position the switch-rail lies against the main rail. Therefore the angle α is always an angle whose sine equals 6 inches (or 0.5 foot) divided by the length of the switch-rail in feet. In Fig. 153, the point D is not on the gauge line of the main rail but at a point $\frac{1}{4}''$ away from it, and the point M $6\frac{1}{4}''$ away from it. The straight rail BF consists of a point-rail at one end, the "closure rails," and one of the toe rails of the frog at the other end. The closure rails will in general consist of one rail cut to a computed length and one or more rails from 24 to 33 feet long, the lengths being in even feet. The curved rail DF will also consist of a point-rail, a frog toe-rail, and one or more lengths of closure rail, but the closure rails in this case are slightly longer than those for the straight rail. Since it is always practically easier to measure to the "actual point" of a frog (see Fig. 134), rather

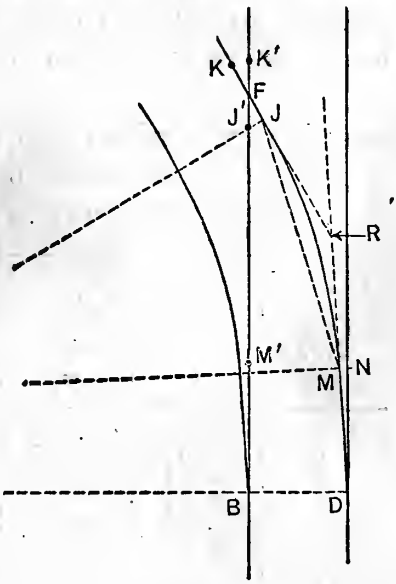


FIG. 153.

than to the theoretical point, Table III gives the distance L', which is the distance $L = BF$, plus the "frog bluntness," which is found by multiplying $\frac{1}{2}''$ (=0.0417 foot) by the frog number.

The curvature for a curved switch-rail (for a straight track) is most readily determined by measuring off a series of ordinates whose origin is at the switch-point D, Fig. 153, the points being the center and the quarter points of the actual curve. More accurately, the origin is on the gauge line of the main rail, opposite D, which is $\frac{1}{4}''$ from the gauge line. These ordinates, as computed on the basis of "practical leads," by the A. R. E. A. committee, are quoted below. It should be remembered that the system of practical leads usually involves a very short tangent adjacent to either M or J, and that the line MJ for "practical leads" is not entirely an arc.

TABLE XXV.—RECTANGULAR COORDINATES TO THE QUARTER AND CENTER POINTS ON THE GAUGE SIDE OF CURVED RAIL, REFERRED TO POINT OF SWITCH-RAIL AS ORIGIN.

Frog No.	Measured along main rail.			Measured perpendicular to main rail.		
	X	X_1	X_2	Y	Y_1	Y_2
5	17.92	24.83	31.75	0.97	1.69	2.69
6	19.19	27.37	35.56	1.03	1.79	2.83
7	26.71	36.92	47.12	0.98	1.72	2.76
8	28.10	39.71	51.31	1.005	1.77	2.80
9	28.75	40.98	53.19	1.02	1.76	2.75
10	30.28	44.05	57.81	1.04	1.79	2.78
11	40.74	56.47	72.19	1.08	1.84	2.87
12	43.99	60.65	77.28	1.15	1.90	2.91
14	41.10	60.21	79.31	1.08	1.87	2.91
15	52.00	74.00	96.00	1.03	1.81	2.86
16	53.23	76.46	99.69	1.04	1.83	2.89
18	54.73	79.46	104.19	1.06	1.86	2.91
20	57.75	85.50	113.25	1.10	1.91	2.95

If the position of the switch-block is definitely determined, then the rails must be cut accordingly; but when some freedom is allowable (which never need exceed 16.5 feet and may require but a few inches), one rail-cutting may be avoided. Mark on the rails at B, F, and D; measure off the length DN and locate the point M at the distance $6\frac{1}{4}''$ from N. If the frog must be placed during the brief period between the running times of trains, it will be easier to joint up to the heel of the frog (the point K', Fig. 153), a piece of rail, the farther end of which will just reach the next joint and also joint up to the toe of the frog the straight closure rail and the point-rail. Then, when all is ready, the rails are loosened from the ties back to B, the joint beyond the frog is removed and the whole rail back to B is swung outward. The new combination is shoved into place and spiked, even the point-rail being temporarily spiked to hold it in place as a main track rail, until the other switch-rail and the tie rods can be placed. When the frog is thus in place, the point J becomes located. The curved closure rails, as called for in Table III, should prove to be just long enough, when properly curved, to fill in the gap between M and J. Using the proper pairs of values for X and Y as given above, the three values of X may be measured on the main track rail from the point D, and the corresponding offsets will give points on the curved switch-rail. The old main track rail which was bent outward from B may be utilized as the other switch-rail and set to gauge from the rail just located.

Example.—Given a main track on a 4° curve—a turnout to the outside, using a No. 9 frog; gauge 4′ 8½″; $W=6'.00$; $H=6\frac{1}{4}''$; $S=16'\ 6''$ and $a=1°\ 44'\ 11''$ Then for a *straight* track r would equal 605.18 [$d=9°\ 28'\ 42''$]. For this curved track d will be nearly $9°\ 29'-4°=5°\ 29'$, or r will be 1045.3. L' for a *straight* track would be 72.28, and is here considered to be the same. The closure rails have a total arc length of 49.59, and will here be taken the same. Note that the curved and straight closure rails each have odd lengths which are made by one cut of a 33-foot rail. This avoids all rail waste and also one rail-cutting and the boring of holes.

314. Slips. Track movements in crowded yards are facilitated by using " slips " (see Fig. 154), which may be " single " or " double." The crossing of two rails is done either by operating two movable rails or by using fixed " frogs," but a comparison of the continuity of the running rails, using ordinary frogs (see Fig. 134) and these frogs, will show their radical difference. These slips can be used for frog angles from No. 6 to No. 15. The levers are so connected that the several operations necessary to set the rails for any desired train movement are accomplished by one motion,

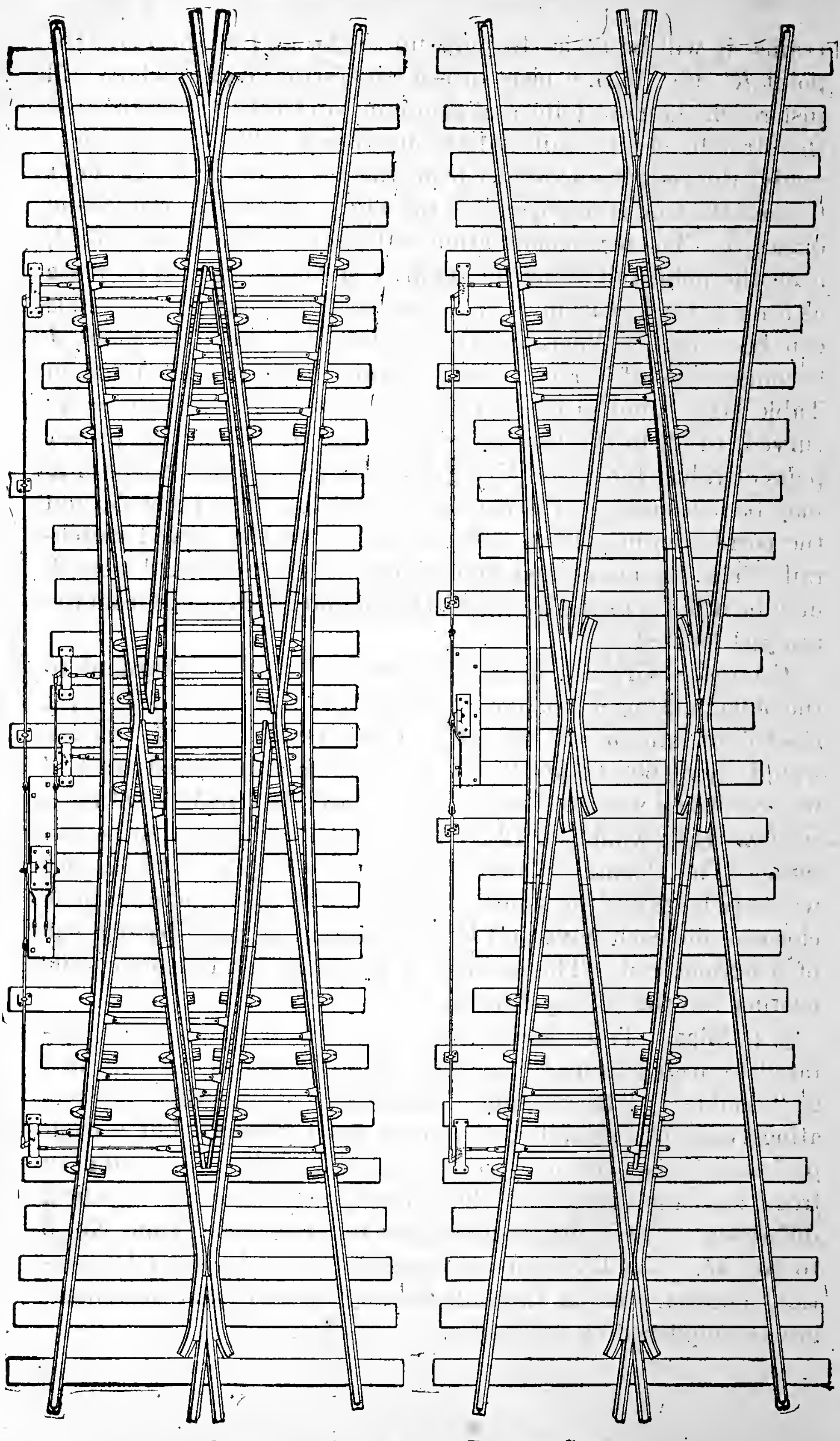


FIG. 154.—SINGLE AND DOUBLE SLIPS.

CROSSINGS.

315. Two straight tracks. When two straight tracks cross each other, four frogs are necessary, the angles of two of them being supplementary to the angles of the other. Since such crossings are sometimes operated at high speeds, they should be

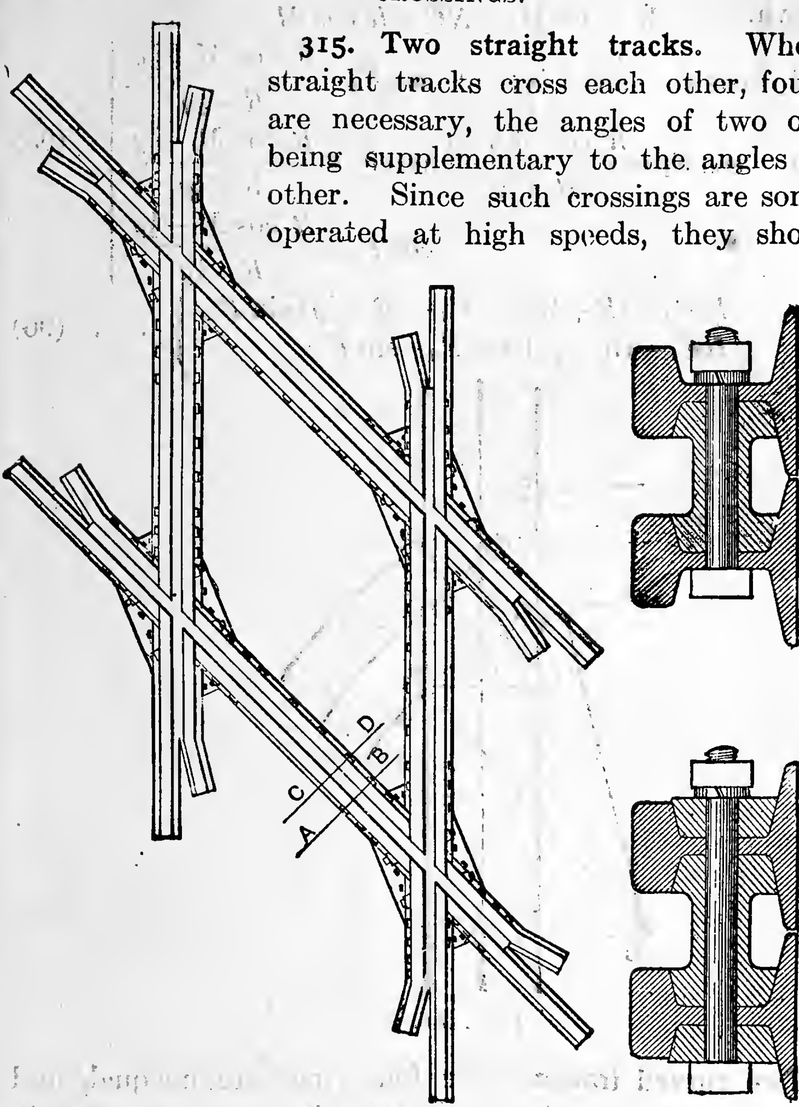


FIG. 155.—CROSSING.

very strongly constructed, and the angles should preferably be 90° or as near that as possible. The frogs will not in general be "stock" frogs of an even number, especially if the angles are large, but must be made to order with the required angles as measured. In Fig. 155 are shown the details of such a crossing. Note the fillers, bolts, and guard-rails.

316. One straight and one curved track. Structurally the crossing is about the same as above, but the frog angles are all unequal. In Fig. 156, R is known, and the angle M, made by the center lines of the tracks at their point of intersection, is also known. $M=NCM. \quad NC=R\cos M.$

$$\left.\begin{aligned} (R-\tfrac{1}{2}g)\cos F_1 &= NC+\tfrac{1}{2}g; \quad \therefore \cos F_1=\frac{R\cos M+\tfrac{1}{2}g}{R-\tfrac{1}{2}g}. \\ \text{Similarly} \quad \cos F_2 &= \frac{R\cos M+\tfrac{1}{2}g}{R+\tfrac{1}{2}g}, \quad \cos F_3=\frac{R\cos M-\tfrac{1}{2}g}{R+\tfrac{1}{2}g}, \\ \cos F_4 &= \frac{R\cos M-\tfrac{1}{2}g}{R-\tfrac{1}{2}g}. \end{aligned}\right\} \quad (95)$$

$$\left.\begin{aligned} F_3F_4 &= (R+\tfrac{1}{2}g)\sin F_3-(R-\tfrac{1}{2}g)\sin F_4; \\ HF_4 &= (R-\tfrac{1}{2}g)(\sin F_4-\sin F_1). \end{aligned}\right\} \quad . \quad . \quad (96)$$

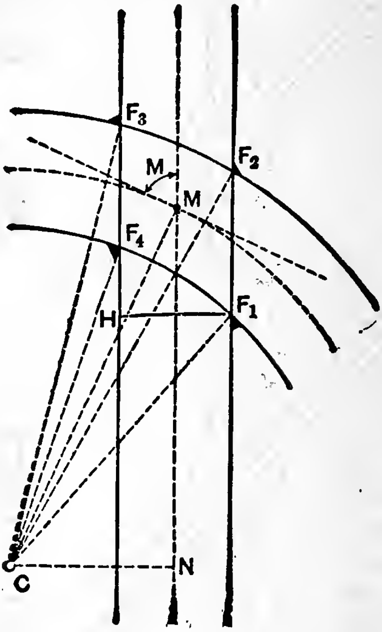


FIG. 156.

317. Two curved tracks. The four frogs are unequal, and the angle of each must be computed. The radii R_1 and R_2 are known; also the angle M. r_1, r_2, r_3 and r_4 are therefore known by adding or subtracting $\frac{1}{2}g$, but the lines are so indicated for brevity. Call the angle $MC_1C_2=C_1$, the angle $MC_2C_1=C_2$, and the line $C_1C_2=c$. Then

$$\tfrac{1}{2}(C_1+C_2)=90^\circ-\tfrac{1}{2}M$$

and

$$\tan\tfrac{1}{2}(C_1-C_2)=\cot\tfrac{1}{2}M\frac{R_2-R_1}{R_2+R_1} \quad . \quad . \quad . \quad . \quad (97)$$

C_1 and C_2 then become known and

$$c=C_1C_2=R_2\frac{\sin M}{\sin C_1} \quad . \quad . \quad . \quad . \quad . \quad (98)$$

In the triangle $F_1C_1C_2$, call $\frac{1}{2}(c+r_1+r_4)=s_1$; $s_2=\frac{1}{2}(c+r_2+r_4)$;

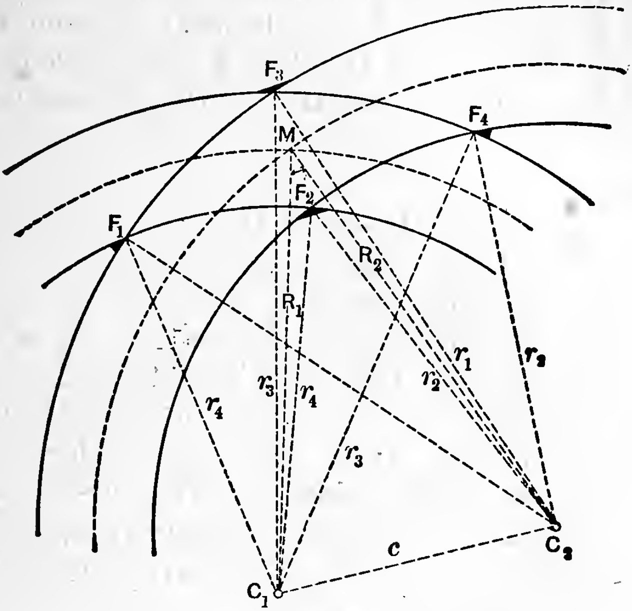


FIG. 157.

$s_3=\frac{1}{2}(c+r_1+r_3)$; and $s_4=\frac{1}{2}(c+r_2+r_3)$. Then, by formula 29, Table XIV,

$$\left.\begin{aligned} \text{vers } F_1 &= \frac{2(s_1-r_1)(s_1-r_4)}{r_1r_4}. \\ \text{Similarly} \qquad \text{vers } F_2 &= \frac{2(s_2-r_2)(s_2-r_4)}{r_2r_4}, \\ \text{vers } F_3 &= \frac{2(s_3-r_1)(s_3-r_3)}{r_1r_3}, \\ \text{vers } F_4 &= \frac{2(s_4-r_2)(s_4-r_3)}{r_2r_3}. \end{aligned}\right\} \quad \ldots\ldots \quad (99)$$

$$\sin C_1C_2F_4 = \sin F_4\frac{r_3}{c};$$

$$\sin C_1C_2F_2 = \sin F_2\frac{r_4}{c};$$

$$\therefore \quad F_2C_2F_4 = C_1C_2F_4 - C_1C_2F_2, \quad \ldots\ldots \quad (100)$$

$$\sin F_1C_1C_2 = \sin F_1\frac{r_1}{c};$$

$$\sin F_2C_1C_2 = \sin F_2\frac{r_2}{c},$$

$$\therefore \quad F_1C_1F_2 = F_1C_1C_2 - F_2C_1C_2; \quad \ldots\ldots \quad (101)$$

from which the chords F_1F_2 and F_2F_4 are readily computed.

F_1F_2 and F_2F_4 are nearly equal. When the tracks are straight and the gauges equal, the quadrilateral is equilateral.

Problem. Required the frog angles and dimensions for a crossing of two curves ($D_1=4°$; $D_2=3°$) when the angle of their tangents at the point of intersection $=62° 28'$ (the angle M in Fig. 157).

Solution

$$R_1=1432.7;\ R_2=1910.1;$$
$$r_1=R_2+\tfrac{1}{2}g=1910.1+2.35=1912.45;$$
$$r_2=R_2-\tfrac{1}{2}g=1910.1-2.35=19C7.75;$$
$$r_3=R_1+\tfrac{1}{2}g=1432.7+2.35=1435.05;$$
$$r_4=R_1-\tfrac{1}{2}g=1432.7-2.35=1430.35.$$

Eq. 97. $\log\cot\tfrac{1}{2}M=0.21723$

$R_2-R_1=477.4;$ $\log=2.67888$

$R_2+R_1=3342.8;$ $\log=3.52411;$ co-log $=6.47589$

$\tfrac{1}{2}(C_1-C_2)=13° 15' 07'';$ $\tan 13° 15' 07''=9.37200$

$\tfrac{1}{2}(C_1+C_2)=58° 46'$ $[\tfrac{1}{2}(C_1+C_2)=90°-\tfrac{1}{2}M]$

$C_1=72° 01' 07''$

$C_2=45° 30' 53''$

Eq. 98. $\log R_2=3.28105$

$\log\sin M=\bar{9}.94779$

$\log\sin C_1=9.97825;$ co-log $=0.02175$

$c=C_1C_2=1780.7;$ $\log C_1C_2=3.25059$

Eq. 99.

$c=1780.7$	$c=1780.7$	$c=1780.7$	$c=1780.7$
$r_1=1912.45$	$r_2=1907.75$	$r_1=1912.45$	$r_2=1907.75$
$r_4=1430.35$	$r_4=1430.35$	$r_3=1435.05$	$r_3=1435.05$
2|5123.50	2|5118.80	2|5128.20	2|5123.50
$s_1=2561.75$	$s_2=2559.40$	$s_3=2564.10$	$s_4=2561.75$
$s_1-r_1=$ 649.30	$s_2-r_2=$ 651.65	$s_3-r_1=$ 651.65	$s_4-r_2=$ 654.00
$s_1-r_4=1131.40$	$-r_4=1129.05$	$s_3-r_3=1129.05$	$s_4-r_3=1126.70$

$\log 2=0.30103$

$(s_1-r_1);$ $\log 649.30=2.81244$

$(s_1-r_4);$ $\log 1131.40=3.05361$

$r_1=1912.45;$ $\log=3.28159;$ co-log $=6.71841$

$r_4=1430.35;$ $\log=3.15544;$ co-log $=6.84456$

$F_1=62° 25' 31'';$ log vers $62° 25' 31''=9.73006$

$\log 2=0.30103$

$(s_2-r_2);$ $\log 651.65=2.81401$

$(s_2-r_4);$ $\log 1129.05=3.05271$

$r_2=1907.75;$ $\log=3.28052;$ co-log $=6.71948$

$r_4=1430.35;$ $\log=3.15544;$ co-log $=6.84456$

$F_2=62° 33' 55'';$ log vers $62° 33' 55''=9.73180$

	log 2 = 0.30103
	$(s_3 - r_1)$; log 651.65 = 2.81401
	$(s_3 - r_3)$; log 1129.05 = 3.05271
r_1 = 1912.45; log = 3.28159;	co-log = 6.71841
r_3 = 1435.05; log = 3.15686;	co-log = 6.84313
F_3 = 62° 21′ 57″;	log vers 62° 21′ 57″ = 9.72930
	log 2 = 0.30103
	$(s_4 - r_2)$; log 654.00 = 2.81558
	$(s_4 - r_3)$; log 1126.70 = 3.05181
r_2 = 1907.75; log = 3.28052;	co-log = 6.71948
r_3 = 1435.05; log = 3.15686;	co-log = 6.84313
F_4 = 62° 30′ 14″;	log vers 62° 30′ 14″ = 9.73103

As a check, the *mean* of the frog angles = 62° 27′ 54′, which is within 6″ of the value of M.

Eq. 100.	log sin F_4 = 9.94794
	log r_3 = 3.15686
log c = 3.25059;	co-log c = 6.74940
$C_1C_2F_4$ = 45° 37′ 51″;	sin $C_1C_2F_4$ = 9.85421
	log sin F_2 = 9.94818
	log r_4 = 3.15544
	co-log c = 6.74940
$C_1C_2F_2$ = 45° 28′ 17″;	sin $C_1C_2F_2$ = 9.85303
$F_2C_2F_4$ = 45° 37′ 51″ − 45° 28′ 17″ = 0° 09′ 34″.	
	log 2 = 0.30103
	log r_2 = 3.28052
½(0° 09′ 34″) = 0° 04′ 47″;	log sin = (4.68557, 2.45788)
F_2F_4 = 5.309;	log F_2F_4 = 0.72500
Eq. 101.	sin F_1 = 9.94763
	log r_1 = 3.28159
	co-log c = 6.74940
$F_1C_1C_2$ = 72° 10′ 22″;	sin $F_1C_1C_2$ = 9.97863
	sin F_2 = 9.94818
	log r_2 = 3.28052
	co-log c = 6.74940
$F_2C_1C_2$ = 71° 57′ 38″;	sin $F_2C_1C_2$ = 9.97811
$F_1C_1F_2$ = 72° 10′ 22″ − 71° 57′ 38″ = 0° 12′ 44″.	
	log 2 = 0.30103
	log r_4 = 3.15544
½(0° 12′ 44″) = 0° 06′ 22″;	log sin = (4.68557, 2.58206)
F_1F_2 = 5.298;	log F_1F_2 = 0.72411

As a check, F_2F_4 and F_1F_2 are very nearly equal, as they should be.

The foregoing problems on switches, connecting curves and crossings cover only a few of the most common of the problems encountered by the engineer. For the solution of a far wider range of problems, the engineer is referred to "Track Formulæ and Tables," by S. S. Roberts. [Wiley & Sons.]

CHAPTER XII.

MISCELLANEOUS STRUCTURES AND BUILDINGS.

WATER-STATIONS AND WATER-SUPPLY.

318. Location. The water-tank on the tender of a locomotive has a capacity of from 3000 to 10000 gallons—sometimes less, rarely very much more. The consumption of water is very variable, and will correspond very closely with the work done by the engine. On a long down grade it is very small; on a ruling grade, going up, using full stroke, an engine with 28-in. cylinders, 30-in. stroke, 180 lbs. boiler pressure, will use 4.59 lbs. of steam, or water, per stroke or 18.36 pounds per revolution. With 63-in. drivers, the circumference is 16.5 feet and there will be 320 revolutions per mile. The engine will use 5875 lbs. or 700 gallons of water per mile. This engine has a tank capacity of 9000 gallons, which would permit running about 12 miles at full stroke. But it is very rare that a locomotive must work for such long distances at full stroke. After starting and attaining full normal speed, the valves may be set to cut off at one-fourth stroke, or even at one-fifth or one-sixth for high speed running. With ordinary grades, such an engine might average 200 gallons per mile, in both directions. A quoted numerical case is that of a 106-ton engine using 7,500,000 gallons during an annual mileage of 45000 miles. This means an average of 167 gallons per mile. Observations were taken in 1910, on the N. Y. Central R.R., where the grades are moderate, showing that the heavy passenger trains of eight to twelve cars consumed 80 to 100 gallons of water per mile and that freight trains of about fifty loaded cars consumed from 110 to 130 gallons per mile. These figures are far less than those given above, but the grades on the N. Y. Central are very light.

Freight engines, running at lower speeds and longer cut-off, require more frequent water-tanks than passenger engines. Even before a road is built, the water-tank requirements and the minimum spacing may be computed on the basis of the steam consumption (see § 454), of the locomotives with which it is expected to handle the estimated traffic of the road. Usually tanks will be located at intervals of 10 to 20 miles.

In the early history of some of the Pacific railroads it was necessary to attach one or more tank-cars to each train in order to maintain the supply for the engine over stretches of 100 miles and over where there was no water. Since then water-stations have been obtained at great expense by boring artesian wells. The individual locations depend largely on the facility with which a sufficient supply of suitable water may be obtained. Streams intersecting the railroad are sometimes utilized, but if such a stream passes through a limestone region the water is apt to be too hard for use in the boilers. More frequently wells are dug or bored. When the local supply at some determined point is unsuitable, and yet it is necessary to locate a water-station there, it may be found justifiable to pipe the water several miles. The construction of municipal water-works at suitable places along the line has led to the frequent utilization of such supplies. In such cases the railroad is frequently the largest single consumer and obtains the most favorable rates. When possible, water-stations are located at regular stopping points and at division termini.

319. Required qualities of water. Chemically pure water is unknown except as a laboratory product. The water supplied by wells, springs, etc., is always more or less charged with calcium and magnesium carbonates and sulphates, as well as other impurities. The evaporation of water in a boiler precipitates these impurities to the lower surface of the boiler, where they sometimes become incrusted and are difficult to remove. The protection of the iron or steel of a boiler from the fierce heat of the fire depends on the presence of water on the other side of the surface, which will absorb the heat and prevent the metal from assuming an excessively high temperature. If the water side of the metal becomes covered or incrusted with a deposit of chemicals, the conduction of heat to the water is much less free, the metal will become more heated and its deterioration or destruction will be much more rapid. An especially common effect is the production of leaks around the joints between tubes and tube-sheets and the joints in the boiler-plates. Such injury can only be prevented by the application of one (or more) of three general methods—(*a*) the mechanical cleaning of the boilers, (*b*) the chemical purification of the water before its introduction into the boiler, and (*c*) the use of some "boiler compound" which is introduced directly into the boiler and which causes precipitation of the harmful ingredients as non-incrusting solids which can be readily blown out.

320. Mechanical cleaning, as a sole dependence is impracticable except in the comparatively rare localities where the water is so "soft" that no incrusting deposits will be made and such precipitation as does take place is of such a character that it is removable by blowing out the boiler. There are many railroads, especially the smaller ones, which do not give any chemical treatment to any of their engine water-supply, and yet which are not fortunate enough to obtain even approximately soft water. The only method by which such roads can prevent a great waste of heat and the rapid deterioration of boiler tubes and sheets is by frequent mechanical cleaning.

321. Chemical purification before the water enters the boiler has the advantage of removing the troublesome ingredients, leaving nothing further to be done except the occasional removal, by blowing out, of the suspended matter or harmless matter precipitated by boiling. Sodium carbonate is the most common reagent. It is commercially sold as "soda crystals, sal soda, washing soda, Scotch soda, concentrated crystal soda, sesquicarbonate of soda, crystal carbonate of soda, black ash, soda ash and pure alkali." Although often chemically impure, it can now readily be obtained with a purity of 97 to 99%. The chemicals which are most common as incrustants are calcium and magnesium carbonates and sulphates. The effect of sodium carbonate on calcium sulphate is to produce soluble sodium sulphate—which is non-incrustant—and calcium carbonate, which precipitates into a sludge at the bottom of the water softener tank. The action on magnesium sulphate is similar. When this is done in a purifying tank, the purified water is drawn off from the top of the tank and supplied pure to the engines. The precipitants are drawn off from the settling-basin at the bottom of the tank. This purification, which makes no pretense of being chemically perfect, may be accomplished for a few cents per 1000 gallons. There are manufacturers which make a specialty of machinery, working more or less automatically, which introduces into the raw water a measured amount of chemical which, by analysis, has been calculated to be necessary with that particular quality of water. In spite of the automatic features, such machinery needs constant attention, and the water, both raw and treated, needs frequent analysis to insure efficiency, since the character of the raw water may change.

Sodium hydrate, or "caustic soda," has the same general chemical effect as sodium carbonate, and acts more quickly and powerfully, but its caustic nature makes it somewhat objectionable to handle. Common lime, barium hydrate, and many other chemicals are also more or less used.

In the following tabular form is given the quantities of reagents required per unit of scaling or corroding substance held in solution, the table being copied from the 1915 Manual of the Amer. Rwy. Eng. Assoc. "Where the commercial product is not chemically pure, the proportion of reagents should be increased to correspond with an equivalent quantity of pure reagent. Given the analysis of a water, the pounds of incrusting or corrosive matter held in solution per 1000 gallons can be obtained by dividing the grains per gallon of each substance by seven, or the parts per 100,000 by twelve. In order to ascertain the full amount of lime necessary, the amount of free carbonic acid contained in the water should be determined, as well as the solids contained in solution, since this free acid must be eliminated in

TABLE XXVI. QUANTITY OF PURE REAGENTS REQUIRED TO REMOVE ONE POUND OF INCRUSTING OR CORROSIVE MATTER FROM THE WATER.

Incrusting or corrosive substance held in solution.	Amount of reagent (pure).	Foaming matter increased
Sulphuric acid	0.57-lb. lime plus 1.08 lbs. soda ash	1.45 lbs.
Free carbonic acid	1.27 lbs. lime	None
Calcium carbonate	0.56-lb. lime	None
Calcium sulphate	0.78-lb. soda ash	1.04 lbs.
Calcium chloride	0.96-lb. soda ash	1.05 "
Calcium nitrate	0.65-lb. soda ash	1.04 "
Magnesium carbonate	1.33 lbs. lime	None
Magnesium sulphate	0.47-lb. lime plus 0.88 lb. soda ash	1.18 lbs.
Magnesium chloride	0.59-lb. lime plus 1.11 lbs. soda ash	1.22 "
Magnesium nitrate	0.38-lb. lime plus 0.72-lb. soda ash	1.15 "
Calcium carbonate	3.15 lbs. barium hydrate	None
Magnesium carbonate	3.76 lbs. barium hydrate	None
Magnesium sulphate	2.62 lbs. barium hydrate	None
Calcium sulphate *	2.32 lbs. barium sulphate	None

* In precipitating the calcium sulphate, there would also be precipitated 0.74 lb. of calcium carbonate or 0.31 lb. of magnesium carbonate, the 2.32 lbs. of barium hydrate performing the work of 0.41 lb. of lime and 0.78 lb. of soda ash, or for reacting on either magnesium or calcium sulphate, 1 lb. of barium hydrate performs the work of 0.18 lb. of lime plus 0.34 lb. of soda ash, and the lime treatment can be correspondingly reduced.

order to obtain efficient treatment of water and reduce scaling matter to the minimum."

322. Foaming and priming. This phenomenon is the foaming or frothing of the water for a considerable height above its normal level in the boiler. The rapid flow of steam into the steam pipe in the dome mechanically carries some of this froth into the steam pipe and causes water to accumulate in the steam pipe and also in the cylinders, with considerable resulting loss in efficiency. Foaming in treated water is largely due to the presence of sodium salts as a result of treatment for incrusting sulphates, and this constitutes one of the objections to the use of soda in treating water. The presence of suspended matter in the water aggravates and even causes foaming. The constant withdrawal of the water from the boiler leaves these suspended solids in the boiler and they keep accumulating until the concentrations reach a critical point, which is about 100 grains per gallon. Beyond this point foaming will be experienced unless the water is changed, which is done by a systematic blowing-off and an occasional complete blowing-down and washing. But blowing-off involves the wastage of water which has been heated to boiler temperature and which has, perhaps, been chemically treated. Even the raw water costs something, perhaps several cents per 1000 gallons. The blowing-off required to keep the concentration below the proper limit may be so excessive that some anti-foaming agent may be necessary. The required effect is physical rather than chemical, the object being to reduce the surface tension, which is done chiefly by the use of oils, petroleum and castor oil being used. Tannic acids are also used for such a purpose.

323. Boiler compounds. Chemical treatment at special plants along the road is unquestionably the most efficient method, but it is costly. The use of boiler compounds, often patented, obviates the erection of any plant, but, since the water at each water-supply station has its own characteristics and it is impracticable to vary the chemicals used at each supply-station according to the character of the water, the treatment is very imperfect. Minute instructions to enginemen to introduce definite amounts of chemical at each water-station have proved unsatisfactory and impractical. Sometimes the chemical is mixed with enough water to partially suspend it and then it is thrown into the tender tank, this method having the advantage that a considerable part of the precipitation takes place promptly and the sludge never enters the boiler. Sometimes a siphon attached to the feed-pipe outside of the injector, or, perhaps, a special injector, leads from a reservoir in which the chemical, suspended in water, has been placed. Sometimes a stick or "brick" of the chemical is placed directly in the boiler, through a hand-hole, during one of its periodical cleanings. In spite of the inefficiency of the method, 70% of replies to a circular inquiry reported the use of some kind of boiler compound. The chemicals used, some of which are patented compounds, are in general the same as those used in the outside chemical plants. Sodium carbonate is the most common constituent.

324. **Tanks. Height above rail.** Whatever the source, the water must be led or pumped into tanks which are supported on columns so that the bottoms of the tanks are high enough above the track to force a flow of 2500 gallons of water per minute through a 12-inch spout. The frictional resistance in the pipes, elbows, valves, etc., are such that, allowing that the spout is 12 feet above the rail, the bottom of the tank should be about 16 feet above the rail. If the water flows from the tank into a "stand-pipe," see § 327, there is additional frictional resistance, to allow for which the height of the support or "tower" is increased to perhaps 30 feet. The standard heights for towers are 16, 20 and 30 feet. **Sub-structure.** A standard plan, recommended by the Water Service committee of the A. R. E. A., is to support such tanks on twelve 12″×12″ posts, arranged in a double cross, four posts in each line, each post resting on a concrete footing. The posts are suitably cross-braced as in trestle work, and are surmounted by cast iron caps. These support 12″×14″ timber caps, which carry 4″×14″ joists, spaced 14″, which are immediately under the bottom of the tank. **Size.** Two sizes of tanks are standard. The "16×24" has a net height inside of 15′ 4″ and a net inside diameter of 24′ 0″. Although the capacity, brimming full, would be nearly 52,000 gallons, it is called a "50,000-gallon" tank since the outlet pipe must be several inches below the top. The "20×30" tank has a net inside diameter of 30′ 0″ and net height of 19′ 4″. It will contain 100,000 gallons when the water depth is slightly less than 19 feet. Since it is found that the 100,000-gallon tank costs but 10% more than a 75,000-gallon tank, the committee recommended that the 50,000-gallon and the 100,000-gallon tanks should be considered the two standard sizes.

Details. Cylindrical tanks are recommended, rather than tapered. The staves are machine-dressed so that the edges have the proper bevel toward the tank axis, and the outside is dressed to the proper convex cylindrical surface so that the hoops have a bearing for the full width of the stave. The "croze," $2\frac{5}{8}''$ wide and $\frac{5}{8}''$ deep, into which the bottom planks, 3″ thick, slightly beveled at the ends, are inserted for a tight joint, is 4″ above the bottom of the staves. When the jointing edges are properly made, the tank will be water-tight without any plugging or caulking, which should not be permitted. The weight of the tank should be transmitted through the bottom planks and in no case by means of the staves. Round hoop-rods, rather than elliptical or flat, are recommended. They should be made of refined double-rolled wrought iron. Each hoop should have three sections for 16×24 tanks and four sections for 20×30 tanks. On the basis of a maximum working stress of 12,500 pounds per square inch on the area at the base of the screw threads, the safe working load in pounds is as follows:

$\frac{3}{4}''$, 3750; $\frac{7}{8}''$, 5250; 1″, 6875; $1\frac{1}{8}''$, 8625.

The spacing of hoops may be computed from the formula:

$$\text{Spacing in inches} = \frac{\text{safe load for the given hoop in pounds}}{2.6 \text{ diameter (ft.)} \times \text{depth in feet}}.$$

In the above formula, "depth" means the distance from top of stave to location of hoop. One hoop should be placed within two inches of the top and two hoops around the bottom opposite the croze. One of these is assumed to take up the bursting pressure due to the swelling of the bottom planks when water soaked, and that it does not withstand water pressure. The spacing should never exceed 21 inches. Hoop "lugs," made of cast or malleable iron, are used to connect the sections of the hoops. Each end of each rod should be threaded for $4\frac{1}{2}''$ and be provided with two hexagon nuts.

325. Pumping. (*a*) **Steam-pumps.** When coal is very cheap or "when 100 lbs. of coal in the pumphouse is cheaper than one gallon of fuel oil in the storage tank," and especially when steam can be procured from the railroad repair-shop plant, direct-acting steam pumps may be preferable and more economical, but they always require skilled attendance. (*b*) **Gasoline-engines.** These have been so highly developed in recent years that they are very efficient and are nearly "fool-proof," so that they may be oper-

TABLE XXVIII.—COST OF FUEL FOR VARIOUS TYPES OF PUMPS AND ENGINES.

Type.		Fuel.		B. H. P. hour.		Eff. H. P.	
Pump.	Engine.	Kind.	Price.	Fuel used.	Cost.	No.	Cost 10 hrs.
Reciprocating . . .	Steam (slide valve)	Bit. coal	$2.00 per ton	14 lbs.	$0.0126	40	$3.15
" . . .	Internal combustion	Gasoline	0.16 " gal.	$\frac{1}{8}$ gal.	0.0200	50	4.00
" . . .	" "	Ill. gas	0.75 M cu. ft.	12 cu. ft.	0.0090	50	1.90
" . . .	" "	Nat. "	0.25 " " "	8 cu. ft.	0.0020	50	0.40
" . . .	" "	Fuel oil	0.06 per gal.	$\frac{1}{8}$ gal.	0.0075	50	1.50
" . . .	Electric motor	Electric	0.03 K. W. hr.	.746 K.W.	0.0224	50	4.48
Centrifugal . . .	" "	"	0.03 " " "	.746 "	0.0224	50	4.48
" . . .	Internal combustion	Gasoline	0.16 per gal.	$\frac{1}{8}$ gal.	0.0200	50	4.00
" . . .	" "	Fuel oil	0.06 " "	$\frac{1}{8}$ "	0.0075	50	1.50

NOTE.—The last column "Eff. H. P., Cost 10 hrs." covers the work required to elevate 400 gal. per minute 100 ft., this being equivalent to a delivery of 240,000 gal. per day of 10 hours and is an average requirement condition of a railroad water-station.

ated by unskilled labor, although skilled attention is periodically necessary. But the rising cost of gasoline has directed attention to other fuels. (*c*) **Oil-engines.** Crude petroleum, when refined, will give off approximately the following: Ether, 2%; gasoline, 6%; naphtha and benzine, 8%; kerosene, 44%; 39° power distillate, 10%; gas oil, 10%; lubricating oils and petrolatum, 15%, and "slops" 5%. The "fuel oil," as supplied for oil engines, is a mixture of the slops with enough of some other constituent, usually the "power distillate," which is at the time the cheapest, to make the gravity of the mixture about 29°. The fuel oil costs approximately 40% as much as gasoline. Gasoline engines have been converted into fuel oil engines by attaching a mixing chamber in which the oil is heated by the exhaust of the engine. (*d*) **Gas-engines,** using natural gas. Where natural gas is available at 25 cents per 1000 cu.ft. or less, it is an economical fuel. (*e*) **Electric power.** Where this is obtainable at a low rate, it may be a cheaper source of power than steam, gasolene or fuel oil. The electric motor either operates a centrifugal pump, or a slow-speed motor is direct-connected to a triplex reciprocating pump.

A Committee of the Amer. Rwy. Eng. Assoc. reported in 1915 the comparative cost (see Table XXVIII) of pumping 240,000 gallons per day of 10 hours. By comparing the data with that of any given locality a fair idea of relative costs and of the proper choice for that particular station may be made.

326. Track tanks. These are chiefly required as one of the means of avoiding delays during fast-train service. A trough, made of steel plate, is placed between the rails on a stretch of *perfectly level* track. A scoop on the end of a pipe is lowered from under the tender into the tank while the train is in motion. The rapid motion scoops up the water, which then flows into the tender tank. They should preferably be located on tangents, although the Penn. R. R. has track tanks at Atglen on a 2° curve where the track has 4 inches superelevation. Since the inside width of the tank (19″) is almost exactly $\frac{1}{3}$ of the gauge, the water is about $1\frac{1}{3}$ inches deeper on the side toward the inner rail, but this much lack of symmetry does not seem to have interfered with successful operation. The length of the tanks varies from 1200 to 2500 feet; the net inside width is usually 19 inches. The scoops are usually 12 to 13 inches wide, which gives allowance for swaying. The tanks are made of sheet steel $\frac{3}{16}$″ to $\frac{1}{4}$″ thick. The usual cross-section is that of a wide and shallow U, 19″ wide, 6″ to $7\frac{1}{2}$″ deep, reinforced on the sides with angles. The ties are usually dapped, especially for the deeper tanks, so that the upper edges will not be higher than the rail. At each end there is a double inclined plane on which the scoops may slide without catching if the scoop should be lowered too soon or if it is not raised before the far end of the tank is reached. Experiments have shown that, at a speed as low as 20 m.p.h., more water is wasted by slopping over the sides than the amount collected by the scoop. At a speed of 45 to 50 m.p.h. the amount wasted becomes minimum and the amount scooped up becomes maximum. At higher speeds the amount scooped up decreases and the wastage increases. The best results show a wastage of at least one-eighth of the total. These same tests showed that at 45 to 50 m.p.h. the 13″ scoop in a 19″ tank will scoop up about 625 gallons per inch of immersion per 1000 feet of tank, or say 2500 gallons per 1000 feet for a 4-inch immersion.

The amount scooped up is practically proportional to the depth of immersion when that depth is over $2\frac{3}{4}$ inches. **Heating.** The water must be heated in winter to prevent freezing. There are two general methods: (*a*) Live steam is forced into the tank through nozzles about 40 feet apart; (*b*) a "circulatory system" by which steam is forced into a water main which feeds the tank in such a way that the water is in constant circulation through the main, into the tank and then back again into the main to be reheated. For the climatic conditions of the N. Y. Central R. R. a steam capacity of 100 H. P. is considered essentail to heat 7000 sq. ft. of tank surface, which means about 4400 lineal feet of 19-inch tank, or two good-length tanks on a double track. On account of the great amount of water splashed over the track and its scouring action on any ordinary ballast, a large item in the cost of an installation is the reconstruction of the track. The certainty of quick freezing in winter, at least in high latitudes, demands that a drainage system, to carry away the spilled water, shall be effective and thorough. Scouring is prevented by a pavement of cobbles, 6-inch quarry spalls, or large flat stones, laid over the ballast. A layer of large stones under the ballast facilitates drainage to numerous cross drains and to longitudinal drains laid between the tracks. For further details the student is referred to a monograph by Geo. W. Vaughan, Eng. Main. of Way, N. Y. Central R. R., in Vol. XIV, Proc. Am. Rwy. Eng. Assoc.

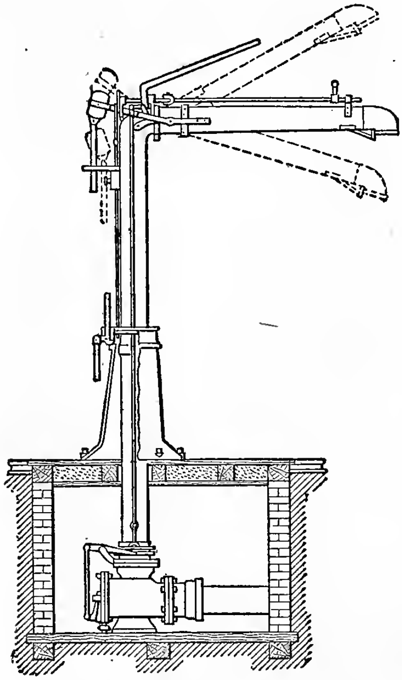


FIG. 159.—STAND-PIPE.

327. Stand-pipes. These are usually manufactured by those who make a specialty of such track accessories, and who can ordinarily be trusted to furnish a correctly designed article. In Fig. 159 is shown a form manufactured by the Sheffield Car Co. Attention is called to the position of the valve and to the device for holding the arm parallel to the track when not in use so that it will not be struck by a passing train. When a stand-pipe is located between parallel tracks, the strict requirements of clearance demand that the tracks shall be bowed outward slightly. If the tracks were originally straight, they may be shoved over by the trackmen, the shifting gradually running out at about 100 feet each side of the stand-pipe. If the tracks were originally curved, a slight change in radius will suffice to give the necessary extra distance between the tracks.

BUILDINGS.

328. Station platforms. These are most commonly made of planks at minor stations. Concrete is used in better-class work, also paving brick. An estimate of the cost of a platform of paving brick laid at Topeka, Kan., was $4.89 per 100 square feet when laid flat and $7.24 per 100 square feet when laid on edge. The curbing cost 36 cents per linear foot. Cinders, curbed by timbers or stone, bound by iron rods, make a cheap and fairly durable platform, but in wet weather the cinders will be tracked into the stations and cars. Three inches of crushed stone on a cinder foundation is considered to be still better, after it is once thoroughly packed, than a cinder surface.

Elevation.—The elevation of the platform with respect to the rail has long been a fruitful source of discussion. Some roads make the platforms on a level with the top of the rail, others 3 inches above, others still higher. As a matter of convenience to the passengers, the majority find it easier to enter the car from a high platform, but experience proves that accidents are more numerous with the higher platforms, unless steps are discarded altogether and the cars are entered from level platforms, as is done on elevated roads. As a railroad must generally pay damages to the stumbling passenger, they prefer to build the lower platform. Convenience requires that the rise from the platform to the lowest step should not be greater than the rise of the car steps. This rise is variable, but with the figures usually employed the application of the rule will make the platform 5 ins. to 15 ins. above the rail.

Position with respect to tracks.—Low platforms are generally built to the ends of the ties, or, if at the level of the top of the rail, are built to the rail head. Car steps usually extend 4 ft. 6 ins. from the track center and are 14 ins. to 24 ins. above the rail. The platform must have plenty of clearance, and when the platform is high its edge is generally required to be 5 ft. 6 ins. from the track center.

329. Minor stations. The Amer. Rwy. Eng. Assoc. recommend one general waiting room (without reference to separate waiting room for colored people), for a passenger station of medium size for the following reasons: (See 1915 Manual, p. 187).

(1) It permits the general waiting room to be properly proportioned.

(2) It permits proper development of a retiring room for women, with private entrance to the lavatory.

Fig. 160.—Division of Floor Area Recommended for Passenger Stations with One General Waiting Room.

(3) It readily admits of the other rooms being properly proportioned.

(4) It permits ease of access from the agent's office to the trains, to the baggage room and to the waiting room.

(5) It permits the ticket office to be of proper size and location for general office purposes.

(6) It admits of the station being contracted in size without detriment to facilities.

(7) It offers economy in heating.

In the Southern States a separate waiting room for colored people is provided and is sometimes even required by law. The older design, combining a residence for the agent with the station, is now obsolete for new construction, although many such still exist. "Combination stations" (for both passenger and freight business) were formerly quite popular for very small stations and are still considered desirable when all responsible freight and passenger business must be handled by one man. But it is desirable to separate them whenever the volume of business will justify the employment of two responsible men.

In Gillette's Handbook of Cost Data (1910 ed.), is given in detail the cost of several station buildings. Such figures can be utilized when unit prices are given or can be derived. For example, in one case the building was 24×60 ft., exclusive of platforms; there was no masonry foundation nor plastering. The summary was as follows:

Materials.	Total.	Per cent.	Per sq. ft. of floor.
30,057 ft. B. M. at $13.23 (aver.)	$296.97	33.2	21 ft. B. M.
20 M shingles at $1.10	22.00	2.4	
Millwork	55.75	6.1	3.9 cents
Hardware	37.50	4.1	2.6 "
23 gal. paint at 70 cents	16.10	1.8	1.1 "
1100 brick, at $8.00 per M	8.80	1.0	
Total materials	$437.12	48.6	30.4 "
Labor:			
176.2 days' labor, building at $2.32	$406.38	45.3	28.2 cents
2 days' labor, put up ladders, at $2.50	5.00	0.6	
14 days' labor, painting at $1.75	24.50	2.8	1.7 cents
4 days' labor, building chimney, at $4.00	16.00	1.8	
8 days' labor, filling cinders, at $1.20	8.50	0.9	
Total labor	$460.38	51.4	31.9 "
Total, materials and labor	$897.50	100.0	
Freight, 55 tons, 200 miles ½c. ton-m.	55.00		
Tools (excessive in this case)	38.50		
Grand total	$990.00		68.8 cents

The cost of lumber was very low and even the unit cost of labor (carpenters, $2.50; masons, $4.00; average of all, $2.32), were lower than must frequently be paid. But the figures can be utilized by noting the percentages of the various items to the total and applying local unit costs for material and labor. The total cost per square foot ($0.688), is abnormally low, partly because of no masonry foundation nor cellar, which would add 40 to 50 cents per square foot. Note also that no expenses were included for lighting, plumbing, or heating—except a chimney.

FREIGHT HOUSES.

330. Two types. The freight house, or freight room, at a station where the business is small, is merely a small ordinary building or a room attached to the station building. As the business becomes larger, efficient operation requires that two types of buildings must be designed—the **inbound** and the **outbound** freight house. These types agree in requiring certain details in common, but there are also differences.

331. Fire-risk. A small freight house in the country usually has a minimum of actual fire-risk and of valuable freight stored at any one time. This may justify an inexpensive type of frame building which is in no sense fireproof. On the other hand, a building in the heart of a city, closely surrounded by other buildings and stored with a large amount of valuable freight, justifies an expensive type of fireproof construction. The term "fireproof" is only relative. Certain devices and added expenditures will reduce more and more the probability of destructive fires. Certain principles of construction which reduce fire-risk are as follows: (*a*) Use of noncombustible materials for floor, side walls and roof; (*b*) avoidance of space under wooden main floor, between foundations, where combustible rubbish may accumulate; (*c*) fire-walls dividing large houses so that there is not more than 5000 square feet of floor between fire-walls; fire-walls to be never more than 200 feet apart; (*d*) minimum number of doors through a fire-wall; no door larger than 80 square feet; all doors fireproof and automatically self-closing; (*e*) fireproofing protection of walls and roof for at least five feet each side of a fire-wall; (*f*) provision for fire stand-pipes and hose racks not more than 150 feet apart; the stand-pipe should run up about 8 feet above floor where there should be 50 feet of 2-inch linen hose in a hose rack; the valve should be in a pit (*always* accessible), and so far below floor level that there is little or no danger of freezing, since freight houses are ordinarily *not* heated.

332. Dimensions. A freight house usually has a track on one side and a vehicle driveway on the other, the floor being utilized for the more or less temporary storage of freight, which in this case is always in "less than carload" (L. C. L.) lots, carload shipments being transferred directly between cars and vehicles. Since small shipments can usually be loaded into cars (outbound shipments) with less delay than the delivery of freight to vehicles (inbound shipments), the required space for outbound shipments can be less than that for inbound. Experience has shown that for outbound freight only, a **width** of 30 feet is desirable; for both outbound and inbound, the width may be 30 to 40 feet;

for inbound only it should be 40 to 60 feet. Too great a width needlessly increases the amount of hand-trucking. The **length** is indefinite and should correspond to the amount of business to be handled. Freight houses are usually single-storied, except where galleries or partial second stories are built to accommodate offices, file and stationery rooms, toilet and locker rooms, the room for "over, short and damaged" freight and the cooperage room for repairing broken packages.

333. **Platforms.** The platform on the track side should preferably be 8 to 10 feet wide, which will avoid the necessity of spotting cars with their doors directly in front of freight-house doors. The platform should be not more than 4 feet above the top of the rail. Even this would be too high to permit opening the doors of refrigerator cars, which swing outward. An occasional refrigerator car could be handled, even with a high platform, by opening the doors before placing the car. The M. C. B. standard, for regular use of refrigerator cars, is "not more than 3 ft. 8 ins." The P. R. R. standard is 3 ft. 5 ins. The minimum distance from track center to edge of platform is 5 ft. 9 ins. The P. R. R. standard is 6 ft. $1\frac{1}{4}$ ins. If there is a platform on the driveway side, it should be 3 to 4 feet above the driveway level. At an outbound house, where the freight is delivered from the vehicle into the freight house, the height should be not more than 3 feet. Platforms should slope away from the house with a grade of about 1 in. to 8 ft. for drainage.

334. **Floors.** The designed floor loading should be 250 lbs. per square foot. In § 347 are described several types of floors suitable for engine houses, many of which are also suitable for freight houses. In selecting a type, it should be remembered that hand-trucking is apt to be concentrated along certain rather narrow paths and that this wears out the floor surface, requiring premature renewals along these paths, unless these paths are overlaid with iron or steel plates. When a solid type of floor is used (supported on sub-soil), the flooring should be independent of the side walls, which avoids trouble due to floor settlement. For inbound freight houses the floor should slope about 1 inch in 8 feet from the track side toward the driveway side, the slope continuing to the outer edge of the driveway platform, since this is in the direction of traffic and aids it, but the track platform must slope the other way for drainage. For outbound freight houses, the slope is exactly reversed.

335. Doors. Ordinary swinging doors are unsuitable. Lifting doors, counterbalanced, which sometimes fold as they lift, are used. Rolling metal shutters are, perhaps, most satisfactory, but are expensive. Sliding doors require that a guarded space be made so that stored freight does not interfere with the sliding. They also limit the possible total door width to less than half the side of the house. All lifting types permit opening up the whole side of the house (if desired), except the space occupied by the posts. Continuous doors are particularly necessary when there is no platform between the house and the track. Doors should be at least 8 feet high. On the track side this is sufficient, since the car door cannot be higher. On the driveway side a greater height might be desirable.

336. Roofs projecting over platforms. These are desirable as a protection when loading or unloading during storms. That over the driveway platform should be at least 10 feet above the platform or 14 feet above the driveway. When not forbidden by State laws, the roof may be extended beyond the edge of the track platform, but it should be, at least, 17 feet above the rail and 18 inches from the track center, thus leaving a walking space on top of the car.

337. Lighting. Daylight lighting should be obtained by windows through the side-walls above the doors, or by vertical sashes in a monitor roof, which will also provide for ventilation. Skylights, especially when nearly flat, are expensive both for construction and for maintenance. Artificial lighting should be obtained from electricity, with wires run according to the strictest specifications of the National Board of Underwriters. Platforms should be illuminated. A series of push plugs should be placed along the platform wall face, from which extension cords with bulbs may be run to light car interiors.

338. Scales. Outbound houses need scales, with capacity of 8000 lbs., to weigh outgoing freight. "From 50 to 80 feet apart is good practice."

339. Ramps. These are slopes from the driveway level to the car level which facilitate the loading or unloading of agricultural implements and all heavy vehicles running on their own wheels. They are usually built at the end of an extension of the platform, with as low a grade as the circumstances will permit.

"Buildings and Structures of American Railroads," by Walter

G. Berg, although now (1916) somewhat old, contains many plans, showing considerable detail, of station and other buildings. "Railroad Structures and Estimates" by J. W. Orrock, also shows some plans.

340. **Section houses.** These are houses built along the right-of-way by the railroad company as residences for the trackmen. The liability of a wreck or washout at any time and at any part of the road, as well as the convenience of these houses for ordinary track labor, makes it all but essential that the trackmen should live on the right-of-way of the road, so that they may be easily called on for emergency service at any time of day or night. This is especially true when the road passes through a thinly settled section, where it would be difficult if not impossible to obtain suitable boarding places. It is in no sense an extravagance for a railroad to build such houses. Even from the direct financial standpoint the expense is compensated by the corresponding reduction in wages, which are thus paid partly in free house rent. And the value of having men on hand for emergencies will often repay the cost in a single night. Where the country is thickly settled the need for such houses is not so great, and railroads will utilize or perhaps build any sort of suitable house, but on Southern or Western roads, where the need for such houses is greater, standard plans have been studied with great care, so as to obtain a maximum of durability, usefulness, comfort, and economy of construction. (See Berg's Buildings, etc., noted above.) On Northwestern roads, protection against cold and rain or snow is the chief characteristic; on Southern roads good ventilation and durability must be chiefly considered. Such houses may be divided into two general classes—(*a*) those which are intended for trackmen only and which may be built with great simplicity, the only essential requirements being a living room and a dormitory, and (*b*) those which are intended for families, the houses being then distinguished as "dwelling-houses for employees."

ENGINE HOUSES.*

341. **Form.** When not more than three or four engines are to be housed at once and when no turntable is to be provided,

* Condensed and abbreviated from Committee Report, Am. Ry. Eng. Assoc., 1915.

the rectangular form is preferable. All large engine houses are "circular," with a turntable at the center of the circle, except some very large houses, which are really repair shops, where it seems advisable to install a transfer table.

342. **Doors.** The clear opening should be not less than 13 feet wide by 16 feet high. The doors should fold outward and should have such a design that a pilot door may be inserted.

343. **Length.** The length of stall along the center line of the track should be 15 feet greater than the overall length of the longest locomotive, which will provide a walkway behind the tender, a trucking space in front of the pilot and a sufficient distance in which to stop the engine so that the side rods will be in any desired position.

344. **Materials of construction.** Wood was formerly very commonly used, but it is too inflammable. The walls should be made of brick, stone, or plain concrete—not reinforced, at least "for that portion of the wall directly in line of track where engine is liable to run into it." The roof is the difficult problem, since wood is inflammable and iron or steel, even for framing, is very rapidly corroded by coal gas from the engines. Reinforced concrete is the only thoroughly satisfactory material but "when the roof is of reinforced concrete, the columns and roof beams should be of the same material," i. e., it is useless to support a reinforced concrete slab on steel beams.

345. **Engine pits.** These "should be not less than 60 feet in length, with convex floor, with drainage toward the turntable. The walls and floors may be of concrete. Proper provision should be made for the support of the jacking timbers." The engine should stand with its tender toward the turntable.

346. **Smokejacks.** Locomotives leave an engine house under their own steam, which requires starting their fires considerably beforehand, and the smoke must be removed. The precise position of the locomotive on the track is variable, since it must be adjusted to the place where the side rods are in a proper position for repairs. A smokejack is essentially a funnel whose base is at the minimum height above the track which will give the smokestack a proper clearance. The base should be 42 inches wide and long enough for the adjustment as stated above, which means at least 10 feet. The sides should slope upward gradually to a flue whose area should be not less than 7 square feet. There should be a drip trough around the base of the jack.

The material should be "non-combustible," but the choice is troublesome. Sheet iron, even when heavily painted, corrodes rapidly. Wood, covered with "fireproof paint," has been tried. Cast iron has been tried but is exceedingly heavy as well as expensive. Asbestos is being used on several important roads. Patented designs, of which there are several, are used on the majority of roads.

347. **Floors.** (*a*) **Stone screenings.** Subsoil should be good; all soft spots cleaned out and filled with good material; subsoil rolled. Foundation of cinders or gravel, 6 ins. thick. Top coat, 2 inches of stone screenings, perhaps mixed with a little clay or crude oil, the surface being thoroughly rolled. Special foundations for machinery necessary. Surface is not good for heavy wheeling. (*b*) **Planks.** Subsoil same as above; 6 ins. cinders or gravel, with 4″×6″ creosoted sleepers, spaced about 3 feet, embedded in upper surface of cinders; then 3-inch plank. Again, special foundations for machinery and at jacking-up places are necessary. (*c*) **Creosoted wood-block.** The wood blocks, 4 ins. deep, fiber vertical, should be laid on a 1-inch cushion coat of sand which is supported by a 6-inch layer of concrete. A 6-inch layer of cinders, as specified above, is also recommended as a bed for the concrete, but this may depend on the character of the subsoil. The joints should be filled with asphaltic mastic, and an expansion joint 1 inch wide should be provided every 50 feet. (*d*) **Wood floor on concrete.** Sleepers, spaced about 3 feet, trapezoidal, 4-inch top, 6-inch bottom, 4 inches deep, embedded in a 6-inch layer of concrete, so that the sleepers project $\frac{1}{2}$ inch above concrete. Then layer of 2-inch plank, covered with $1\frac{1}{8}$-inch maple flooring. (*e*) **Brick.** Same as (*c*) except that bricks are used in place of wood block. (*f*) **Concrete.** Same foundation as above; 6-inch course of concrete overlaid with 1-inch surface coat (1:2) laid on before base has taken initial set. (*g*) **Asphalt.** Same as (*f*) except that surface coat is $1\frac{1}{2}$ inches of rock mastic. Expert workmen are needed for satisfactorily mixing and laying the asphalt, but the floor is ideal.

348. **Drop pits** are necessary, where pairs of truck, driving and trailer wheels may be dropped from their journals and removed from the engine for repairs or renewals.

349. **Heating.** The primary object of heating is to thaw out the engines so that they may be returned to service as quickly

as possible, rather than to heat the building, whose general temperature should be kept at 50° to 60°. Therefore heat should be concentrated at the pits. Hot air should be forced through permanent ducts, preferably laid under the floor. The outlets should have dampers, which may be closed when men are working in the pits. Fresh air should be drawn from outdoors and no recirculation permitted. The air should be heated by passing over coils containing exhaust steam, supplemented by live steam, if necessary. The air passes out of the building through annular openings around the smokejacks, and also through openings between the wall plates and the roof rafters. These openings should extend entirely around the building.

350. **Window lighting.** Skylights are undesirable because of preponderant disadvantages. The windows in the outer walls should be as large, wide and as high as safe construction will permit, the sill not more than 4 feet from the floor. Windows should be placed over the locomotive doors. Windows set into locomotive doors cause heavy maintenance charges on the doors.

351. **Electric lighting.** Numerous lights should be provided to avoid shadows. Plugged outlets for incandescent lights in alternate spaces between pits should be provided.

352. **Piping.** Pipes for air, steam and water supply should be provided, and where desired, piping for a washout and refilling system should be installed. Where this system is installed, the blow-off lines should be led to a central reservoir; where it is not used, the blow-off lines should be led outside the house. The steam outlet should be located near the front end of the boiler. The blow-off pipe, the air, the washout and refilling water and the cold water connections should be near the front end of the firebox. Connections need only be provided in alternate spaces between stalls.

353. **Tools.** There should ordinarily be facilities provided for hand tools and for the location of a few machine tools, preferably electrically driven.

354. **Hoists.** Hoists with differential blocks are generally used for handling heavy repair parts, and suitable provision should be made for supporting them.

355. **Turntables.** The turntable should be long enough to balance the engine when the tender is empty. The deck form is preferable to the through form. Power should be provided at turntables having great service. Electric power is best and least

expensive when it is available. Compressed air, supplied either by a pumping plant or by the locomotive itself, is sometimes used. The turntable pit should be thoroughly drained and preferably paved. The circle wall should be of concrete or brick, with proper supports and fastenings for rails on the coping. The circle rail should preferably bear directly on concrete base. The use of wood ties and tie-plates supported by masonry is desirable for the circle rail under some conditions. Easy access to the parts of a turntable for the oiling of bearings, painting and inspection should be provided in the design of the turntable pit, unless ample provision is made in the turntable itself.

LOCOMOTIVE COALING STATIONS.

356. **Hand shoveling.** For roads of the smallest traffic, particularly at terminals where locomotives lie overnight, hand shoveling direct from coal cars or from platforms provided with a jib crane and one-ton buckets, is the most economical.

357. **Locomotive crane.** A locomotive crane, equipped with buckets, provides an efficient method of transferring coal from the coal car to a tender, particularly when the crane can be profitably employed at other times.

358. **Coaling trestle.** This method requires a trestle with an approach not exceeding 5%, so that coal may fall from bottom-dumping cars into a pocket and then be discharged through chutes into the tender on a track on either side of the trestle. This method is satisfactory when two coaling tracks are sufficient and when there is available space for the approach track.

359. **Coal conveyors.** When more than two coaling tracks are essential, a conveyor system may be preferable. The coal is brought to the plant in bottom-dumping gondola cars, which dump the coal on to a conveyor which conveys it up and drops it into the bin, from which it may fall either into the tender or into an elevated conveyor car which runs it across a system of parallel tracks and dumps it into a tender, spotted there for the purpose. Incidentally, such a plant usually has also an **ash conveyor** onto which ashes are dumped from the engine. This conveyor carries the ashes to a place where the conveyor buckets dump them into a waiting gondola car, which when full is hauled away.

360. Oil houses * should be fireproof and should be separated from other buildings. Above ground there should be a masonry building, 20′×40′, or perhaps less, with one fireproof door and one or more windows, having wire glass. This room contains a row of pumps, one for each kind of oil; also a series of inlet pipes in the floor leading to tanks in the basement. The floor should be 4 feet above the track rail outside and there should be a

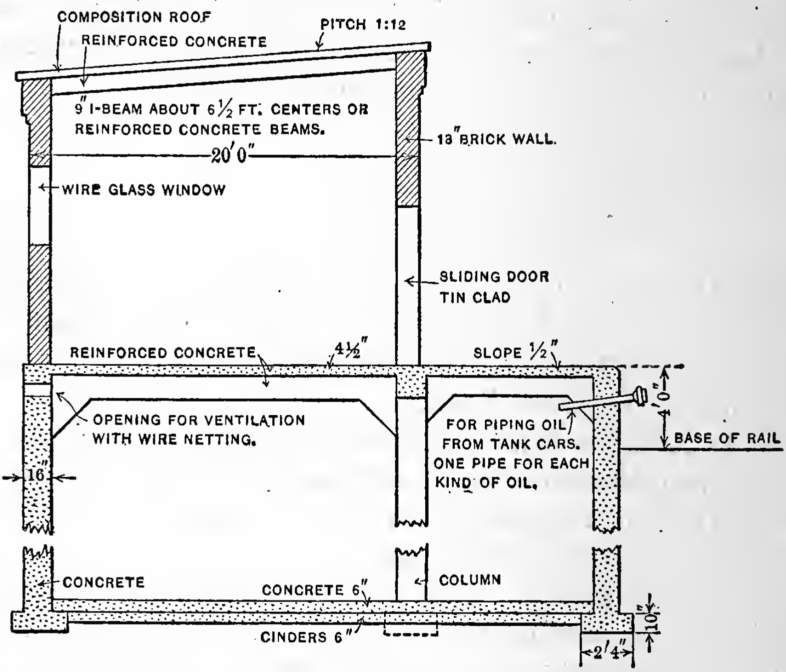


FIG. 161.—CROSS-SECTION OF TYPICAL OIL-HOUSE.

platform between the house and the track. The storage space for oil is entirely in the basement and includes the area under the floor and also the area under the platform. The height depends on the required storage space for tanks. A series of pipes, one for each kind of oil, pass through the outer vertical face of the platform, for the convenient emptying of tank cars into the storage tanks. The inlet pipes through the floor are only for small quantities of oil drawn from barrels.

The delivery system from the storage tanks to the faucets should be such that the oil can be delivered quickly and measured automatically. The delivery should also be such that there will

* Condensed from the Manual of the Am. Rwy. Eng. Assoc., 1915 Ed.

be a minimum of dripping at the faucet and that the dripping may drain back to the storage tanks. Openings for ventilation should be provided above the level of the top of the tanks. Lighting, when required, should be by electricity and heating by steam. For fire protection purposes a live-steam line should be run to the oil storage space, controlled by a valve outside the house.

361. Section tool houses. For small-traffic roads these should be 10′×14′, the short dimension parallel with the track, with double swinging doors, swinging out on the end nearest the track. For roads of larger traffic the dimension parallel with the track should be 18 to 20 feet and the other dimension 12 to 14 feet. There should be a sliding door, 8 feet in clear, at extreme end, on track side, to permit the storing of hand car. A sliding wooden shutter (instead of glass) may serve as a window for fair weather. It should *not* be made so convenient and comfortable that it will become a lounging place for trackmen in stormy or wintry weather. The building should be of wooden frame construction, resting on wooden posts, or on masonry piers if the location can be considered permanent. Drop siding on the sides and some kind of prepared roofing will usually be most economical.

362. Sand houses. Sand is a necessity in the operation of locomotives. Ordinarily it is obtained in a more or less moist and caked condition. It must be made thoroughly dry, so that it will flow readily through a pipe having sufficient slope. The plant consists essentially of a "wet storage bin," about 12′×16′, which adjoins a "drying room" of about the same size. This room contains a screen, which is usually necessary to screen out the coarser particles; also a furnace to dry the sand, and a coal bin. For small traffic roads it may be sufficient to store the dry sand in a bin or even in buckets which are lifted by hand to the engine. For heavier traffic it may be justifiable to raise the sand to a bin or hopper whose lowest point is at least 22 feet above the rail, from which the sand may flow through a jointed pipe, somewhat similar to a water-supply pipe, directly into the sand box on the engine. Of course the bottom of the hopper must have sufficient slope so that the sand will always flow over it. The sand is hoisted to the hopper, either by some mechanical conveyor system, or is forced through a pipe by compressed air. The building should be located about 8 feet from the nearest track center.

363. Ash pits. A locomotive must dump the ashes from its ash pan at frequent intervals. The operation is usually timed to be done at terminal or divisional points, just before taking on water, coal, etc. These several plants are, therefore, grouped together in the yard. When there are no facilities for removing ashes by a conveyor at the same time that coal is being loaded on to the tender (see §§ 356–359), the ashes are dumped into a pit. The poorest roads dump them on the track under the engine, but this burns the ties, is dangerous, and is uneconomical, since they must be immediately removed. The simplest form of ash pit is made by dropping the ties about a foot, and then laying the rails on a pair of stringers about 12″×12″. The stringers and ties must be covered with sheet iron to protect them from hot ashes. The capacity of such a pit is so small that the ashes must be removed quite frequently, which must usually be done by hand shoveling over the side of a gondola car on an adjacent track. The next development is a deeper pit, with concrete walls. Even then, the rails must be fastened to longitudinal wooden stringers, protected with sheet iron, or to cast-iron chairs which are embedded in the concrete. The ashes may be shoveled out by hand after the locomotive has passed, or they may be dropped from the ash pan into buckets or small cars, which run on a narrow track at the bottom of the pit, and which may be lifted out by a jib crane. Another development is to widen the pit, running one rail on one wall and the other rail on a series of cast-iron columns. The pit has much greater capacity and the ashes may be hoisted out at any time, even if the locomotive is still on the ash track. Great economy in the disposal of ashes is obtained when it is practicable to construct a depressed track, with its track center about 14 feet away from the ash track and 9 feet or more lower. The ashes may then be dropped onto a platform about 3 feet below the ash track, the platform extending to the top of a vertical retaining wall whose face is 5 ft. 6 ins. from the center of the depressed track, and from there the ashes are easily shoveled over the side of a gondola car placed on the lower track. No lifting of the ashes by hand is necessary. As in the previous plan, one rail of the ash track is supported by a wall, while the rail toward the depressed track is supported on cast-iron columns. The platform space is thus 10 to 11 feet wide.

Ashes should be quenched promptly after being deposited, so as to reduce their heating effect even on metal and masonry. This requires a hose and a water supply. The pits should be graded so as to drain to a sump, which should have an overflow sufficiently above the bottom so that periodical cleaning out will suffice to keep the drain pipe from getting clogged with detritus from the ashes.

SNOW STRUCTURES.

364. **Snow-fences.** Snow structures are of two distinct kinds—fences and sheds. A snow-fence implies drifting snow—snow carried by wind—and aims to cause all drifting snow to be deposited away from the track. Some designs actually succeed in making the wind an agent for clearing snow from the track where it has naturally fallen. A snow-fence is placed at right angles to the prevailing direction of the wind and 50 to 100 feet away from the tracks. When the road line is at right angles to the prevailing wind, the right-of-way fence may be built as a snow-fence—high and with tight boarding. Hedges have sometimes been planted to serve this purpose. When the prevailing wind is oblique, the snow fences must be built in sections where they will serve the best purpose. The fences act as wind breakers, suddenly lowering the velocity of the wind and causing the snow carried by the wind to be deposited along the fence. Portable fences are frequently used, which are placed (by permission of the adjoining property owners) outside of the right-of-way. If a drift forms to the height of the portable fence the fence may be replaced on the top of the drift, where it may act as before, forming a still higher drift. When the prevailing wind runs along the track line, snow-fences built in short sections on the sides will cause snow to deposit around them while it scours its way along the track line, actually clearing it. Such a method is in successful operation at some places on the White Mountain and Concord divisions of the Boston & Maine Railroad. Snow-fences, in connection with a moderate amount of shoveling and plowing, suffice to keep the tracks clear on railroads not troubled with avalanches. In such cases snow-sheds are the only alternative.

365. **Snow-sheds.** These are structures which will actually keep the tracks clear from snow regardless of its depth outside. Fortunately they are only necessary in the comparatively rare situations where the snowfall is excessive and where the snow

is liable to slide down steep mountain slopes in avalanches. These avalanches frequently bring down with them rocks, trees, and earth, which would otherwise choke up the road-bed and render it in a moment utterly impassable for weeks to come. The sheds are usually built of 12″×12″ timber framed in about the same manner as trestle timbering; the "bents" are sometimes placed as close as 5 feet, and even this has proved insufficient to withstand the force of avalanches. The sheds are there-

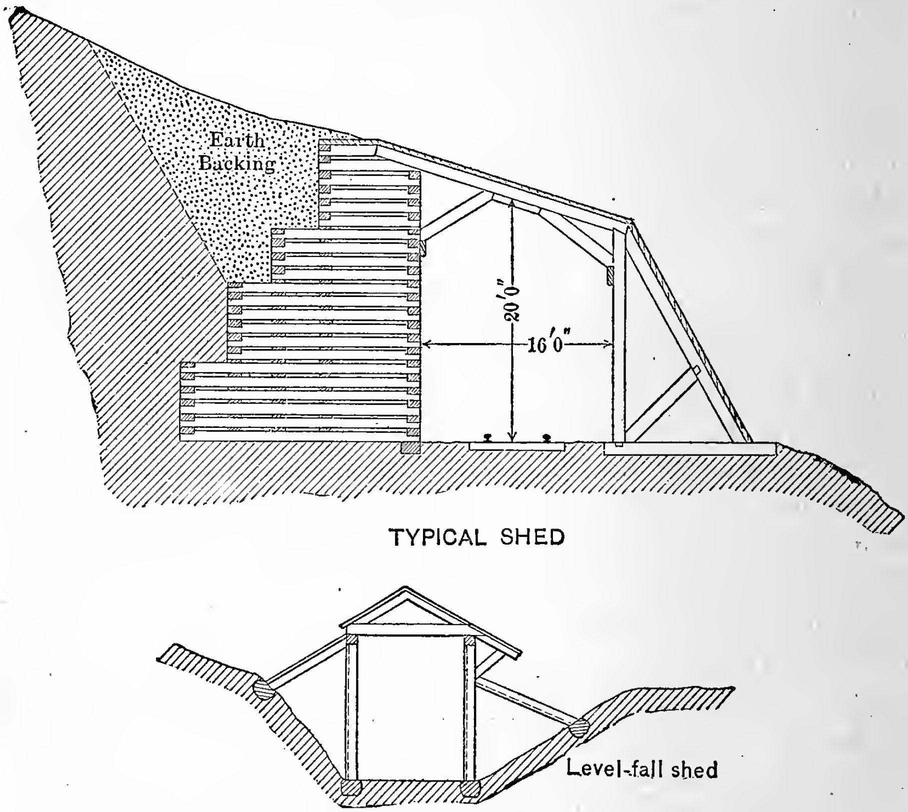


FIG. 162.—SNOW-SHEDS—CANADIAN PACIFIC RAILROAD.

fore so designed that the avalanche will be *deflected* over them instead of spending its force against them. Although these sheds are only used in especially exposed places, yet their length is frequently very great and they are liable to destruction by fire. To confine such a fire to a limited section, "fire-breaks" are made—i.e., the shed is discontinued for a length of perhaps 100 feet. Then, to protect that section of track, a V-shaped deflector will be placed on the uphill side which will deflect all descending material so that it passes over the sheds. Solid crib work is largely used for these structures. Fortunately suitable timber for such construction is usually plentiful and cheap where these structures are necessary. Sufficient ventilation is obtained by longitudinal openings along one side immediately under the roof. "Summer" tracks are usually built outside the sheds to avoid the discomfort of passing through these semi-tunnels in pleasant weather. The fundamental elements in the design of such structures is shown in Fig. 162, which illustrates some of the sheds used on the Canadian Pacific Railroad.

FENCES.

366. Wire fences. The following is condensed from the conclusions adopted by the Amer. Rwy. Eng. Assoc. and incorporated in their 1915 Manual. The recommended standard right-of-way fence is a wire fence, supported on wood or concrete posts. The wiring is to consist of five to nine longitudinal strands, with vertical stay wires spaced 12 to 24 inches apart. The longitudinal and vertical wires are to be locked or fastened with a mechanical lock which will prevent slipping either longitudinally or vertically, or the wires shall be electrically welded. The wire shall be galvanized so as to stand the following test: "The **galvanizing** shall consist of an even coating of zinc, which shall withstand one-minute immersion tests in a solution of commercial sulphate of copper crystals and water, the specific gravity of which shall be 1.185 and whose temperature shall be from 60° to 70° F. Immediately after each immersion the sample shall be washed in water and wiped dry. If the zinc is removed, or a copper-colored deposit formed at the end of the fourth immersion, the lot of material from which the sample is taken shall be rejected. The fence shall be so fabricated as not to remove the galvanizing or impair the tensile strength of the wire." Electrically welded fencing should be galvanized after it has been fabricated.

367. Types. Class A fence has 9 horizontal smooth wires whose spacing, starting at the ground, is 5, 4, 4½, 5, 5½, 6, 7, 8 and 9 inches. To make it "hog-tight" the bottom space (5″) is reduced to 3 inches and a barbed wire is inserted midway in the 3-inch space. The top and bottom smooth wires are No. 7 gauge wire and the 7 intermediate wires are No. 9. The vertical stay wires, spaced 12 inches, shall be No. 9 gauge.

Class B fence has 7 horizontal wires, with vertical wires spaced 18 inches—all wires No. 9 gauge. The spacing, starting at the ground, is 7, $6\frac{1}{2}$, 7, $7\frac{1}{2}$, 8, $8\frac{1}{2}$ and 9 inches.

Class C fence has 5 horizontal wires, with vertical wires spaced 24 inches—all wires No. 9 gauge. The spacing, starting at the ground, is 9, $7\frac{1}{2}$, 8, $8\frac{1}{2}$ and 9 inches.

Class D fence has 5 horizontal wires and no vertical stay wires, the wires being No. 9 gauge. The spacing, starting at the ground, is 10, 10, 10, 12 and 12 inches.

368. Posts. End, corner, anchor and gate posts shall be at least 8 feet long and set 3 feet 4 inches in the ground, even if blasting must be resorted to. Intermediate posts shall be at least 7 feet long and set 2 feet 4 inches in the ground. Where rock is encountered at intermediate post holes, the intermediate posts, if of wood and not more than two in succession, may be set on sills, $6'' \times 6'' \times 4'\ 0''$, braced on both sides by braces $2'' \times 6'' \times 3'\ 0''$. End, corner, anchor and gate posts, when of wood, shall be 8 inches in diameter at the small end; when of concrete, shall be 6 inches square at the top, 8 inches square at the base and shall be reinforced with four $\frac{3}{8}$-inch square twisted rods. Intermediate wood posts shall be at least 4 inches in diameter at the small end; intermediate concrete posts shall be 4 inches thick at the top, $5\frac{1}{2}$ inches at the bottom and reinforced with three (or four, depending on design) $\frac{1}{4}$-inch square twisted rods.

369. Braces. End, corner, anchor and gate posts shall be braced by $4'' \times 4''$ sawed lumber, or round posts at least 4 inches in diameter, or by concrete struts, $4'' \times 4''$, reinforced with four $\frac{1}{4}$-inch twisted rods. The strut braces shall extend from a point about 12″ below the top of the braced post to a point about 12″ from the ground line at the adjacent intermediate post. In addition, a tie, made of a double strand of No. 9 galvanized soft wire, looped around the end, corner, anchor or gate post near the ground line, and around the next intermediate or line post about 12 inches from the top, shall be put on and twisted until the top of the next intermediate or line post is drawn back about 2 inches.

370. Concrete posts. These are recommended. They may be made of one part of cement to four parts of pit gravel; or one part cement, two parts sand and four parts of stone of low absorption or screened gravel, the aggregate in any case being not less than $\frac{1}{4}''$ nor more than $\frac{1}{2}''$. The molds should be oiled or soaped and should be vibrated while concrete is poured to make the concrete more compact. The concrete should have a "quaking" consistency. The pouring should not be done out of doors in freezing weather. The concrete should not be exposed to sun, should be sprinkled every day for 8 or 10 days and should have 90 days for curing. They should be packed in sawdust or straw for shipment. Posts are usually made tapering and the cross-section is variously a square, a rectangle, or an isosceles triangle, the corners being chamfered. The reinforcement should be placed not more than $\frac{1}{2}''$ from the surface and should be wired by bands spaced about 12″. The fencing is sometimes fastened to the posts merely by wires tied tightly about the post or may be fastened to metal lugs which are embedded in the soft concrete during molding.

371. Construction details. Wood posts shall be **anchored** by gaining and spiking two cleats, $2'' \times 6'' \times 2'\,0''$, on the side of the post below the ground line. **Staples** shall be 1 inch long for hard wood, and $1\frac{1}{2}$ inch for soft wood, made of No. 9 galvanized steel wire. They shall be driven diagonally with the grain of the wood, the top wires double-stapled. Staples, No. 9 wire, 1 inch long, weigh 108 to the pound; $1\frac{1}{2}$ inch long, 72 to the pound.

Wire. No. 7 wire is 0.177 inch in diameter, weighs 439 pounds to the mile, or 12.05 feet to the pound. No. 9 wire is 0.148 inch in diameter, weighs 306 pounds to the mile or 17.24 feet to the pound. Smooth wire is preferable to barbed. A heavy smooth wire or a plank should be used at the top of a barbed-wire fence. Wires shall be placed on the side of the post away from the track. **Splicing** shall be done as follows: "The ends of the wires shall be carried 3 inches past the splicing tools and wrapped around both wires backward from the tool for at least five turns, and after the tool is removed, the space occupied by it shall be closed by pulling the ends together." After erection, wood posts should be sawed off, on a one-fourth pitch, the high side being next to the wire and 2 inches above it.

Gates should be hinged to swing away from the track; should be at least 12 feet wide and 4 feet 6 inches above the ground; should swing shut by gravity, and the free end should overlap the post so that it cannot be swung open toward the track. All-metal construction is preferable.

SIGNS.

372. Highway signs. The crossing sign recommended by the Amer. Rwy. Eng. Assoc. is essentially as follows: Two wooden blades, 12 inches wide, 8 feet long, with mitered ends, are placed diagonally, with an angle of 50° between the blades, on an $8'' \times 8'' \times 16'\ 0''$ wooden post sunk 4 feet in the ground. The lower 9 feet is painted black, the upper 7 feet white. The blades are painted white with black letters and a $\frac{1}{2}$-inch black border around the blades. The border and lettering is on both sides. The lettering is Egyptian style 9 inches high with the exception of the connecting terms, as "for the" in the recommended sign, which should be 4 inches high. The recommended wording is "RAILROAD CROSSING" on one blade and "LOOK OUT FOR THE LOCOMOTIVE" on the other blade. The width of band of the letters is $1\frac{1}{4}$ inches. If two railroads parallel each other within 400 feet, another blade marked "TWO CROSSINGS" should be added. The laws in some states prescribe what the lettering shall be.

373. Trespass signs. The specifications for these signs are applicable to many other public warnings which must be displayed. A cast-iron plate, $\frac{1}{4}$ inch thick, stiffened on the back by $\frac{3}{8}$-inch diagonal cast ribs and having the letters and border cast on the front by raising the surface about $\frac{1}{8}$ inch, is set on an iron post 10 feet long, which is embedded 2 feet in a block of concrete, which serves as foundation. The letters should be about 2 inches high. A socket is cast on the rear side of the plate of such dimensions that it will set on the pipe and be fastened with a $\frac{1}{2}$-inch set screw. The posts may be made of $2\frac{1}{2}$-inch wrought iron pipe or of good second-hand boiler tubes, which should be filled with cement grout. The face of the letters and the borders should be painted black while the background is painted white. The tablet will usually be about 30 inches wide by 18 inches high with rounded corners, although the dimensions will vary in accordance with the lettering to be placed on it. The following trespass signs frequently need to be displayed:

RAILROAD PROPERTY TRESPASSING FORBIDDEN UNDER PENALTY OF LAW	DANGER DO NOT TRESPASS ON THE RAILROAD

DANGER DO NOT TRESPASS ON THIS BRIDGE

374. Marker posts. **Mile posts** are most economically made, considering their durability, of skeletonized cast iron. The post is made up of two slabs of cast iron ½ inch thick, 8 feet long, the width tapering from 10 inches to 12 inches, the two slabs being formed in one piece and connected at intervals by ½-inch webs and a top and bottom plate. They should be set 3 feet 6 inches in the ground and have a 4-inch slab of concrete or a heavy, flat stone as a base. The mile post numbers should be cast in raised letters on the face, the letters being 4½ inches high. The two faces should be at right angles with each other and should each stand at an angle of 45° with the track. They should be set at least 8 feet from the gauge line of the nearest rail and 11 feet away, where it is practicable. The numbers should be so set that, on approach, the distance to the terminus or division point beyond will be indicated.

The separating line between divisions is indicated to track men by an iron sign, called a **division post**, which is structurally the same as that of the mile posts. The two divisions are indicated by raised lettering on the faces of the posts. Of course there must be a variation in the lettering or numbering and a special post must be cast for each location of division post or mile post.

Whistle signs are made similarly except that there is but one slab, suitably reinforced with ribs, and which faces in the desired direction. The letter **W** 7½ ins. high is cast in raised letters near the top. The **ring sign** is made similarly by using the letter **R.** The separating line between sections is indicated to the trackmen by a cast-iron sign, called a **section post,** which is made similarly to the Trespass Signs, except that the tablet is much smaller. Such a sign will have two consecutive numbers, for example, 24–25, to indicate that the sign is at the separating line between section 24 and section 25.

375. Bridge warning. When possible the headroom beneath overhead bridges is made at least 22 ft., which will make it safe for a trainman to stand on the top of a freight car which is

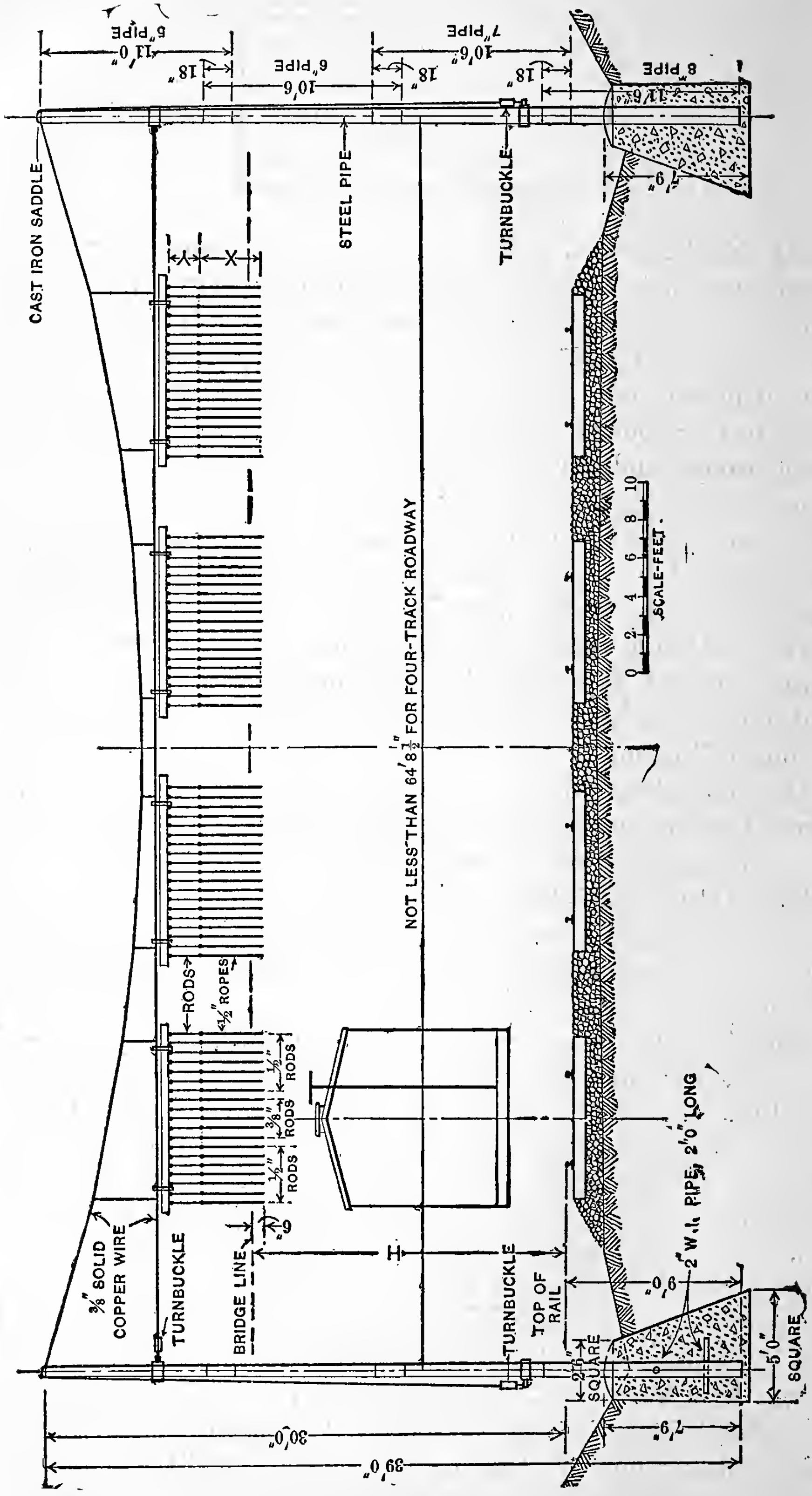


FIG. 163.—BRIDGE WARNING. Penn. R. R. Standard (1911).

passing under the bridge, but it is not always possible to have that amount of headroom. Under such circumstances, a warning for trainmen is necessary. These are made by suspending "ticklers," which are a series of ropes spaced 6 ins. apart which are suspended over the track at a sufficient distance from the bridge or tunnel so that the trainman shall have sufficient warning if he is struck by the dangling ropes. For a single track road the tickler may be suspended from a horizontal arm fastened to a pole planted at least 10 ft. from the track center, the arm being braced by a tie from the top of the pole and also by a short strut underneath. When several tracks are to be spanned, two poles will be used and a catenary cable, between the tops of the poles, supports a horizontal cable by means of a pair of suspenders over each track. The standard on the Pennsylvania Railroad has 19 ticklers 6 ins. apart over each track. The bottoms of the several ropes are 6 ins. below the bottom line of the bridge, the ropes having a length varying from 3 ft. to 5 ft. 3 ins. The ropes are fastened to $\frac{1}{4}$ in. or $\frac{3}{8}$ in. iron rods which swing on ring-bolts which are run through a wooden arm or hanger. The distance from the warning to the bridge or tunnel should be about 100 to 200 ft., depending somewhat on the grade, since that affects the time of the average freight train in passing the interval.

CHAPTER XIII.

YARDS AND TERMINALS.

376. **Value of proper design.** A large part of the total cost of handling traffic, particularly freight, is that incurred at terminals and stations. It amounts to about 15% of the total operating expenses of a railroad. Freight arrives at any one of the hundreds of thousands of freight stations of the country, to be shipped to any other one of those stations. It may consist of a single package or several carloads of bulk freight. It may have to be transferred from car to car, or the car itself transferred from road to road. In any case, the classification and handling of the freight, whether in individual packages or in carloads, is complicated and expensive and any device for reducing the labor of handling such freight, or which saves time in doing it, has a definite money value. Assume that an improvement in the design of the yard will permit a saving of the use of one switching engine, or for example, that the work may be accomplished with three switching engines instead of four. Assuming a daily cost of $25, we have in 313 working days an annual saving of $7825, which, capitalized at 5%, gives $156,500, enough to reconstruct any ordinary yard.

377. **Definitions.** (Compiled from Proc. Amer. Rwy. Eng. Assoc.)

Yard. A system of tracks within defined limits provided for making up trains, storing cars, and other purposes, over which movements not authorized by timetable or by train order may be made, subject to prescribed signals, rules and regulations.

Receiving yard. A yard for receiving trains.

Classification yard. A yard in which cars are classified or grouped in accordance with requirements.

Departure or forwarding yard. A yard in which cars are assembled in trains for forwarding.

Storage yard. A yard in which cars are held awaiting disposition.

Summit or hump yard. A yard in which the movement of cars is accomplished by pushing them over a summit, beyond which they run by gravity.

Body track. Each of the parallel tracks of a yard, upon which cars are switched or stored.

Ladder track. A track connecting successively the body tracks of a yard.

Lead track. An extended track connecting either end of a yard with the main track.

Running track. A track reserved for movement through a yard.

Crossover track. A track connecting two adjacent tracks.

Stub track. A track connected with another at one end only.

Spur track. A stub track of indefinite length diverging from a main line or track.

House track. A track alongside of (or entering) a freight house; used for cars receiving or delivering freight at the house.

Team track. A track where freight is transferred directly between cars and wagons.

378. General principles. It should be recognized at the start that at many places an ideally perfect yard is impossible, or at least impracticable, generally because ground of the required shape or area is practically unobtainable. But there are some general principles which may and should be followed in every yard and other ideals which should be approached as nearly as possible. Nevertheless every yard is an independent problem.

Body tracks should be spaced 13 feet to 14 feet center to center, under ordinary conditions, and where they are parallel to main track or other important running track, the first body track should be spaced not less than 15 feet center to center from such main or important track.

Ladder tracks should be spaced not less than 15 feet center to center from any parallel track. Frogs of greater angle than No. 8 should not be generally used, and the angle between the ladder track and body tracks will be governed by the distance on ladder tracks required for a turnout.

To facilitate train movements the connections of **lead tracks** with the main track should be interlocked.

Running tracks should be provided for movements in either direction to enable yard engines to pass freely from one position of the yard to the other; also to enable road and yard engines to pass to and from the engine house and other points where facilities are provided.

Crossover tracks should be located at most convenient points where they will least interfere with regular movements.

Caboose tracks should be so located, where conditions permit, that cabooses can be placed on and removed from trains in the order of their arrival, and should be so constructed that cabooses can be dropped by gravity onto the rear of trains made up for departure.

Scale tracks should be so located that weighing can be done with least delay and without drilling over scale. Where many cars are to be weighed they should pass separately over the scale by gravity, being weighed while in motion.

Coaling, ashpit, sand and engine tracks should be located on the route leading to and from the engine house and should provide sufficient storage for the reception of engines by the hostler. They should be so arranged that water, coal and sand can be taken and ashes disposed of in convenient rotation, and that switching engines may clean fires, take coal, water and sand and pass around waiting engines.

Bad-order tracks. Where cars are classified, one or more classification tracks, easy of access, should be provided for setting off cars in bad order, from which they may be readily removed to the repair tracks.

Repair tracks should preferably be connected at both ends and have a maximum capacity of about 15 cars each, spaced alternately 16 feet and 24 feet center to center and be connected conveniently to bad-order tracks.

Icing tracks should be so located that the work of shifting out, icing and classifying cars for movement can be performed in the least time.

The **Main tracks** of both single and double track roads should be located, if it is possible to so arrange, on the outside of yard, and the engine house, coaling station, etc., should be centrally located.

The **Coach cleaning yard** should be located near the terminal station. The tracks should be of sufficient length to hold full trains, with a car cleaners' repair and supply building adjacent thereto.

Roadways. Where the freight house is on one side and a wall on the other, the minimum width of roadway should be 30 feet; but where a freight house is on one side and a team track or another freight house is on the other, the minimum clear width of roadway should be 40 feet.

A **Transfer Station** should be located at a point where traffic is concentrated and where a necessity exists for consolidating freight into a less number of cars for movement to a certain destination, or for separating and reloading freight into a greater number of cars or into system cars for further movement to final delivery.

The **car capacity** of freight tracks should be computed on the basis of 42 feet for each car.

Frogs. Although not absolutely necessary, there is an advantage in having all frog numbers and switch dimensions uniform. No. 8 frogs are recommended. Sharper-angled frogs make easier riding, less resistance and less chance of derailment, but on the

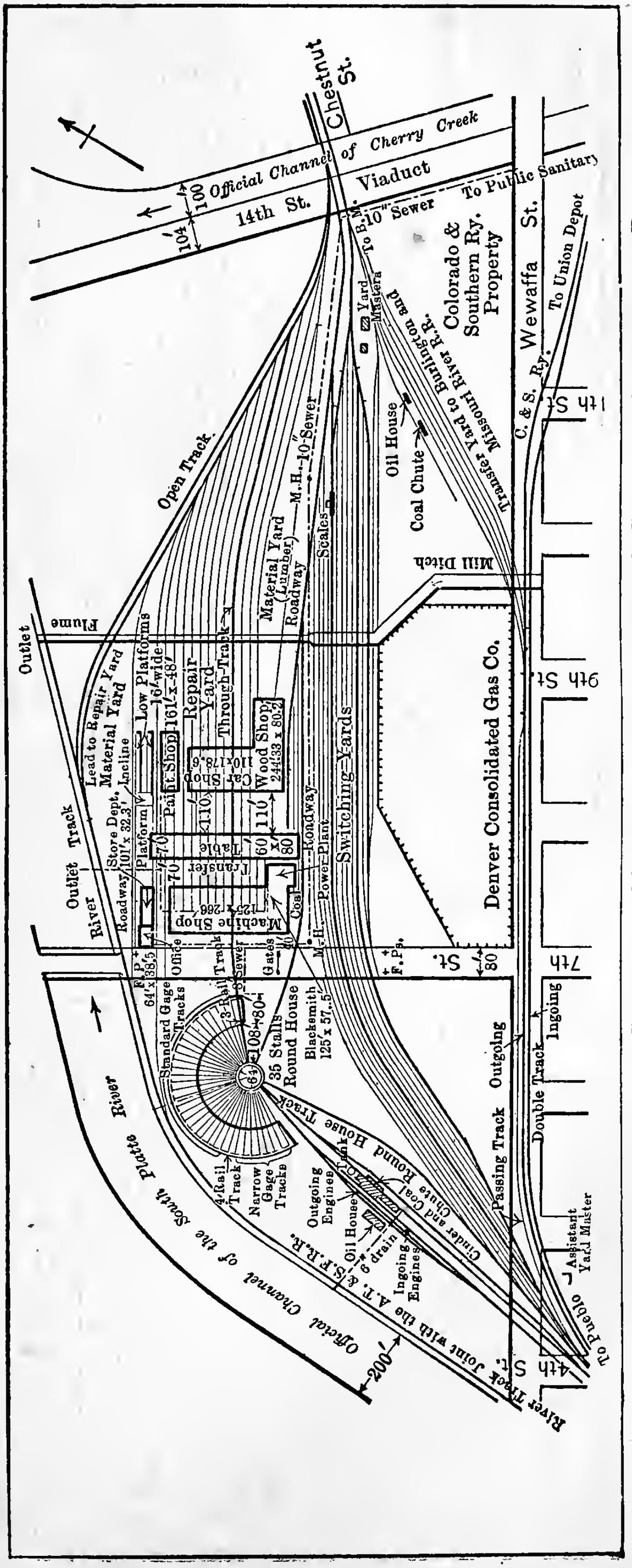


FIG. 164.—PLAN OF THE SHOPS AND YARDS OF THE COLORADO & SOUTHERN RAILWAY AT DENVER.

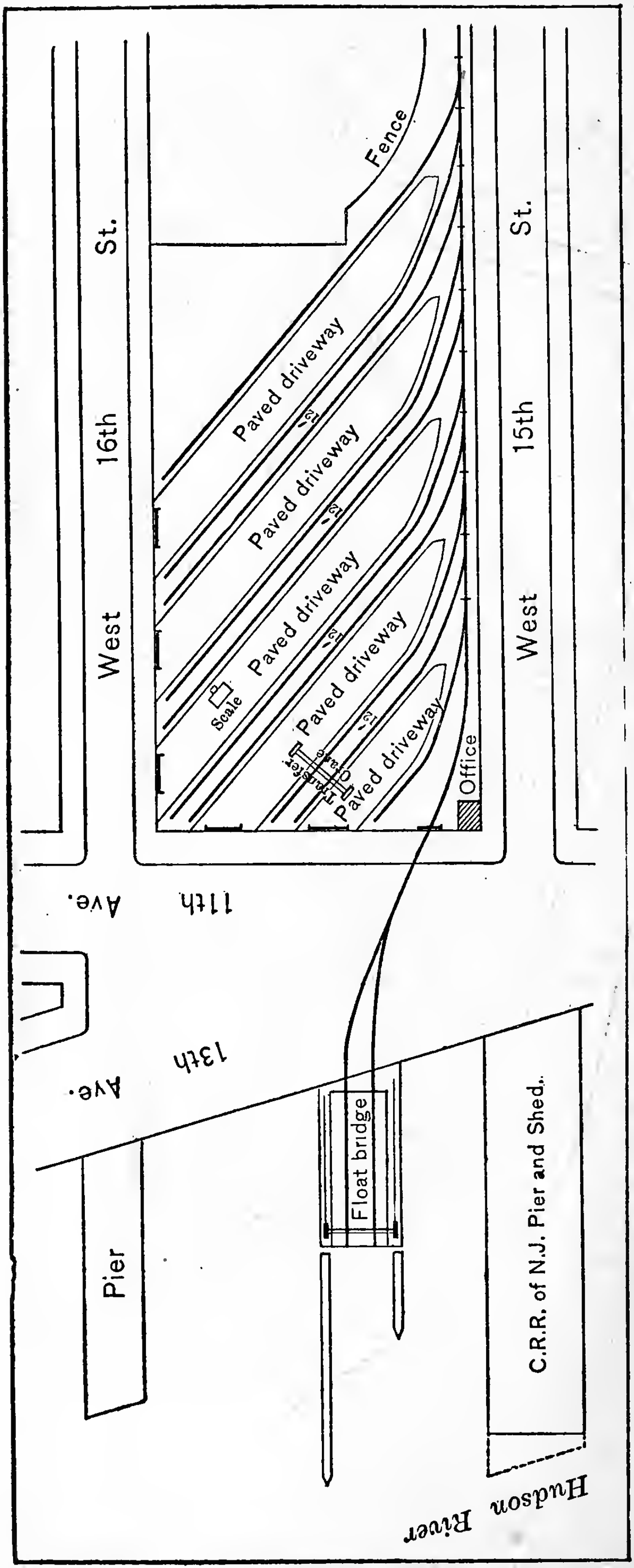


FIG. 165.—MINOR FREIGHT YARD.

other hand require longer leads and more space. No. 7 and even No. 6 frogs are sometimes used on account of economy of space, but they have the disadvantages of greater tractive resistance, greater wear and tear on track and rolling stock, and greater danger of derailment.

The design of an existing yard is best studied by first picking out the ladder tracks and the through tracks which lead from one division of the yard to another. These are tracks which must always be kept open for the passage of trains, in contradistinction to the tracks on which cars may be left standing, even though it is only for a few moments, while drilling is being done. Such a set of tracks, which may be called the skeleton of the yard, is shown by heavy lines in Fig. 164. Each line indicates a pair of rails. The tracks of the storage yards are shown by the lighter lines.

379. Minor freight yards. Fig. 165 illustrates a freight yard on the New York harbor front to which cars are brought on floats. Ten team tracks for the transfer of freight between cars and teams have been provided in a very limited space. Great ingenuity is often required to obtain the desired facilities without the use of excessively sharp curvature. The limiting radius which will permit cars to pass a curve without adjacent corners touching is about 175 feet. Extension coupler bars, although inconvenient, will make possible the use of still sharper curves.

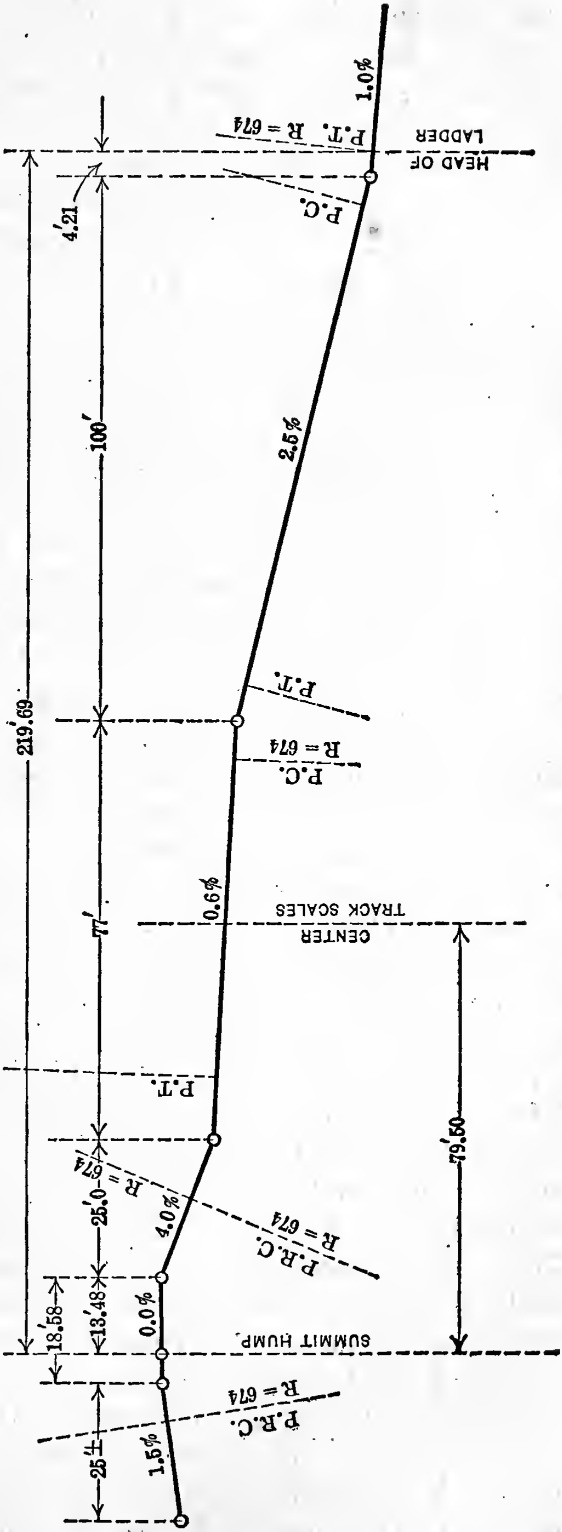


FIG. 166.—RECOMMENDED HUMP PROFILE FOR WARM CLIMATE.

380. **Hump yards.** The operation of hump yards makes it possible to develop the necessary potential energy for car movement by a switching engine with the maximum of economy, while the classification is accomplished in the minimum of time. The cars are pushed up the grade and over the summit, from which they begin immediately to descend on a grade which is preferably 4%. As each "cut" of one or more cars reaches the 4% grade, gravity accelerates its motion and it separates automatically from the cars behind it. Each cut then passes down the ladder track until it reaches the particular body track on which it is desired to be run. **Grades.** In Chapter XVI, it is elaborated that track resistance is greater in winter than in summer, and also that it is much greater on switch tracks than on straight unbroken track. The difference between cold-weather and warm-weather resistance is so great that the length or rate of the acceleration grade required to furnish the necessary energy varies with the temperature or climate. The Amer. Rwy. Eng. Assoc. in 1917 adopted three typical profiles for humps, designed for "cold, moderate and warm climates." The designs also include the location of track scales (see § 382) which modify the grading. Some of the grades are only nominal since the transition from one grade to another requires such long vertical curves (see §§ 84–87) that they occupy the entire length of the nominal grades, and the profile over the hump, and for some distance beyond, consists of a series of compounded vertical curves. For example, the profile which is recommended for warm climates is shown in Fig. 166. Nominally the summit is reached by a short length of 1.5% grade, with a level grade at the summit followed by 25 feet of 4% down-grade and then 77 feet of 0.6% down-grade, on which is located the track scales. But Fig. 166 shows that a vertical curve of 674 feet radius starts from the 1.5% grade, is tangent to the level grade at the summit, and reaches the 4% grade, where it reverses into an up-curving 674-ft. curve which joins the 0.6% grade. The recommended profiles for "moderate and cold" climates can be constructed, similar to that in Fig. 166 from the data in the tabular form. Note that the length or steepness of the acceleration grades and of the ladder track is increased as the climate is colder. If the grades are too low the cars will not reach their desired destinations; if too steep, there must be an unnecessary use of brakes or a destructive bumping of cars on the body tracks. Never-

Locality.	Hump-level length.	Accel. grade.	Scale grade.	Accel. grade.	Ladder track.	Radius vert. curve.
Warm climate	18.58′	25′ 4%	77′ 0.6%	100′ 2.5%	1.0%	674′
Moderate "	28.75′	37.5′ 4	89′ 0.8	100′ 3.0	1.25	1040′
Cold "	39.30′	50′ 4	100′ 1.0	100′ 4.0	1.5	1428.6′

theless, as will be shown in § 438, the actual resistance of cars through switches is so variable that an excess of power *must* be provided to prevent the stalling of *some* cars before they reach their destination. The grade from the receiving track to the hump should be such that one engine can push the maximum train over the hump. Since empty cars have a greater tractive resistance per ton than loaded cars, they require a steeper grade to maintain the same velocity, and, therefore, when tracks are set aside for the use of empty cars, the grade leading to such empty tracks should be increased if possible. **Operation.** To operate such a hump efficiently, the yard clerk makes up a triple (or quadruple) list for each freight train arriving at the yard for distribution. One of these lists is given to the man cutting off the cars at the top of the hump, and one to the towerman, if the switches are operated from the tower, or one to each switch tender if the switches are hand-operated. Each list contains in the first column the consecutive number of the cut, in the second column the number of the track on which that cut of cars is to be placed, and in the third column the number of cars cut. Cut No. 1 is the first car (or cars) to go over the hump. A brakeman, or "rider," accompanies each car, or group of cars. To avoid the great waste of time required for these riders to walk back to the hump, it has been found economical in some large yards to have a track for the exclusive use of a car, especially fitted for easy jumping on or off, operated, perhaps, by a switching engine, or possibly by gasoline, which picks up the riders and carries them back to the hump. The aggregate time saved justifies the expenditure. The **scale grade** has been designed in each case so that each car will pass over the scale with a maximum velocity of four miles per hour, which means that the car shall be entirely on the scale platform for a minimum time of three seconds. Although the grade over the scales may be as high as 1% for motion weighing, the weighing mechanism must be installed on a level plane and the weighing rails are blocked up to the desired grade.

381. Ladder tracks. Twenty-seven types of ladder tracks are shown in the 1917 Committee report to the A. R. E. A., but nearly one-half of the ladders reported in actual use belong to type *a*, Fig. 166*a*, and about one-half of the remainder belong to types *b* and *c*. The other twenty-four types are chiefly expansions and developments of the three types shown. Note that in types *a* and *c*, the switches are, in each case, in a straight line along

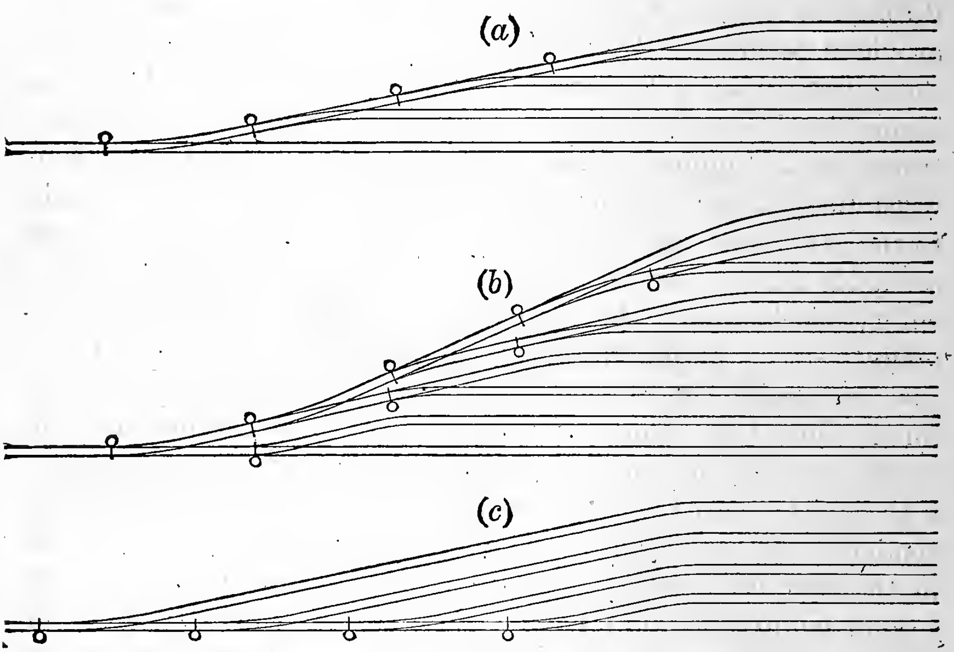


FIG. 166*a*.—TYPES OF LADDER TRACKS.

one of the tracks, which simplifies the working of the switches, whether they are worked from a tower or on the ground by hand.

382. Track scales. The standard design for a hump yard, § 380, shows a track-scale grade, as an integral part of the design, located just beyond the hump. It has been found that it is practicable to weigh cars with sufficient accuracy while the cars are in motion, provided the speed does not exceed 4 miles per hour, or 5.87 feet per second, and provided that the length of the scale is such that the car is entirely and alone on the scale for a minimum of three seconds. This condition will be fulfilled when the scale is 17.6 feet longer than the distance from front to rear axle of the car. Scales with lengths of 50, 56 and 60 feet are considered standard. The **sensibility reciprocal** is the weight required to be added or removed from the live rails to turn the beam from a horizontal position of equilibrium in the center of the trig loop to a position of equilibrium at either limit of its travel; such weight shall not exceed 50 lbs. in any case. The **tolerance** to be allowed on the first field test, after installation corrections, of all new railroad track scales, shall not exceed $\frac{1}{20}$ of 1%, or 50 lbs. per 100,000 lbs. for any position of the test-car load on the scale. The minimum test-car load shall be 30,000 lbs. **Location.** The scale should be elevated above the other tracks of the yard so that surface drainage shall not drain into the pit. The location of the scale near a hump summit fits in with this requirement. The **foundations** should be made of concrete. The finished floor of the pit should be at least 7 feet below the base of the rails; the floor should be at least 6 inches thick and as much thicker as a soft sub-soil might demand. The concrete of the walls and floor should be effectively waterproofed to exclude sub-soil water. A sump, with provision for drainage outfall, should be provided to dispose of any rainfall or other drainage which might accumulate in the pit. **Approach.** There should be at least 50 feet of tangent track on each approach. The approach tracks should be carried on approach walls or piers extending 15 to 25 feet from the end walls of the pit, so that accurate line and surface of the approach tracks is maintained and so that the approach rails may be absolutely anchored against creeping. **Dead rails,** offsetted 16″ from the live rails, will carry cars over the scale pit, when so desired, without any stress or influence on the scale mechanism. One dead rail may be supported on the side wall of the pit and the other on pedestals or on transverse floor beams which are spaced (usually) 2′ 6″ and which are independent of the weighing platform. Details must conform to the somewhat varying plans of various manufacturers.

383. Transfer cranes. These are almost an essential feature for yards doing a large business. The transportation of built-up girders, castings for excessively heavy machinery, etc., which weigh 5 to 30 tons and even more, creates a necessity for machinery which will easily transfer the loads from the car to the truck and *vice versa*. An ordinary "gin-pole" will serve the purpose for loads which do not much exceed 5 tons. A fixed framework, covering a span long enough for a car track and a team space, with a trolley traveling along the upper chord, is the next design in the order of cost and convenience. Increasing the span so that it covers two car tracks and two team spaces

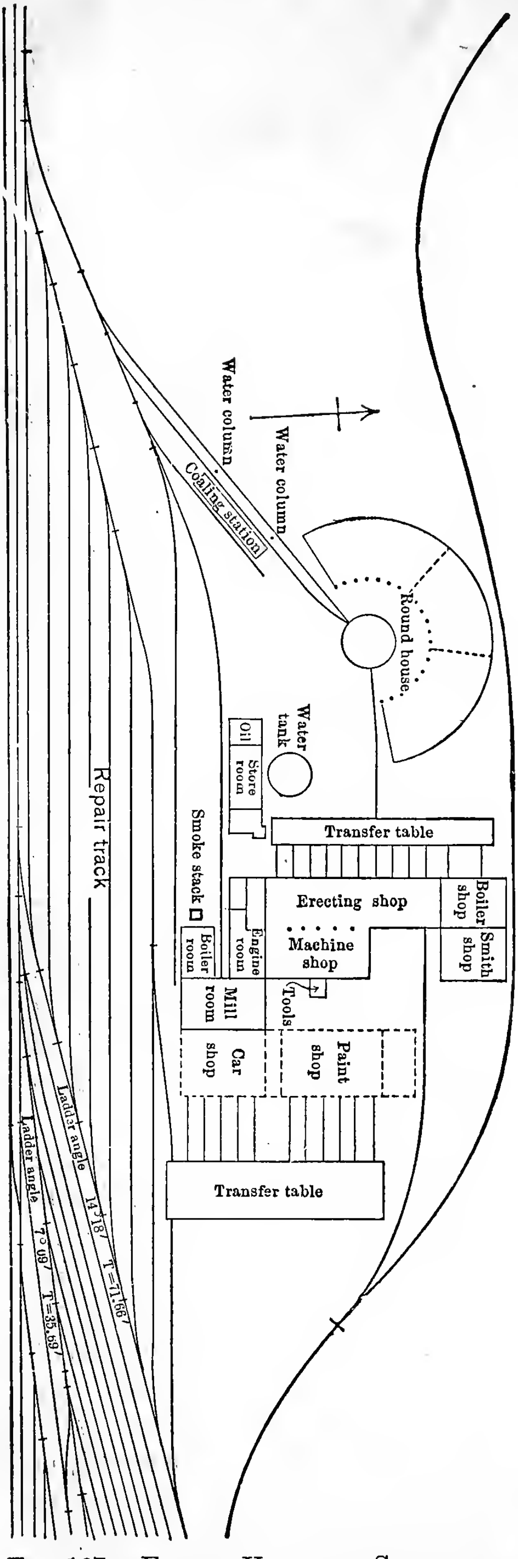
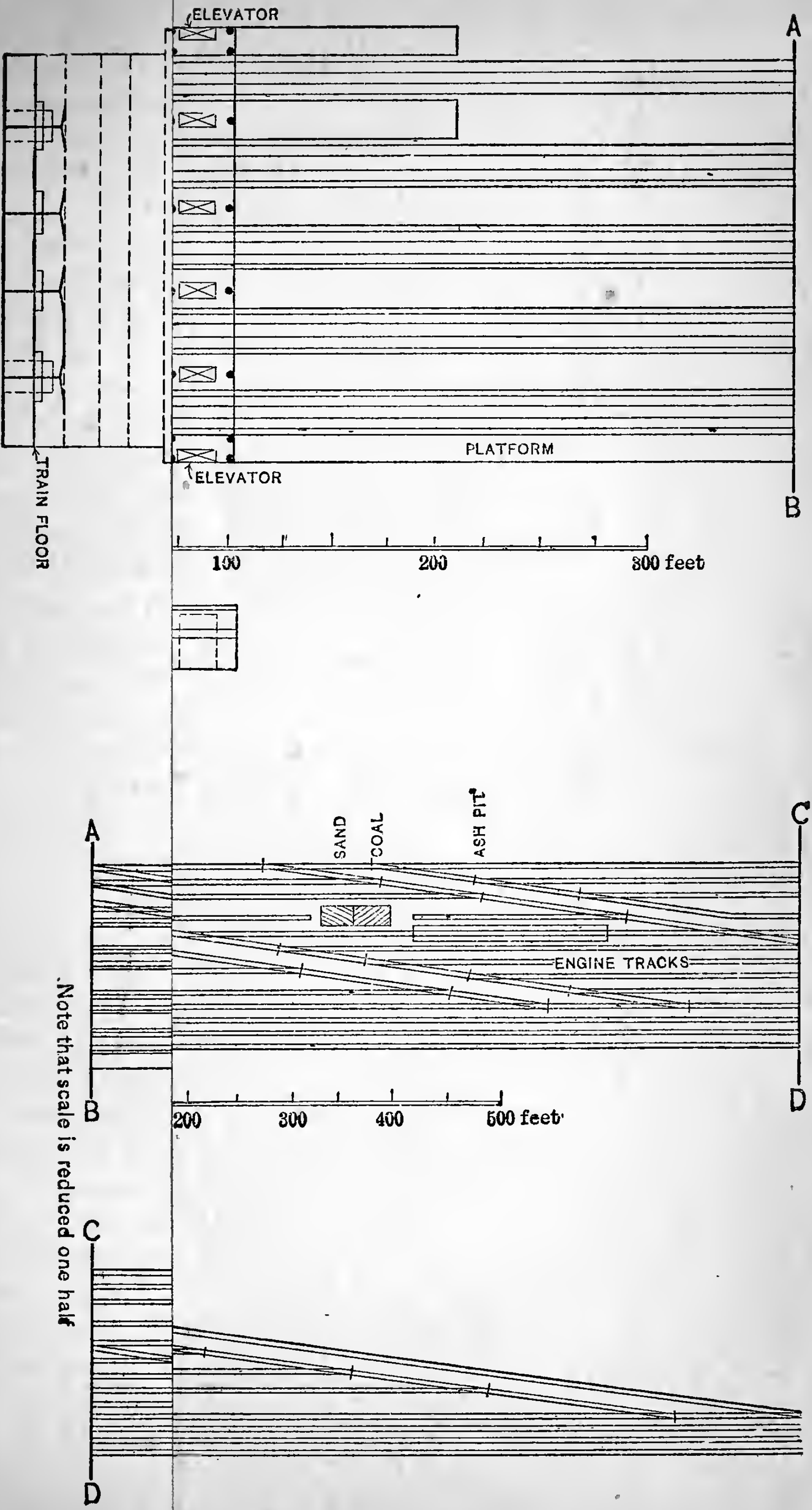


FIG. 167.—ENGINE YARD AND SHOPS, URBANA, ILL.

will very materially increase the capacity. Making the frame movable so that it travels on tracks which are parallel to the car tracks, giving the frame a longitudinal motion equal to two or three car lengths, and finally operating the raising and traveling mechanism by power, the facility for rapidly disposing of heavy articles of freight is greatly increased. Of course only a very small proportion of freight requires such handling, and the business of a yard must be large or perhaps of a special character to justify and pay for the installation of such a mechanism. A transfer crane, evidently of the fixed type, is indicated in Fig. 165.

384. Engine Yards or Terminals. These should be located so that there is easy access to both the main line and the various yards, with the fewest possible reverse or conflicting movements. The yards must contain all the tracks, buildings, structures, and facilities which are necessary for the maintenance, care, and storage of locomotives and for providing them



ND PASSENGER TERMINAL.

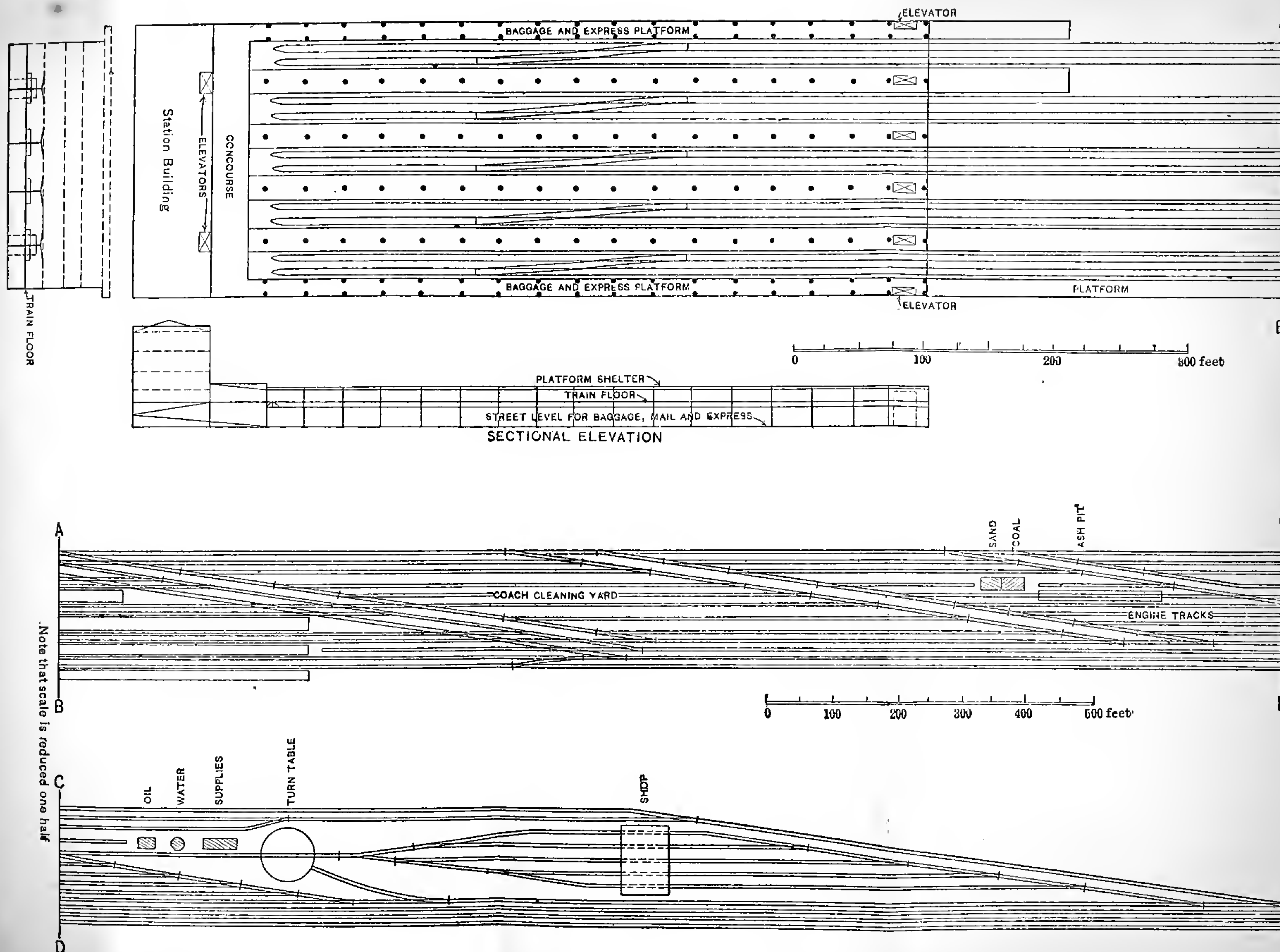
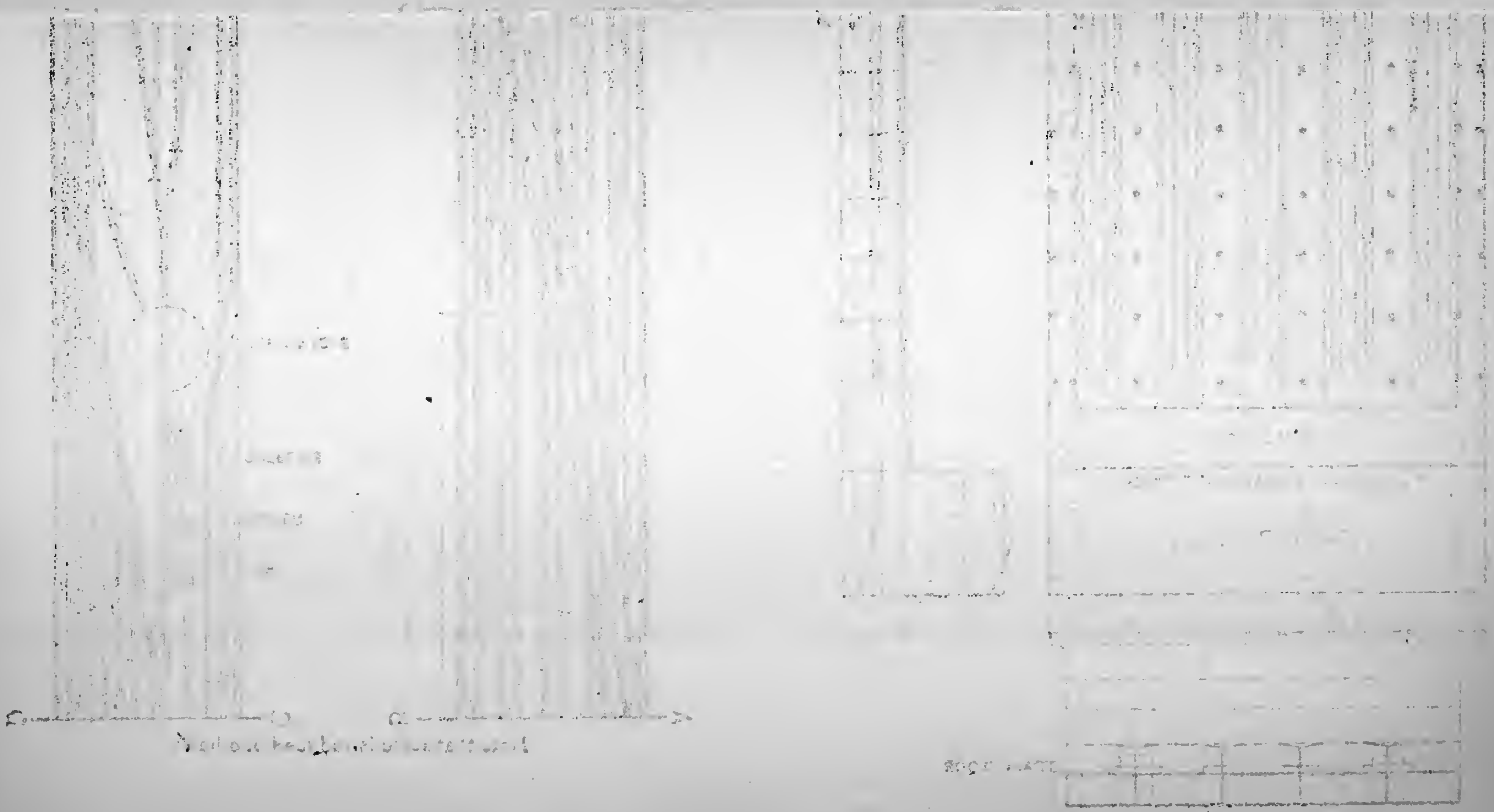


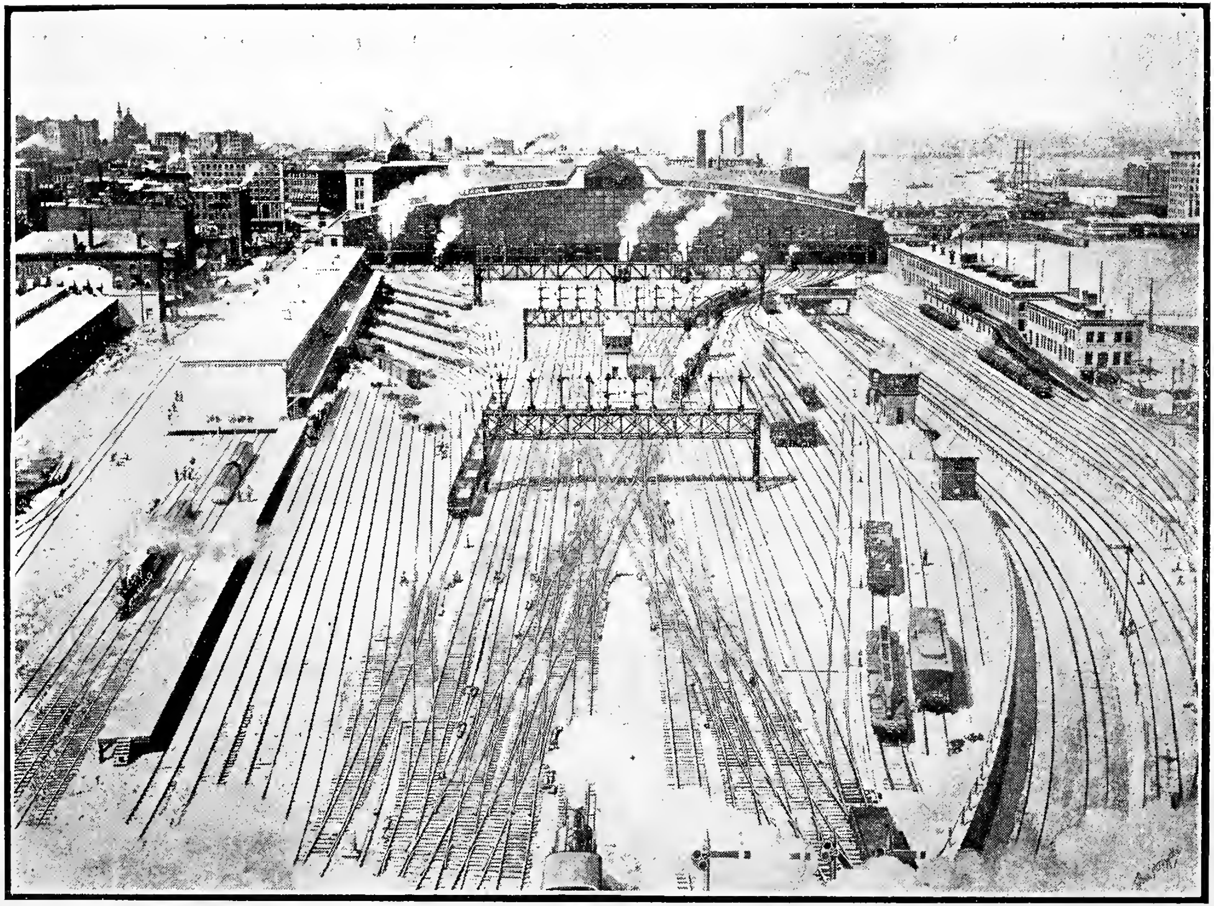
Fig. 167a.—Dead-end Passenger Terminal.



with all needed supplies. The supplies are fuel, water, sand, oil, waste, tallow, etc. Ash-pits are generally necessary for the prompt and economical disposition of ashes; engine-houses are necessary for the storage of engines and as a place where minor repairs can be quickly made. A turntable is another all but essential requirement. The arrangement of all these facilities in an engine yard should properly depend on the form of the yard. In general they should be grouped together and should be as near as possible to the place where through engines drop the trains just brought in and where they couple on to assembled outgoing trains, so that all unnecessary running light may be avoided. Switching engines should be able to dump ashes, take their supplies and pass around waiting road engines. In Figs. 164, 167 and 167*a* are shown designs which should be studied with reference to the relative arrangement of the yard facilities.

384a. Passenger terminals. The word **terminal** is applied not only to a railway station at an actual terminus, beyond which no trains are run, but also to an important intermediate station, where trains are assembled, assorted, classified and relayed. The two types are called dead-end and through terminals. The Am. Rwy. Eng. Assoc. has adopted standard plans for each of these two types. Even when there is good reason for modifying some of the details, certain principles should be observed, as far as possible. Some of these principles, which sometimes apply to both types, are as follows:

(a) **Dead-end terminals.** See Fig. 167*a*. The track level and train floor is raised above the street level, so as to permit any intersecting cross streets to run *under* the tracks. A **ramp** on an easy grade is indicated in the section of the terminal building. Each **platform** serves a pair of tracks whose centers are 28′ apart. Allowing 5′ 6″ from the track center to the edge of the platform, the platforms themselves are 17′ wide. The length of the platforms vary from about 600 to over 1100 feet, but the length and their number should depend on the extent of business to be handled. The intermediate platforms are protected for about 500 feet of their length by "butterfly" roofs supported on a line of columns, the roofs draining inward to longitudinal gutters in the center, which discharge into leaders alongside the columns. Two sets of **ladder tracks,** with single or double **slips** (§ 314) connect with each one of the platform tracks, so that



(Published through courtesy of Union Switch and Signal Co.)

[*To face page* 411.]

SOUTH BOSTON TERMINAL.

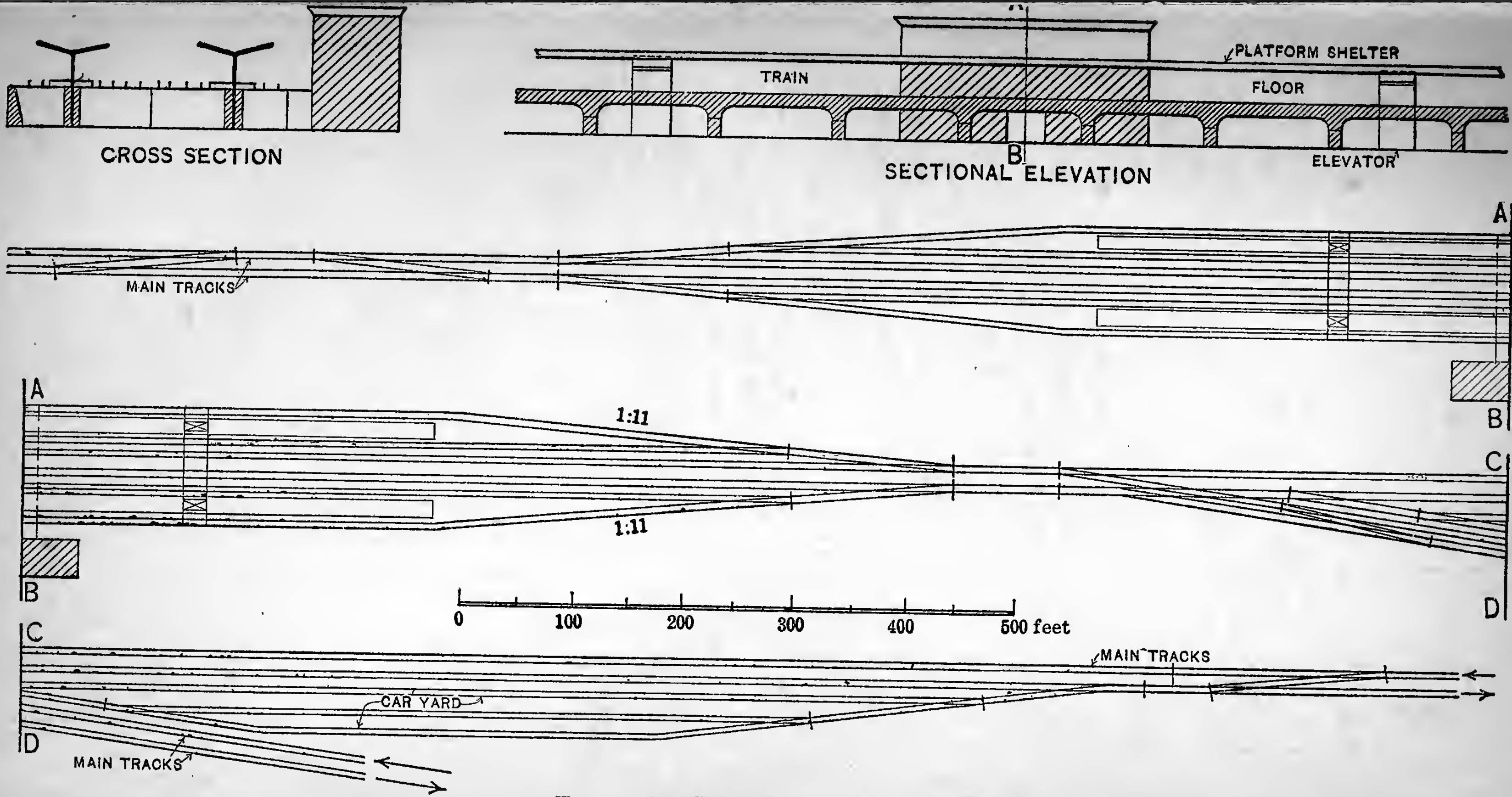


FIG. 167b.—THROUGH PASSENGER TERMINAL.

either main track may be directly connected with any platform track. The space under the tracks, and at the street level, is utilized for rooms for baggage, mail and express, which are carried to the track level by **elevators**, one to each platform. The **coach cleaning yard** has a series of parallel tracks 13′ to 18′ apart c.c. between a pair of parallel ladder tracks. The **engine yard** has a sand and coaling station, ash-pit with ash-car track, oil-house, water tank, engine supply house, turntable, shop and shop-yard tracks.

(**b**) **Through terminals.** See Fig. 167*b*. As above, the train floor level is above the street level. A passage way runs transversely under the tracks, from which two pairs of stairways run in each direction to the station platforms. As before, the baggage, mail and express rooms are on the street level, under the tracks, and connect with the platforms by elevators. The two middle tracks are main tracks, which may be used by any trains, through freight or passenger, which do not stop at the station. The two platforms each have two tracks, one on each side. The three tracks of each group run into one main track for each direction of movement, at either end of each platform. The two main tracks are connected by two crossovers, arranged for direct and reversed movement. The figure also shows an arrangement of switches for the junction of a branch line with the main line, with three car-yard tracks in the Y of the junction.

CHAPTER XIV.

BLOCK SIGNALING.

GENERAL PRINCIPLES.

385. **Two fundamental systems.** The growth of systems of block signaling has been enormous within the last few years—both in the amount of it and in the development of greater perfection of detail. The development has been along two general lines: (*a*) the *manual*, in which every change of signal is the result of some definite action on the part of some signalman, but in which every action is so controlled or limited or subject to the inspection of others that a mistake is nearly, if not quite, impossible; (*b*) the *automatic*, in which the signals are operated by mechanism, which cannot set a wrong signal as long as the mechanism is maintained in proper order. The fundamental principles of the two systems will be briefly outlined, after which the chief details of the most common systems will be pointed out.

386. **Manual systems.** Small traffic roads are usually operated on the basis of the "train-order system." A "train dispatcher" controls the movement of every train on his division and telegraphs orders to men (who are frequently station agents) at various points along the line, who transmit these orders to the trainmen as the trains reach these points. A train-order signal station, whether at a regular traffic station or in a special cabin, has "train-order signals" which, when in the stop position, inform the engineman and conductor that they are to receive orders at the telegraph office; the clear position informs them that there are no orders for them. When more than one train is allowed on a single track between two consecutive train-order stations, the engineman and conductor of each train has strict orders with reference to the other train, for example, that the trains are to pass at some siding where there is no telegraphic station. A very strict code of rules has been developed which, when literally followed, ensures safety of operation, but these rules cannot eliminate the human element, or the liability of personal negligence or error. When such a system is applied to a double-track road, or even to a single-track road, with train-order signal

stations located so frequently that only one train will be allowed between two consecutive offices at once, it virtually becomes a block system even though it is not called such. When such a system is adhered to rigidly, it is called an *absolute block* system. But when operating on this system, a delay of one train will necessarily delay every other train that follows closely after. A portion, if not all, of the delay to subsequent trains may be avoided, although at some loss of safety, by a system of permissive blocking. By this system an operator may give to a succeeding train a "clearance card" which permits it to pass into the next block, but at a reduced speed and with the train under such control that it may be stopped on very short notice, especially near curves. One element of the danger of this system is the *discretionary* power with which it invests the signalmen, a discretion which may be wrongfully exercised. A modification (which is a fruitful source of collisions on single-track roads) is to order two trains to enter a block approaching each other, and with instructions to pass each other at a passing siding at which there is no telegraph-station. When the instructions are properly made out and literally obeyed, there is no trouble, but every thousandth or ten thousandth time there is a mistake in the orders, or a misunderstanding or disobedience, and a collision is the result. The telegraph line, a code of rules, a corps of operators, and signals under the immediate control of the operators, are all that is absolutely needed for the simple manual system.

387. Development of the manual system. One great difficulty with the simple system just described is that each operator is practically independent of others except as he may receive general or specific orders from a train-dispatcher at the division headquarters. Such difficulties are somewhat overcome by a very rigid system of rules requiring the signalmen at each station to keep the adjacent signalmen or the train-dispatcher informed of the movements of all trains past their own stations. When these rules (which are too extensive for quotation here) are strictly observed, there is but little danger of accident, and a neglect by any one to observe any rule will generally be apparent to at least one other man. Nevertheless the safety of trains depends on *each* signalman doing his duty, and a little carelessness or forgetfulness on the part of any one man may cause an accident. The signaling between stations *may* be done by ordinary telegraphic messages or by telephone, but is frequently done by electric bells, according to a code of signals, since these may be readily learned by men who would have more difficulty in learning the Morse code.

In order to have the signalmen mutually control each other, the "controlled manual" system has been devised. The first successful system of this kind which was brought into extensive use is the "Sykes" system, of which a brief description is as follows: Each signal is worked by a lever; the lever is locked by a latch, operated by an electro-magnet, which, with other necessary apparatus, is inclosed in a box. When a signal is set at danger, the latch falls and locks the lever, which cannot be again set free until the electro-magnet raises the latch. The magnet is energized only by a current, the circuit of which is closed by a "plunger" at the *next* station ahead; just above the plunger is an "indicator," also operated by the current, which displays the words *clear* or *blocked*. (There are variations on this detail.) When a train arrives at a block station (A), the signalman should have previously signaled to the station *ahead* (B) for permission to free the signal. The man ahead (B) pushes in the "plunger" on his instrument (assuming that the previous train has already passed him), which electrically opens the lock on the lever at the previous station (A). The signal at A can then be set at "safety." As soon as the train has passed A the signal at A must be set at "danger." A further development is a device by which the mere passage of the train over the track for a few feet beyond the signal will automatically throw the signal to "danger." After the signal once goes to danger, it is automatically locked and cannot be released except by the man in advance (B), who will not do so until the train has passed him. The "indicator" on B's instrument shows "blocked" when A's signal goes to danger after the train has passed A, and B's plunger is then locked, so that he cannot release A's signal while a train is in the block. As soon as the train has passed A, B should prepare to get his signals ready by signaling ahead to C, so that if the block between B and C is not obstructed, B may have his signals at "safety" so that the train may pass B without pausing. The student should note the great advance in safety made by the Sykes system; a signal cannot be set free except by the combined action of two men, one the man who actually operates the signal and the other the man at the station ahead, who frees the signal electrically and who by his action certifies that the block immediately ahead of the train is clear.

A still further development makes the system still more "automatic" (as described later), and causes the signal to fall to danger or to be kept locked at danger, if even a single pair of wheels comes on the rails of a block, or if a switch leading from a main track is opened.

388. Permissive blocking. "Absolute" blocking renders accidents due to collisions almost impossible unless an engineer runs by an adverse signal. The signal mechanism is usually so designed that, if it gets out of order, it will inevitably fall to "danger," i.e., as described later, the signal-board is counterbalanced by a weight which is much heavier. If the wire breaks, the counterweight will fall and the board will assume the horizontal position, which always indicates "danger."* But it sometimes happens that when a train arrives at a signal-station, the signalman is unable to set the signal at safety. This may be because the previous train has broken down somewhere in the next block, or because a switch has been left open, or a rail has become broken, or there is a defect of some kind in the electrical connections. In such cases, in order to avoid an indefinite blocking of the whole traffic of the road, the signalman may give the engineer a "caution-card" or a "clearance card," which authorizes him to proceed slowly and with his train under complete control into the block and through it if possible. If he arrives at the next station without meeting any obstruction it merely indicates a defective condition of the mechanism, which will, of course, be promptly remedied. Usually the next section will be found clear, and the train may proceed as usual. On roads where the "controlled manual" system has received its highest development, the rules for permissive blocking are so rigid that there is but little danger in the practice, unless there is an absolute disobedience of orders.

389. Automatic systems. By the very nature of the case, such systems can only be used to indicate to the engineers of trains something with reference to the passage of previous

* This was written on the basis of the older system, in which the semaphore swings through the *lower* right-hand quadrant. The most recent practice swings the semaphore through the *upper* right-hand quadrant. A break in the wire holding the semaphore vertical will cause it to fall to horizontal position without the aid of a counterweight.

trains. The complicated shifting of switches and signals which is required in the operation of yards and terminals can only be accomplished by "manual" methods, and the only automatic features of these methods consist in the mechanical checks (electric and otherwise), which will prevent wrong combinations of signals. But for long stretches of the road, where it is only required to separate trains by at least one block length, an automatic system is generally considered to be more reliable. As expressed forcibly by a railroad manager, "an automatic system does not go to sleep, get drunk, become insane, or tell lies when there is any trouble." The same cannot always be said of the employés of the manual system.

The basic idea of all such systems is that when a train passes a signal-station (A), the signal automatically assumes the "danger" position. This may be accomplished electrically, pneumatically, or even by a direct mechanism. When the train reaches the end of the block at B and passes into the next one, the signal at B will be set at danger and the signal at A will be set at safety. The lengths of the blocks are usually so great that the only practicable method of controlling from B a mechanism at A is by electricity, although the actual motive power at A may be pneumatic or mechanical. At one time the current from A to B was run only through wires. This method has the very positive advantage of reliability, definite resistance to the current, and small probability of short-circuiting or other derangement. But now all such systems use the rails for a track circuit and this makes it possible to detect the presence of a single pair of wheels on the track anywhere in the block, or an open switch, or a broken rail. Any such circumstances, as well as a defect in the mechanism, will break or short-circuit the current and will cause the signal to be set at danger. To prevent an indefinite blocking of traffic owing to a signal persistently indicating danger, most roads employing such a system have a rule substantially as follows: When a train finds a signal at danger, after waiting one minute (or more, depending on the rules), it may proceed slowly, expecting to find an obstruction of some sort; if it reaches the next block without finding any obstruction and finds the next signal clear, it may proceed as usual, but must promptly report the case to the superintendent. Further details regarding these methods will be given later. See § 394.

390. "Distant" signals. The close running of trains that is required on heavy-traffic roads, especially where several branches combine to enter a common terminal, necessitates the use of very short blocks. A heavy train running at high speed can hardly make a "service" stop in less than 2000 feet, while the curves of a road (or other obstructions) frequently make it difficult to locate a signal so that it can be seen more than a few hundred feet away. It would therefore be impracticable to maintain the speed now used with heavy trains if the engineer had no foreknowledge of the condition in which he will find a signal until he arrives within a short distance of it. To overcome this difficulty the "distant" signal was devised. This is placed about 1800 or 2000 feet from the "home" signal, and is interlocked with it so that it gives the *same* signal. The distant signal is frequently placed on the same pole as the home signal of the previous block. When the engineer finds the distant signal "clear," it indicates that the succeeding home signal is also clear, and that he may proceed at full speed and not expect to be stopped at the next signal; for the distant signal cannot be cleared until the succeeding home signal is cleared, which cannot be done until the block succeeding that is clear. A clear distant signal therefore indicates a clear track for two succeeding blocks. When the engineer finds the distant signal blocked, he need not stop (providing the home signal is clear). It simply indicates that he must be prepared to stop at the next home signal and must reduce speed if necessary. It may happen that by the time he reaches the succeeding home signal it has already been cleared, and he may proceed without stopping. This device facilitates the rapid running of trains, with no loss of safety, and yet with but a moderate addition to the signaling plant.

391. "Advance" signals. It sometimes becomes necessary to locate a signal a few hundred feet short of a regular passenger-station. A train might be halted at such a signal because it was not cleared from the signal-station ahead—perhaps a mile or two ahead. For convenience, an "advance" signal may be erected immediately beyond the passenger-station. The train will then be permitted to enter the block as far as the advance signal and may deliver its passengers at the station. The advance signal is interlocked with the home signal back of it, and cannot be cleared until the home signal is cleared and the entire block ahead is clear. In one sense it adds another block, but the signal is entirely controlled from the signal station back of it.

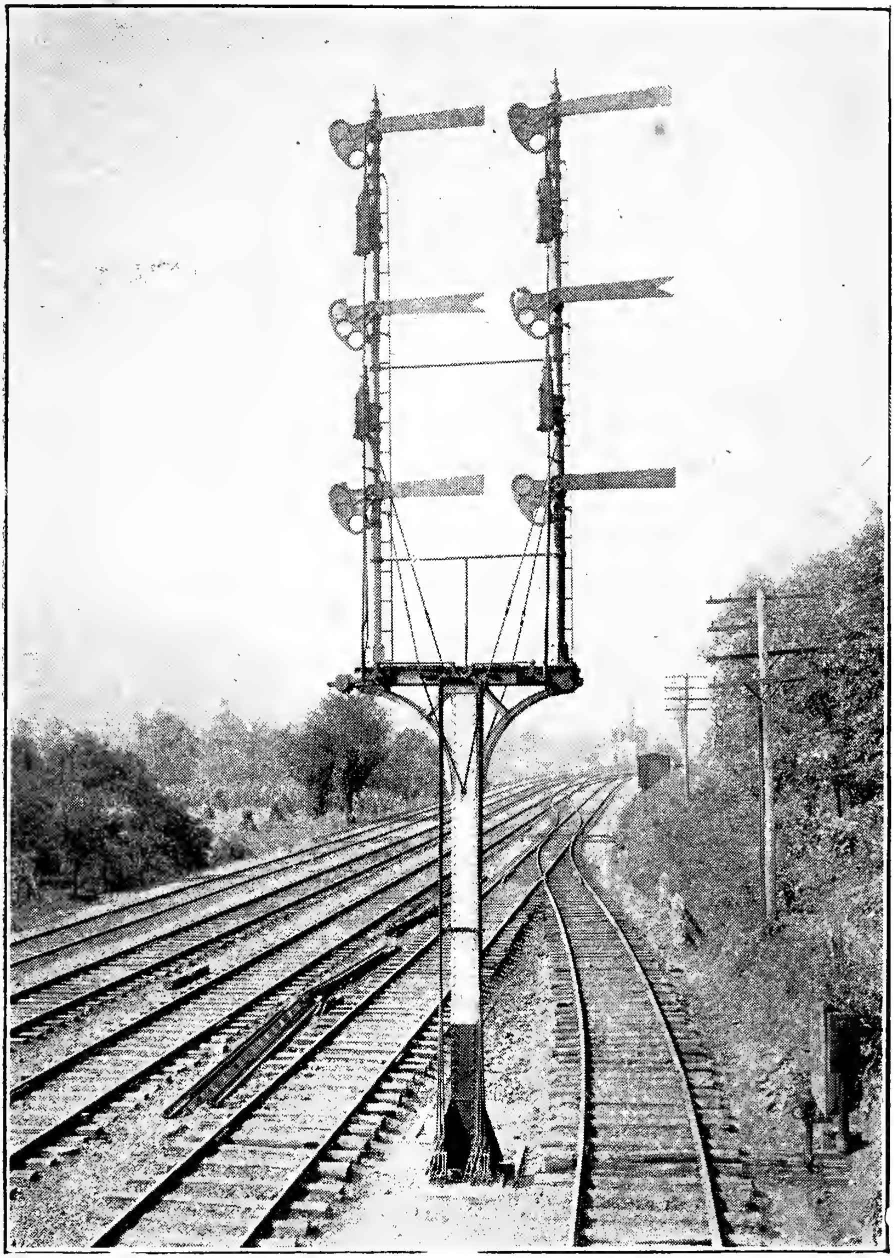
MECHANICAL DETAILS.

308. Signals. The primitive signal is a mere cloth flag. A better signal is obtained when the flag is suspended in a suitable place from a fixed horizontal support, the flag weighted at the bottom, and so arranged that it may be drawn up and out of sight by a cord which is run back to the operator's office. The next step is the substitution of painted wood or sheet metal for the cloth flag, and from this it is but a step to the standard semaphore on a pole, as is illustrated in Fig. 168. The simple flag, operated for convenience with a cord, is the signal employed on thousands of miles of road, where they perhaps make no claim to a block-signal system, and where the trains are run on the "train-order system."

Semaphore boards. These are about 5 feet long, 8 inches wide at one end, and tapered to about 6 inches wide at the hinge end. The boards are fastened to a casting which has a ring to hold a red glass which may be swung over the face of a lantern, so as to indicate a red signal. "Distant" signal-boards usually have their ends notched or pointed; the "home" signal-boards are square ended. The boards are always to the *right* of the hinge when a train is approaching them. The "home" signals are generally painted red and the "distant" signals green, although these colors are not invariable. The backs of the boards are painted white. Therefore any signal-board which appears on the *left* side of its hinge will also appear *white*, and is a signal for traffic in the opposite direction, and is therefore of no concern to an engineman.

Poles and bridges. When the signals are set on poles, they are always placed on the right-hand side of the track. When there are several tracks, four or more, a bridge is frequently built and then each signal is over its own track. The signals for two tracks, operated in the same direction, may be placed on one pole by having a cross-piece which supports two "masts," see Fig. 168. In that figure the signals on the left-hand mast control the second track at the left of the signal; those on the right-hand mast control the track just to the left of the signal.

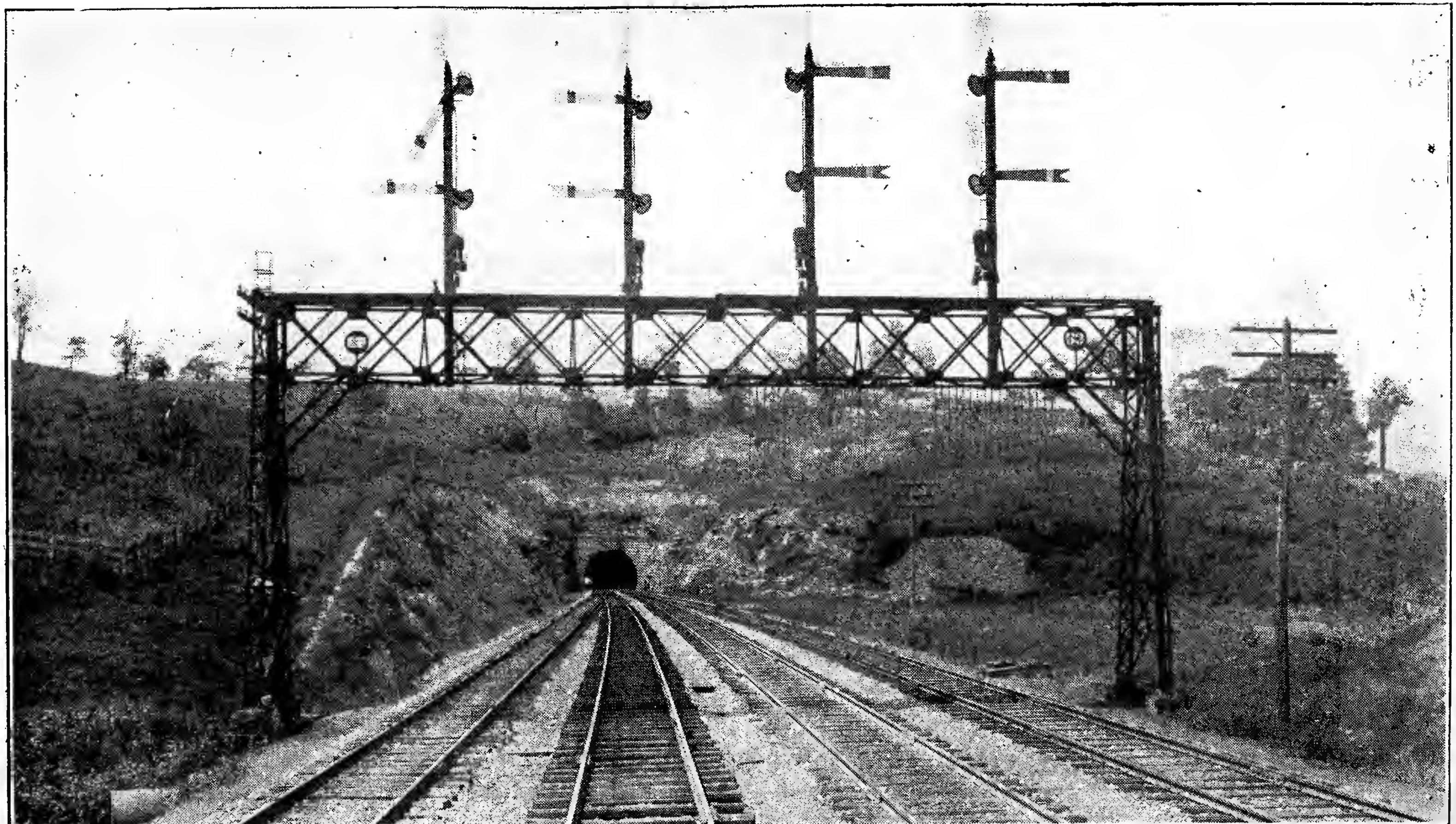
(To face page 418.)



Courtesy of the Union Switch and Signal Co.

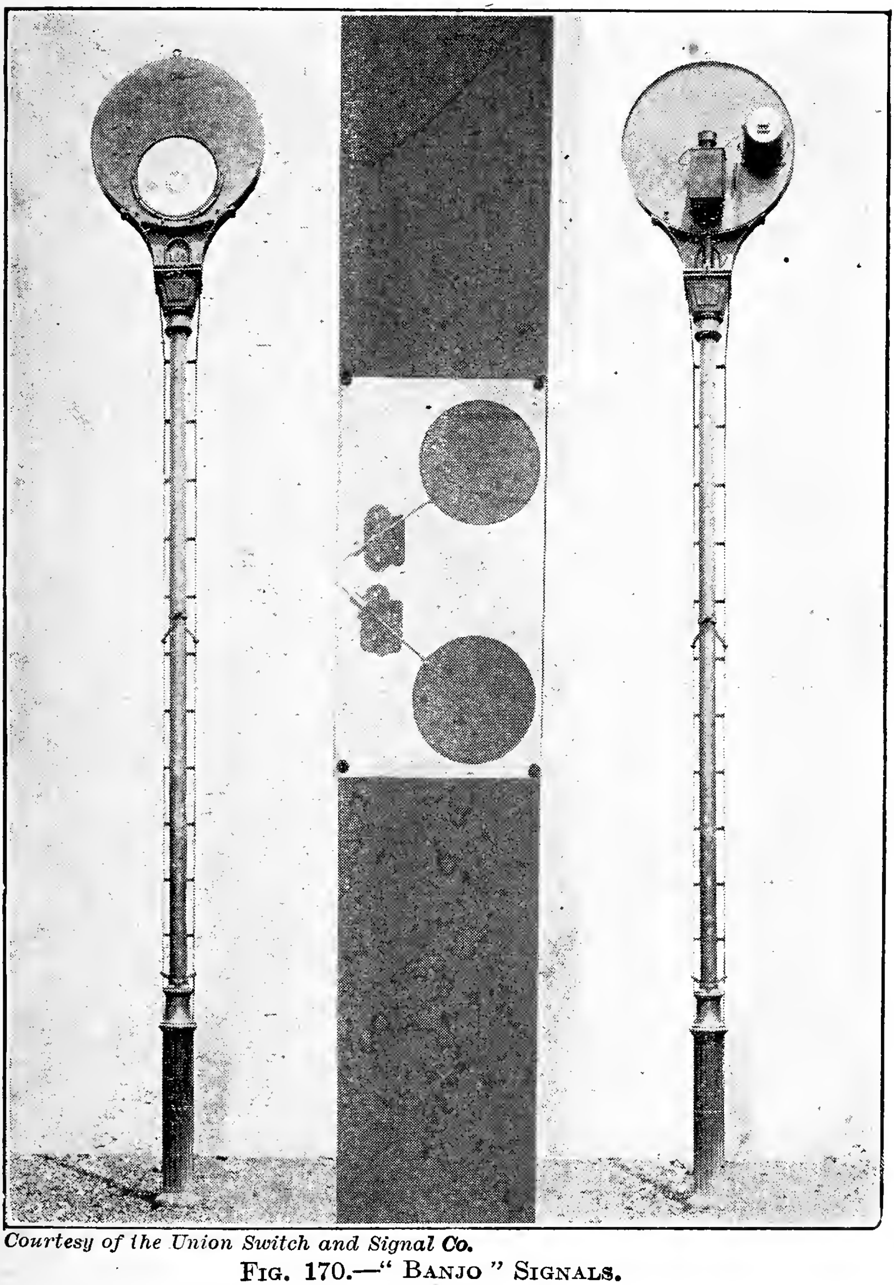
FIG. 168.—SEMAPHORES.

(*To face page* 418.)



Courtesy of the Union Switch and Signal Co.

(To face page 418.)



Courtesy of the Union Switch and Signal Co.

FIG. 170.—"BANJO" SIGNALS.

A train movement, from the switch track at the right of the signal on to the main track, is controlled by the "dwarf" signal at the right of the switch track. The signals controlling the two tracks at the extreme left are not shown. The building at the left of the track in the extreme background is apparently the signal tower controlling this signal.

In Fig. 169 is shown a "bridge" and the two signals (home and distant), for each track. The two pairs of signals on the two right-hand poles are extended to the right and show that the movement of trains on those tracks is away from the observer. The darkness of the blades in the picture shows that they are painted dark, probably orange or red. The other blades show light (because painted white), and extend to the left but would appear to the right to an engineman on either left-hand track coming toward the observer. Incidentally the picture shows, over the two right-hand tracks, the ropes of a "tickler" (see § 375), to protect brakemen on the tops of cars which will enter the tunnel shown in the background.

"Banjo" signals. This name is given to a form of signal, illustrated in Fig. 170, in which the indication is taken from the *color* of a round disk inclosed with glass. The great argument in their favor is that they may be worked by an electric current of low voltage, which is therefore easily controlled; that the mechanism is entirely inside of a case, is therefore very light, and is not exposed to the weather. The argument urged against them is that it is a signal of *color* rather than *form* or *position*, and that in foggy weather the signal cannot be seen so easily; also that unsuspected color-blindness on the part of the engineman may lead to an accident. Notwithstanding these objections, this form of signal is used on thousands of miles of line in this country.

393. Wires and pipes. Signals are usually operated by levers in a signal-cabin, the levers being very similar to the reversing-lever of a locomotive. The distance from the levers to the signals is, of course, very variable, but it is sometimes 2000 feet. The connecting-link for the most distant signals is usually No. 9 wire; for nearer signals and for all switches operated from the cabin it may be 1-inch pipe. When not too long, one pipe will serve for both motions, forward and back. When wires are used, it is sometimes so designed (in the cheaper systems) that one wire serves for one motion, gravity being depended on for the other, but now all good systems require two wires for each signal.

Compensators. Variations of temperature of a material with as high a coefficient as iron will cause very appreciable difference of length in a distance of several hundred feet, and a dangerous lack of adjustment is the result. To illustrate: A fall of 60° F. will change the length of 1000 feet of wire by

$$1000 \times 60 \times .0000065 = 0.39 \text{ foot} = 4.68 \text{ inches}.$$

A much less change than this will necessitate a readjustment of length, unless automatic compensators are used. A compensator for pipes is very readily made on the principle illustrated in Fig. 171. The problem is to preserve the distance between a and d constant regardless of the temperature. Place the compensator half-way between a and d, or so that $ab = cd$. A fall of temperature contracts ab to ab'. Moving b to b' will cause c to move to c', in which $bb' = cc'$. But cd has also shortened to $c'd$; therefore d remains fixed in position.

The regulations of the Am. Rwy. Eng. Assoc. require that "A compensator shall be provided for each pipe line over fifty (50) feet in length and under eight hundred (800) feet, with crank-arms eleven by thirteen (11×13) inch centers. From eight hundred (800) to twelve hundred (1200) feet in length, crank-arms shall be eleven by sixteen (11×16) inch centers. Pipe lines over twelve hundred (1200) feet in length shall be provided with an additional compensator.

"Compensators shall have one sixty (60) degree and one one hundred and twenty (120) degree angle-cranks and connecting link, mounted in cast iron base, having top of center pins supported. The distance between center of pin-holes shall be twenty-two (22) inches."

The compensator should be placed in the middle of the length when only one is used. When two are used they should be placed at the quarter points. Note that in operating through a compensator the *direction* of motion changes; i.e., if a moves to the right, d moves to the left, or if there is compression in ab there is tension in cd, and *vice versa*. Therefore this form of compensator can only be used with pipes which will withstand compression. It has seemed impracticable to design an equally satisfactory compensator for wires, although there are several designs on the market.

The change of length of these bars is so great that allowance must be made for the temperature at the time of installation. On the basis of 50° as the mean temperature, the pipes are so adjusted that the distance between the points *b* and *c* of Fig. 171 is made greater or less than 22 inches, according to the temperature of installation. For example, if the temperature were 80° and the length of the piping were 900 feet, the length of the pipes should be adjusted so that *bc* is *less* than 22 inches by an amount equal to $900 \times (80° - 50°) \times .0000065 = 0.1755$ feet =

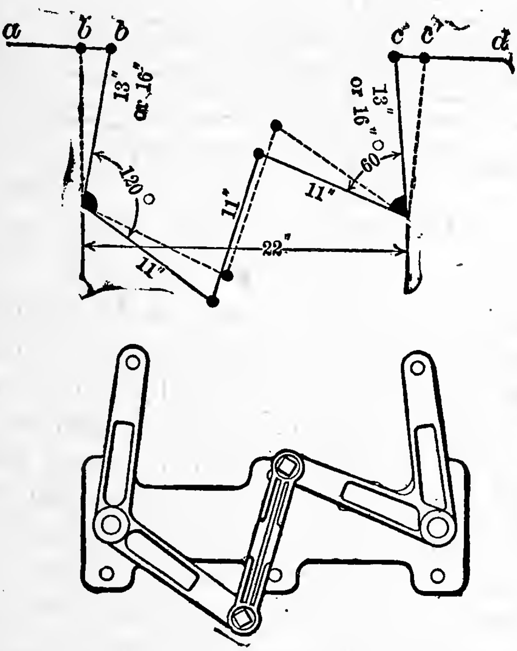


Fig. 171.—Standard Pipe Compensator.

2.106 inches. The length should therefore be 19.9 inches instead of 22 inches. If the mean temperature was very different (say in Florida) some higher temperature should be taken as normal, so that the extreme range above and below the normal shall be approximately the same.

Guides around curves and angles. When wires are required to pass around curves of large angle, pulleys are used, and a length of chain is substituted for the wire. For pipes, when the curve is easy the pipes are slightly bent and are guided through pulleys. When the angle is sharper, "angles" are used. The operation of these details is self-evident from an inspection of Fig. 172.

394. Track circuit for automatic signaling. The fundamental principle of the track circuit method of indicating a track obstruction or breakage, using direct current, is as follows: A current of low potential is run from a battery at one end of a section through one line of rails to the other end of the section, then through a relay, and then back to the battery through the other line of rails. To avoid the excessive resistance which would occur at rail joints which may become badly rusted, a wire

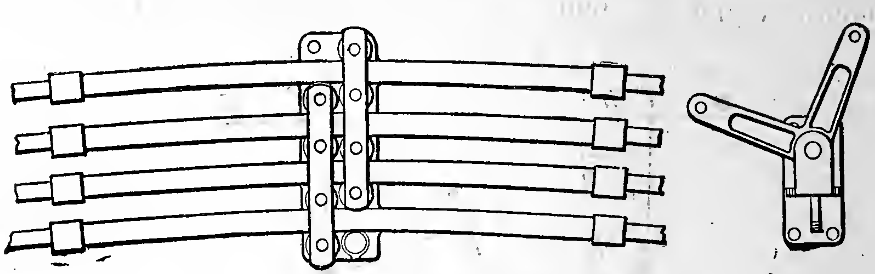


FIG. 172.—DEFLECTING-RODS AND ANGLE.

suitably attached to the rails is run around each joint. In order to insulate the rails of one section from the rails at either end and yet maintain the rails structurally continuous, the ends of the rails at these dividing points are separated by an insulator and the joint pieces are either made of wood or have some insulating material placed between the rails and the ordinary metal joint. The bolts must also be insulated. When the relay is energized by a current, it closes a local circuit at the signal-station, which will set the signal there at "safety." The resistance of the relay is such that it requires nearly the whole current to work it and to keep the local circuit closed. Therefore, when there is any considerable loss of current from one rail to the other, the relay will not be sufficiently energized, the local circuit will be broken, and the signal will automatically fall to danger. This diversion of current from one rail to the other before the current reaches the relay may be caused in several ways: the presence of a pair of wheels on the rails anywhere in the section will do it; also the breakage of a rail; also the opening of a switch anywhere in the section; also the presence of a pair of wheels on a siding between the "fouling point" and the switch. (The "fouling point" of a siding is that point where the rails first commence to approach the main track.) In Fig. 173 is shown all of the above details as well as some others.

At *A*, *B*, and the "fouling point" are shown the insulated joints. The batteries and signals are arranged for train motion to the *right*. When a train has passed the points near *A*, where the wires leave the rails for the relay, the current from the "track battery" at *B* will pass through the wheels and axles, and although no electrical connection is broken, so much current will be shunted through the wheels and axles that the weak current still passing through the relay is not strong enough to energize it against its spring and the "signal-magnet" circuit is broken, and the signal *A* goes to "danger." At the turnout the rails between the fouling point and the switch are so connected (and insulated) that a pair of wheels on these rails will produce the same effect as a pair of the main track. This is to guard against the effect of a car standing too near the switch, even though it is not on the main track. When the train passes *B*, if there is no other interruption of the current, the track battery at *B* again energizes the relay at *A*, the signal-magnet circuit at *A* is closed, and the signal is drawn to "safety."

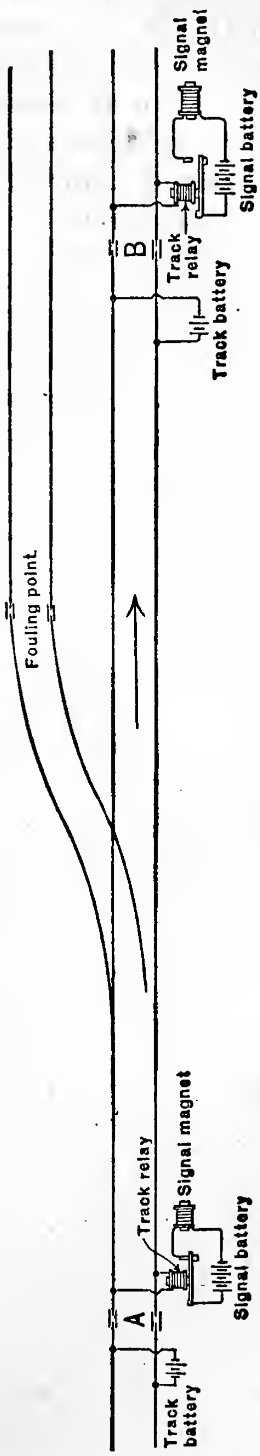


Fig. 173.

About 1903 the application of *alternating current* to signaling circuits was invented. This not only permits the substitution of a. c. circuit for track batteries, but also makes it possible to utilize the track circuit method to indicate obstructions or rail breakages even when the track is the return circuit for an electrified road. But an explanation of this development would be too long for this text-book. It is given in a 548-page book called "Alternating Current Signaling," published by the Union Switch & Signal Co., Swissvale, Pa.

This chapter also omits all references to "interlocking plants," which are essential features of the operation of large terminal yards. Even an elementary treatment of the present development of signaling and interlocking would require a large textbook, and, therefore, nothing more than the above brief outline will be here given.

CHAPTER XV.

ROLLING-STOCK.

(It is perhaps needless to say that the following chapter is in no sense a course in the design of locomotives and cars. Its chief idea is to give the student the elements of the construction of those vehicles which are to use the track which he may design—to point out the mutual actions and reactions of vehicle against track and to show the effect on track wear of variations in the design of rolling-stock. The most of the matter given has a direct practical bearing on track-work, and it is considered that all of it is so closely related to his work that the civil engineer may study it with profit. For "Stresses in Track," see Chap. XXV.)

WHEELS AND RAILS.

395. **Effect of rigidly attaching wheels to their axles.** The wheels of railroad rolling-stock are invariably secured rigidly to the axles, which therefore revolve with the wheels. The chief reason for this is to avoid excessive wear between the axles and the wheels.

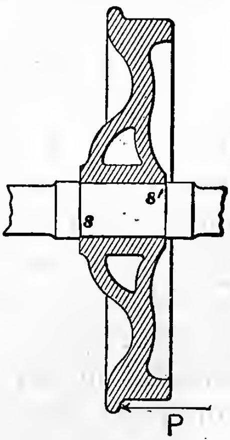


FIG. 174.

Any axle must always be somewhat loose in its journals. A sidewise force P (see Fig. 174) acting against the circumference of the wheel will produce a much greater pressure on the axle at S and S', and if the wheel moves on the axle, the wear at S and S' will be excessive. But when the axle is fitted to the wheel with a "forced fit" and does not revolve, the mere *pressure* produced at S is harmless. When two wheels are fitted tight to an axle, as in Fig. 175, and the axle revolves in the journals aa, a sidewise pressure of the rail against the wheel flange will only produce a slight and harmless increase of the journal pressure Q, although at Q there is sliding contact. Twisting action in the journals is thus practically avoided, since a small pressure at the journal-boxes at each end of the axle suffices to keep the axle truly in line.

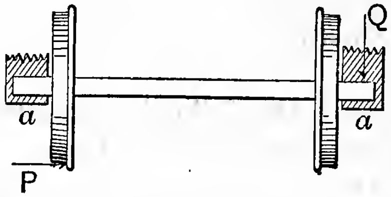


FIG. 175.

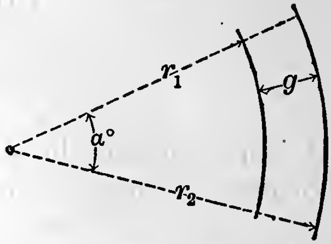


FIG. 176.

On the other hand, when the wheels are rigidly attached to their axles, both wheels must turn together, and when rounding curves, the inner rail being shorter than the outer rail, one wheel must slip by an amount equal to that difference of length. The amount of this slip is readily computable:

$$\text{Longitudinal slip} = \frac{2\pi a°}{360°}(r_2 - r_1) = \frac{2\pi g}{360°}a° = Ca°, \quad . \quad (102)$$

in which C is a constant for any one gauge, and $g =$ the track gauge $= (r_2 - r_1)$. For standard gauge (4.708) the slip is .08218 foot per degree of *central angle.* This shows that the longitudinal slipping around any curve of any given central angle will be *independent of the degree of the curve.* The constant (.08218) here given is really somewhat too small, since the true gauge that should be considered is the distance between the lines of tread on the rails. This distance is a somewhat indeterminate and variable quantity, and probably averages 4.90 feet, which would increase the constant to .086. The slipping may occur by the inner wheel slipping ahead or the outer wheel slipping back, or by both wheels slipping. The total slipping will be constant in any case. The slipping not only consumes power, but wears both the wheels and the rail. But even these disadvantages are not sufficient to offset the advantages resulting from rigid wheels and axles.

396. Effect of parallel axles. Trucks are made with two or three parallel axles (except as noted later), in order that the axles shall mutually guide each other and be kept approximately perpendicular to the rails. If the curvature is very sharp and the wheel-base comparatively long (as is notably the case for four-wheeled street cars passing around street corners), the front

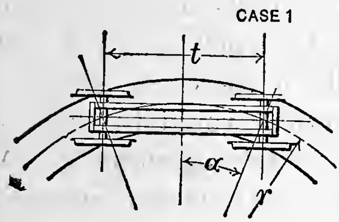


FIG. 177.

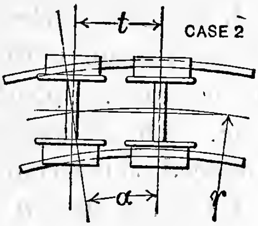


FIG. 178.

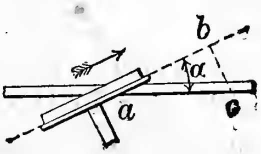


FIG. 179.

and rear wheels will stand at the same angle (a) with the track, as shown in Fig. 177, which also applies to easy curvature whenever the rear outer wheel-flange is forced against the rail, which is claimed by some to be the normal position. Others claim that for ordinary curvature the rear axle will take a position normal to the curve, as shown in Fig. 178. But it is certain that track irregularities cause the rear wheels to sway within the limits of the play of the gauge and that the angle α varies. For Case 1, $\sin \alpha = t \div 2r$; for Case 2, $\sin \alpha = t \div r$.

When the two parallel axles are on a curve (as shown), the wheels tend to run in a straight line. In order that they shall run on a curve they must slip laterally. The principle is illustrated in an exaggerated form in Fig. 179. The wheel *tends* to roll from a toward b. Therefore in passing along the track from a to c it must actually slip laterally an amount bc which equals $ac \sin a$. The lateral slipping *per unit* of distance traveled therefore equals $\sin a$. For Case 1, both front wheels slip laterally toward the curve center, and both rear wheels slip laterally away from the center. For Case 2, both front wheels slip laterally toward the center, but the slip per unit of forward distance is only one-half that of Case 1, while the rear axle, being radial does not slip laterally at all. Neither Case 1 nor Case 2 (nor any other combination) is constantly applicable.

From the above it might be inferred that the flanges of the forward wheels will have much greater wear than those of the rear wheels. Since cars are drawn in both directions about equally, no difference in flange wear due to this cause will occur, but locomotives (except switching-engines) run forward almost exclusively, and the excess wear of the front wheels of the pilot- and tender-trucks is plainly observable.

For a given curve the angle a (and the accompanying resistance) is evidently greater the greater the distance between the axles. On the other hand, if the two axles are very close together, there will be a tendency for the truck to twist and the wheels to become jammed, especially if there is considerable play in the gauge. The flange friction would be greater and would perhaps exceed the saving in lateral slipping. A general rule is that the axles should never be closer together than the gauge; usually it is considerably more.

Although the slipping per unit of length along the curve varies directly as the degree of curvature, the length of curve necessary to pass between two tangents is inversely as the degree of curve, and the total slipping between the two tangents is independent of the degree of curve. Therefore when a train passes between two tangents, the total slipping of the wheels on the rails, longitudinal and lateral, is a quantity which depends **only** on the **central angle** and is **independent** of the **radius** or **degree of curve.**

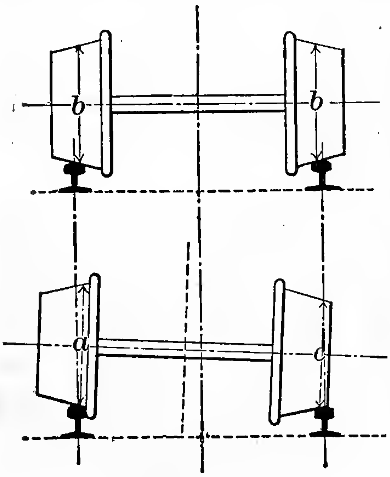


FIG. 180.

397. Effect of coning wheels. The wheels are always set on the axle so that there is some "play" or chance for lateral motion between the wheel-flanges and the rail. The treads of the wheel are also "coned." This coning and play of gauge are shown in an exaggerated form in Fig. 180. When the wheels are on a tangent, although there will be occasional oscillations from side to side, the normal position will be the symmetrical position in which the circles of tread bb are equal. When centrifugal force throws the wheel-flange against the rail, the circle of tread a is larger than b, and much larger than c; therefore the wheels will tend to roll in a circle whose radius equals the slant height of a cone whose elements would pass through the unequal circles a and c. If this radius equaled the radius of the track, and if the axle were free to assume a radial position, the wheels would roll freely on the rails without any slipping or flange pressure. Under such ideal conditions, coning would be a valuable device, but it is impracticable to have all axles radial, and the radius of curvature of the track is an extremely variable quantity. It has been demonstrated that with parallel axles the influence of coning diminishes as the distance between the axle increases, and that the effect is practically inappreciable when the axles are spaced as they are on locomotives and car-trucks. The coning actually used is very slight (see Chapter XV, § 420) and has a different object. It is so slight that even if the axles were radial it would only prevent the slipping on a very light curve—say a 1° curve.

398. **Effect of flanging locomotive driving-wheels.** If all the wheels of all locomotives were flanged it would be practically impossible to run some of the longer types around sharp curves. The track-gauge is always widened on curves, and especially on sharp curves, but the widening would need to be excessive to permit a consolidation locomotive to pass around an 8° or 10° curve if all the drivers were flanged. The action of the wheels on a curve is illustrated in Figs. 181, 182, and 184. All small truck-wheels are flanged. The rear drivers are always flanged and four-driver engines usually have all the drivers flanged. Consolidation engines have only the front and rear drivers flanged. Mogul and ten-wheel engines have one pair of drivers blank. On Mogul engines it is always the middle pair. On ten-wheel engines, when used on a road having sharp curves, it is preferable to flange the front and rear driving-wheels and use a "swing bolster" (see § 399); when the curvature is easy, the middle and rear drivers may be flanged and the truck made with a rigid center. The blank drivers have the same total width as the other drivers and of course a much wider tread, which enables these drivers to remain on the rail, even though the curvature is so sharp that the tread overhangs the rail considerably.

399. **Action of a locomotive pilot-truck.** The purpose of the pilot-truck is to guide the front end of a locomotive around a curve and to relieve the otherwise excessive flange pressure that would be exerted against the driver-flanges. There are two classes of pilot-trucks—(*a*) those having fixed centers and (*b*) those having shifting centers. This second class is again subdivided into two classes, which are radically different in their action—(b_1) four-wheeled trucks having two parallel axles

and (b_2) two-wheeled trucks which are guided by a "radius-bar." The action of the four-wheeled fixed-centered truck (a) is shown in Fig. 181. Since the center of the truck is forced

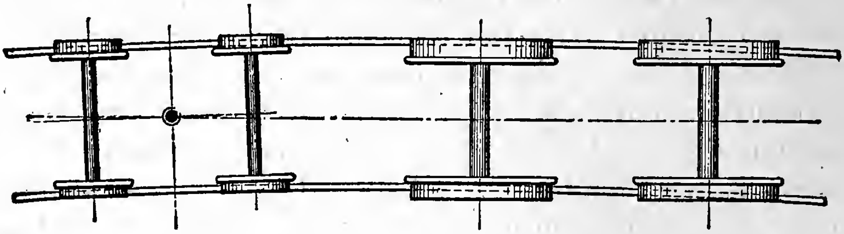


FIG. 181.—FIXED CENTER PILOT-TRUCK.

to be in the center of the track, the front drivers are drawn away from the outer rail. The rear outer driver tends to roll *away* from the outer rail rather than toward it, and so the effect

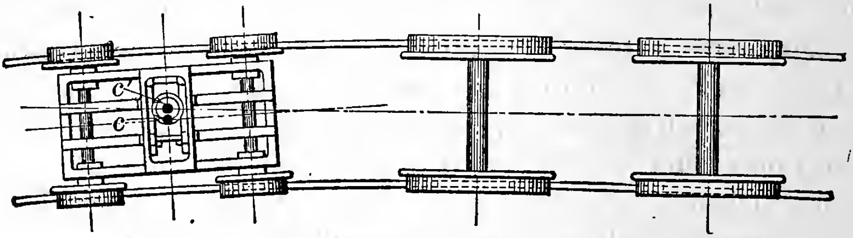


FIG. 182.—FOUR-WHEELED TRUCK—SHIFTING CENTER.

of the truck is to relieve the driver-flanges of any excessive pressure due to curvature. The only exception to this is the case where the curvature is sharp. Then the front inner driver may be pressed against the *inner* rail, as indicated in Fig. 181. This limits the use of this type of wheel-base on the sharper curves.

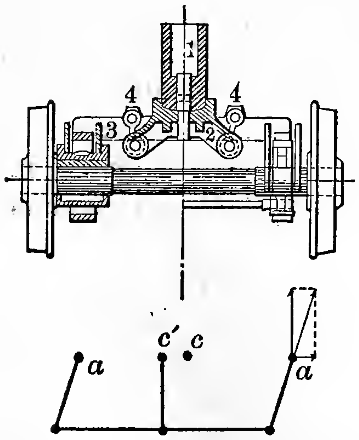


FIG. 183.—ACTION OF SHIFTING CENTER.

The next type—(b_1) four-wheeled trucks with shifting centers—is much more flexible on sharp curvature; it likewise draws the front drivers away from the outer rail. The relative position of the wheels is shown in Fig. 182, in which c' represents the position of center-pin and c the displaced truck center. The structure and action of the truck is shown in Fig. 183. The "center-pin" (1) is supported on the "truck-bolster" (2), which is hung by the "links" (4) from the "cross-ties" (3). The links are therefore in tension and when the wheels are forced to one side by the rails the *links* are inclined and the front of the engine is drawn inward by a force equal to the weight on the bolster times the tangent of the angle of inclination of the links. This assumes that all links are vertical when the truck is in the center. Frequently the opposite links are normally inclined to each other, which somewhat complicates the above simple relation of the forces, although the general principle remains identical.

The two-wheeled pilot-truck with shifting center is illustrated in Fig. 184. The figure shows the facility with which

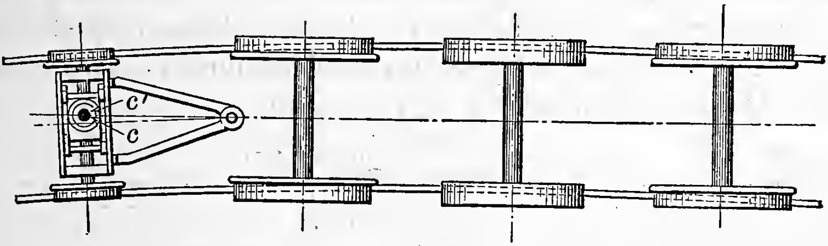


FIG. 184.—TWO-WHEELED TRUCK—SHIFTING CENTER.

an engine with long wheel-base may be made to pass around a comparatively sharp curve by omitting the flanges from the middle drivers and using this form of pilot-truck. As in the previous case, the eccentricity of the center of the truck relative to the center-pin induces a centripetal force which draws the front of the engine inward. But the swing-truck is not the only source of such a force. If the

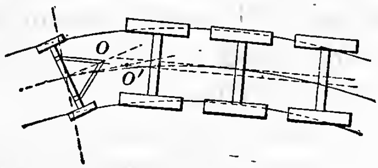


FIG. 185.—ACTION OF TWO-WHEELED TRUCK.

"radius-bar pin" were placed at O' (see Fig. 185), the truck-axle would be radial. But the radius-bar is always made somewhat shorter than this, and the pin is placed at O, a considerable distance ahead of O', thus creating a tendency for the truck to run toward the inner rail and draw the front of the locomotive in that direction. This tendency will be objectionably great if the radius-bar is made too short, as has been practically demonstrated in cases when the radius-bar has been subsequently lengthened with a resulting improvement in the running of the engine. This type of pilot truck is used on both Mogul and Consolidation locomotives and explains why these long engines can so easily operate on sharp curves.

400. Types of locomotive wheel-bases. The variations in locomotive service have developed all conceivable types as to total weight, ratio of total weight to weight on drivers, types of running gear, relation of steaming-capacity to tractive power, etc. The method of classification on the basis of the running gear is very simple. The number of wheels on both rails of the pilot truck, if any, is placed as the first of three numbers. If there is no pilot truck, the character 0 is used. This is followed by the number of drivers and then by the number of trailing wheels, if any. For example, a Pacific type engine has four wheels on the pilot truck, six driving wheels, and two trailing wheels under the rear of the boiler. The wheel-base is symbolized as 4–6–2. The most common types of locomotives, with their popular names and wheel base symbols, are

American	4–4–0	Consolidation	2–8–0
Columbia	2–4–2	Mikado	2–8–2
Atlantic	4–4–2	Mastodon	4–8–0
Mogul	2–6–0	Santa Fe	2–10–2
Prairie	2–6–2		
Ten-wheel	4–6–0	Mallet	A–B–B–A
Pacific	4–6–2	A = truckwheels, usually	2 or 0
Six-wheel switcher	0–6–0	B = drivers, varying from	4 to 10

The "**Mallet**" type of locomotive is one which combines sufficient flexibility to operate on ordinary railroad curves, wheel loads on the drivers which are not excessive, a very great increase in the total tractive power and yet operated by one engineman. In one respect it is like coupling two or three locomotives together, but the saving consists in reducing the number of enginemen and firemen which would be needed to run the two or three locomotives. Excluding freak variations, they are usually "four-cylinder compounds," one pair of cylinders discharging into the other pair and then exhausting. This type has from five to ten driving axles and has a length of engine wheel-base up to about 60 ft., but this wheel-base is flexible, so that it will bend on a curved track. Sometimes the boiler is made flexible by having a set of accordion-shaped steel rings forming a joint in the boiler shell. The boiler itself is on one side of this flexible joint and the feed-water heater, the reheater, and perhaps the superheater are on the other side of the joint. In this case each half of the flexible boiler is carried on a frame supported by one of the sets of driving wheels, the two frames being connected by a suitable joint. The boiler shell is made rigid; one end is rigidly attached to the frame carrying the high-pressure cylinders and the other end is supported on a bearing on the truck frame which carries the low-pressure cylinders and the drivers operated by them. The low-pressure truck frame swings around a pivot in the fixed frame. This flexibility has been made so great that these locomotives are operated successfully on 20° curves. The Baldwin Locomotive Works have developed this type still further by building a locomotive for the Erie R. R. which has three wheel frames, mutually flexible with each other, the third frame being under the tender. Each wheel frame has eight driving wheels. The total load carried by the twenty-four drivers is 761,600 lbs. or an average of 31,733 lbs. per driver. There are six cylinders of equal size. The two cylinders on the center frame use high-pressure steam and exhaust into the other four cylinders. The total weight of locomotive and tender is 853,050 lbs. On a test trip it pulled a train with a total length of 8547 ft. or 1.6 miles, the total weight of the train being 18,338 tons. The maximum draw-bar pull, registered by the dynamometer car, was 130,000 lbs. The adhesion between the drivers and the rails must have been considerably more. Such engines are chiefly used for hauling long trains of slow-speed freight. Their boilers cannot produce steam fast enough to develop their enormous tractive power at high speeds and the power falls off rapidly with increase in speed. They are frequently equipped with automatic stokers for burning coal, or with oil-burning outfits, since the great amount of power developed can only be produced by the consumption of a corresponding amount of fuel, and a fireman would be physically incapable of shoveling coal as rapidly as the production of such an amount of power would demand.

LOCOMOTIVES.

GENERAL STRUCTURE.

401. Frame. The frame or skeleton of a locomotive consists chiefly of a collection of forged wrought-iron bars, as shown in Figs. 186 and 187. These bars are connected at the

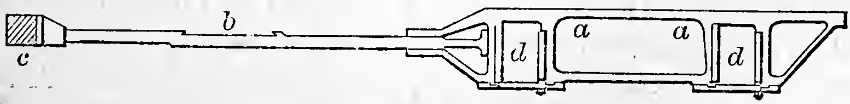


FIG. 186.—ENGINE-FRAME.

front end by the "bumper" (*c*), which is usually made of wood.

A little further back they are rigidly connected at *bb* by the cylinders and boiler-saddle. The boilers rest on the frames at *aaaa* by means of "pads," which are bolted to the fire-box, but which permit a free expansion of the boiler along the frame. This expansion is sometimes as much as $\frac{5}{16}''$. On a "consolidation" engine (frame shown in Fig. 187) it is frequently

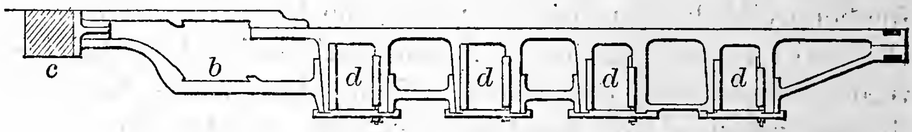


FIG. 187.—ENGINE-FRAME—CONSOLIDATION TYPE.

necessary to use vertical swing-levers about 12″ long instead of "pads." The swinging of the levers permit all necessary expansion. At the back the frames are rigidly connected by the iron "foot-plate." The driving-axles pass through the "jaws" *dddd*, which hold the axle-boxes. The frame-bars have a width (in plan) of 3″ to 4″. The depth (at *a*) is about the same. Fig. 186 shows a frame for an "American" type of locomotive; Fig. 187 shows a frame for a "Consolidation" type (see § 400).

402. Boiler. A boiler is a mechanism for transferring the latent heat of fuel to water, so that the water is transformed from cold water into high-pressure steam, which by its expansion will perform work. The efficiency of the boiler depends largely on its ability to do its work rapidly and to reduce to a minimum the waste of heat through radiation. The boiler contains a fire-box (see Fig. 188), in which the fuel is burned. The gases of consumption pass from the fire-box through the numerous boiler-tubes into the "smoke-box" *S* and out through the smoke-stack. The fire-box consists of an inner and outer shell separated by a layer of water **3″ to 5″** thick. The exposure of water-surface to the influence of the fire is thus very complete. The efficiency of this transferal of heat is somewhat indicated by the fact that, although the temperature of the gases in the fire-box is probably from 3000° to 4000° F., the temperature in the smoke-box is generally reduced to 500° to 600° F. If the steam pressure is 180 lbs., the temperature of the water is about 380° F., and, considering that heat will not pass from the gas to the water unless the gas is hotter than the water, the water evidently absorbs a large part of the theoretical maximum. Nevertheless gases at a temperature of

600° F. pass out of the smoke-stack and such heat is utterly wasted.

The tubes vary from $1\frac{3}{4}''$ to $2''$, inside diameter, with a thickness of about $0''.10$ to $0''.12$. The aggregate cross-sectional

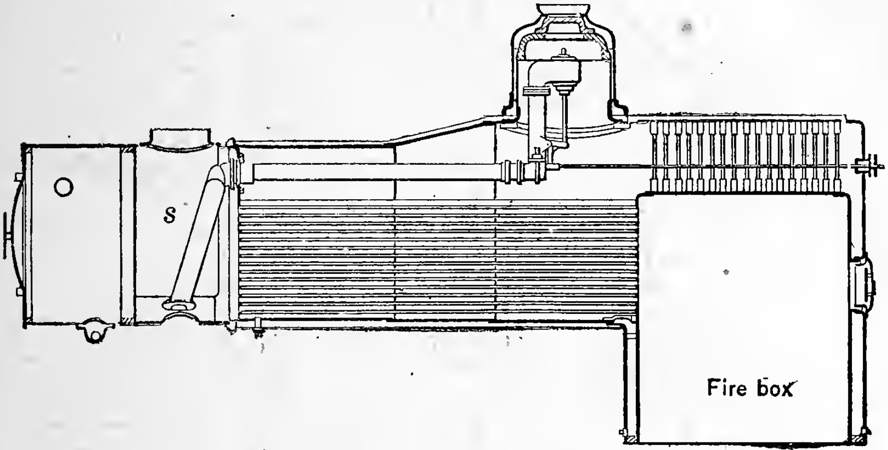


Fig. 188.—Locomotive-boiler.

area of the tubes should be about one-eighth of the grate area. The number will vary from 140 to 375. The length varies from 11′ to 21′, but the length is virtually determined by the type and length of engine.

403. Fire-box. The fire-box is surrounded by water on the four sides and the top, but since the water is subjected to the

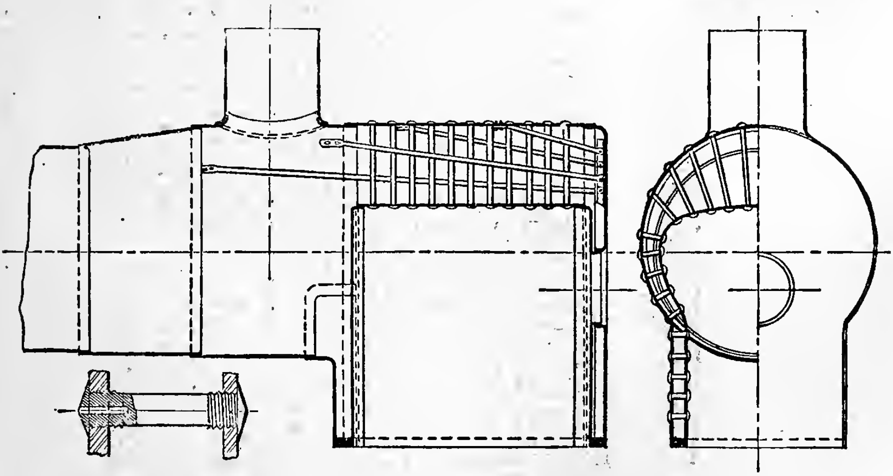
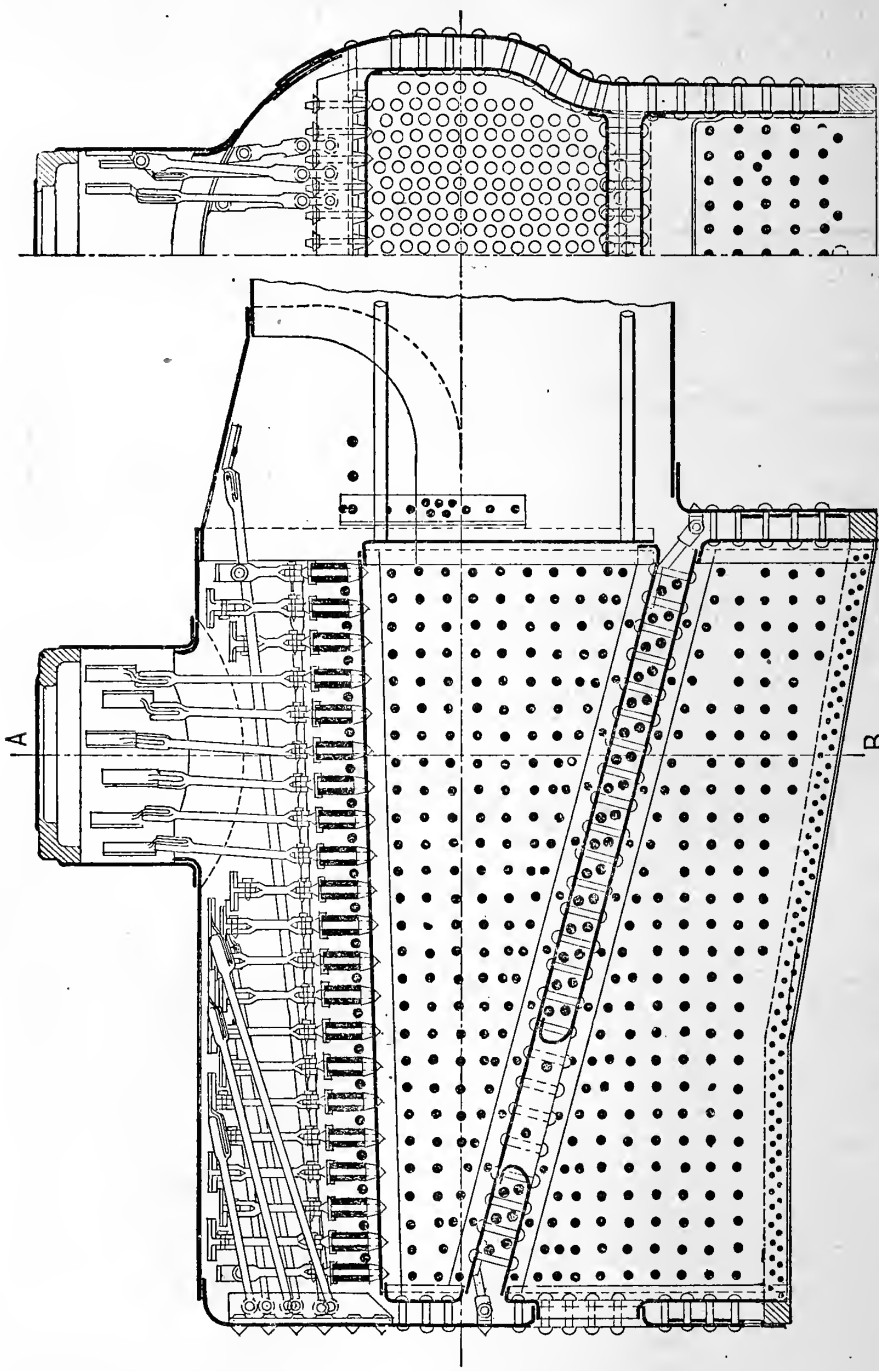


Fig. 189. Fig. 190.

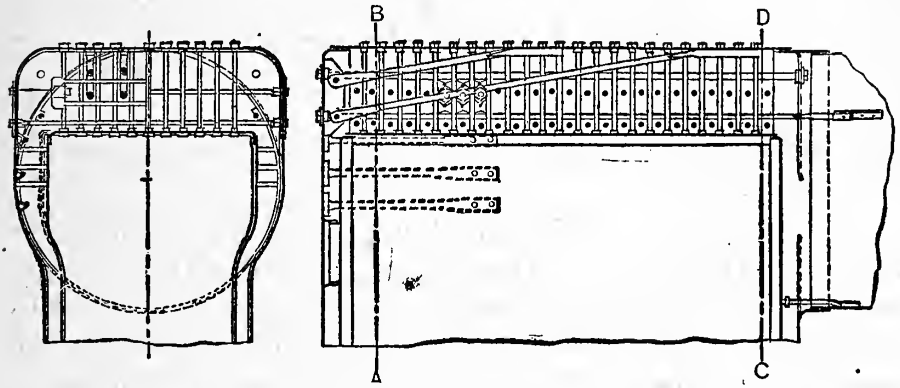
boiler pressure, the plates, which are $\frac{5}{16}''$ to $\frac{5}{8}''$ thick, must be stayed to prevent the fire-box from collapsing. This is easily accomplished over the larger part of the fire-box surface by having the outside boiler-plates parallel to the fire-box plates and separated from them by a space of 3″ to 5″. The plates



Half-section through *AB*.

FIG. 191.—BOILER SHOWING CROWN-BARS AND WATER-TABLE.

are then mutually held by "stay-bolts." See Fig. 189. These are about $\frac{7}{8}''$ in diameter and spaced 4″ to $4\frac{1}{2}''$. The $\frac{3}{16}''$ hole, drilled $1\frac{1}{4}''$ deep, indicated in the figure, will allow the escape of steam if the bolt breaks just behind the plate, and thus calls attention to the break. The stay-bolts are turned down to a diameter equal to that at the root of the screw-threads. This method of supporting the fire-box sheets is used for the two sides, the entire rear, and for the front of the fire-box up to the boiler-barrel. The "furnace tube-sheet"—the upper part of the front of the fire-box—is stayed by the tubes. But the top of the fire-box is troublesome. It must always be covered with water so that it will not be "burned" by the intense heat. It must therefore be nearly, if not quite, flat. There are three general methods of accomplishing this.



Thru AB | Thru CD
Half-sections.

Fig. 192.—"Belpaire" Fire-box.

(a) **Radial stays.** This construction is indicated in Fig. 190. Incidentally there is also shown the diagonal braces for resisting the pressure on the back end of the boiler above the fire-box. It may be seen that the stays are not perpendicular to either the crown-sheet or the boiler-plate. This is objectionable and is obviated by the other methods.

(b) **Crown-bars.** These bars are in pairs, rest on the side furnace-plates, and are further supported by stays. See Fig. 191.

(c) **Belpaire fire-box.** The boiler above the fire-box is rectangular, with rounded corners. The stays therefore are perpendicular to the plates. See Fig. 192.

Fire-brick arches. These are used, as shown in Fig. 193, to force all the gases to circulate through the upper part of the fire-box. Perfect combustion requires that all the carbon shall be turned into carbon dioxide, and this is facilitated by the forced circulation.

Water-tables. The same object is attained by using a water-table instead of a brick arch—as shown in Fig. 191. But it has the further advantages of giving additional heating-surface and avoiding the continual expense of maintaining the bricks. One feature of the design is the use of a number of steam-jets which force air into the fire-box and assist the combustion.

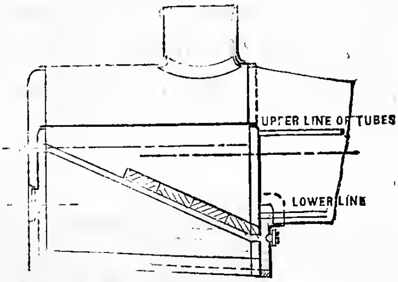


FIG. 193.—FIRE-BRICK ARCH.

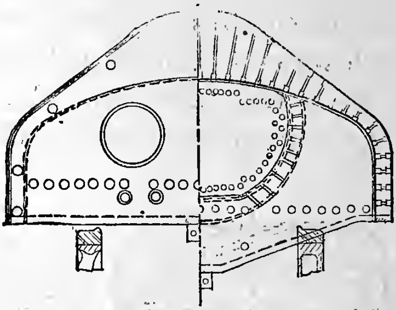


FIG. 194.—WOOTTEN FIRE-BOX.

404. Area of grate. The older types of engines, as represented by the "American," "Mogul" or "Consolidation" type, always had the fire-box set between the drivers, which practically meant that the maximum effective inside width of the fire-box was limited to about 3 ft. 5 ins. for standard-gauge locomotives. The maximum distance over which a fireman can properly control a fire is perhaps 10 to 11 ft., but such extreme lengths are objectionable. The grate area was thus quite definitely limited. The Wootten fire-box, illustrated in Fig. 194, obtained a fire-box eight feet wide by raising it above the level of the drivers, as shown, but this required that the drivers should be objectionably small in diameter, except for low-speed engines, or that the fire-box would be set objectionably high. The last difficulty has been solved by engines of the "Columbia," "Atlantic," "Pacific," "Mikado," and "Santa Fe" types, all of which have a pair of trailing wheels, 36 to 45 ins. in diameter, set back of the driving wheels and under the fire-box, which may thus be widened to 7 or 8 ft., the entire fire-box being placed back of the driving wheels.

405. Superheaters. Inside of a boiler the steam has a temperature corresponding to its pressure. For example, if the pressure is 180 lbs., the temperature is about 379° F. When the steam of a locomotive is superheated, the steam is conducted from the throttle to the cylinders through pipes which are purposely placed in the path of the flue gases on their way to the smokestack. A simple form of superheater is a series of tubes and drums located in the smokebox. Here the temperature is perhaps 600° F., which is sufficient to heat the steam from 30° to 50° above the boiler temperature and to produce substantial economies. In another more effective but more costly type a considerable number of the ordinary $2\frac{1}{4}$-inch boiler tubes are replaced by $5\frac{1}{2}$-inch tubes, inside of each of which is a pipe loop extending from the smokebox headers to within a short distance of the fire-box, where the temperature approaches the fire-box temperature, which is perhaps 2000° F. The live steam passes through these loops and is so heated that, even after it reaches the cylinder, it has a superheat of 150° to 200° over the boiler temperature, but since its pressure is substantially the boiler pressure, the *quantity* (or weight) of steam required to fill the cylinder at that temperature and pressure is much less than the quantity of steam at the same pressure but lower temperature. Superheating also has the advantage of making the steam more dry and of preventing condensation in the cylinders until the steam has lost in temperature at least the amount of its superheat. Superheating is chiefly advantageous for use with passenger engines, when they must work at high power for long, continuous runs. An economy of 15 to 25% in coal consumption (and even 30% in some tests), can ordinarily be obtained by the use of superheaters, but the economy is somewhat offset by the additional cost for installation and for subsequent repairs and maintenance.

406. Reheaters. A reheater is substantially the same as a superheater in its general principle of construction. When steam has been exhausted from a high-pressure cylinder, the temperature and pressure are both considerably lower than their boiler values. If the steam is to be again used, an economy is obtained and the steam is dried by passing it through a reheater. They are generally used on Mallet engines to reheat the steam in its passage from the high-pressure to the low-pressure cylinders.

407. Coal consumption. No form of steam-boiler (except a boiler for a steam fire-engine) requires as rapid production of steam, considering the size of the boiler and fire-box, as a locomotive. The combustion of coal per square foot of grate per hour for stationary boilers averages about 15 to 25 lbs. and seldom exceeds that amount. An ordinary maximum for a locomotive is 125 lbs. of coal per square foot of grate-area per hour, and in some recent practice 220 lbs. have been used. Of course such excessive amounts are wasteful of coal, because a considerable percentage of the coal will be blown out of the smoke-stack unconsumed, the draft necessary for such rapid consumption being very great. The only justification of such rapid and wasteful coal consumption is the necessity for rapid production of steam. The best quality of coal is capable of evaporating about 14 lbs. of water per pound of coal, i.e., change it from water at 212° to steam at 212°; the heat required to change water at ordinary temperatures to steam at ordinary working pressure is (roughly) about 20% more. From 6 to 9 lbs. of water per pound of coal is the average performance of ordinary locomotives, the efficiency being less with the higher rates of combustion. Some careful tests of locomotive coal consumption gave the following figures: when the consumption of coal was 50 lbs. per square foot of grate-area per hour, the rate of evaporation was 8 lbs. of water per pound of coal. When the rate of coal consumption was raised to 180, the evaporation dropped to 5 lbs. of water per pound of coal. It has been demonstrated that the efficiency of the boiler is largely increased by an increased length of boiler-tubes. The actual consumption of coal per mile is of course an exceedingly variable quantity, depending on the size and type of the engine and also on the work it is doing—whether climbing a heavy grade with its maximum train-load or running easily over a level or down grade. A test of a 50-ton engine, running without any train at about 20 to 25 miles per hour, showed an average consumption of 21 lbs. of coal per mile. Statistics of the Pennsylvania Rail road show a large increase (as might be expected, considering the growth in size of engines and weight of trains) in the average number of pounds of coal burned per *train*-mile—some of the figures being 55 lbs. in 1863, 72 lbs. in 1872, and nearly 84 lbs. in 1883. Figures are published showing an average consumption of about 10 lbs. of coal per passenger-car mile, and 4 to 5 lbs. per freight-car mile. But these figures are always obtained by dividing the total consumption per train-mile by the number of cars, the coal due to the weight of the engine being thrown in. Wellington developed a rule, based on the actual performance of a very large number of passenger-trains, that the number of pounds of coal per mile = 21.1 + 6.74 times the number of passenger-cars. The amount of coal assigned to the engine agrees remarkably with the test noted above For freight-trains the amount assigned to the engine should be much greater (since the engine is much heavier), and that assigned to the individual cars much less, although the great increase in freight-car weights in recent years has caused an increase in the coal required per car.*

There is a **physical limit to the amount of coal which** can be shovelled into a firebox by a fireman. Tests have shown that the average fireman can handle about 4000 lbs. of coal per hour and keep up such work almost indefinitely. For a short time he can shovel coal at the rate of 80 or 90 lbs. per minute, and this may be necessary to keep up steam while the train is going over some hump, but it must be followed by some relief which will make the average about the same. **Automatic stokers** have been devised for locomotives which can feed as much as 6000 lbs. of coal per hour when the grate area is less than 70 square feet and up to 8000 lbs. per hour when the grate area is 70 square feet or over. These are necessary on some of the most powerful locomotives in order to produce steam fast enough to develop their maximum capacity.

408. Oil-burning locomotives. In 1912 over one-sixth of all the locomotives west of the Mississippi River used oil as fuel. Some of the advantages in using oil are as follows: (1) the British thermal units in one pound of oil vary from about 19,000 to 21,000; those in a pound of coal vary from perhaps 14,000 for the very best down to 5000 for the poorer grades of lignite found in the western parts of the United States, and this means a great reduction in the cost of carrying and storing fuel, measured in heat units; (2) the cost of handling fuel is reduced and that of disposing of ashes is eliminated; (3) engine repairs are reduced in many respects, although it is said that the increased cost of fire-box repairs, due to the intense heat of the oil flame, offsets any reduction in other items; (4) the fires can be more easily controlled and waste of heat reduced during stoppages or when drifting down grade; (5) wayside fires due to sparks are altogether eliminated; (6) there is a practical limitation (see § 407), to the amount of coal that one fireman can feed to a fire; but there is no such limitation when using oil; (7) there is an equality in cost of heat units when a 42-gallon barrel of oil, weighing 7.3 lbs. per gallon, costs 60 cents and a ton (2000 lbs.) of coal, having

* See Chap. XVIII for further discussion of relation of coal consumed topower produced.

two-thirds as many heat units per pound, costs $2.61, or 4.35 times as much. The other items of difference almost invariably favor the oil and might make it more desirable even when the ratio of cost seemed to favor the coal. The extensive use of oil west of the Mississippi River is due to the fact that in many localities a very suitable quality of crude oil is plentiful and cheap while coal is expensive and of low calorific power.

409. Heating-surface. The rapid production of steam requires that the hot gases shall have a large heating-surface to which they can impart their heat. From 50 to 75 square feet of heating-surface is usually designed for each square foot of grate-area. A more recently used rule is that there should be from 60 to 70 square feet of tube heating-surface per square foot of grate-area for bituminous coal. 40 or 50 to 1 is more desirable for anthracite coal. Almost the whole surface of the fire-box has water behind it, and hence constitutes heating-surface. Although this surface forms but a small part of the total (nominally), it is really the most effective portion, since the difference of temperature of the gases of combustion and the water is here a maximum, and the flow of heat is therefore the most rapid. The heating-surface of the tubes varies from 85 to 93% of the total, or about 7 to 15 times the heating-surface in the fire-box. By dividing the total weight of a well-designed engine (exclusive of tender) by the number of square feet of heating-surface (fire-box and tubes), we get a quotient which varies from 60 to 80 or over. For example, a light engine, weighing only 96,450 lbs. had a total heating surface of 1449 square feet, or about 67 lbs. per square foot. On the other hand, a Mikado engine, weighing 297,500 lbs., had 4359 square feet of heating surface, or 68 lbs. per square foot.

410. Loss of efficiency in steam pressure. The effective work done by the piston is never equal to the theoretical energy contained in the steam withdrawn from the boiler. This is due chiefly to the following causes:

(*a*) The steam is "**wire-drawn,**" i.e., the pressure in the cylinder is seldom more than 85 to 90% of the boiler pressure. This is due largely to the fact that the steam-ports are so small that the steam cannot get into the cylinder fast enough to exert its full pressure. Partially closing the throttle, so that the steam will be used less rapidly, also wire-draws the steam.

(*b*) **Entrained water.** Steam is always drawn from a dome placed over the boiler so that the steam shall be as far above the water-surface as possible, and shall be as dry as possible. In spite of this the steam is not perfectly dry and carries with it water at a temperature of, say, 361°, and pressure of 140 lbs. per square inch. When the pressure falls during the expansion and exhaust, this hot water turns into steam and absorbs the necessary heat from the hot cylinder-walls. This heat is then carried out by the exhaust and wasted.

(*c*) The **back pressure** of the exhaust-steam, which depends on the form of the exhaust-passages, etc. This amounts to from 2 to 20% of the power developed.

(*d*) **Clearance-spaces.** When cutting off at full stroke this waste is considerable (7 to 9%), but when the steam is used expansively the steam in these clearance-spaces expands and so its power is not wholly lost.

(*e*) **Radiation.** In spite of all possible care in jacketing the cylinders, some heat is lost by radiation.

(*f*) **Radiation into the exhaust-steam.** This is somewhat analogous to (*b*). Steam enters the cylinder at a temperature of, say, 361°; the walls of the cylinder are much cooler, say 250°; some heat is used in raising the temperature of the cylinder-walls; some steam is vaporized in so doing; when the exhaust is opened the temperature and pressure fall; the heat temporarily absorbed by the cylinder-walls is reabsorbed by the exhaust-steam, re-evaporating the vapor previously formed, and thus a certain portion of heat-energy goes **through** the cylinder without doing any useful work. With an early cut-off the loss due to this cause is very great.

The sum of all these losses is exceedingly variable. They are usually less at lower speeds. The loss in *initial pressure* (the difference between boiler pressure and the cylinder pressure at the beginning of the stroke) is frequently over 20%, but this is not all a net loss With an early cut-off the average cylinder pressure for the whole stroke is but a small part of the boiler pressure, yet the horse-power developed may be as great as, or greater than that developed at a lower speed, later cut-off, and higher average pressure

411. Tractive power The work done by the two cylinders during a complete revolution of the drivers evidently = area of pistons × average steam pressure × stroke × 2 × 2. The resistance overcome evidently = tractive force at circumference of drivers times distance traveled by drivers (which is the circumference of the drivers) Therefore

$$\text{Tractive force} = \left\{ \frac{\text{area pistons} \times \text{average steam pressure} \times \text{stroke} \times 2 \times 2.}{\text{circumference of drivers}} \right.$$

Dividing numerator and denominator by π (3.1415), we have

$$\text{Tractive force} = \left\{ \frac{(\text{diam piston})^2 \times \text{average steam pressure} \times \text{stroke}}{\text{diameter of driver}} \right., \quad . \quad (103)$$

which is the usual rule Although the rule is generally stated in this form, there are several deductions In the first place the net effective area of the piston is less than the nominal on account of the area of the piston-rod. The ratio of the areas of the piston-rod and piston varies, but the effect of this reduction is usually from 1.3 to 1.7%. No allowance has been made for friction—of the piston, piston-rod, cross-head, and the various bearings This would make a still further reduction of several per cent. Nevertheless the above simple rule is used, because, as will be shown, no great accuracy can be utilized.

The maximum draw bar pull is limited by the adhesion between the driving wheels and the rails. This is usually about one-fourth of the weight. The use of sand may increase it to one-third. But this ratio is important only when starting or at very low speeds. The adhesion is always ample for the much lower cylinder power which can be developed at higher speeds. This is considered more fully in Chapter XVIII.

RUNNING GEAR.

412. Equalizing-levers. The ideal condition of track, from the standpoint of smooth running of the rolling stock, is that the rails should always lie in a plane surface. While this condition is theoretically possible on tangents, it is unobtainable on curves, and especially on the approaches to curves when the outer rail is being raised. Even on tangents it is impossible to *maintain* a perfect surface, no matter how perfectly the track may have been laid. In consequence of this, the points of contact of the wheels of a locomotive, or even of a four-wheeled truck, will not ordinarily lie in one plane. The rougher and more defective the track, the worse the condition in this respect. Since the frame of a locomotive is practically rigid, and the frame rests on the driver-axles through the medium of springs at each axle-bearing, the compression of the springs (and hence the pressure of the drivers on the rail) will be variable if the bearing-points of the drivers are not in one plane. This variable pressure affects the tractive power and severely strains the frame. Applying the principle that a tripod will stand on an uneven surface, a mechanism is employed which

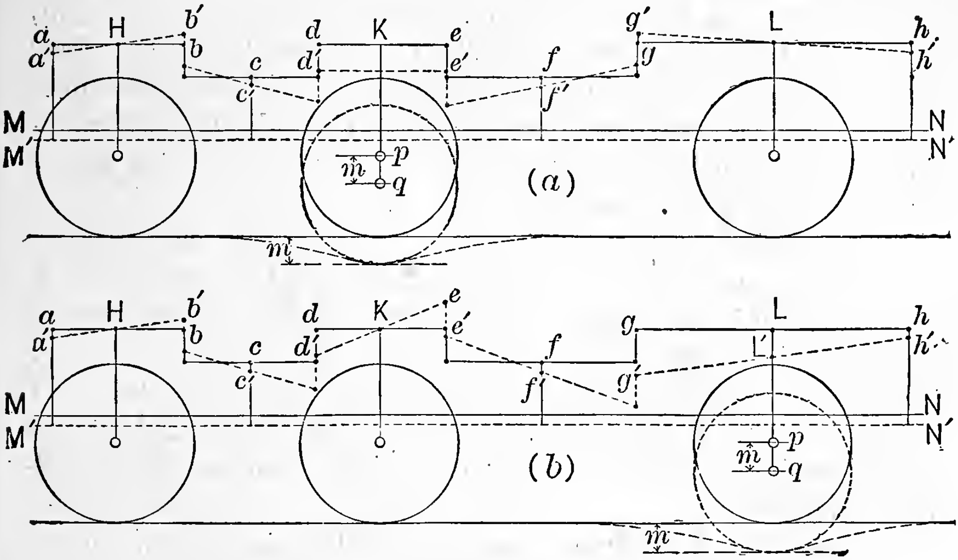


FIG. 195.—ACTION OF EQUALIZING-LEVERS.

virtually supports the locomotive on three points, of which one is usually the center-bearing of the forward truck. On each side the pressure is so distributed among the drivers that even if a driver rises or falls with reference to the others, the load carried by each driver is unaltered, and that side of the engine rises or falls by one *n*th of the rise or fall of the single driver, where *n* represents the number of wheels. The principle involved is shown in an exaggerated form in Fig. 195. In the diagram, *MN* represents the normal position of the frame when the wheels are on line. The frame is supported by the hangers at *a*, *c*, *f*, and *h*. *ab*, *de*, and *gh* are horizontal levers vibrating about the points *H*, *K*, and *L*, which are supported by the axles. While it is *possible* with such a system of levers to make

MN assume a position not parallel with its natural position, yet; by an extension of the principle that a beam balance loaded with equal weights will always be horizontal, the effect of raising or lowering a wheel will be to move MN parallel to itself. It only remains to determine *how much* is the motion of MN relative to the rise or drop of the wheel.

The dotted lines represent the positions of the wheels and levers when one wheel drops into a depression. The wheel center drops from p to q, a distance m. L drops to L', a distance m (see Fig. 195, b); M drops to M', an unknown distance x; therefore $aa'=x$; $bb'=x$; $cc'=x$; $dd'=3x=ee'$; $ff'=x$; $\therefore\ gg'=5x$; $hh'=x$; $LL'=\frac{1}{2}(gg'+hh')=\frac{1}{2}(6x)=m$; $\therefore\ x=\frac{1}{3}m$; i.e., MN drops, parallel to itself, $1/n$ as much as the wheel drops, where n is the number of wheels. The resultant effect caused by the simultaneous motion of two wheels with reference to the third is evidently the algebraic sum of the effects of each wheel taken separately.

The practical benefits of this device are therefore as follows:—

(a) When any driver reaches a rough place in the track, a high place or a low place, the stress in all the various hangers and levers is unchanged.

(b) The motion of the frame (represented by the bar MN in Fig. 195) is but $1/n$ of the motion of the wheel, and the jar and vibration caused by a roughness in the track is correspondingly reduced.

The details of applying these principles are varied, but in general it is done as follows:

(a) American and ten wheeled types. Drivers on each side form a system. The center-bearing pilot-truck is the third point of support. The method is illustrated in Fig. 196.

(b) Mogul and consolidation types. The front pair of drivers is connected with the two-wheeled pilot-truck (as illustrated in Fig. 197) to form one system. The remaining drivers on each side are each formed into a system.

The device of equalizers is an American invention. Until recently it has not been used on foreign locomotives. The necessity for its use becomes less as the track is maintained with greater perfection and is more free from sharp curves. A locomotive not equipped with this device would deteriorate very rapidly on the comparatively rough tracks which are usually found on light-traffic roads. It is still an open ques-

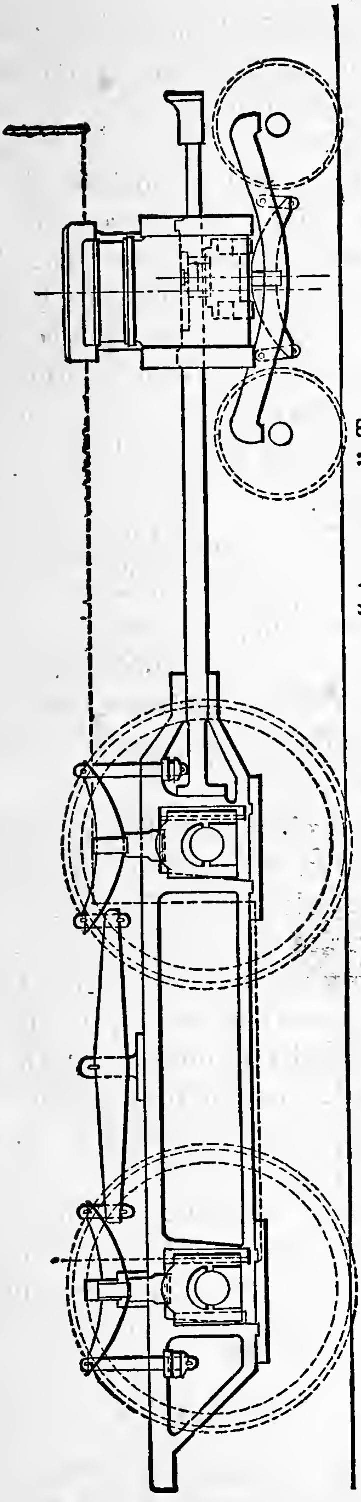


FIG. 196.—EQUALIZING-LEVERS FOR "AMERICAN" TYPE.

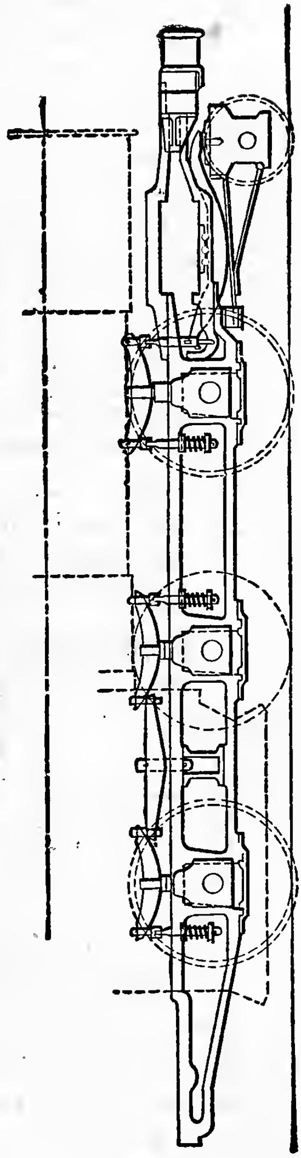


FIG. 197.—EQUALIZING-LEVERS FOR "MOGUL" TYPE.

tion to what extent the neglect of this device is responsible for the statistical fact that average freight-train loads on foreign trains are less in proportion to the weight on the drivers than is the case with American practice. The recent increasing use of this device on foreign heavy freight locomotives is perhaps an acknowledgment of this principle.

413. Counterbalancing. At very high velocities the centrifugal force developed by the weight of the rotating parts becomes a quantity which cannot be safely neglected. These rotating parts include the crank-pin, the crank-pin boss, the side rod, and that part of the weight of the connecting-rod which may be considered as rotating about the center of the crank-driver. As a numerical illustration, a driving-wheel 62″ in diameter, running 60 miles per hour, will revolve 325 times per minute. The weights are:

Crank-pin	110 lbs.
" boss	150 "
One-half side rod	240 "
Back end of connecting-rod (56%)	190 "
Total	690 lbs.

If the stroke is 24″, the radius of rotation is 12″, or 1 foot. Then

$$\frac{Gv^2}{gr}=\frac{690\times 4\pi^2 1^2\times 325^2}{32.2\times 1\times 60^2}=24821 \text{ lbs.},$$

which is half as much again as the weight on a driver, 16000 lbs. Therefore if *no* counterbalancing were used, the pressure between the drivers and the rail would always be less (at any velocity) when the crank-pin was at its highest point. At a velocity of about 48 miles per hour the pressure would become zero, and at higher velocities the wheel would actually be thrown from the rail. As an additional objection, when the crank-pin was at the lowest point, the rail pressure would be increased (velocity 60 miles per hour) from 16000 lbs. to nearly 41000 lbs., an objectionably high pressure. These injurious effects are neutralized by "counterbalancing." Since all of the above-mentioned weights can be considered as concentrated at the center of the crank-pin, if a sufficient weight is so placed in the drivers that the center of gravity of the eccentric weight is diametrically opposite to the crank-pin, this centrifugal force can be wholly balanced. This is done by filling up a portion of the space between the spokes. If the center of gravity of the counterbalancing weight is 20″ from the center, then, since the crank-pin radius is 12″, the required weight would be $690\times\frac{12}{20}=414$ lbs.

In addition to the effect of these revolving parts there is the effect of the sudden acceleration and retardation of the reciprocating parts. In the engine above considered the weights of these reciprocating parts will be:

Front end of connecting-rod (44%) . .	150 lbs.
Cross-head	174 "
Piston and piston-rod	300 "
Total	624 lbs.

Assume as before that the reciprocating parts may be considered as concentrated at one point, the point *P* of the diagram in Fig. 198. Since the motion of *P* is horizontal only, the force required to overcome its inertia at any point will exactly equal the *horizontal component* of the force required to overcome the inertia of an *equal* weight at *S* revolving in a circular path. Then evidently the horizontal component of the force required to keep *W* in the circular path will exactly balance the force required to overcome the inertia of *P*. Of course $W=P$. But a smaller weight W', whose weight is inversely proportional to its radius of rotation, will evidently accomplish the same result. In the above numerical case, if the center of gravity of the counterweights is 20″ from the center, the required weight to completely counterbalance the reciprocating parts would be $624\times\frac{12}{20}=374.4$ lbs. This counterweight need not be all placed on the driver carrying the main crank-pin, but can be (and is) distributed among all the drivers. Suppose it were divided between the two drivers in the above case. At 60 miles per hour such a counterweight would produce an additional pressure of 11211 lbs. when the counterweight was down, or a lifting force of the same amount when the counterweight was up. Although this is not sufficient to lift the driver from the rail, it would produce an objectionably high pressure on the rail (over 27000 lbs.), thus inducing just what it was desired to avoid on account of the eccentric rotating parts. Therefore a compromise must be made. Only a portion (one half to three fourths) of the weight of the reciprocating parts is balanced. Since the effect of the rotating

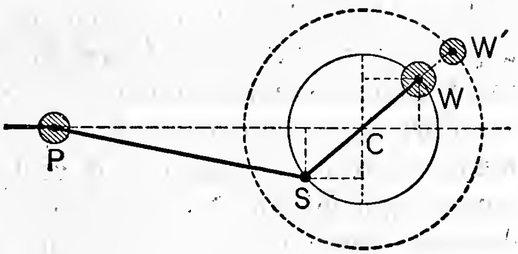


FIG. 198.—ACTION OF COUNTERBALANCE.

weights is to cause variable pressure on the rail, while the effect of the reciprocating parts is to cause a horizontal wobbling or "nosing" of the locomotive, it is impossible to balance both. Enough counterweight is introduced to partially neutralize the effect of the reciprocating parts, still leaving some tendency to horizontal wobbling, while the counterweights which were introduced to reduce the wobbling cause some variation of pressure. The vertical or horizontal pressure developed by the unbalanced rotating and reciprocating parts is called the **dynamic augment.**

An additional injurious effect on the track of the dynamic augment is due to the fact that the center of gravity of the side rod is several inches outside of the vertical plane in which the counterweight revolves, and that the center of gravity of the main rod, or connecting rod, is still further outside. The dynamic augment will be increased by the ratio of the distance between these planes of rotation to the distance between the centers of the companion drivers. This ratio averages about 11% for the side rods and for the part of the pin within the side rod; the corresponding figure for the main rod is about 23%. The physical effect of the dynamic augment on the stresses produced in the track is further discussed in Chapter XXV.

By using hollow piston-rods of steel, ribbed cross-heads, and connecting- and side-rods with an I section, the weight of the reciprocating parts may be greatly lessened without reducing their strength, and with a decrease in weight the effect of the unbalanced reciprocating parts and of the "excess balance" (that used to balance the reciprocating parts) is largely reduced.

Current practice is somewhat variable on three features:

(*a*) The proportion of the weight of the connecting-rod which should be considered as revolving weight.

(*b*) The proportion of the total reciprocating weight that should be balanced.

(*c*) The distribution among the drivers of the counterweight to balance the reciprocating parts.

The principal rules which have been formulated for counterbalancing may be stated as follows, although there is considerable variation in the figures used in rules 2 and 3.

1. Each wheel should be balanced correctly for the revolving parts connected with it.

2. *In addition,* introduce counterbalance sufficient for 50% of the weight of the reciprocating parts for ordinary engines, increasing this to 75% when the reciprocating parts are excessively heavy (as in compound locomotives) or when the engine is light and unable to withstand much lateral strain or when the wheel-base is short.

3. Consider the weight of the connecting-rod as $\frac{1}{2}$ revolving and $\frac{1}{2}$ reciprocating when it is over 8 feet long; when shorter than 8 feet, consider $\frac{6}{10}$ of the weight as revolving and $\frac{4}{10}$ as reciprocating.

4. The part of the weight of the connecting-rod considered as revolving should be entirely balanced in the crank-driver wheel.

5. The "excess balance" should be divided equally among the drivers.

6. Place the counterbalance as near the rim of the wheel as possible and also as near the outside of the wheel as possible in order that the center of gravity shall be as near as possible opposite the center of gravity of the rods, etc., which are all outside of even the plane of the face of the wheel.

In Fig. 199 is shown a section of a locomotive driver with the cavities in the casting for the accommodation of the lead which is used for the counterbalance weight. Incidentally several other features and dimensions are shown in the illustration.

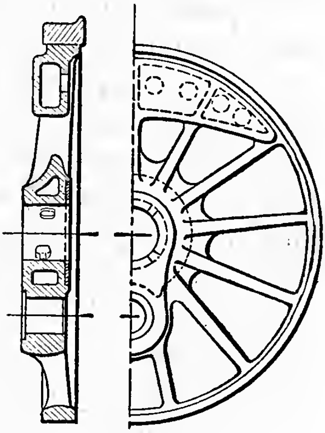


FIG. 199.—SECTION OF LOCOMOTIVE-DRIVER.

414. Mutual relations of the boiler power, tractive power, and cylinder power for various types. The design of a locomotive includes three *distinct* features which are varied in their mutual relations according to the work which the engine is expected to do.

(a) **The boiler power.** This is limited by the rate at which steam may be generated in a boiler of admissible size and weight. Engines which are designed to haul very fast trains which are comparatively light must be equipped with very large grates and heating surfaces so that steam may be developed with great rapidity in order to keep up with the very rapid consumption.

Engines for very heavy freight work are run at very much lower velocity and at a lower piston speed in spite of the fact that more strokes are required to cover a given distance and the demand on the boiler for *rapid* steam production is not as great as with high-speed passenger-engines. The capacity of a boiler to produce steam is therefore limited by the limiting weight of the general type of engine required. Although improvements may be and have been made in the design of fire-boxes so as to increase the steam-producing capacity without adding proportionately to the weight, yet there is a more or less definite limit to the boiler power of an engine of given weight.

(b) **The tractive power.** This is limited by the possible driver adhesion. The absolute limit of tractive adhesion between a steel-tired wheel and a steel rail is about one-third of the pressure, but not more than one-fourth of the weight on the drivers can be depended on for adhesion and wet rails will often reduce this to one fifth and even less. The tractive power is therefore absolutely limited by the practicable weight of the engine. In some designs, when the maximum tractive power is desired, not only is the entire weight of the boiler and running gear thrown on the drivers, but even the tank and fuel-box are loaded on. Such designs are generally employed in switching-engines (or on engines designed for use on abnormally heavy mountain grades) in which the maximum tractive power is required, but in which there is no great tax on the boiler for *rapid* steam production (the speed being always very low), and the boiler and fire-box, which furnish the great bulk of the weight of an engine, are therefore comparatively light, and the requisite weight for traction must, therefore, be obtained by loading the drivers as much as possible. On the other hand, engines of the highest speed cannot possibly produce steam fast enough to maintain the required speed unless the load be cut down to a comparatively small amount. The tractive power required for this comparatively small load will be but a small part of the weight of the engine, and therefore engines of this class have but a small proportion of their weight on the drivers; generally have but two driving-axles and sometimes but one.

(c) **Cylinder power.** The running gear forms a mechanism which is simply a means of transforming the energy of the boiler into tractive force and its power is unlimited, within the practical conditions of the problem. The power of the running gear depends on the steam pressure, on the area of the piston, on the diameter of the drivers, and on the ratio of crank-pin radius to wheel radius, or of stroke to driver diameter. It is always possible to increase one or more of these elements by a relatively small increase of expenditure until the cylinders are able to make the drivers slip, assuming a sufficiently great resistance. Since the power of the engine is limited by the power of its weakest feature, and since the running gear is the most easily controlled feature, the power of the running gear (or the "cylinder power") is always made somewhat excessive on all well-designed engines. It indicates a badly designed engine if it is stalled and unable to move its drivers, the steam pressure being normal. If it is attempted to use a freight-engine on *fast* passenger service, it will probably fail to attain the desired speed on account of the steam pressure falling. The tractive power and cylinder power are superabundant, but the boiler cannot make steam as fast as it is needed for high speed, especially when the drivers are small. The practical result would be a comparatively low speed kept up with a forced fire. If it is attempted to use a high-speed passenger-engine on heavy freight service, the logical result is a slipping of the drivers until the load is reduced. The boiler power and cylinder power are ample, but the weight on the drivers is so small that the tractive power is only sufficient to draw a comparatively small load.

These relations between boiler, cylinder, and tractive power are illustrated in the following comparative figures referring to a fast passenger-engine, a heavy freight-engine, and a switching-engine. The weights of the passenger- and freight-engines are about the same, but the passenger-engine has only 74% *

Kind.	Cylinders.	Total W'ght.	Wt. on Driv'rs	Heating Surface, sq. ft.	Grate area sq. ft.	Steam Pressure in Boiler.	Stroke. / Diam. Driver.
Fast passenger.	19″×24″	126700	81500	1831.8	26.2	180	$\frac{24}{78}=.31$
Heavy freight.	20″×24″	128700	112600	1498.3	31.5	140	$\frac{24}{50}=.48$
Switcher......	19″×24″	109000	109000	1498.0	22.8	160	$\frac{24}{50}=.48$

* Computed from Eq. 103.

of the tractive power of the freight. But the passenger-engine has 22% more heating-surface and can generate steam much faster; it makes less than two-thirds as many strokes in covering a given distance, but it runs at perhaps twice the speed and probably consumes steam much faster. The switch-engine is lighter in total weight, but the tractive power is a little greater than the freight and much greater than the passenger-engine. While the heating-surfaces of the freight- and switching engines are practically identical, the grate area of the switcher is much less; its speed is always low and there is but little necessity for rapid steam development.

While these figures show the general tendency for the relative proportions, and in this respect may be considered as typical, there are large variations. The recent enormous increase in the dead weight of passenger-trains has necessitated greater tractive power. This has been provided sometimes by using the "Pacific" type, which combines rapid steaming capacity and great tractive power. On the other hand, the demand for fast-freight service, and the possibility of safely operating such trains by the use of air-brakes, has required that heavy freight-engines shall be run at comparatively high speeds, and that requires the rapid production of steam, large grate areas and heating surfaces. But in spite of these variations, the normal standard for passenger service is a four-driver engine carrying about two-thirds of the weight of the engine on the drivers, which are very large; the normal standard for freight work is an 8-driver engine with perhaps 90% of the weight on the drivers, which are small, but which must have the pony truck for such speed as it uses; and finally the normal standard for switching service has all the weight on the drivers and has comparatively low steam-producing capacity.

415. Life of Locomotives. The life of locomotives (as a whole) may be taken as about 800000 miles or about 22 to 24 years. While its life should be and is considered as the period between its construction and its final consignment to the scrap pile, parts of the locomotive may have been renewed more than once. The boiler and fire-box are especially subject to renewal. The mileage life is much longer than formerly. This is due partly to better design and partly to the custom of drawing the fires less frequently and thereby avoiding some of the destructive strains caused by extreme alternations of heat and cold. Recent statistics give the average annual mileage on twenty-three leading roads to be 41000 miles.

CARS.

416. Capacity and size of cars. The capacity of freight-cars has been enormously increased of late years. In 1870 the usual live-load capacity for a box-car was about 20000 lbs. In 1916, out of 58299 box cars owned by the Pennsylvania R. R., 32923 or 56% had a capacity of 100000 or over; 49597 or 85% had a capacity 70000 or over; only 555, less than 1%, had a capacity of less than 60000 lbs., and the most of these were refrigerator cars or cars for special service. The Norfolk & Western R. R. had (in 1916), 750 gondola drop-bottom coal cars, each with a nominal capacity of 180000 lbs.; their length is 46 feet $10\frac{3}{4}$ inches, and the extreme width 10 feet $4\frac{1}{2}$ inches. These cars are carried on six-wheel trucks. The usual width of freight-cars is about 9 to 10 feet, while parlor-cars and sleepers are generally 10 feet wide and sometimes 11 feet. The highest point of a train is usually the smokestack of the locomotive, which is generally 15 feet above the rails and occasionally over 16 feet. A sleeping-car usually has the highest point of the car about 14 feet above the rails. Box-cars are usually about 8 feet high (above the sills), with a total height of 13 to 14 feet. Some furniture and automobile cars, whose unit live load per cubic foot of space is not high, have a total height of over 15 feet. The *average* length of freight cars, as required in the design of freight yards, is now considered to be 42 feet; the allowance for each car was formerly 40 feet. The P. R. R. standards vary between 38 feet 1 inch and 44 feet 6 inches in length. Day coaches have an extreme length varying from 45 to 80 feet. An 80-foot all-steel coach weighs about 118000 lbs. and has a seating capacity of 88. Allowing the high average weight of 150 lbs., the maximum live load would be 13200 lbs., a little over 11% of the dead load, which shows that the tractive force required to haul the car will be almost constant, whether the car is full or empty. A dining-car may weigh 150000 lbs. and a sleeper even more. The weight of the 25 or 30 passengers it *may* carry is hardly worth considering in comparison.

417. Stresses to which car-frames are subjected. A car is structurally a truss, supported at points at some distance from the ends and subjected to transverse stress. There is, therefore, a change of flexure at two points between the trucks. Besides this stress the floor is subjected to compression when the cars are suddenly stopped and to tension when in ordinary motion, the tension being greater as the train resistance is greater and as the car is nearer the engine. The shocks, jars, and sudden strains to which the car-frames are subjected are very much harder on them than the mere static strains due to their maximum loads if the loads were quiescent. Consequently any calculations based on the static loads are practically valueless, except as a very rough guide, and previous experience must be relied on in designing car bodies. As evidence of the increasing demand for strength in car-frames, it has been recently observed that freight-cars, built some years ago and built almost entirely of wood, are requiring repairs of wooden parts which have been *crushed* in service, the wood being perfectly sound as regards decay.

418. The use of metal. The use of metal in car construction

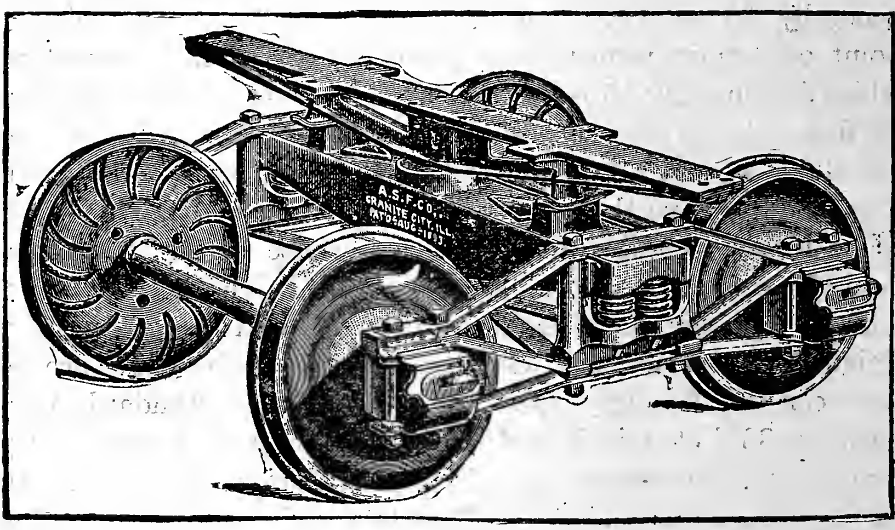
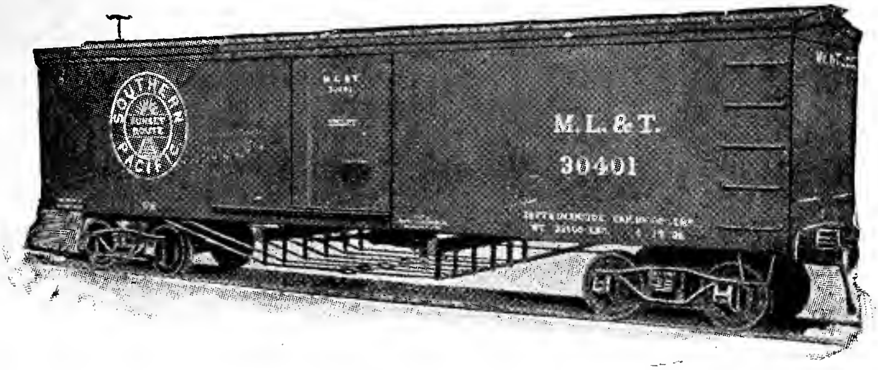
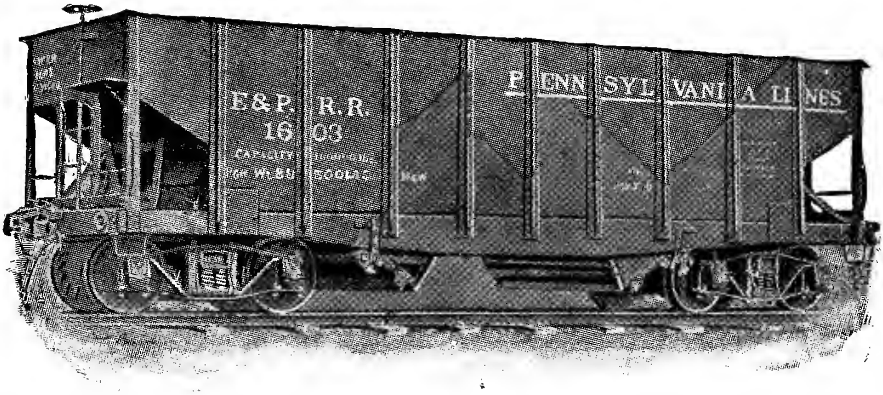


FIG. 201.

is very rapidly increasing. The demand for greater strength in car-frames has grown until the wooden framing has become so heavy that it is found possible to make steel frames and trucks at a small additional cost, the steel frames being twice as strong and yet reducing the dead weight of the car about 5000 lbs., a consideration of no small value, especially on roads having heavy grades. Another reason for the increasing use of metal is the great reduction in the price of rolled or pressed



100,000-lb. Box Car.



Steel Coal Car.

Wooden Box Car; Steel Frame.

Fig. 200.—Some Heavy Freight Cars.

(To face page 456.)

steel, while the cost of wood is possibly higher than before. The advocates of the use of steel advise steel floors, sides, etc. For box-cars a wooden floor has advantages. For ore and coal-cars an all-metal construction has advantages. (Fig. 200.) In Germany, where steel frames have been almost exclusively in use for many years, they have not yet been able to determine the normal age limit of such frames; none have yet *worn* out. The life is estimated at 50 to 80 years

Brake beams are also best made of metal rather than wood, as was formerly done. Metal brake-beams are generally used on cars having air-brakes, as a wooden beam must be excessively large and heavy in order to have sufficient rigidity.

Truck-frames (see Fig. 201), which were formerly made principally of wood, are now largely made of pressed steel. It makes a reduction in weight of about 3000 lbs. per car. The increased durability is still an uncertain quantity.

419. Draft gear. The enormous increase in the weight and live load capacities of rolling stock have necessitated a corresponding development in draft gear. Even within recent years, "coal-jimmies," carrying a few tons have been made up into trains by dropping a chain of three big links over hooks on the ends of the cars. But the great stresses due to present loadings would tear such hooks from the cars or tear the cars apart if such cars were used in the make-up of long heavy trains as now operated. The next stage in the development of draft gear was the invention of the "spring coupler," by which the energy due to a sudden tensile jerk or the impact of compression may be absorbed by heavy springs and gradually imparted to the car body. Such devices, for which there are many designs, seemed to answer the purpose for cars of 25 to 40 tons capacity. The use of 100,000-pound steel cars soon proved the inadequacy of even spring couplers. The friction-draft gear was then invented. The general principle of such a gear is that, when acting at or near its maximum capacity, it harmlessly transforms into heat the excessive energy developed by jerks or compression. There are several different designs of such gear, but the general principle underlying all of them may be illustrated by a description of the Westinghouse draft gear. The gear employs springs which have sufficient stiffness to act as ordinary spring-couplers for the ordinary pushing and pulling of train operations. Sections of the gear are shown in Fig. 202,

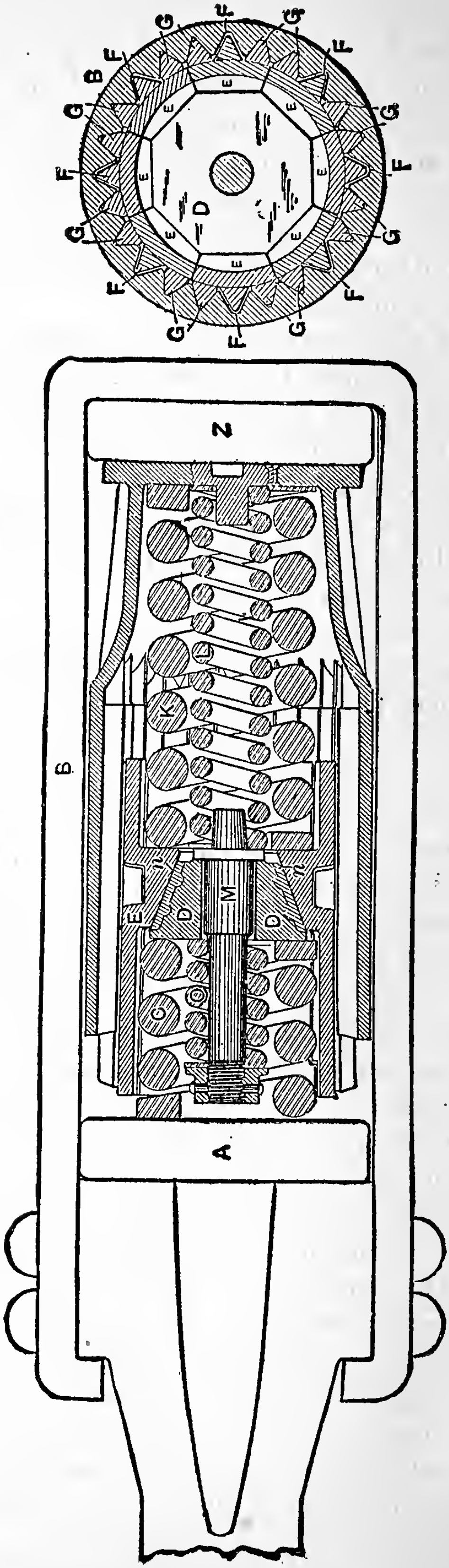


FIG. 202.—WESTINGHOUSE DRAFT GEAR. DETAILS.

while the method of its application to the framing of a car of the pressed steel type is shown in Fig. 203, *a* and *b*. When the draft gear is in tension the coupler, which is rigidly attached to *B*, is drawn to the left, drawing the follower *Z* with it. Compression is then exerted through the gear mechanism to the follower *A* which, being restrained by the shoulders *RR*, against which it presses, causes the gear to absorb the compression. The coil-spring *C* forces the eight wedges *n* against the eight corresponding segments *E*. The great compression of these surfaces against the outer shell produces a friction which retards the compression of the gear. The total possible movement of the gear, as determined by an official test, was 2.42 inches, when the maximum stress was 180,000 pounds. The work done in producing this stress amounted to 18,399 foot-pounds. Of this total energy 16,666 foot-pounds, or over 90%, represents the amount of energy absorbed and dissipated as heat by the frictional gear. The remaining 10% is given back by the recoil. The main release spring *K* is used for returning the segments and friction strips to their normal position after the force to close them has been removed. It also gives additional capacity to the entire mechanism. The auxiliary spring *L* releases the wedge *D*, while the release pin *M* releases the pressure of the auxiliary spring *L* against the wedge during frictional operation. If we omit from the above design the frictional features and consider only the two followers *A* and *Z*, separated by the springs *C* and *K*, acting as one spring, we have the essential elements of a spring-draft gear. In fact, this gear acts exactly like a spring-draft gear for all ordinary service, the frictional device only acting during severe tension and compression.

420. **Gauge of wheels and form of wheel-tread.**—In Fig. 204 is shown the standard adopted by the Master Car Builders' Association at their twentieth annual convention. Note the normal position of the gauge-line on the wheel-tread. In Fig. 118, § 267, the relation of rail to wheel-tread is shown on a smaller scale. It should be noted that there is no definite position where the wheel-flange is absolutely "chock-a-block" against the rail. As the pressure increases the wheel mounts a little higher on the rail until a point is soon reached when the resistance is too great for it to mount still higher. By this means is avoided the shock of unyielding impact when the car

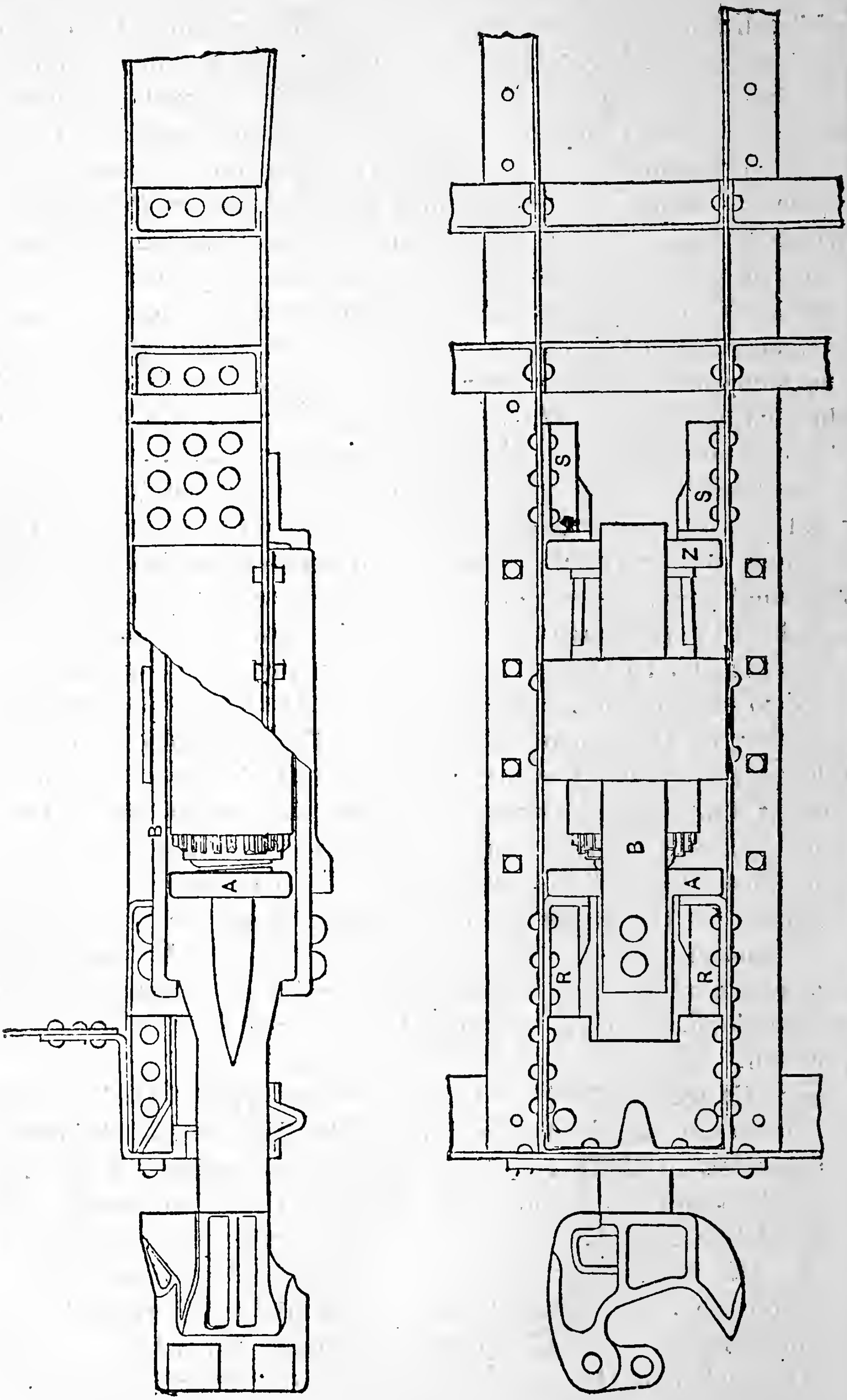


FIG. 203.—WESTINGHOUSE DRAFT GEAR.

sways from side to side. When the gauge between the inner faces of the wheels is greater or less than the limits given in the figure, the interchange rules of the Master Car Builders' Association authorize a road to refuse to accept a car from another road for transportation. At junction points of railroads inspectors are detailed to see that this rule (as well as many others) is complied with in respect to all cars offered for transfer.

TRAIN-BRAKES.

421. Introduction. Owing to the very general misapprehension that exists regarding the nature and intensity of the action of brakes, a complete analysis of the problem is considered justifiable. This misapprehension is illustrated by the common notion (and even practice) that the effectiveness of braking a car is proportional to the brake pressure, and therefore a brakeman is frequently seen using a bar to obtain a greater leverage on the brake-wheel and using his utmost strength to obtain the maximum pull on the brake-chain while the car is skidding along with locked wheels.

When a vehicle is moving on a track with a considerable velocity, the mass of the vehicle possesses kinetic energy of translation and the wheels possess kinetic energy of rotation. To stop the vehicle, this energy must be destroyed. The rotary kinetic energy will vary from about 4 to 8% of the kinetic energy of translation, according to the car loading (see § 435). On steam railroads brake action is obtained by pressing brake-shoes against car-wheel treads. As the brake-shoe pressure increases, the brake-shoes retard with increasing force the rotary action of the wheels. As long as the wheels do not slip or "skid" on the rails, the adhesion of the rails forces them to rotate with a circumferential velocity equal to the train velocity. The retarding action of the brake-shoe checks first the rotative kinetic energy (which is small), and the remainder develops a *tendency* for the wheel to slip on the rail. Since the rotative kinetic energy is such a small percentage of the total, it will hereafter be ignored, except as specifically stated, and it will be assumed for simplicity that the only work of the brakes is to overcome the kinetic energy of translation. The possible effect of grade in assisting or preventing retardation, and the effect of all other track resist-

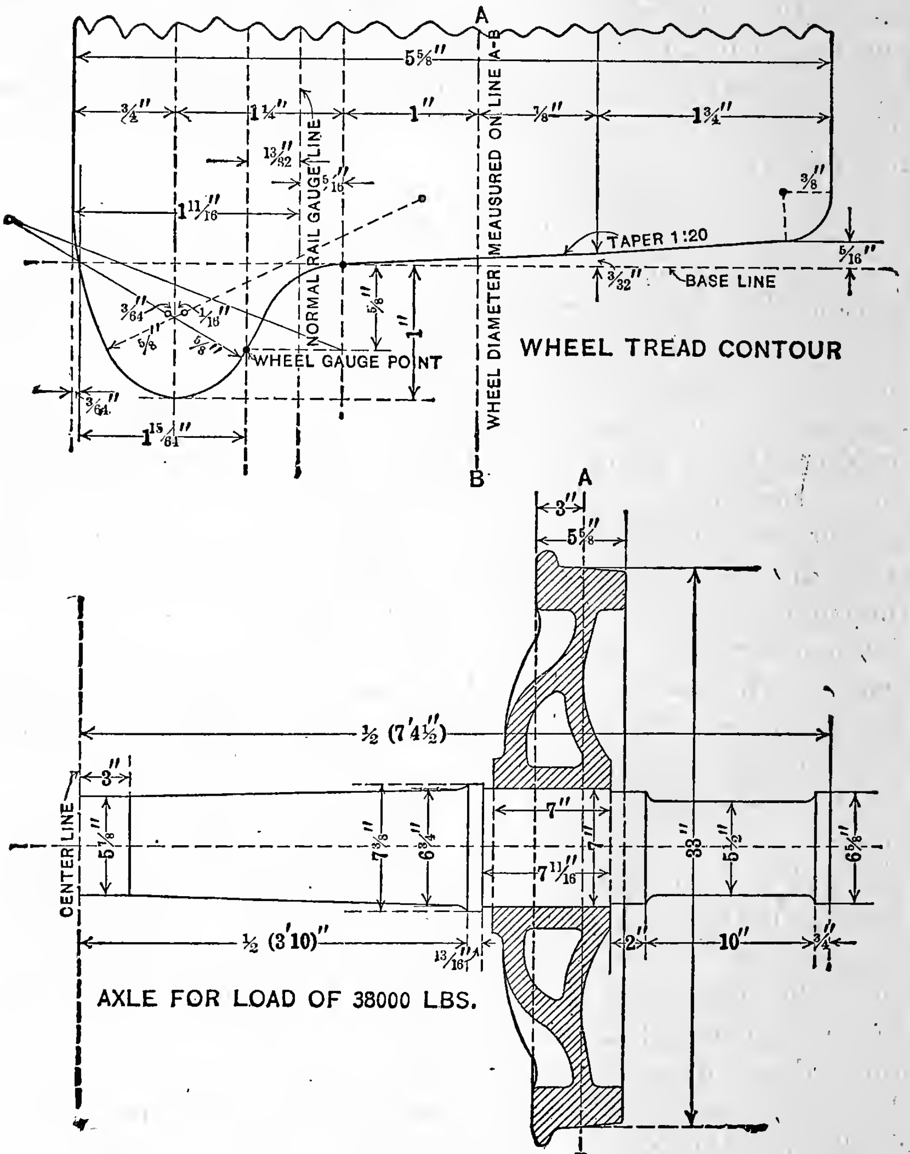


FIG. 204.—M. C. B. STANDARD WHEEL-TREAD AND AXLE. (1918.)

ances, is also ignored. The amount of the developed force which retards the train movement is limited to the possible adhesion or *static* friction between the wheel and the rail. When the friction between the brake-shoe and the wheel exceeds the adhesion between the wheel and the rail, the wheel skids, and then the friction between the wheel and the rail at once drops to a much less quantity. It must therefore be remembered at the outset that the retarding action of brake-shoes on wheels as a means of stopping a train is absolutely limited by the possible static friction between the braked wheels and the rails.

422. Laws of friction as applied to this problem. Much of the misapprehension regarding this problem arises from a very common and widespread misstatement of the general laws of friction. It is frequently stated that friction is independent of the velocity and of the unit of pressure. The first of these so-called laws is not even approximately true. A very exhaustive series of tests were made by Capt. Douglas Galton on the Brighton Railway in England in 1878 and 1879, and by M. George Marié on the Paris and Lyons Railway in 1879, with trains which were specially fitted with train-brakes and with dynagraphs of various kinds to measure the action of the brakes. Experience proved that variations in the condition of the rails (wet or dry), and numerous irregularities incident to measuring the forces acting on a heavy body moving with a high velocity, were such as to give somewhat discordant results, even when the conditions were made as nearly identical as possible. But the tests were carried so far and so persistently that the general laws stated below were demonstrated beyond question, and even the numerical constants were determined as closely as they may be practically utilized. These laws may be briefly stated as follows:

(*a*) The coefficient of friction between cast-iron brake-blocks and steel tires is about .3 when the wheels are "just moving"; it drops to about .16 when the velocity is about 30 miles per hour, and is less than .10 when the velocity is 60 miles per hour. These figures fluctuate considerably with the condition of the rails, wet or dry.

(*b*) The coefficient of friction is greatest when the brakes are first applied; it then reduces very rapidly, decreasing nearly one third after the brakes have been applied 10 seconds, and dropping to nearly one half in the course of 20 seconds. Although the general truth of this law was established beyond question, the tests to demonstrate the law of the variation of friction with time of application were too few to determine accurately the numerical constants.

(*c*) The friction of skidded wheels on rails is always very much less than the adhesion when the wheel is rolling on the rail—sometimes less than one third as much.

(*d*) An analysis of the tests all pointed to a law that the friction developed does *not* increase as rapidly as the *intensity* of pressure increases, but this may hardly be considered as an established law.

(*e*) The adhesion between the wheel and the rail appears to be independent of velocity. The adhesion here means the force that must be developed before the wheel will slip on the rail.

The practical effect of these laws is shown by the following observed phenomena:

(*a*) When the brakes are first applied (the velocity being very high), a brake pressure far in excess of the weight on the wheel (even three or four times as much) may be applied without skidding the wheel. This is partly due to the fact that the wheel has a very high rotative kinetic energy (which varies as the square of the velocity, and which must be overcome first), but it is chiefly due to the fact that the coefficient of friction at the higher velocity is very small (at 60 miles per hour it is about .07), while the adhesion between the wheel and the rail is independent of the velocity.

(*b*) As the velocity decreases the brake pressure must be decreased or the wheels will skid. Although the friction decreases with the time required to stop and increases with the reduction of speed, and these two effects tend to neutralize each other, yet unless the stop is very slow, the increase in friction due to reduction of speed is much greater than the decrease due to time, and therefore the brake pressure must not be greater than the weight on the wheel, unless momentarily while the speed is still very high.

(*c*) The adhesion between wheels and rails varies from .20 to .25 and over when the rail is dry. When wet and slippery it may fall to .18 or even .15. The use of sand will always raise it above .20, and on a dry rail, when the sand is not blown away by wind, it may raise it to .35 or even .40.

(*d*) Experiments were made with an automatic valve by which the brake-shoe pressure against the wheel should be reduced as the friction increased, but since (1) the essential requirement is that the friction produced by the brake-shoes shall not exceed the adhesion between rail and wheel, and since (2) the rail-wheel adhesion is a very variable quantity, depending on whether the rail is wet or dry, it has been found impracticable to use such a valve, and that the best plan is to leave it to the engineer to vary the pressure, if necessary, by the use of the brake-valve.

MECHANISM OF BRAKES.

423. Hand-brakes. The old style of brakes consists of brake-shoes of some type which are pressed against the wheel-treads by means of a brake-beam, which is operated by means of a hand-windlass and chain operating a set of levers. It is desirable that brakes shall not be set so tightly that the wheels shall be locked, and then slide over the track, producing flat places on them, which are very destructive to the rolling-stock and track afterward, on account of the impact occasioned at each revolution. With air-brakes the maximum pressure of the brake-shoes can be quite carefully regulated, and they are so designed that the maximum pressure exerted by any pair of brake-shoes on the wheels of any axle shall not exceed a certain per cent. of the weight carried by that axle when the car is *empty*, 90% being the figure usually adopted for passenger-cars and 70% for freight-cars. Consider the case of a freight-car of 100000 lbs. capacity, weighing 33100 lbs., or 8275 lbs. on an axle, and equipped with a hand-brake which operates the levers and brake-beams, which are sketched in Fig. 205. The dead weight on an axle is 8275 lbs.; 70% of this is 5792 lbs., which is the maximum allowable pressure per brake-beam, or 2896 lbs. per brake-shoe. With the dimensions shown, such a pressure will be produced by a pull of about 1158 lbs. on the brake-chain. The power gained by the brake-wheel is not equal to the ratio of the brake-wheel diameter to the diameter of the shaft, about which the brake-chain winds, which is about 16 to $1\frac{1}{2}$. The ratio of the circumference of the brake-wheel to the length of chain wound up by one complete turn would be a closer figure. The loss of efficiency in such a clumsy mechanism also reduces the effective ratio. Assuming the *effective* ratio as 6:1 it would require a pull of 193 lbs. at the circumference of the brake-wheel to exert 1158 lbs. pull on the brake-chain, or 5792 lbs. pressure on the wheels at *B*, and even this will not lock the wheels when the car is empty, much less when it is loaded. Note that the pressures at *A* and *B* are unequal. This is somewhat objectionable, but it is unavoidable with this simple form of brake-beam. More complicated forms to avoid this are sometimes used. Hand-brakes are, of course, cheapest in first cost, and even with the best of automatic brakes, additional mechanism to operate the brakes by hand in an emergency is always provided, but their slow operation when a quick stop is desired makes it exceedingly dangerous to attempt to run a train at high speed unless some automatic brake directly under the control of the engineer is at hand. The great increase in the

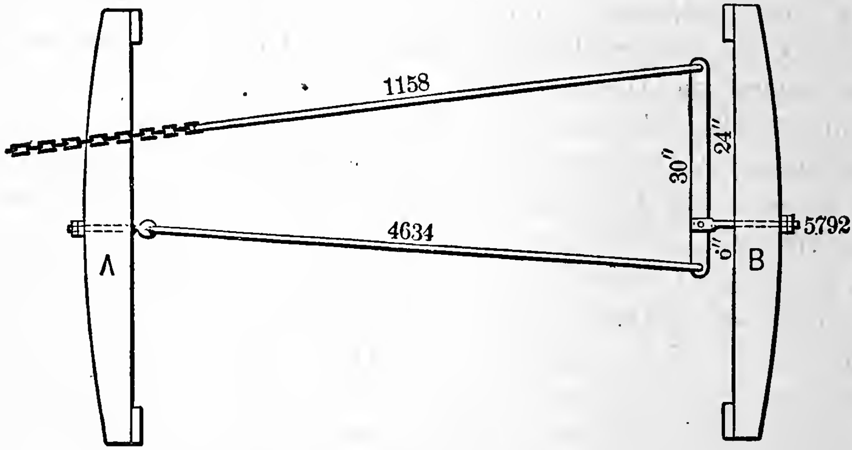


FIG. 205.—SKETCH OF MECHANISM OF HAND-BRAKE.

average velocity of trains during recent years has only been rendered possible by the invention of automatic brakes.

424. "Straight" air-brakes. The essential constructive features of this form of brake are (1) an air-pump on the engine, operated by steam, which compresses air into a reservoir on the engine; (2) a "brake-pipe" running from the reservoir to the rear of the engine and pipes running under each car, the pipes having flexible connections at the ends of the cars and engine; (3) a cylinder and piston under each car which operates the brakes by a system of levers, the cylinder being connected to the brake-pipe. The reservoir on the engine holds compressed air at about 45 lbs. pressure. To operate the brakes, a valve on the engine is opened which allows the compressed air to flow from the reservoir through the brake-pipe to each cylinder, moving the piston, which thereby moves the levers and applies the brakes. The *defects* of this system are many: (1) With a long train, considerable time is required for the air to flow from the reservoir on the engine to the rear cars, and for an emergency-stop even this delay would often be fatal; (2) if the train breaks in two, the rear portion is not provided with power for operating the brakes, and a dangerous collision would often be the result; (3) if an air-pipe coupling bursts under any car, the whole system becomes absolutely helpless, and as such a thing might happen during some emergency, the accident would then be especially fatal.

This form of brake has almost, if not entirely, passed out of use. It is here briefly described in order to show the logical development of the form which is now in almost universal use, the automatic.

425. Automatic air-brakes. The above defects have been overcome by a method which may be briefly stated as follows: A reservoir for compressed air is placed under each car and the tender; whenever the pressure in these reservoirs is reduced for any reason, it is automatically replenished from the main reservoir on the engine; whenever the pressure in the brake-pipe is reduced for any cause (opening a valve at any point of its length, parting of the train, or bursting of a pipe or coupler), valves are automatically moved under each car to operate the piston and put on the brakes. *All* the brakes on the train are thus applied almost simultaneously. If the train breaks in two, *both* sections will at once have *all* the brakes applied automatically; if a coupling or pipe bursts, the brakes are at once applied and attention is thereby attracted to the defect; if an emergency should arise, such that the conductor desires to stop the train instantly without even taking time to signal to the engineer, he can do so by opening a valve placed on each car, which admits air to the train-pipe, which will set the brakes on the whole train, and the engineer, being able to discover instantly what had occurred, would shut off steam and do whatever else was necessary to stop the train as quickly as possible. The most important and essential detail of this system is the "automatic triple valve" placed under each car. Quoting from the Westinghouse Air-brake Company's Instruction Book, "A moderate reduction of air pressure in the train-pipe causes the greater pressure remaining stored in the auxiliary reservoir to force the piston of the triple valve and its slide-valve to a position which will allow the air in the auxiliary reservoir to pass directly into the brake-cylinder and apply the brake. A sudden or violent reduction of the air in the train-pipe produces the same effect, and in addition causes supplemental valves in the triple valve to be opened, permitting the pressure from the train-pipe to also enter the brake-cylinder, augmenting the pressure derived from the auxiliary reservoir about 20%, producing practically instantaneous action of the brakes to their highest efficiency throughout the entire train. When the pressure in the brake-pipe is again restored to an amount in excess of that remaining in the auxiliary reservoir, the piston- and slide-valves are forced in the opposite direction to their normal position, opening communication from the train-pipe to the auxiliary reservoir, and permitting the air in the brake-cylinder to escape to the atmosphere, thus releasing the brakes. If the engineer wishes to apply the brake, he moves the handle of the engineer's brake-valve to the right, which first closes a port, retaining the pressure in the main reservoir, and then permits a portion of the air in the train-pipe to escape. To release the brakes, he moves the handle to the extreme left, which allows the air in the main reservoir to flow freely into the brake-pipe, restoring the pressure therein."

426. Tests to measure the efficiency of brakes. Let v represent the velocity of a train in feet per second; W, its weight; F, the retarding force due to the brakes; d, the distance in feet required to make a stop; and g, the acceleration of gravity (32.16 feet per square second); then the kinetic energy possessed by the train (disregarding for the present the rotative kinetic energy of the wheels) $=\frac{Wv^2}{2g}$. The work done in stopping the train $=Fd$. $\therefore Fd=\frac{Wv^2}{2g}$. The ratio of the retarding force to the weight,

$$\frac{F}{W}=\frac{v^2}{2gd}=.0155\frac{v^2}{d}.$$

In order to compare tests made under varying conditions, the ratio $F \div W$ should be corrected for the effect of grade (+ or −), if any, and also for the proportion of the weight of the train which is on *braked* wheels. For example, a train weighed 146076 lbs., the proportion on braked wheels was 67%, speed 60 feet per second, length of stop 450 feet, track level. Substituting these values in the above formula, we find $(F \div W) = .124$. This value is really unduly favorable, since the ordinary track resistance helps to stop the train. This has a value of from 6 to 20 lbs. per ton, averaging say 10 lbs. per ton during the stop, or .005 of the weight. Since the effect of this is small and is nearly constant for all trains, it may be ignored in comparative tests. The grade in this case was level, and therefore grade had no effect. But since only 67% of the weight was on braked wheels, the ratio, on the basis of *all* the wheels braked, or of the weight reduced to that actually on the braked wheels, is $0.124 \div .67 = 0.185$. This was called a "good" stop, although as high a ratio as 0.200 has been obtained.

427. Brake-shoes. Brake-shoes were formerly made of wrought iron, but when it was discovered that cast-iron shoes would answer the purpose, the use of wrought-iron shoes was abandoned, since the cast-iron shoes are so much cheaper. A cheap practice is to form the brake-shoe and its head in one piece, which is cheaper in first cost, but when the wearing-surface is too far gone for further use, the whole casting must be renewed. The "Christie" shoe, adopted by the Master Car Builders' Association as standard, has a separate shoe which is fastened to the head by means of a wrought-iron key. The shoe is beveled $\frac{1}{4}''$ in a width of $3\frac{3}{8}''$ to fit the coned wheel. This is a greater bevel than the standard coning of a car-wheel. It is perhaps done to allow for some bending of the brake-beam and also so that the maximum pressure (and wear) should come on the outside of the tread, rather than next to the flange, where it might tend to produce sharp flanges. By concentrating the brake-shoe wear on the outer side of the tread, the wear on the tread is more nearly equalized, since the rail wears the wheel-tread chiefly near the flange. This same idea is developed still further in the "flange-shoes," which have a curved form to fit the wheel-flange and which bear on the wheel on the flange and on the outside of the tread. It is claimed that by this means the standard form of the tread is better preserved than when the wear is entirely on the tread. The Congdon brake-shoe is one of a type in which wrought-iron pieces are inserted in the face of a cast-iron shoe. It is claimed that these increase the life of the shoe.

CHAPTER XVI.

TRAIN RESISTANCE.

428. Classification of the various forms. The various resistances which must be overcome by the power of the locomotive may be classified as follows:

(*a*) *Resistances internal to the locomotive*, which include friction of the valve-gear, piston- and connecting-rods, journal friction of the drivers; also all the loss due to radiation, condensation, friction of the steam in the passages, etc. In short, these resistances are the sum-total of the losses by which the power at the circumference of the drivers is less than the power developed by the boiler.

(*b*) *Velocity resistances*, which include the atmospheric resistances on the ends and sides; oscillation and concussion resistances, due to uneven track, etc.

(*c*) *Wheel resistances*, which include the rolling friction between the wheels and the rails of *all* the wheels (including the drivers); also the journal friction of all the axles, except those of the drivers.

(*d*) *Grade and curve resistances*, which include those resistances which are due to grade and to curves, and which are not found on a straight and level track.

(*e*) *Brake resistances*. As shown later, brakes consume power and to the extent of their use increase the energy to be developed by the locomotive.

(*f*) *Inertia resistances*. The resistance due to inertia is not generally considered as a train resistance because the energy which is stored up in the train as kinetic energy may be utilized in overcoming future resistances. But in a discussion of the demands on the tractive power of the engine, one of the chief items is the energy required to *rapidly* give to a starting train its normal velocity. This is especially true of suburban trains, which must acquire speed very quickly in order that their general average speed between termini may be even reasonably fast.

429. Resistance internal to the locomotive. These are resistances which do not tax the adhesion of the drivers to the rails, and hence are frequently considered as not being a part of the train resistance properly so called. If the engine were considered as lifted from the rails and made to drive a belt placed around the drivers, then all the power that reached the belt would be the power that is ordinarily available for adhesion, while the remainder would be that consumed internally by the engine. The power developed by an engine may be obtained by taking indicator diagrams which show the actual steam pressure in a cylinder at any part of a stroke. From such a diagram the average steam pressure is easily obtained, and this average pressure, multiplied by the length of the stroke and by the net area of the piston, gives the energy developed by one half-stroke of one piston. Four times this product divided by 550 times the time in seconds required for one stroke gives the "indicated horse-power" Even this calculation gives merely the power behind the piston, which is several per cent. greater than the power which reaches the circumference of the drivers, owing to the friction of the piston, piston-rod, cross-head, connecting-rod bearings, and driving-wheel journals. (See § 411, Chapter XV.) By measuring the amount of water used and turned into steam, and by noting the boiler pressure, the energy possessed by the steam used is readily computed. The indicator diagrams will show the amount of steam that has been effective in producing power at the cylinders. The steam accounted for by the diagrams will ordinarily amount to 80 or 85% of the steam developed by the boiler, and the other 15 or 20% represents the loss of energy due to radiation, condensation, etc.

Locomotive resistance has been estimated and tabulated by a Committee of the Amer. Rwy. Eng. Assoc. and the results are given in Table XXIX, which is taken from the Manual of that Association. As a numerical illustration, what is the computed resistance for a Mikado locomotive of which the total weight of engine and tender is 315,000 lbs. of which 153,200 lbs. is carried on the drivers, at a velocity of 6 miles per hour? In this case, Item A $=(18.7\times76.6)+(80\times4)=1432$ lbs. The weight carried on the engine and tender trucks $=315{,}000-153{,}200=161{,}800$

$=80.9$ tons. Item $B=(2.6\times80.9)+(20\times6)=330$ lbs. Item C is comparatively insignificant at this low velocity. From the table, we read 9 lbs. Then the sum of A, B, and C = 1771 lbs., which must be subtracted from a computed tractive effort to obtain the estimated draw-bar pull.

TABLE XXIX. LOCOMOTIVE RESISTANCES.

Total Locomotive Resistance $=A+B+C$, in which

A = resistance between cylinder and rim of drivers, and in pounds
$=18.7T+80N$

in which T = tons weight on drivers, and
N = number of driving axles;

B = resistance of engine and tender trucks, and in pounds
$=2.6T+20N$

in which T = tons weight on engine and tender trucks
and N = number of truck axles;

C = head end or "air" resistance, and in pounds
$=.002V^2A$

in which V = velocity in miles per hour, and
A = end area of locomotive.

On the basis that the end area averages 125 square feet, the formula becomes $C=0.25V^2$. The number of pounds air resistance for various velocities is as given below.

Vel.	Res.	Vel.	Res.	Vel.	Res.	Vel.	Res.	Vel.	Res.	Vel.	Res.
1	0.25	8	16.00	15	56	22	121	29	210	36	324
2	1.00	9	20.25	16	64	23	132	30	225	37	342
3	2.25	10	25.00	17	72	24	144	31	240	38	361
4	4.00	11	30	18	81	25	156	32	256	39	380
5	6.25	12	36	19	90	26	169	33	272	40	400
6	9.00	13	42	20	100	27	182	34	289	50	625
7	12.25	14	49	21	110	28	196	35	306	60	900

Draw-bar pull on level tangent equals the cylinder tractive power less the sum of the engine resistances.

At low speeds, the adhesion of the drivers should be considered and available draw-bar pull should never be estimated greater than 30% of weight on drivers at starting with use of sand, 25% of weight on drivers at running speeds.

Taken from Table 7 in "Economics" section of Manual of the Amer. Rwy. Eng. Assoc., 1915 edition.

430. Velocity resistance. (*a*) *Atmospheric.* This consists of the head and tail resistances and the side resistance. The head and tail resistances are nearly constant for all trains of given velocity, varying but slightly with the varying cross-sections of engines and cars. The side resistance varies with the length of the train and the character of the cars, box-cars or flats, etc. Vestibuling cars has a considerable effect in reducing this side resistance by preventing much of the eddying of air-currents between the cars, although this is one of the least of the advantages of vestibuling. Atmospheric resistance is generally assumed to vary as the square of the velocity, and although this may be nearly true, it has been experimentally demonstrated to be at least inaccurate. Values for head resistance are given in Table XXIX, which are probably accurate enough for all practical purposes, especially at ordinary freight train velocities. A freight-train composed partly of flat-cars and partly of box-cars will encounter considerably more atmospheric resistance than one made exclusively of either kind, other things being equal. The definite information on this subject is very unsatisfactory, but this is possibly due to the fact that it is of little practical importance to know just how much such resistance amounts to.

(*b*) *Oscillatory and concussive.* These resistances are considered to vary as the square of the velocity. Probably this is nearly, if not quite, correct on the general principle that such resistances are a succession of impacts and the force of impacts varies as the square of the velocity. These impacts are due to the defects of the track, and even though it were possible to make a precise determination of the amount of this resistance in any particular case, the value obtained would only be true for that particular piece of track and for the particular degree of excellence or defect which the track *then* possessed. The general improvement of track maintenance during late years has had a large influence in increasing the possible train-load by decreasing the train resistance. The expenditure of money to improve track will give a road a large advantage over a competing road with a poorer track, by reducing train resistance, and thus reducing the cost of handling traffic.

431. Wheel resistances. (*a*) *Rolling friction of the wheels.* To determine experimentally the rolling friction of wheels, apart from all journal friction, is a very difficult matter and has never been satisfactorily accomplished. Theory as well as practice shows that the higher and the more perfect the elasticity of the wheel and the surface, the less will be the rolling friction. But the determination, if made, would be of theoretical interest only.

The combined effect of rolling friction and journal friction is determinable with comparative ease. From the nature of the case no great reduction of the rolling friction by any device is possible. It is only a very insignificant part of the total train resistance.

(*b*) *Journal friction of the axles.* This form of resistance has been studied quite extensively by means of the measurement of the force required to turn an axle in its bearings under various conditions of pressure, speed, extent of lubrication, and temperature. The following laws have been fairly well established: (1) The coefficient of friction increases as the pressure diminishes; (2) it is higher at very slow speeds, gradually diminishing to a minimum at a speed corresponding to a train velocity of about 10 miles per hour, then slowly increasing with the speed; it is very dependent on the perfection of the lubrication, it being reduced to one sixth or one tenth, when the axle is lubricated by a bath of oil rather than by a mere pad or wad of waste on one side of the journal; (3) it is much lower at higher temperature, and *vice versa.* The practical effect of these laws is shown by the observed facts that (1) loaded cars have a less resistance per ton than unloaded cars, the figures being, for speeds of about 10 miles per hour, approximately:

For passenger- and loaded freight-cars..	4	lbs.	per	ton
" empty freight-cars..............	8	"	"	"
" street-cars....................	10	"	"	"
" freight-trucks without load........	14	"	"	"

(2) When starting a train, the resistances are about 20 lbs. per ton, notwithstanding the fact that the velocity resistances are practically zero; at about 2 miles per hour it will drop to 10 lbs. per ton and above 10 miles per hour it may drop to 4 lbs. per ton if the cars are in good condition. (3) The resistance could probably be materially lowered if some practicable form of journal-box could be devised which would give a more perfect lubrication. (4) It is observed that freight-train loads must be cut down in winter by about 10 or 15% of the loads that the same engine can haul over the same track in summer. This is due partly to the extra roughness and inelasticity of the

track in winter, and partly to increased radiation from the engine wasting some energy, but this will not account for all of the loss, and the effect, which is probably due largely to the lower temperature of the journal-boxes, is very marked and costly. It has been suggested that a jacketing of the journal-boxes, which would prevent rapid radiation of heat and enable them to retain some of the heat developed by friction, would result in a saving amply repaying the cost of the device.

Roller journals for cars have been frequently suggested, and experiments have been made with them. It is found that they are very effective at low velocities, greatly reducing the starting resistance, which is very high with the ordinary forms of journals. But the advantages disappear as the velocity increases. The advantages also decrease as the load is increased, so that with heavily loaded cars the gain is small. The excess of cost for construction and maintenance has been found to be more than the gain from power saved.

432. Grade resistance. The amount of this may be computed with mathematical exactness. Assume that the ball or cylinder (see Fig. 206) is being drawn up the plane. If W

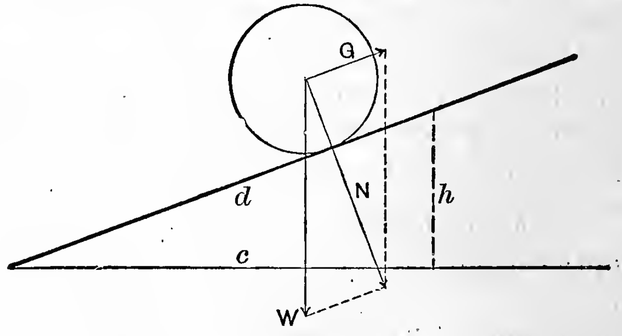


FIG. 206.

is the weight, N the normal pressure against the rail, and G the force required to hold it or to draw it up the plane with uniform velocity, the rolling resistances being considered zero or considered as provided for by other forces, then

$$G : W :: h : d, \quad \text{or} \quad G = \frac{Wh}{d};$$

but for all ordinary railroad grades, $d = c$ to within a tenth of 1%, i.e., $G = \frac{Wh}{c} = W \times$ rate of grade. In order that the student may appreciate the exact amount of this approximation the percentage of slope distance to its horizontal projection is given in the following tabular form:

Grade in per cent.	1	2	3	4	5
$\frac{\text{Slope dist.}}{\text{hor. dist.}} \times 100$........	100.005	100.020	100.045	100.080	100.125

Grade in per cent.	6	7	8	9	10
$\frac{\text{Slope dist.}}{\text{hor. dist.}} \times 100$........	100.180	100.245	100.319	100.404	100.499

This shows also the error on various grades of measuring with the tape on the ground rather than held horizontally. Since almost all railroad grades are less than 2% (where the error is but .02 of 1%), and anything in excess of 4% is unheard of for normal construction, the error in the approximation is generally too small for practical consideration.

If the rate of grade is 1 : 100, $G = W \times \frac{1}{100}$, i.e., $G = 20$ lbs. per ton; ∴ for *any* per cent. of grade, $G = (20 \times \text{per cent. of grade})$ pounds per ton. When moving up a grade this force G is to be overcome in addition to all the other resistances. When moving down a grade, the force G assists the motion and may be more than sufficient to move the train at its highest allowable velocity. The force required to move a train on a level track at ordinary freight-train speeds (say 20 miles per hour) is about 7 lbs. per ton. A down grade of $\frac{7}{20}$ of 1% will furnish the same power; therefore on a down grade of 0.35%, a freight-train would move indefinitely at about 20 miles per hour. If the grade were higher and the train were allowed to gain speed freely, the speed would increase until the resistance at that speed would equal W times the rate of grade, when the velocity would become uniform and remain so as long as the conditions were constant. If this speed was higher than a safe permissible speed, brakes must be applied and power wasted. The fact that one terminal of a road is considerably higher than the other does not necessarily imply that the extra power needed to overcome the difference of elevation is a total waste of energy, especially if the maximum grades are so low that brakes will never need to be applied to reduce a dangerously high velocity, for although more power must be used in ascending the grades, there is a considerable saving of power in descending the grades. The amount of this saving will be discussed more fully in Chapter XXIII.

433. Curve resistance. Some of the principal laws will be here given without elaboration. A more detailed discussion will be given in Chapter XXII.

(*a*) While the total curve resistance increases as the degree of curve increases, the resistance *per degree of curve* is much greater for easy curves than for sharp curves; *e.g.*, the resistance on the excessively sharp curves (radius 90 feet) of the elevated roads of New York City is very much less *per degree of curve* than that on curves of 1° to 5°. (*b*) Curve resistance increases with the velocity. (*c*) The total resistance on a curve depends on the central angle rather than on the radius; i.e., two curves of the same central angle but of different radius would cause about the same total curve resistance. This is partly explained by the fact that the longitudinal slipping will be the same in each case. (See § 395, Chapter XV.) In each case also the trucks must be twisted around and the wheels slipped laterally on the rails by the same amount $\Delta°$. (See § 396, Chapter XV.)

434. Brake resistances. If a down grade is excessively steep so that brakes must be applied to prevent the train acquiring a dangerous velocity, the energy consumed is hopelessly lost without any compensation. When trains are required to make frequent stops and yet maintain a high average speed, considerable power is consumed by the application of brakes in stopping. All the energy which is thus turned into heat is hopelessly lost, and in addition a very considerable amount of steam is drawn from the boiler to operate the air-brakes, which consume the power already developed. It can be easily demonstrated that engines drawing trains in suburban service, making frequent stops, and yet developing high speed between stops, will consume a very large proportion of the total power developed by the use of brakes. Note the double loss. The brakes consume power already developed and stored in the train as kinetic or potential energy, while the operation of the brakes requires additional steam power from the engine.

435. Inertia resistance. The two forms of train resistance which under some circumstances are the greatest resistances to be overcome by the engine are the grade and inertia resistances, and fortunately both of these resistances may be computed with mathematical precision. The problem may be stated as follows: What constant force P (in addition to the forces required to overcome the various frictional resistances, etc.) will be required to impart to a body a velocity of v feet per second in a distance of s feet? The required number of foot-pounds of energy is evidently Ps. But this work imparts a kinetic energy which may be expressed by $\frac{Wv^2}{2g}$. Equating these values, we have $Ps=\frac{Wv^2}{2g}$, or

$$P=\frac{Wv^2}{2gs}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (104)$$

The force required to increase the velocity from v_1 to v_2 may likewise be stated as $P=\frac{W}{2gs}(v_2{}^2-v_1{}^2)$. Substituting in the formula the values $W=2000$ lbs. (one ton), $g=32.16$, and $s=$ 5280 feet (one mile), we have

$$P=.00588(v_2{}^2-v_1{}^2).$$

Multiplying by $(5280\div3600)^2$ to change the unit of velocity to miles per hour, we have

$$P=.01267(V_2{}^2-V_1{}^2).$$

But this formula must be modified on account of the rotative kinetic energy which must be imparted to the wheels of the cars. The precise additional percentage depends on the particular design of the cars and their loading and also on the design of the locomotive. Consider as an example a box-car, 60000 lbs. capacity, weighing 33000 lbs. The wheels have a diameter of 36″ and their radius of gyration is about 13″. Each wheel weighs 700 lbs. The rotative kinetic energy of each wheel is 4877 ft.-lbs. when the velocity is 20 miles per hour, and for the eight wheels it is 39016 ft.-lbs. For greater precision (really needless) we may add 192 ft.-lbs. as the rotative kinetic energy of the axles. When the car is fully loaded (weight 93000 lbs.) the kinetic energy of translation is 1,244,340 ft.-lbs.; when empty (weight 33000 lbs.) the energy is 441540 ft.-lbs. The rotative kinetic energy thus adds (for this particular car) 3.15% (when the car is loaded) and 8.9% (when the car is empty) to the kinetic energy of translation. The kinetic energy which is similarly added, owing to the rotation of the wheels and axles of the locomotive, might be similarly computed. For one type of locomotive it has been figured at about 8%. The variations in design, and particularly the fluctuations of loading, render useless any great precision in these computations. For a train of "empties" the figure would be high, probably 8 to 9%; for a fully loaded train it will not much exceed 3%. Wellington considered that 6% is a good average value to use (actually used 6.14% for "ease of computation"), but considering (*a*) the increasing proportion of live load to dead load in modern car design, (*b*) the greater care now used to make up *full* train-loads, and (*c*) the fact that *full* train-loads are the critical loads, it would appear that 5% is a better average for the conditions of modern practice. Even this figure allows something for the higher percentage for the locomotive and something for a few empties in the train. Therefore, adding 5% to the coefficient in the above equation, we have the true equation

$$P = .0133(V_2^2 - V_1^2), \quad . \quad . \quad . \quad . \quad . \quad . \quad (105)$$

in which V_2 and V_1 are the higher and lower velocities respectively, in *miles per hour*, and P is the force required *per ton* to impart that difference of velocity in a distance of *one mile*. If more convenient, the formula may be used thus: *

$$P_1 = \frac{70}{s}(V_2^2 - V_1^2), \quad . \quad . \quad . \quad . \quad . \quad . \quad (106)$$

in which s is the distance in feet and P_1 is the corresponding force.

As a numerical illustration, the force required per ton to impart a kinetic energy due to a velocity of 20 miles per hour in a distance of 1000 feet will equal

$$P_1 = \frac{70(400-0)}{1000} = 28 \text{ lbs.},$$

which is the equivalent (see § 432) of a 1.4% grade. Since the velocity enters the formula as V^2, while the distance enters only in the first power, it follows that it will require *four* times

* The slight approximation involved in the transformation from Eq. 105 to 106, by using the even number 70, is covered by allowing 4.6%, instead of 5% for rotary kinetic energy.

the force to produce twice the velocity in the same distance, or that with the *same* force it will require four times the distance to attain twice the velocity.

As another numerical illustration, if a train is to increase its speed from 15 miles per hour to 60 miles per hour in a distance of 2000 feet, the force required (in addition to all the other resistances) will be

$$P_1 = \frac{70(3600-225)}{2000} = 118 \text{ lbs. per ton.}$$

This is equivalent to a 5.9% grade and shows at once that it would be impossible unless there were a very heavy down grade, or that the train was very light and the engine very powerful.

436. **Dynamometer tests.** These are made by putting a "dynamometer-car" between the engine and the cars to be tested. Suitable mechanism makes an automatic record of the force which is transmitted through the dynamometer at any instant, and also a record of the velocity at any instant. One of the practical difficulties is the *accurate* determination of the velocity at any instant when the velocity is fluctuating. When the velocity is decreasing, the kinetic energy of the train is being turned into work and the force transmitted through the dynamometer is less than the amount of the resistance which is actually being overcome. On the other hand, when the velocity is increasing, the dynamometer indicates a larger force than that required to overcome the resistances, but the excess force is being stored up in the train as kinetic energy. Grade has a similar effect, and the force indicated by the dynamometer may be greater or less than that required at the given velocity on a level by the force which is derived from, or is turned into, potential energy. The effect of curvature should be eliminated by subtracting from the dynamometer record 0.6 to 0.8 pound per ton per degree of curve, according to the rules for compensation of curvature as developed in § 511. Correct for grade by subtracting from the dynamometer record twenty pounds per ton for each percent of grade, assuming that the test train is moving *up* a grade; if the train is moving down grade, *add* a similar amount. Add (or subtract) the effect of *change* in velocity, as computed in § 435. Usually each dynamometer observation will need to be corrected by one or all of these corrections in order to determine what would have been the resistance on a *straight*, *level* track, at some definite *uniform* velocity.

In 1908–09 the Railway Eng. Dep't of the Univ. of Illinois conducted a series of tests, under the direction of Prof. E. C. Schmidt,* which were so elaborate and thorough that they definitely demonstrated that (*a*) the resistance per ton of any car depends very considerably upon the weight of the car, which is graphically shown in Fig. 206 *a*, and (*b*) the actual resistance per ton is variable and uncertain, and therefore no formula or resistance curve can assume to represent such resistance with a close percentage of accuracy. This uncertainty is illustrated by the fact that, in spite of the most elaborate tare to eliminate all observational error and obtain uniform results, one typical group of plotted points had an average deviation of about 8% from the curve of average resistance and there was one instance of a 23% deviation. The variation in results is probably due to variable condition of the track (see § 430*b*) and shows that no one formula or curve, or set of them, is *closely* applicable to the variable track conditions found in the country or even to the variations found on any one road. The chief object in observing train resistance is to determine the tractive power required to haul a definite amount of traffic under certain known conditions, but these tests have confirmed what operating experience had already pointed out, that actual train resistance is so variable that there must be a considerable margin of tractive power in the locomotive or trains will be frequently stalled. Nevertheless, resistance formulae can be and are utilized for comparing proposed track locations and for computing, with a proper margin, the train load which may be attached to a locomotive of known tractive power.

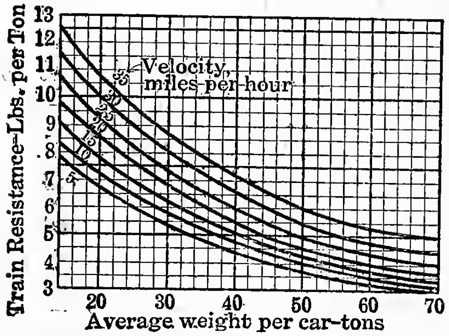


FIG. 206a.—RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT VARIOUS SPEEDS.
(Reduced from Fig. 10, Schmidt, Freight Car Resistance.)

The net result of these tests on 32 freight trains of various weights have been plotted in Fig. 206*b*, which shows ten curves, each for a different average car weight. For each curve, the resistance per ton increases with the velocity, being about 80% more for a velocity of 40 miles per hour than for a velocity of

* Univ. of Ill. Bull. 43, Freight Train Resistance, by Edward C. Schmidt.

5 miles per hour. Note that the upper curve (15 tons per car) is only applicable to a train of empties and the lower curve (75 tons per car) would mean a train of fully loaded cars. It should be fully realized that, in order to practically utilize these or other similar curves as a measure of the tractive power demanded of a locomotive, due allowance should be made for grade, for curvature, and for the inertia effect of change in velocity; also that such figures only claim to measure the resistance behind the tender, and that it does not apply if brakes have been used.

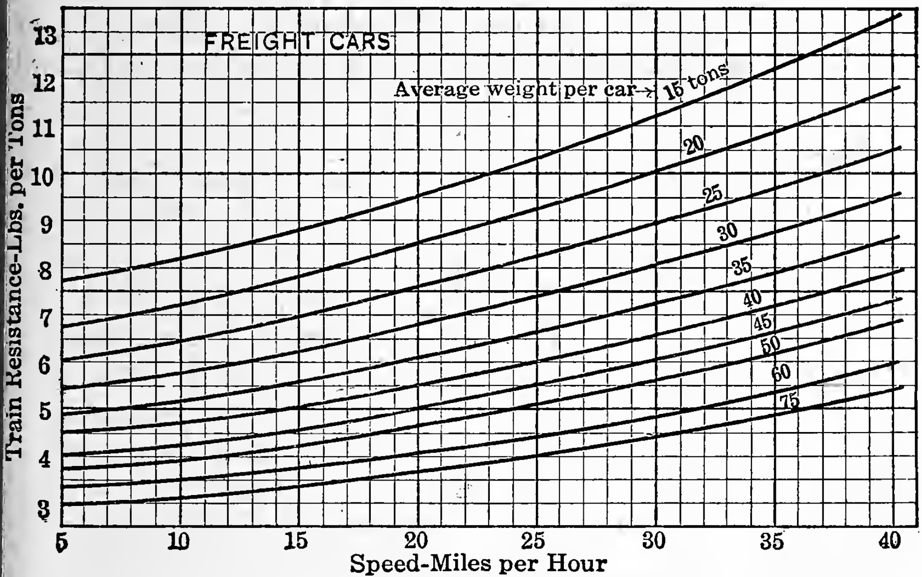


FIG. 206*b*.—RELATION BETWEEN RESISTANCE AND SPEED, FOR VARIOUS AVERAGE WEIGHTS PER FREIGHT CAR.
(Reduced from Fig. 11, Schmidt, Freight Car Resistance.)

437. Gravity or "drop" tests. A drop test utilizes the force of gravity which may be measured with mathematical accuracy. The general method is to select a stretch of track which has a uniform grade of about 0.7% and which is preferably straight for 2 or 3 miles. On such a grade cars with running gear in good condition may be started by a push. The velocity will gradually increase until at some velocity, depending on the resistances encountered, the cars will move uniformly. The only work requiring extreme care with this method is the determination of the velocity. If the velocity is fluctuating, as it is during the time when it is of the greatest importance to know the velocity, it is not sufficient to determine the time required to run some long measured distance, for the average velocity thus obtained would probably differ considerably from the velocity at the beginning and end of that space. If the train consists of five cars or more, the velocity may be determined electrically (as described by Wellington in his "Economic Location," etc., p. 793 *et seq.*) from the automatic record made on a chronograph of the passage of the first wheel and the last, the chronograph also recording automatically the ticks of a clock beating seconds. From this the exact time of the passage of the first and last wheels of the train of cars may be determined to the tenth or twentieth of a second.

Velocity-head. From theoretical mechanics we know that if a body descends through any path by the action of gravity, and

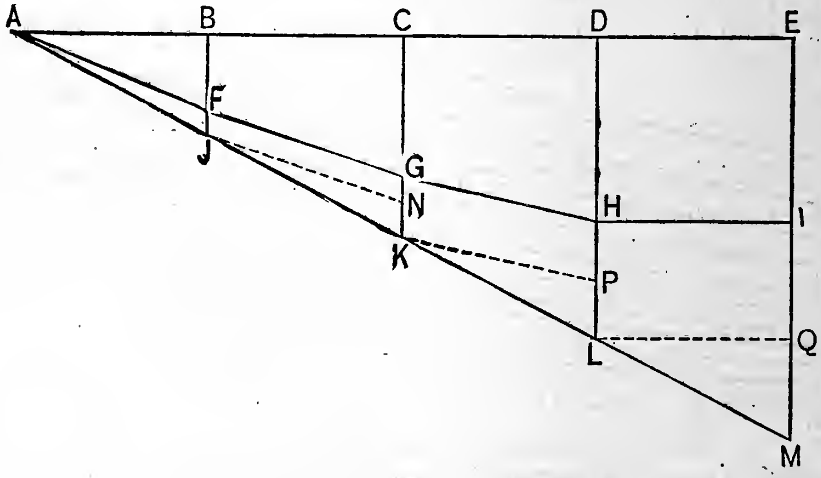


FIG. 207.—LOSS IN VELOCITY-HEAD.

is unaffected by friction, its velocity at any point in the direction of the path of motion is $V=\sqrt{2gh}$. If the body is retarded by resistances, its velocity at any point will be less than this. If AM, Fig. 207, represents any grade (exaggerated of course), then BJ, CK, etc., represent the actual fall at any point. Let BF represent the fall h_1, determined from $h_1=\frac{v_1^2}{2g}$, in which v_1 is the actual observed velocity at J. Then JF = the velocity-head consumed by the resistances between A and J. If the train continues to K, the corresponding h_2 is CG; the remaining fall GK consists of GN ($=JF$, which is the velocity-head lost back of J) and NK, the velocity-head lost between J and K. At some velocity (V_n) on any grade, the velocity will not further increase and the line $AFGHI$ will then be horizontal and at a distance $(h_n) = EI$ below $A \ldots E$. The grade AM is the "grade of repose" for that velocity (V_n); i.e., it is the grade that would just permit the train to move indefinitely at the velocity V_n. The broken line $AFGHI$ should really be a curve, and the grade of repose at any point is the angle between AM and the tangent to that curve at the given point. The "grade of repose" by its definition gives the total resistance of the train at the particular velocity, or multiplying the grade of repose in per cent by 20 gives the pounds per ton of resistance. Thus being able to determine the total resistance in pounds per ton at any velocity, the variation of total resistance with velocity may be determined, and then by varying the resistances, using different kinds of cars, empty and loaded, box-cars and flats, the resistances of the different kinds at various velocities may be determined. Many tests have been made, on the above general plan, to determine track resistance, but, since it is impracticable and even dangerous to use this method for high velocities, the dynamometer-car method has been used for the most recent and reliable tests.

438. **Resistance of cars through switches.** It has always been realized that cars encounter greater resistance while passing through switches than on a straight unbroken track. This additional resistance would have a vital importance in case a passing siding were located on a ruling grade. The additional tractive force required to haul a train from a siding through a switch on to a main track would limit the length of train which might otherwise be hauled. Whenever a passing siding is essential on a ruling grade, the grade should be compensated, but the rate of compensation is still an uncertain quantity. An analogous problem is the rate of grade of a ladder track in a classification yard (see Chapter XIII, § 379) in order that, when switching cars by gravity from a hump, the added resistance, due to passing over the various frogs and switch rails on the ladder track, will not so exhaust the inertia due to the initial velocity that the cars cannot reach the desired locations on the classification tracks. Tests to determine such resistance were made in 1913–14, under the direction of Prof. C. L. Eddy, of the Case School of Applied Science.* The cars, usually singly but occasionally two, three or four together, were dropped from the top of a hump down a short 4% grade, by which they

* Bull, 175, Amer. Rwy. Eng. Assoc., March, 1915.

acquired a velocity varying from 14 to 21 miles per hour at the beginning of the ladder track, which had a downward grade of 1.175%. Velocities were observed at two places on the ladder track, by setting up at each place a pair of "contact points," usually 60 feet apart, by which the time of travelling the 60 feet was automatically recorded on a chronograph, which also recorded half seconds. The mean distance apart of the two pairs of contact points was at first 375 feet; then for other tests 400 feet and then 421.5 feet. Sometimes the velocity of the cars decreased while passing over this measured distance, and sometimes it increased. In any case the impelling force was the constant gravity force of $20 \times 1.175\% = 23$ pounds per ton, plus the inertia force due to the initial velocity. This net force, less the inertia force represented by the final velocity, equals the resisting force, in pounds per ton. As usual in such tests, the results were very variable, varying in 163 observations from a minimum of 4.5 to a maximum of 41.8 pounds per ton. The general average was about 22 pounds per ton, which is very nearly the gravity force (23.5 lbs.) of the ladder track used in this test. Note the increase in the average figure (22) above the average resistance per ton for whole trains of cars on a straight unbroken track, at the same average velocity of 15 to 20 m.p.h., which would vary from 3.5 to 9.5 pounds per ton—see Fig. 206*b*. A very small part of the increase is due to the extra atmospheric resistance *per ton* of one car over that of a train of cars, but the largest part of the excess resistance is that due to the frogs and switch points in the track, which, by their variable surface, variable elasticity and uneven support, cause shock resistances which average three or four times the normal resistance on an unbroken track. The above tests demonstrate (*a*) the very great increase of resistance on switches, and (*b*) that the resistance varies so greatly that no *precise* calculations can be made with respect to it. Although the average resistance was about 22 lbs. per ton, an allowance of 30 lbs. per ton would only cover 91% of the trials in the above test. It should also be noted that the switch work, made up of No. 8 frogs and split switches, was on the New York Central system, and was declared to be "in good order." It cannot therefore be claimed that this switch resistance was abnormally high.

439. American Railway Engineering Association Formula. In 1910, the Association Committee on Economics of Location developed a formula with the special idea of its utilization in the comparative study of alternate locations of a railroad line, or in the operation of trains. An elaborate study of the very numerous formulae which had been published convinced the committee that all such formulae were either intrinsically worthless or that they were inapplicable to present conditions of track and rolling stock. After an exhaustive study of the results of recent dynamometer tests on the resistance of *freight* trains, with velocities varying from 5 to 35 m.p.h., it was declared that a formula which is sufficiently accurate for practical purposes can be put into the form

$$R = at + bn$$

in which t is the total weight of the train, in tons of 2000 lbs. and n is the number of cars; a and b are constants to be determined by tests. The values 2.78 and 113.9 for a and b respectively were first used on the basis of certain tests. Later, on the basis of an accumulation of additional tests, these constants were modified so as to have varying values according to the temperature and the following group of four formulae was recommended.

$$\left.\begin{array}{ll} A \text{ rating, temp.} = 35° \text{ F. or above;} & R = 2.2\,t + 122\,n \\ B \text{ rating, temp.} = 20° \text{ to } 35° \text{ F.;} & R = 3.0\,t + 137\,n \\ C \text{ rating, temp.} = 0° \text{ to } 20° \text{ F.;} & R = 4.0\,t + 153\,n \\ D \text{ rating, temp.} = \text{below } 0° \text{ F.;} & R = 5.4\,t + 171\,n \end{array}\right\} \quad . \quad (107)$$

These formulae apply only to level grade. When using them, suitable corrections for actual rate of grade and curvature, and a proper allowance for inertia, in accordance with the assumed method of operation, should be added to the resistance computed from Eq. 107.

Comparing these formulae with the results of the tests by Schmidt, we should use only the formula for A rating, since Schmidt's tests were all made at temperatures above 35° F. Assume a train of 53 empties, each weighing 18 tons, or a total of 954 tons, which is the value of t; $n = 53$; then the draw bar pull behind the tender equals

$$R = 2.2 \times 954 + 122 \times 53 = 2099 + 6466 = 8565 \text{ pounds.}$$

The mean resistance per ton would be $8565 \div 954 = 8.97$ pounds per ton. By Schmidt's curves (Fig. 206*b*) the resistance would vary from about 7 lbs. per ton for a velocity of 5 m.p.h. to 11.4 lbs. per ton at 35 m.p.h., or a total of 6678 to 10876 lbs. resistance, depending on velocity. At a velocity of slightly over 20 m.p.h. the Schmidt curves show the same average resistance (8.97 lbs. per ton) for 18-ton cars.

A similar computation for a train of 30 cars weighing 70 tons each, or a total of 2100 tons, indicates a total resistance, by Eq. 107, of 8280 lbs. or 3.94 lbs. per ton. This again is the resistance per ton indicated by the Schmidt curves for 70-ton cars when the velocity is a little over 20 m.p.h.

The student should note that although the A.R.E.A. formula is independent of velocity, while the Schmidt curves indicate resistances varying as a function of the first power and also of the square of the velocity, the results at a velocity of about 20 m.p.h. are identical. Secondly both agree (up to 25 m.p.h.) that, although the loaded train weighs considerably more than twice as much as the train of empties, the pull on the draw bar is actually less, which forcibly illustrates the economy of operating full and heavily loaded cars.

The application of Eq. 107 to the operation of trains, or to train rating, is explained in Chapter XVIII, § 467.

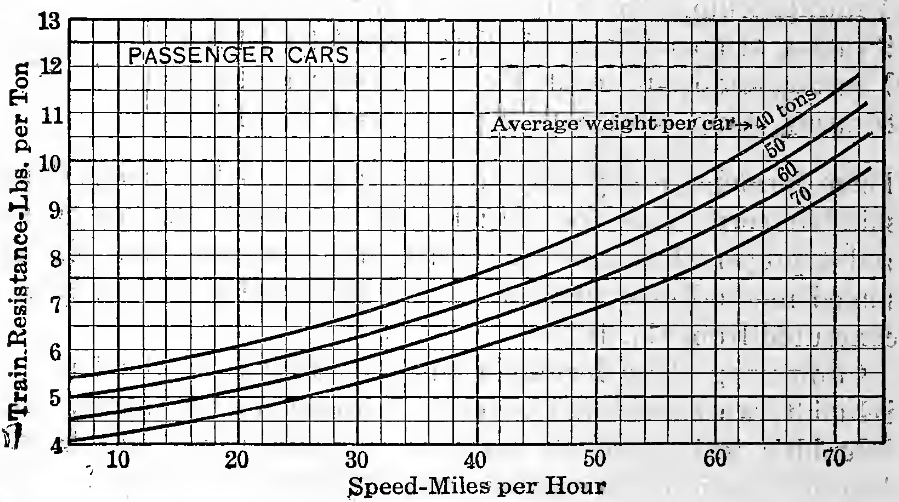


Fig. 207a.—Relation between Resistance and Speed, for Various Average Weights per Passenger Car.

(Reduced from Fig. 6, Schmidt, Passenger Train Resistance.)

439a. Passenger-car resistance. In 1916, Prof. E. C. Schmidt made some tests on passenger-car resistance by the same general methods used in freight-car tests, as described in § 436.* Tests were made on eighteen trains, of which the average car weight varied from 48.7 to 71.1 tons. 83% of the cars had six-wheeled trucks.

The curves plotted from these tests are shown on a reduced scale in Fig. 207*a*, which shows the same general form of curves as those of Fig. 206*b*. It should also be noted that the tests showed that the heavier cars have less resistance per ton than lighter cars, the same as for freight cars. Comparing the curves, where identical conditions make such comparisons possible, it may be noted that, in general, freight cars showed a *less* resistance per ton than passenger cars for the same velocity and weight of car. Many years ago a committee of the Am. Rwy. Master Mechanics Assoc. reported that "six-wheel trucks are found to produce greater resistance, and as a consequence absorb more hauling power than four-wheel trucks carrying the same weight of car." Six-wheeled trucks are considered essential for carrying especially heavy cars at high passenger-train speed, in spite of the proved added per-ton resistance. Since nearly all trains in the above tests included cars with both six-wheeled and four-wheeled trucks, it was impracticable to differentiate the results on this basis, but the fact that about 83% of the cars had six-wheeled trucks probably explains the higher per-ton results. When the passenger-car results are reduced to per-ton-per-axle, the freight-car and passenger-car results are more nearly uniform. Whenever these curves are used, it should be kept in mind that the effect of grade, curvature and inertia resistance have all been eliminated from these results. The tests were made in pleasant weather, during the summer. It should therefore be expected that the resistance in cold and windy weather would be materially greater.

It is interesting to note that the careful calculations made of the weight of the live load (passengers, baggage, mail and express) showed that the maximum load weighed only 5.2% of the gross train load, and therefore the cost of running a passenger train is measurably the same whether it runs full or absolutely empty.

---

* Proceedings, Amer. Rwy. Eng. Assoc., Vol. 18, p. 689.

CHAPTER XVII

COST OF RAILROADS.

440. General considerations. Although there are many elements in the cost of railroads which are roughly constant per mile of road, yet the published reports of the cost of railroads differ very widely. The variation in the figures is due to several causes. (*a*) Economy requires that a road shall be operated and placed on an earning basis as soon as possible. Therefore the reported cost of a road during the first few years of its existence is somewhat less than that reported later. This is well illustrated when a long series of consecutive reports from an old-established road is available; nearly every year there will be shown an addition to the previous figures. And this is as it should be. The magnificent road-beds of some old roads cannot be the creation of a single season. It takes many years to produce such settled perfect structures. (*b*) A large part of the variation is due to a neglect to charge up "permanent improvements" as additions to the cost of the road. For the first few years of the life of a road a great deal of work is done which is in reality a completion of the work of construction, and yet the cost of it is buried under the item "maintenance of way." For example, a long wooden trestle is replaced by an earth embankment and a culvert. Since the original trestle is to be considered a temporary structure, the *excess* of the cost of the permanent structure over that of the temporary structure should evidently be considered as an addition to the cost of the road. But if the filling-in was done slowly, a few train-loads at a time, and the work scattered over many years, the cost of operating the "mud-train" has perhaps been buried under "maintenance" charges. (*c*) The reports from which many of the following figures were taken have not always analyzed the items of cost with the same detail as has been here attempted, and to that is probably due many of the variations and apparent discrepancies.

The various items of cost will be classified as follows:

1. Preliminary financiering.
2. Surveys and engineering expenses.
3. Land and land damages.
4. Clearing and grubbing.
5. Earthwork, including rockwork; tunneling.
6. Bridges, trestles, and culverts.
7. Trackwork, material and track labor.
8. Buildings and miscellaneous structures.
9. Interest on construction.
10. Rolling stock.

441. Item 1. Preliminary Financiering. The cost of this preliminary work is exceedingly variable. The work includes the clerical and legal work of organization, printing, engraving of stocks and bonds, and (sometimes the most expensive of all) the securing of a charter. This sometimes requires special legislative enactments, or may sometimes be secured from a State railroad commission. It has been estimated that about 2% of the railway capital of Great Britain has been spent in Parliamentary expenses over the charters. These expenses are usually but a small percentage of the total cost of the enterprise, but for important lines the gross cost is large, while the amount of money thus spent by organizations which have never succeeded in constructing their roads is, in the aggregate, an enormous amount, although it is of course not ascertainable by any investigator.

Another occasional feature of the financing of a road must be kept in mind. The promoters of a railroad enterprise frequently endeavor to limit their own personal expenditures to the purely preliminary expenses as mentioned above. The project, after having been surveyed, mapped, and written up in a glowing "prospectus," is submitted to capitalists, in the endeavor to have them furnish money for construction, the money to be secured by bonds. If the project will stand it, the amount of the bond issue is made sufficient to pay the entire cost of the road, even with a discount of perhaps 15%. The bond issue may also provide for a very generous commission to the broker who is the intermediary between the promoters and the capitalists. The bond issue may even provide for repaying the promoters for their preliminary expenses. Frequently a considerable proportion of the capital stock goes to the capitalists who take the bonds, the promoters retaining only such proportion as may be agreed upon. In such a case, the capital stock is "pure velvet," and costs nothing. Its future value, whatever it may be, is so much clear profit. The effect of such a financial policy is to burden the project with a capitalization which is far in excess of the actual cost of constructing the road. Comparatively few projects will stand such over-capitalization. The apparent financial failure of many railroads, which have gone into the hands of receivers is due to their inability to make returns on an over-capitalization rather than because they could not earn enough to pay the legitimate cost of their construction. These features of financiering are really foreign to the engineer's work, but he should know that many projects which would return a handsome profit on an investment amounting only to the legitimate cost, will be rejected by capitalists because it is apparent that there is not enough "velvet" in it.

442. Item 2. SURVEYS AND ENGINEERING EXPENSES. The comparison of a large number of itemized reports on the cost of construction shows that the cost of the "engineering" will average about 2% of the total cost of construction. This includes the cost of surveys and the cost of laying out and superintending the constructive work. The cost of mere surveying up to the time when construction actually commences has been variously quoted at $60, $75, and even $300 per mile. The lower figures generally refer to the hasty, ill-considered work which was formerly common and which has resulted in so much badly located road, much of which has been reconstructed, when improvements are practicable. See the introductory paragraphs of Chapter I. Except when the topography limits the location to one very obvious route, a thorough survey may cost about $300 per mile. In the estimate given at the end of this chapter the cost of "engineering and office expenses" is given at 5% of the cost of the construction work. The item then includes the cost of the very considerable amount of clerical work and superintendence incident to the expenditure of such a large sum of money.

443. Item 3. Land and Land Damages. The cost of this item varies from the extreme, in which not only the land for right-of-way but also grants of public land adjoining the road are given to the corporation as a subsidy, to the other extreme where the right-of-way can only be obtained at exorbitant prices. The width required is variable, depending on the width that may be needed for deep cuts or high fills, or the extra land required for yards, stations, etc. A strip of land 1 mile long and 8.25 feet wide contains precisely 1 acre. An average width of 4 rods (66 feet), therefore, requires 8 acres per mile. On the Boston & Albany Railroad the expenditure assigned to "land and land damages" averages over $25000 per mile. Of course this includes some especially expensive land for terminals and stations in large cities. Less than $300 per mile was assigned to this item by an unimportant 18-mile road.

444. Item 4. CLEARING AND GRUBBING. The cost of this may vary from zero to 100% for miles at a time, but as an average figure it may be taken as about 3 acres per mile at a cost of say $50 per acre. The possibility of obtaining valuable timber, which may be utilized for trestles, ties, or otherwise, and the value of which may not only repay the cost of clearing and grubbing, but also some of the cost of the land, should not be forgotten.

445. Item 5. EARTHWORK. This item also includes rock-work. The methods of estimating the cost of earthwork and rockwork have been discussed in Chapter III. The percentage of this item to the total cost is very variable. On a western prairie it might not be more than 5 to 10%. On a road through the mountains it will run up to 20 or 25%, and even more. The item also includes tunneling, which on some roads is a heavy item.

446. Item 6. BRIDGES, TRESTLES, AND CULVERTS. This item will usually amount to 5 or 6% of the total cost of the road. In special cases, where extensive trestling is necessary, or several large bridges are required, the percentage will be much higher. On the other hand, a road whose route avoids the watercourses may have very little except minor culverts. On the Boston & Albany the cost is given as $5860 per mile; on the Adirondack Railroad, $2845 per mile. Considering their relative character (double and single track), these figures are relatively what we might expect.

447. Item 7. Trackwork. This item will be considered as including everything above subgrade, except as otherwise itemized.

(a) Ballast. As already elaborated in Chapter VII, Ballast, the standards for depth of ballast, in order to produce a uniform pressure on sub-grade, have so increased that former estimates are inapplicable. The increased depth now called for is usually provided by using a layer of sub-ballast made of comparatively inexpensive material, such as cinders, which, being a by-product, has only a nominal cost. The unit cost of ballast per cubic yard varies from merely nominal to the cost of broken stone, which may cost \$1.50 or even \$2.00 per cubic yard.

(b) Ties. Ties cost anywhere from \$1.40 down to 50 c. and even less. At an average figure of 80c., 2640 ties per mile will cost \$2112 per mile of single track. The cheaper ties are usually smaller and more must be used per mile, and this tends to compensate the difference in cost.

The following tabular form is convenient for reference:

TABLE XXX.—NUMBER OF CROSS-TIES PER MILE OF TRACK.

Number per 33′ rail.	Average spacing center to center.	Number per mile.
22	18.0 inches	3520
21	18.9 "	3360
20	19.8 "	3200
19	20.9 "	3040
18	22.0 "	2880
17	23.3 "	2720
16	24.75 "	2560
15	26.4 "	2400
14	28.3 "	2240
13	30.5 "	2080

(c) Rails. The total weight of the rails used per mile may best be seen by the tabular form.

A convenient and useful rule to remember is that the number of *long* tons (2240 lbs.) per mile of single track equals the weight of the rail per yard times $\frac{11}{7}$. The rule is exact. For example, there are 3520 yards of rail in a mile of single track; at 70 lbs. per yard this equals 246,400 lbs., or 110 long tons (exactly); but $70 \times \frac{11}{7} = 110$.

Any calculation of the required weight of rail for a given weight of rolling-stock necessarily depends on the assumptions which are made regarding the support which the rails receive from the ties. This depends not only on the width and spacing of the ties (which are determinable), but also on the support

TABLE XXXI.—TONS PER MILE OF RAILS OF VARIOUS WEIGHTS.

Weight in lbs. per yd.	Tons (2240 lb.) per mile of single track.	Weight in lbs. per yd.	Tons (2240 lb.) per mile of single track.	Weight in lbs. per yd.	Tons (2240 lb.) per mile of single track.	Weight in lbs. per yd.	Tons (2240 lb.) per mile of single track.
8	12.571	25	39.286	55	86.429	85	133.571
10	15.714	30	47.143	60	94.286	90	141.429
12	18.857	35	55.000	65	102.143	95	149.286
14	22.000	40	62.857	70	110.000	100	157.143
16	25.143	45	70.714	75	117.857	110	172.857
20	31.429	50	78.571	80	125.714	120	188.571

About two per cent (2%) extra should be allowed for waste in cutting.

which the ties receive from the ballast, which is not only very uncertain but variable. No general rule can therefore claim any degree of precision, but the following is given by the Baldwin Locomotive Works: The weight per wheel which can be safely carried for each pound weight of rail per yard is approximately as follows:

Light rails; 60 lbs. and less per yard; 250 lbs.;
Medium rails; 60 lbs. to 90 lbs. per yard; 300 lbs.;
Heavy rails; 90 lbs. and over per yard; 350 lbs.

This assumes that the rails are properly supported by cross ties, not less than 14 per 30-ft. rail. For example, a Mikado locomotive with 153,200 lbs. on 8 drivers has a load of 19,150 lbs. per wheel. This divided by 300 gives 63.8. According to the rule, the rails for such a locomotive should weigh at least 63.8 lbs. per yard. But it should be noted that railroads which use Mikado locomotives will also have their track laid with heavier than 63.8 (or 65) pound rails. The rule should therefore be considered as the *minimum* permissible. A road with even one high-speed train, or a Class A road (§ 234), should use 80 to 90 lb. rails, even if not required by the above rule.

On the basis of 33-foot lengths, and 10% shorter lengths, varying by even feet down to 25 feet (see § 273 *e*), the average length, assuming an equal number each of the shorter length rails, would be 32.55 feet. Calculating similarly for 30-ft. rails, with 10% shorts to 24 feet, the average length would be 29.65 feet. 60-ft. rails, used extensively for electric roads, with 10% shorts to 40 feet, will have average length of 58.95 feet.

(d) Splice-bars, track-bolts, and spikes. These are usually sold by the pound, except the patented forms of rail-joints, which are sold by the pair. In any case they are subject to market fluctuations in price. As an approximate value the following prices are quoted: Splice-bars, 2.50 cents per pound; track-bolts, 4.0 cents; spikes, 3.25 cents. The weight of the splice-bars will depend on the precise pattern adopted—its cross-section and length.

In Table XXXII are quoted, from a catalogue of the Illinois Steel Co., the weights per foot of sections of angle-bars which they recommend for various weights of rail and which are designed to fit standard A. S. C. E. rail sections of those weights. The net weight of the angle-bars may be approximated by subtracting about 2.5% to 4% from the gross weight to allow for the bolt-holes. A deduction of 2.5% is usually about right for the heavier sections. Their recommendations regarding lengths of angle-bars do not include those for rails heavier than 50 pounds per yard. On the basis of a length of 24 inches for four-hole splices and of 32 inches for six-hole splices, the weights of splice-bars have been computed for the several styles of splices for heavier rails, allowing 2.5% for the holes. The lengths recommended for track bolts are those which will allow about $\frac{1}{2}$ inch for the nutlock and for margin, except for the lighter rails.

TABLE XXXII.—SPLICE-BARS FOR VARIOUS WEIGHTS OF RAILS.

Weight of rail.	Length of angle-bar.	Weight per foot.	Weight of pair.	Proper size of track-bolt.	Proper size of spikes.
30	21″	4.49	15.1	$2\frac{1}{2}'' \times \frac{5}{8}''$	$4'' \times \frac{1}{2}''$
35	21″	4.7	15.9	$2\frac{3}{4}'' \times \frac{5}{8}''$	$4\frac{1}{2}'' \times \frac{1}{2}''$
40	21″	5.54	18.8	$3'' \times \frac{5}{8}''$	$5'' \times \frac{1}{2}''$
45	21″	6.3	21.5	$3'' \times \frac{5}{8}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
50	21″	6.97	23.4	$3\frac{1}{2}'' \times \frac{3}{4}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
55	24″	7.5	29.2	$3\frac{3}{4}'' \times \frac{3}{4}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
60	24″	8.4	32.8	$3\frac{3}{4}'' \times \frac{3}{4}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
65	24″	9.2	35.9	$4'' \times \frac{3}{4}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
	32″	9.6	49.9	$4\frac{1}{4}'' \times \frac{7}{8}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
70	24″	9.0	35.1	$4'' \times \frac{3}{4}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
	32″	10.0	52.0	$4'' \times \frac{3}{4}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
75	24″	10.68	42.6	$4\frac{1}{4}'' \times \frac{3}{4}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
	32″	11.9	61.9	$4'' \times \frac{3}{4}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
80	24″	10.61	42.3	$4\frac{1}{4}'' \times \frac{7}{8}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
	32″	14.65	76.2	$4\frac{1}{2}'' \times \frac{7}{8}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$
85	32″	12.4	64.5	$4\frac{1}{2}'' \times \frac{7}{8}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$ or $\frac{5}{8}''$
90	32″	13.5	70.2	$4\frac{3}{4}'' \times \frac{7}{8}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$ or $\frac{5}{8}''$
95	32″	14.7	76.4	$4\frac{3}{4}'' \times \frac{7}{8}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$ or $\frac{5}{8}''$
100	32″	15.78	82.1	$4\frac{3}{4}'' \times \frac{7}{8}''$	$5\frac{1}{2}'' \times \frac{9}{16}''$ or $\frac{5}{8}''$

(e) **Track-laying.** Much depends on the force of men employed and the use of systematic methods; $528 per mile was the

TABLE XXXIII.—RAILROAD SPIKES.

Size measured under head.	Average number per keg of 200 pounds	Ties 24″ between centers, 4 spikes per tie, number per mile.		Suitable weight of rail.
		Pounds.	Kegs.	
$5\frac{1}{2}'' \times \frac{5}{8}''$	275	7680	38.40	90 to 100
$5\frac{1}{2}'' \times \frac{9}{16}''$	375	5632	28.16	45 " 100
$5'' \times \frac{9}{16}''$	400	5280	26.40	40 " 56
$5'' \times \frac{1}{2}''$	450	4692	23.46	40
$4\frac{1}{2}'' \times \frac{1}{2}''$	530	3984	19.92	35
$4'' \times \frac{1}{2}''$	600	3520	17.60	30
$4\frac{1}{2}'' \times \frac{7}{16}''$	680	3104	15.52	25 to 30

TABLE XXXIV.—TRACK-BOLTS.

Average number in a keg of 200 pounds.

Size of bolt.	Square nut.	Hexagonal nut.	Suitable rail.
$3'' \times \frac{5}{8}''$	366	395	40 pound
$3'' \times \frac{3}{4}''$	250	270	
$3\frac{1}{4}'' \times \frac{3}{4}''$	243	261	
$3\frac{1}{2}'' \times \frac{3}{4}''$	236	253	50
$3\frac{3}{4}'' \times \frac{3}{4}''$	229	244	55 to 60
$4'' \times \frac{3}{4}''$	222	236	65 " 70
$4\frac{1}{4}'' \times \frac{3}{4}''$	215	228	75
$3\frac{1}{2}'' \times \frac{7}{8}''$	170	180	
$3\frac{3}{4}'' \times \frac{7}{8}''$	165	175	
$4'' \times \frac{7}{8}''$	161	170	
$4\frac{1}{4}'' \times \frac{7}{8}''$	157	165	80
$4\frac{1}{2}'' \times \frac{7}{8}''$	153	160	85
$4\frac{3}{4}'' \times \frac{7}{8}''$	149	156	90

TABLE XXXV.—RAIL-JOINTS AND TRACK-BOLTS. NUMBER PER MILE OF TRACK.

Length of rail. Feet.	Average length of rail. Feet.	Number of rails or complete joints.	Number of bolts.	
			4-bolt.	6-bolt.
All 30	30	352	1408	2112
30–24	29.65	356.2	1425	2137
All 33	33	320	1280	1920
33–27	32.65	323.4	1294	1941
All 60	60	176	704	1056
60–40	58.95	179.1	717	1075

estimate formerly employed by the Pennsylvania Railroad. $500 per mile is the estimate given in § 451. See note at bottom of p. 536.

448. Item 8. Buildings and Miscellaneous Structures. Except for rough and preliminary estimates, these items must be individually estimated according to the circumstances. The subitems include depots, engine-houses, repair-shops, water-stations, section- and tool-houses, besides a large variety of smaller buildings. The structures include turn-tables, cattle-guards, fencing, road-crossings, overhead bridges, telegraph line, etc. The detailed estimate, given in § 451, illustrates the cost of these smaller items.

449. Item 9. Interest on Construction. The amount of capital that must be spent on a railroad before it has begun to earn anything is so very large that the interest on the cost during the period of construction is a very considerable item. The amount that must be charged to this head depends on the current rate of money on the time required for construction and on the ability of the capitalists to retain their capital where it will be earning something until it is actually needed to pay the company's obligations. Of course, it is not necessary to have the entire capital needed for construction on hand when construction commences. Assuming money to be worth 6%, that the work of construction will require one year, that the money may be retained where it will earn something for an average period of six months after construction commences, or, in other words, it will be out of circulation six months before the road is opened for traffic and begins to earn its way, then we may charge 3% on the total cost of construction.

450. Item 10. Rolling Stock. The cost depends on the traffic to be handled and bears very little relation to the total or the mileage cost of the roadbed and track. In each case the cost, at proper unit prices, of the locomotives and cars necessary to handle the estimated traffic must be computed.

451. Detailed estimate of the cost of a line of road. The following estimate was given in the *Engineering News* of Dec. 27, 1900, of the cost of the Duluth, St. Cloud, Glencoe & Mankato Railroad, 157.2 miles long.

The estimate is exactly as copied from the *Engineering News*. There are some numerical discrepancies. Item 26 should evidently be based on the sum of the first 25 items, and item 27 on the sum of the first 26. The figures in parentheses ( ) are deduced from the figures given.

1.	Right-of-way: 1905.3 acres (12.12 acres per mile) @ $100 per acre		$190530
2.	Clearing and grubbing. 144 acres (0.916 acre per mile) @ $50 per acre		7200
3.	Earth excavation. 1907590 cu. yds. (12135 cu. yds. per mile) @ 15 c		286138
4.	Rock excavation. 5100 cu. yds. (32.44 cu. yds. per mile) @ 80 c.		4080
5.	Wooden-box culverts. 508300 ft. B.M. @ $30 per M.	$15249	
	Iron-pipe culverts. 879840 lbs. @ 3c. per lb.	26395	41644
6.	Pile trestling. 4600 lin. ft. @ 35 c. per lin. ft.	1610	
	Timber trestling. 509300 ft. B.M. @ $30 per M.	15279	16889
7.	Bridge masonry: 5520 cu. yds. @ $8 per cu. yd.	44160	
	Bridges, iron, 100 spans. 2000000 lbs. @ 4 c. per lb.	80000	124160
8.	Cattle-guards		8750
9.	Ties (2640 per mile). 419813 (159.02 miles) @ 35 c.		146935
10.	Rails (70 lbs. per yd.): 110 tons per mile, 17492.2 tons (159.02 miles @$26.		384797
11.	Rail sidings (70 lbs. per yd.): 110 tons per mile, 3300 tons (30 miles @ $26		85800
12.	Switch timbers and ties		3300
13.	Spikes: 5920 lbs. per mile, 1107040 (187 m.) @ 1.75. c. per lb.		19373
14.	Splice-bars. 2635776 lbs. @ 1.35 c. per lb.		35583
15.	Track-bolts (2 to joint (?)): 188458.3 lbs. @ 2.4 c. per lb.		4520
16.	Track-laying 187.2 miles @ $500 per mile		93600
17.	Ballasting: 2152 cu. yds. per mile, 402854 (187.2 m.) @ 60 c.		241712
18.	Turn-out and switch furnishings		6450
19.	Road-crossings, 68040 ft. B.M. @ $30 per M.		2041
20.	Section and tool-houses, 16 @ $800		12800
21.	Water-stations		15000
22.	Turn-tables, 6 @ $800		4800
23.	Depots, grounds, and repair-shops		78000
24.	Terminal grounds and special land damages		150000
25.	Fencing, 314 miles ($150 per mile)		47100
26.	Engineering and office expenses (5% of $1984458)		99222
27.	Interest on construction (3% of $2083680)		62510
28.	Rolling-stock ($5000 per mile)		786000
29.	Telegraph line: 157 miles @ $200 per mile		31400
			$3060340

Average cost per mile ready for operation, $19467.

Approximate cost of 130 miles from St. Cloud to Duluth, estimated at $23000 per mile.

Approximate cost of entire line from Albert Lea to Duluth, 287.2 miles, $6050340 ($21060 per mile).

Although the above estimate is now (1921) so old that the prices are obsolete, the list is retained since it is a typical analysis and may be utilized by making the proper changes in unit prices, which is always more or less necessary.

CHAPTER XVIII.

THE POWER OF A LOCOMOTIVE.

452. **Pounds of steam produced.** The power that can be developed by a locomotive depends very greatly on the quality of the coal burned and the design of the locomotive must correspond to the general kind or quality of coal to be used. A British thermal unit (symbolized as B.t.u.), is the quantity of heat required to raise the temperature of 1 lb. of pure water 1° F., when the water is at or near its maximum density at 39.1° F. When it is said that a certain grade of coal has 14000 B.t.u. it means that the heat in 1 lb. of that coal will raise the temperature of 14000 lbs. of water 1°, or, approximately, 100 lbs. of water 140°. But, although it only requires 180.9 heat units to heat water from 32° to 212°, it requires 965.7 more heat units to change it from water at 212° to steam at 212°. It requires only 53.6 more heat units to change it from steam at 212° to steam at 387.6° or with a pressure of 200 lbs. per square inch.

A study of locomotive tests made at the St. Louis Exposition resulted in the compilation of Table XXXVI, which is copied from the Proceedings of the American Railway Engineering Association, and is now included as Table I, in the "Economics" section of their Manual. It was found that the steam produced per square foot of heating surface is very nearly proportional to the coal burned per square foot of heating surface. The results are purposely made about 5% below the results obtained in the St. Louis tests to allow for ordinary working conditions.

453. **Numerical example.** The theory developed in this chapter will be illustrated numerically by applying it to a Mikado type of locomotive whose dimensions are as follows:

Cylinder	diam. 22″	Weight, driving wheels	153,200 lbs.
Cylinder	stroke 28″	engine alone	196,100 lbs.
Driving wheel	diam. 57″	engine and tender	315,000 lbs.
Boiler pressure	185 lbs.	Heating surface, fire-box	
Fire-box	length $102\frac{3}{8}$″	and tubes	2565 sq. ft.
Fire-box	width $65\frac{1}{8}$″	superheating surface	550 sq. ft.
Grate area	46.8 sq. ft.		

TABLE XXXVI.—AVERAGE EVAPORATION IN LOCOMOTIVE BOILERS BURNING BITUMINOUS AND SIMILAR COALS OF VARIOUS QUALITIES, AND FOR VARIOUS QUANTITIES CONSUMED PER SQUARE FOOT OF HEATING SURFACE PER HOUR.

(Based on feed water at 60° Fahrenheit, and boiler pressure 200 pounds)

Coal per square foot of heating surface per hour (lb.)	Steam per pound of coal of given thermal value (lb.)					
	15,000 B.t.u.	14,000 B.t.u.	13,000 B.t.u.	12,000 B.t.u.	11,000 B.t.u.	10,000 B.t.u.
0.8	7.86	7.34	6.81	6.29	5.76	5.24
0.9	7.58	7.07	6.57	6.06	5.56	5.05
1.0	7.31	6.82	6.34	5.85	5.36	4.87
1.1	7.06	6.59	6.12	5.65	5.18	4.71
1.2	6.82	6.37	5.91	5.46	5.00	4.55
1.3	6.59	6.15	5.71	5.27	4.83	4.39
1.4	6.37	5.95	5.52	5.10	4.67	4.25
1.5	6.17	5.76	5.35	4.94	4.52	4.11
1.6	5.97	5.57	5.18	4.78	4.38	3.98
1.7	5.79	5.40	5.02	4.63	4.25	3.86
1.8	5.61	5.24	4.86	4.49	4.12	3.74
1.9	5.44	5.08	4.71	4.35	3.99	3.63
2.0	5.27	4.92	4.57	4.22	3.86	3.51
2.1	5.12	4.78	4.44	4.10	3.75	3.41
2.2	4.97	4.64	4.31	3.98	3.64	3.31
2.3	4.83	4.51	4.19	3.86	3.54	3.22
2.4	4.69	4.38	4.07	3.75	3.44	3.13
2.5	4.56	4.26	3.95	3.65	3.34	3.04
2.6	4.44	4.14	3.84	3.55	3.25	2.96
2.7	4.32	4.03	3.74	3.46	3.17	2.88
2.8	4.21	3.93	3.64	3.37	3.09	2.80
2.9	4.10	3.83	3.55	3.28	3.01	2.73
3.0	3.99	3.73	3.46	3.19	2.93	2.66

The quantity of steam evaporated for intermediate quantities or qualities of coal can be found by interpolation.

On bad-water districts deduct the following from tabular quantities:

For each $\frac{1}{16}$ inch of accumulated scale.......... 10 per cent

For each grain per U. S. gallon of foaming salts in the average feed water................. 1 per cent

Assume that this locomotive is using coal whose air-dried mine samples tested 13000 B.t.u.; then the average run-of-car coal would have about 90% of this or 11700 B.t.u. On the basis that a fireman can handle 4000 lbs. of coal per hour and maintain such work throughout his run, the coal may be fed at the rate of (4000÷2565)=1.56 lbs. per hour per square foot of heating surface. Interpolating in Table XXXVI for 1.56 and 11700 we find that the pounds of steam per pound of coal would be 4.72. The tests at St. Louis showed that a reduction in boiler pressure increased very slightly the amount of steam produced, but that this amount was only 0.5% greater when the pressure was 160 lbs. instead of 200 lbs. The effect of variation of pressure can therefore be ordinarily ignored. In this case it might add 0.2% or make the figure 4.73. Considering that a superheater adds from 15 to 25% to the efficiency, we will assume the average of 20% and say that 0.80 lb. of the superheated steam produced may be considered as having the same volume and pressure as 1 lb. of saturated steam. Then the amount of steam developed by 1 lb. of coal would be the equivalent of $4.73 \div 0.80 = 5.91$ lbs. Then the equivalent amount of steam developed per hour equals $5.91 \times 4000 = 23640$ lbs.

454. Weight of steam per stroke at full cut-off. This may be computed most easily by utilizing Table XXXVII, which is also taken (but somewhat amplified), from the Proceedings of the American Railway Engineering Association, and is now included as Table 2 in the "Economics" section of their Manual. The weight of steam per foot of stroke for 22 ins. diameter and 185 lbs. gauge pressure is 1.161 lbs. and for a stroke of 28 ins. ($2\frac{1}{3}$ ft.) it is 2.709 lbs. For a complete revolution of the drivers it is $4 \times 2.709 = 10.836$ lbs. Since the engine can develop the equivalent of 23640 lbs. of steam per hour and will use 10.836 lbs. at one revolution, it can run at a speed of $23640 \div 10.836 = 2182$ revolutions per hour, or 36.36 revolutions per minute, at full stroke and maintain full boiler pressure. The drivers are 57 ins. in diameter and, therefore, have a circumference of $(57 \div 12) \times 3.1416 = 14.923$ ft. The maximum engine speed for full stroke is $36.36 \times 14.923 = 542.6$ ft. per minute. Multiplying by 60 and dividing by 5280, or dividing by 88, we have 6.167 miles per hour as the maximum speed at which full stroke can be maintained, which is the value M for these conditions.

455. Pounds of steam and per cent. of cut-off for multiples of *M* velocity. In Table XXXVIII, also taken from the Proceedings of the American Railway Engineering Association and now included at Table 4 in the "Economics" section of the Manual, are given the pounds of steam per indicated horse-power hour for simple and for compound locomotives for various velocities, which are multiples of M, the maximum velocity at which the locomotive can use steam at full stroke and yet the boiler can maintain steam at full pressure. The table is computed on the basis of 200 lbs. gauge pressure, but factors are

TABLE XXXVII.—WEIGHT OF STEAM USED IN ONE FOOT OF STROKE IN LOCOMOTIVE CYLINDERS.

(Cylinder diameter is for high-pressure cylinders in compound locomotives)

Diameter of cylinder (inches)	Weight of steam per foot of stroke for various gauge pressures.						
	220 lbs. per sq. in. (lb.)	210 lbs. per sq. in. (lb.)	200 lbs. per sq. in. (lb.)	190 lbs. per sq. in. (lb.)	180 lbs. per sq. in. (lb.)	170 lbs. per sq. in. (lb.)	160 lbs. per sq. in. (lb.)
12	0.405	0.389	0.370	0.354	0.337	0.321	0.304
13	0.475	0.456	0.435	0.415	0.396	0.376	0.357
14	0.551	0.529	0.504	0.482	0.459	0.436	0.414
15	0.633	0.607	0.579	0.553	0.527	0.501	0.476
15½	0.675	0.649	0.618	0.590	0.562	0.535	0.508
16	0.720	0.691	0.658	0.629	0.599	0.570	0.541
17	0.812	0.780	0.744	0.710	0.676	0.643	0.611
18	0.911	0.875	0.834	0.796	0.759	0.722	0.685
18½	0.962	0.924	0.881	0.841	0.801	0.762	0.724
19	1.015	0.975	0.928	0.887	0.845	0.804	0.763
19½	1.069	1.027	0.978	0.934	0.890	0.847	0.804
20	1.125	1.080	1.029	0.983	0.936	0.891	0.836
20½	1.181	1.134	1.081	1.032	0.984	0.936	0.888
21	1.240	1.191	1.134	1.083	1.032	0.982	0.932
22	1.361	1.307	1.245	1.189	1.133	1.078	1 023
23	1.487	1.428	1.361	1.300	1.238	1.178	1.118
24	1.620	1.555	1.482	1.416	1.348	1.283	1.218
25	1.758	1.688	1.608	1.536	1.462	1.392	1.322
26	1.901	1.825	1.739	1.661	1.582	1.506	1.430
27	2.050	1.968	1.875	1.792	1.706	1.624	1.542
28	2.204	2.117	2.017	1.926	1.835	1.745	1.657

For weight of steam used per revolution of drivers at full cut-off: Multiply the tabular quantity by four times the length of stroke in feet for simple and four-cylinder compounds. For two-cylinder compounds multiply by two times the length of stroke.

given for other pressures. For example, continuing the above numerical problem, the pounds of steam per i.h.p.-hour, for a simple locomotive, at M velocity, and at 200 lbs. pressure, taken from Table XXXVIII, is 38.30; for 185 lbs. pressure we must multiply by the factor 1.0095, which makes the quantity 38.66. Dividing this into 23640, the steam produced per hour, we have 611.5, the i.h.p. at M velocity. Multiplying this by 33000, the foot-pounds per minute in one horse-power, and dividing by 542.6, the velocity in feet per minute, we have 37190, the cylinder tractive power in pounds, when burning 4000 lbs. of coal per hour and running at 6.167 m.p.h.

TABLE XXXVIII.—MAXIMUM CUT-OFF AND POUNDS OF STEAM PER I.H.P.-HOUR FOR VARIOUS MULTIPLES OF *M*.

(*M* is maximum velocity in miles per hour at full cut-off, with boiler pressure at 200 pounds per square inch)

Velocity	Cut-off per cent	Pounds steam per I.H.P.-hour		Velocity	Cut-off per cent	Pounds steam per I.H.P.-hour	
		Simple	Compound			Simple	Compound
1.0 *M*	Full	38.30	25.80	2.9 *M*	38.5	24.37	21.04
1.1 "	94.4	36.46	24.36	3.0 "	37.0	24.22	21.21
1.2 "	89.1	34.89	23.24	3.2 "	34.2	24.00	21.57
1.3 "	84.3	33.56	22.35	3.4 "	31.8	23.85	21.93
1.4 "	79.7	32.41	21.65	3.6 "	29.8	23.80	22.27
1.5 "	75.4	31.40	21.14	3.8 "	28.0	23.80	22.57
1.6 "	71.4	30.49	20.77	4.0 "	26.4	23.87	22.85
1.7 "	67.7	29.67	20.52	4.25 "	24.7	24.05	23.22
1.8 "	64.3	28.93	20.40	4.50 "	23.3	24.24	23.56
1.9 "	61.0	28.25	20.40	4.75 "	22.1	24.44	23.85
2.0 "	58.0	27.62	20.40	5.0 "	21.1	24.64	24.15
2.1 "	55.2	27.05	20.40	5.5 "	19.5	24.98	24.70
2.2 "	52.6	26.52	20.40	6.0 "	18.4	25.20	
2.3 "	50.1	26.06	20.40	6.5 "	17.6	25.45	
2.4 "	47.8	25.67	20.40	7.0 "	17.1	25.60	
2.5 "	45.7	25.32	20.47	7.5 "	16.7	25.70	
2.6 "	43.7	25.02	20.60	8.0 "	16.4	25.80	
2.7 "	41.8	24.76	20.73	9.0 "	16.1	25.90	
2.8 "	40.1	24.54	20.88				

For steam per i.h.p.-hour for other boiler pressure take the following percentages of values given in table:

160 lb., 103.0%	180 lb., 101.3%	210 lb., 99.5%
170 lb., 102.1%	190 lb., 100.6%	200 lb., 99.2%

456. Draw-bar Pull. To obtain the draw-bar pull we must deduct the engine resistance. These have already been discussed in § 429 and the numerical value of the resistance of this same locomotive has been there computed to be about 1771 lbs. Subtracting this from 37190 we have 35419 lbs., the estimated draw-bar pull for that speed and coal consumption.

457. Effect of increasing the rate of coal consumption. To note the effect of increasing the rate of coal consumption, the problem may be again worked through on the basis that the rate of coal consumption is increased, even temporarily, from 4000 lbs. to 5000 lbs. per hour. The steam developed per pound of coal is reduced from 5.91 to 5.23, but the total steam produced per hour is increased from 23640 to 26150. The increased capacity comes through a loss of efficiency. The increased steam production raises the velocity at which full stroke may be maintained from 6.167 m.p.h to 6.820 m.p.h and the i.h.p. from 611.5 to 676.4. But the computed cylinder tractive power is practically identical, the numerical computation of 37190 being only changed to 37189. But these cylinder tractive powers are each computed for the "*M*" velocities, the maximum velocities at which full stroke can be maintained, and "*M*" is higher with increased coal consumption. For a real comparison, the figures must be reduced to the same velocity, e.g., the working velocity of 10 m.p.h. 10 ÷ 6.167 = 1.621, the multiple for the original problem. For 5000 lbs. of coal per hour, *M* velocity is

TABLE XXXIX*.—PER CENT CYLINDER TRACTIVE POWER FOR VARIOUS MULTIPLES OF *M*.

(*M* is maximum velocity in miles per hour at which boiler pressure can be maintained with full cut-off)

Velocity	Per cent (Compound)	Per cent (Simple)	Velocity	Per cent (Compound)	Per cent (Simple)	Velocity	Per cent (Compound)	Per cent (Simple)
Start	135.00	106.00	3.6 *M*	32.40	44.75	6.4 *M*		23.59
0.5 *M*	103.00	103.00	3.7 "	31.25	43.56	6.5 "		23.18
1.0 "	100.00	100.00	3.8 "	30.10	42.39	6.6 "		22.79
1.1 "	96.28	95.57	3.9 "	29.14	41.24	6.7 "		22.42
1.2 "	92.55	91.53	4.0 "	28.24	40.10	6.8 "		22.06
1.3 "	88.83	87.83	4.1 "	27.38	39.00	6.9 "		21.71
1.4 "	85.12	84.46	4.2 "	26.56	37.96	7.0 "		21.38
1.5 "	81.40	81.37	4.3 "	25.77	36.97	7.1 "		21.06
1.6 "	77.68	78.55	4.4 "	25.03	36.03	7.2 "		20.75
1.7 "	73.96	75.97	4.5 "	24.34	35.13	7.3 "		20.45
1.8 "	70.25	73.60	4.6 "	23.69	34.26	7.4 "		20.16
1.9 "	66.54	71.41	4.7 "	23.07	33.41	7.5 "		19.88
2.0 "	63.21	69.37	4.8 "	22.48	32.59	7.6 "		19.61
2.1 "	60.20	67.47	4.9 "	21.92	31.82	7.7 "		19.34
2.2 "	57.48	65.67	5.0 "	21.38	31.11	7.8 "		19.08
2.3 "	54.97	63.94	5.1 "	20.87	30.42	7.9 "		18.82
2.4 "	52.68	62.22	5.2 "	20.37	29.75	8.0 "		18.57
2.5 "	50.42	60.55	5.3 "	19.89	29.10	8.1 "		18.33
2.6 "	48.16	58.92	5.4 "	19.43	28.48	8.2 "		18.09
2.7 "	46.08	57.33	5.5 "	18.99	27.87	8.3 "		17.86
2.8 "	44.10	55.78	5.6 "		27.33	8.4 "		17.64
2.9 "	42.29	54.26	5.7 "		26.81	8.5 "		17.43
3.0 "	40.57	52.78	5.8 "		26.30	8.6 "		17.22
3.1 "	38.95	51.33	5.9 "		25.81	8.7 "		17.01
3.2 "	37.42	49.91	6.0 "		25.34	8.8 "		16.82
3.3 "	35.98	48.55	6.1 "		24.88	8.9 "		16.63
3.4 "	34.66	47.24	6.2 "		24.44	9.0 "		16.45
3.5 "	33.53	45.97	6.3 "		24.01			

* Table 5 in "Economics" Section of Manual of American Railway Engineering Association.

6.820 m.p.h., and the multiple is 1.466. From Table XXXIX we find that the percentages of cylinder tractive power for simple engines for these two multiples of M are 78.01 and 82.42, respectively. The higher value is 105.7% of the lower, which shows that, in this case, adding 25% to the rate of coal consumption adds only 5.7 to the cylinder tractive power at 10 m.p.h.

458. Effect of using a better quality of coal. As another instructive variation of the same problem, assume that the coal has effective B.t.u. of 13000, instead of only 11700. It will be found that steam will be produced more rapidly, the M velocity is 6.867 m.p.h. and the horsepower at that velocity is 680.3, but the cylinder power is computed to be 37191 lbs., which is again almost identical with the previous values, although the M velocity is still higher. The multiple for 10 m.p.h. is 1.456 and by Table XXXIX the per cent. of cylinder tractive power is 82.73, which is an increase of 6% over 78.01%, showing that the increase in effective B.t.u. from 11700 to 13000 adds 6% to the cylinder tractive power at 10 m.p.h.

459. Check with approximate rule. Applying Eq. 103 to the above data on the basis that the "effective steam pressure" is 85% of the gauge pressure (185) or 157 lbs., we will have

$$\text{Tractive force} = \frac{22^2 \times 157 \times 28}{57} = 37327 \text{ lbs.}$$

This agrees with the more precise value (37190) computed above to within one-half of one per cent. This rule is more simple as a method of obtaining merely the maximum tractive power at slow velocities, but the previous method, although longer, is preferable, since it computes the critical velocity M, and also the tractive force at higher velocities.

460. Tractive Force at Higher Velocities. At higher velocities than M, the cylinder power falls off quite rapidly, since the steam is cut off at part stroke and is used expansively. The proper per cent of cut-off for any given velocity and the number of pounds of steam per i.h.p. are shown in Table XXXVIII, in which is give the per cent of cylinder tractive power for multiples of M. The table shows, for example, that, for simple engines, the cylinder tractive power is 69.37% of its value for full stroke when the velocity is $2M$ and that when the velocity is increased to $5M$ the tractive power is reduced to 31.11%.

Applying this to the above numerical problem, when $M=6.167$ m.p.h., the cylinder tractive power is reduced to 31.11% of 37190, or 11570 lbs., but, since the velocity is five times as great, the horse-power developed is $31.11\% \times 5 = 1.55$ times as great. It should be noted that Table XXXIX shows a slight excess of tractive power (6% when starting), for the simple engine. This is due to the fact that with very low velocities the cylinder pressure more nearly equals the full boiler pressure and there is not the usual reduction of about 15%. Also, compound locomotives are operated with all the cylinders using full-pressure steam, which increases their effectiveness at starting about 35%, although at some loss in economy of steam due to compounding. But since the starting resistances are so much greater than the resistances above 5 miles per hour, the extra assistance is very timely.

Any competent locomotive designer will, of course, make a design such that there is a proper relation between cylinder power and tractive adhesion. In the above case, 106% of 37190=39421 lbs., which is 25.7% of the weight on the drivers, and this is just about the ratio of adhesion which may be expected.

Velocity.		Cylinder tractive. power		Locomotive resistance pounds.	Draw-bar pull. pounds
Multiples of M.	Miles per hour.	Per cent.	Pounds.		
0.0	0.000	106.00	39421	1762	37659
1.0	6.167	100.00	37190	1771	35419
1.2	7.400	91.53	34040	1776	32264
1.5	9.250	81.37	30261	1783	28478
2.0	12.334	69.37	25799	1800	23999
3.0	18.501	52.78	19629	1847	17782
4.0	24.668	40.10	14913	1913	13000
5.0	30.835	31.11	11570	1999	9571
6.0	37.002	25.34	9424	2104	7320

A graphical illustration of the variation in tractive power and velocity may be obtained by computing first and setting down in tabular form the multiple values of M (6.167); the percentages taken from Table XXXIX, for each multiple of M; the products of each percentage times the tractive force (37190), for M velocity; the locomotive resistance, from Table XXIX, for each velocity; and the net draw-bar pull for each velocity. These several values for cylinder tractive power and for draw-bar pull may be plotted as shown in Fig. 208.

The student should realize that the above values represent the maximum draw-bar pull which the locomotive *can* produce, provided the fire-box is fed with 4000 lbs. of coal per hour. These draw-bar pulls as given will overcome the resistance of a train of some definite weight, at uniform speed, along a straight level track, at the several velocities given. A less weight of train will be drawn somewhat faster; or, it will travel at the same speed by using less coal or by throttling the steam and, perhaps, wasting it at the blow-off. A heavier train could not maintain such speed. While the values given are approximately correct, a variation in the quality of the coal, or in the condition of the

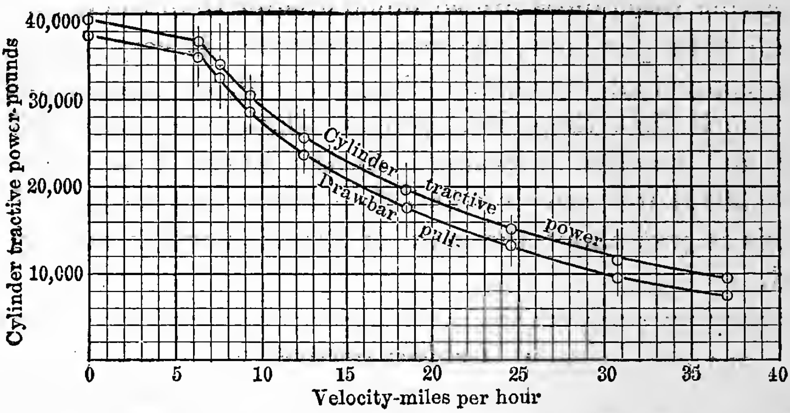


Fig. 208.—Tractive Power, Mikado Locomotive.

track, or in the firing, or in the management by the engineman, will alter the results materially, and they should not be relied on to give an accurate measure of what can and will be accomplished at all times. But the method is useful and dependable in comparing two types of engines, or, for comparing the operating results of light trains at faster speed or heavier trains at slower speed, using the same engine, or, as shown later, of comparing the operating results of using a certain type of engine on two grades and thus estimating the value of reducing the higher grade.

461. Effect of Grade on Tractive Power. The effect of grade on tractive power is best shown by some numerical computations whose results are plotted in Fig. 209. The cylinder tractive power was computed for three engines of greatly different total weight and power, but which had driving-axle loads nearly identical (about 50750 lbs.), and, therefore, by the Baldwin

Locomotive Works rule, given in § 268, could all be operated on the same kind of track. Using the rule, $\frac{1}{2}\times 50750 \div 300 = 84.5$, which means that the rails should weigh at least 85 lbs. per yard. Making computations for these locomotives, using 12000 B.t.u. coal, similar to those already detailed in §§ 453 *et seq.*, it was found that the cylinder tractive powers of the Pacific, Mikado, and Mallet locomotives were 29718, 33575, 49095 lbs., respectively, when the velocity was uniformly 10 m.p.h. and the locomotives each burned 4000 lbs. of coal per hour. The several engine resistances at 10 m.p.h. are easily computed from Table XXIX and are tabulated below.

Engine characteristics (At velocity $V = 10$ m.p.h.)	Pacific 4–6–2 (lb.)	Mikado 2–8–2 (lb.)	Mallet 2–8–8–2 (lb.)
Cylinder tractive power.......	29,718	33,575	49,095
Engine resistance on level.....	2,205	2,648	4,864
Draw-bar pull on level.........	27,513	30,927	44,231
Draw-bar pull on 3% grade....	15,213	18,207	25,631

The net values, or the draw-bar pulls, are plotted on the left-hand vertical line of Fig. 209, and in each case are the left-hand ends of the solid lines which show the tractive powers of the locomotives. On a 3% grade the grade resistances for the locomotives equal 60 lbs. per ton, and are 12300, 12720 and 18600 lbs., respectively. This reduces the effective draw-bar pull approximately 40% in each case. Since this reduction varies uniformly with the grade, we may plot the three values, 15213, 18207 and 25631, on the 3% vertical line and draw straight lines which represent in each case the tractive power of the locomotive at 10 m.p.h. and on any grade within that range.

Assume trains of cars, all averaging 50 tons per car and varying from 10 cars weighing 500 tons to 50 cars weighing 2500 tons. The resistances at 10 m.p.h on a level grade are given by Eq. 121, and may be plotted on the left-hand vertical line of Fig. 209. Grade adds resistance proportional to the grade. For example, on a 0.7% grade the grade resistance per ton is 14 lbs. and for 2500 tons is 35000 lbs. Adding this to 11580, the tractive resistance, we have 46580, which we plot on the 0.7% vertical line. It is indicated by a small circle. Joining the two points gives the resistance line for 2500 tons hauled at 10 m.p.h. The circles on the other lines indicate similar computations. The intersections of these resistance lines with the lines of tractive power indicate the relative power of each locomotive. For example, the 1000-ton train can be hauled by the Pacific locomotive at 10 m.p.h. up a 0.96% grade, but a Mikado can do the same on a 1.1% grade, while the Mallet can do it on a 1.52% grade.

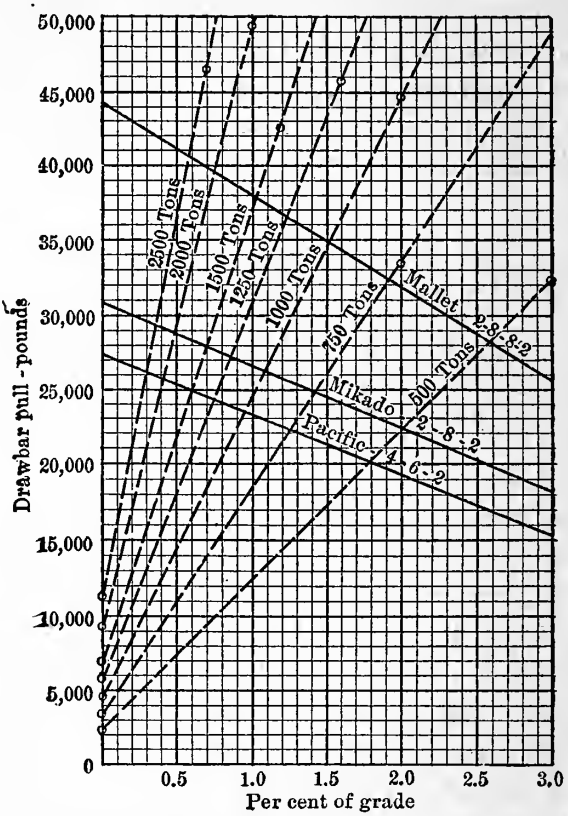


FIG. 209.—CURVES SHOWING EFFECT OF GRADE ON TRACTIVE POWER.

All of these calculations were made on the basis of burning 4000 lbs. of coal per hour, which, as before stated, is the practical limit of what an ordinary fireman can be expected to do for an extended run.

The description of the Mallet locomotive (built by the Baldwin Locomotive Works), stated that its tractive power is 91000 lbs. A computation of its cylinder tractive power at *M* velocity, using 12000 B.t.u. coal, shows it to be 95389 lbs. Subtracting the engine resistance (4843 lbs.), we would have 90546 lbs., which is a very fair check, especially as the Baldwin Locomotive Works method of calculation is different.

462. Acceleration-speed curves. The time required for an engine of given weight and power to haul a train of known weight and resistance over a track with known grades and curvature is an important and necessary matter for an engineer to compute, since the saving in time has such a value as to justify constructive or operating changes which will reduce that time. Fig. 208 shows that the draw-bar pull is very much greater at very low velocities than at the moderate speed of even 15 m.p.h. In spite of the increased resistance at these low velocities the margin of power left for acceleration is also greater and the "speed curve" is really a curve and not a straight line. Its general form may be most easily developed by a numerical example, especially as each case has its own special curve.

Illustrative Example. The Mikado locomotive, whose characteristics have already been investigated in §§ 453 *et seq.*, has draw-bar pulls at various velocities as shown in the tabular form in § 460, to which frequent reference must be made in this demonstration. Assume that this locomotive starts from rest on a 0.4% upgrade, hauling a train of 14 cars, each weighing 50 tons, and a caboose weighing 10 tons. Then the normal level tractive resistance, by Eq. 107, § 439, equals

$$R=(2.2\times710)+(122\times15)=3392 \text{ lbs.}$$

The grade resistance of the cars will be $20\times0.4\times710=5680$ lbs. The extra starting resistance will be considered as 6 lbs. per ton, or 4260 lbs. These three items total 13332 lbs. The average draw-bar pull of the locomotive at velocities between zero and M velocity, which is 6.167 m.p.h., is $\frac{1}{2}(37659+35419)=36539$ lbs., but this must be diminished in this case by $20\times0.4\times157.5=1260$ lbs. for grade and by $157.5\times6=945$ lbs. for starting resistance, leaving a net draw-bar pull of 34334 lbs., excluding the force required for the acceleration of the locomotive. The net force available for acceleration of both the locomotive and the train is $34334-13332=21002$ lbs., or prorated, is $21002\div(157.5+710)=24.21$ lbs. per ton. Transposing Eq. 106, with $V_1=O$, $V_2=6.167$, and $P=24.21$ lbs., we have $s=70(38.03-0)\div24.21$ $=110$ feet, the distance required to attain a velocity of 6.167 m.p.h.

While the velocity is increasing from 1.0 M to 1.2 M, the mean draw-bar pull is $\frac{1}{2}(35419+32264)-1260=32582$ lbs., less the accelerative resistance of the locomotive. Subtracting the tractive and grade resistances of the cars, we have 32582 − 3392 − 5680 = 23510 lbs. Note that there is no longer any starting resistance. The accelerative force in pounds per ton is 23510 ÷ 867.5 = 27.10. The distance s required to increase the velocity from 6.167 m.p.h. to 7.400 m.p.h., is 70(54.76 − 38.03) ÷ 27.10 = 43 feet. Similarly the distances required to increase the velocity from 1.2 M to 1.5 M, from 1.5 M to 2M, etc., are computed as in the accompanying tabular form.

The corresponding distances and velocities have been plotted in Fig. 210. The velocity of 10 m.p.h. is acquired in a little over 300 feet, but it requires 500 feet to acquire a velocity of 12.33 m.p.h. and about 16000 feet to raise it to 29 m.p.h. The force, in pounds per ton, available for acceleration, is maximum at low velocities, after the extra starting resistance is overcome. As the margin per ton for acceleration becomes less and less, the greater is the distance required to increase the velocity 1 mile per hour—especially through the last increments—up to the velocity at which the net draw-bar pull exactly equals the total car resistance and the velocity becomes uniform, which is later computed to be 4.78 M. There is an approximation in using *average* draw-bar pulls between the different velocities at which the draw-bar pull has been definitely computed, but the computed distances are practically correct up to 4 M velocity or 24.67 m.p.h. But the computation for the distance required to increase the velocity from 4 M up to 4.78 M is far less accurate if the average draw-bar pull is used. The effective pull at 4 M velocity equals 13000 − 1260 = 11740, less the accelerative resistance of the locomotive. The tractive and grade resistance of the cars at this velocity is 3392 + 5680 = 9072. This leaves 11740 − 9072 = 2668 lbs. available for acceleration of both locomotive and cars. The reduction in tractive force between 4 M velocity and 5 M velocity (see § 460), is 13000 − 9571 = 3429 lbs. By proportionate interpolation we would then say that the excess force available for acceleration would be exhausted at (2668 ÷ 3429) = .78 of the interval, or at a velocity of 4.78 M, or 29.48 m.p.h. The mean accelerative force is one-half of 2668, or 1334 lbs., which is 1.53 lbs. per ton of train. The distance, by an inversion of Eq. 106, is computed to be 11925 feet. Owing to the approximate equality of working force and resistance and the momentary variations in both, the precise point where the acceleration would cease and the velocity would

DATA AND COMPUTATIONS FOR ACCELERATION AND RETARDATON CURVES.

	Velocities.				Tractive Forces.						Distances.		Time.
	Feet per sec.	Range, miles per hour.		Mean, feet per sec.	Mean draw-bar pull, level, lbs.	Locomotive resistance, grade plus start* lbs.	Actual draw-bar pull, average, lbs.	Car resistance tractive grade, plus start* lbs.	Difference effective for acceleration or retardation. lbs.	Net force per ton, lbs.	Acceleration, or retardation, feet	Total from start feet.	sec.
Acceleration......	0.00	0.00	6.167	4.52	36539	*2205	34334	*13332	21002	24.21	110	110	24
	9.04	6.167	7.40	9.95	33842	1260	32582	9072	23510	27.10	43	153	4
	10.86	7.40	9.25	12.22	30371	1260	29111	9072	20039	23.10	93	246	8
	13.57	9.25	12.33	15.83	26239	1260	24979	9072	15907	18.34	254	500	16
	18.09	12.33	18.50	22.61	20891	1260	19631	9072	10559	12.17	1094	1594	48
	27.13	18.50	24.67	31.66	15391	1260	14131	9072	5059	5.83	3196	4790	101
	36.18	24.67	29.48	39.71	11666	1260	10406	9072	1334	1.53	11925	16715	300
Retardation......	43.24	29.48	24.67	39.71	11662	3780	7882	20432	12550	14.46	1262	1262	32
	36.18	24.67	18.50	31.66	15391	3780	11611	20432	8821	10.17	1832	3094	58
	27.13	18.50	12.33	22.61	20891	3780	17111	20432	3321	3.83	3477	6571	154
	18.09	12.33	12.21	17.99	24106	3780	20326	20432	106	0.122	1681	8252	93

* The extra starting resistance only applies to the first item.

actually become uniform would be be very uncertain. Fortunately the inaccuracy is of little or no practical importance and for the purposes of our calculations we may call this last interval 11925 feet, assuming that the grade is as long as 16715 feet or 3.1 miles. If the 0.4% grade continued indefinitely the train would travel at this uniform velocity as long as the locomotive operated on the basis assumed for this problem. Note that Fig. 210 would have to be extended to nearly three times its

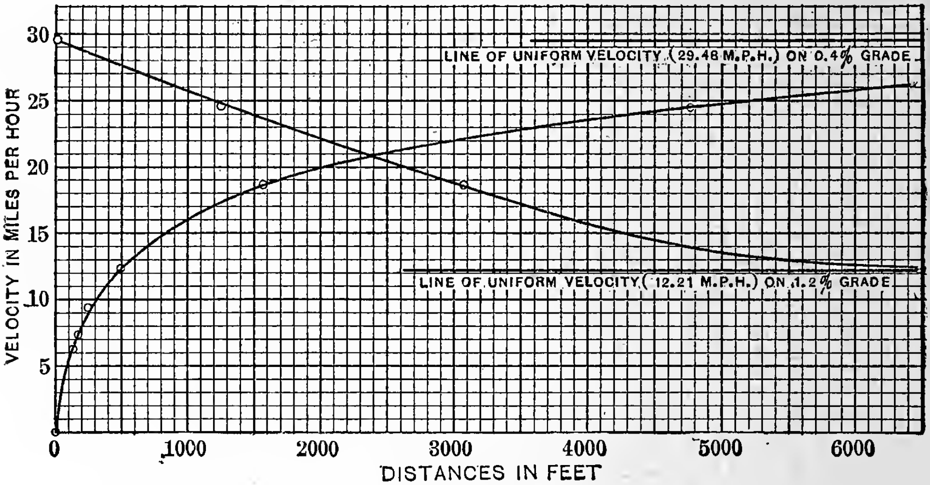


FIG. 210.

present length before the time curve would reach and become tangent to the "line of uniform velocity."

463. Retardation-speed curves. When, on account of grade resistance, the total of tractive and grade resistance is greater than the draw-bar pull, there is retardation.

Illustrative Example. Continuing the numerical problem of § 462, assume that, while moving up the 0.4% grade at a velocity of 4.78 M, or 29.48 m.p.h., the train reaches a grade of +1.2%. The grade resistance of the cars will be $20 \times 1.2 \times 710 = 17040$ lbs. The tractive resistance will be 3392 lbs., as before, making a total of 20432 lbs. Interpolating in the tabular form in § 460 for the draw-bar pull at 4.78 M velocity, we find 10325; at 4 M it is 13000 and the mean is 11662; but from this must be subtracted $20 \times 1.2 \times 157.5 = 3780$ for grade resistance of the locomotive, leaving 7882 lbs. for the net draw-bar pull. The retarding force is $20432 - 7882 = 12550$; or in pounds per ton of train, is $12{,}550 \div 867.5 = 14.46$. As before, using an inversion of

Eq. 106, $s=(29.48^2-24.67^2)70\div14.46=1262$ feet, the distance at which the velocity would reduce to 4 M. As before, the other quantities may be computed and recorded, with less danger of confusion and error, by tabulating them, as given in § 462.

The mean velocity, when retarding from 4.78 M to 4.0 M, reduced to feet per second, is as before 39.71 feet per second, and dividing this into the distance, 1262 feet, gives 32, the time in seconds. The quantities for the reduction in velocity from 4 M to 3 M and from 3 M to 2 M are computed similarly. The level draw-bar pull for 1.5 M is 28478 (see § 460), and by subtracting 3780, we get 24698 lbs. the actual net pull on the grade. Similarly, the actual pull at 2 M is 20219 lbs. The increase from 20219 to 20432 is $\frac{213}{4479}=4.7\%$ of the interval from 20219 to 24698 and $4.7\%\times.5=.02$; therefore, the actual draw-bar pull just equals the resistance at $2.00-.02=1.98M$, or 12.21 m.p.h. The deficiency of draw-bar pull at $2.0\ M=20{,}432-20219=213$ lbs. At 1.98 M the deficiency is zero and, therefore, the mean deficiency is one-half of 213, or 106. Dividing this by 867.5, we have 0.122, which is the value of P in Eq. 106. Then

$$s=(152.01-149.08)70\div0.122=1681 \text{ ft.}$$

Velocities in miles per hour can be readily converted into velocities in feet per second by multiplying by 1.4667. Averaging the two velocities at the beginning and the end of each period gives the mean velocity; and dividing each of these into the distance for that period gives the time in seconds.

464. Drifting. The tractive resistance of the cars of the problem just worked out is 3392 lbs.; the locomotive resistance at 20 m.p.h. is 1862 lbs., or a total of 5254 lbs. Variation in velocity will affect this but little. Dividing by 867.5, the total weight in tons, we have 6.06 lbs., the resistance per ton, from which the equivalent rate of grade is $6.06\div20=.303\%$. This means practically that when this train is running *down* a grade which is over .303% it will run by gravity and steam may be shut off. If the grade is much greater than .303% the acceleration on the downgrade may become so great, if the grade is very long, that the velocity may become objectionably high.

Illustrative Example. Assume that the limiting safe velocity for freight trains, considering the condition of track and rolling stock, is 35 m.p.h.; assume that the train we have been consider- reaches a 0.4% downgrade at a velocity of 15 m.p.h. How far down the grade will it run with steam shut off, before the speed reaches 35 m.p.h. and brakes must be applied? There is no question here of variable tractive power since the only motive power is gravity. The resistance is nearly independent of velocity and we will here assume it to be so and utilize Table XLII. At 15 m.p.h. the train has a velocity head of 7.90 feet. At 35 m.p.h. the velocity head is 43.01 feet. The train can, therefore, drop down the grade a vertical height of $43.01-7.90 = 35.11$ feet before the velocity reaches 35 m.p.h. On a 0.4% grade the distance required for such a fall is $35.11 \div .004 = 8777$ feet. The problem in § 462 assumed that the 0.4% grade is 16715 feet or more, and this shows what will happen to the trains moving in the opposite direction.

But it must not be thought that there is no loss of energy during drifting. Even though no steam is used in the cylinders, some is frequently wasted at the safety valve and more is used in operating brakes and in maintaining the brake air-reservoir at full pressure. But the greatest loss of heat is that due to radiation, especially in winter, in spite of all the jacketing devices to retain heat. Although the results of the numerous tests which have been made are quite variable, the following approximate averages may be used: The loss due to radiation while standing may be figured at 120 lbs. of coal per hour per 1000 square feet of heating surface; while drifting the loss will increase to 220 lbs. per hour. The amount of coal used for firing up will be about 510. This is based on the use of 12000 B.t.u. coal. The better the coal, the less will be used.

Illustrative Example. The Mikado locomotive we have been considering has 2565 square feet of heating surface. It will then require about $2.565 \times 510 = 1308$ lbs. of coal to fire up. While drifting down the grade, referred to above, a distance of 8777 feet, the average velocity is $\frac{1}{2}(15+35) = 25$ m.p.h. $= 36.67$ ft. per sec. and the required time is $8777 \div 36.67 = 239$ seconds $= 3$ min. 59 sec. $= .066$ hour. The coal used while drifting down this short run would be

$$220 \times 2.565 \times .066 = 37 \text{ lbs.}$$

At this point brakes would need to be applied and the time spent in drifting beyond this point must be computed as an item in the total time spent on the run and also to compute the total amount of coal consumed while drifting. Although this item of 37 lbs. is relatively very small, its method of computation is typical of the computation of the several items to make up the total of coal consumed during a trip.

465. Review of computed power of one locomotive. It was assumed that it started on a +0.4% grade with a load of 15 cars weighing 710 tons. After moving 16715 feet (assuming that the grade was that long), and doing it in 493 seconds, or 8 minutes 13 seconds, the train acquired a velocity of 29.48 m.p.h. and the power of the locomotive would then be sufficient, when burning 4000 lbs. of coal per hour, to keep it moving up such a grade indefinitely at that velocity. In case the grade were not as long as 16715 feet, it would be necessary to compute the velocity where the rate of grade changed and make that the basis for the computation on the succeeding grade. But, assuming that the grade were as long as 16715 feet, or more, and that the velocity of 29.48 m.p.h. had been acquired, and that the train had run at that speed for some distance—although this does not modify the problem—the train is assumed to reach a still steeper grade +1.2%. The velocity then begins to decrease and in a total distance of 8252 feet and a total time of 337 seconds, or 5 minutes 37 seconds, the velocity is reduced to 12.21 m.p.h., at which velocity the locomotive is able to make steam fast enough to overcome the higher resistance on the steeper grade. From that point on, assuming that the 1.2% grade is longer than 8252 feet, the train would continue for the remaining length of that grade at the velocity of 12.21 m.p.h.

As before stated, precision in the above results depends on many factors (such as B.t.u. of coal used, or the actual consumption in pounds per hour), which are somewhat variable. Sometimes the variation of these factors from the values used above is known; sometimes it is unknown and then the accuracy of the results is correspondingly uncertain. But whether accurately known or not, when this method is used, employing the best values for the factors which are obtainable, the method shows a valuable *comparison* of two proposed alinements or grades. In such a comparison, any error in the factors will affect both results nearly, if not quite, equally, and the comparative results will still be substantially correct.

466. Selection of route. The preceding articles may be utilized in comparing two routes. If one of the lines is already in operation, the engineer has the great advantage of being able to determine by test exactly what results may be obtained on that line and what factors should be used in computations. It is then only necessary to compute the quantities for the proposed new line. When both lines are "on paper" there is less certainty as to the accuracy of the results, except that the line which is shown to be most advantageous will probably continue to be most advantageous even if the uncertain factors used in the comparison are somewhat changed. Using the methods outlined in §§ 462 to 464, there will be computed the behavior of an assumed type of locomotive, hauling one or more types of train load, and passing over tracks having definite grades and lengths. The effect of curves may be disregarded provided that the grades were properly compensated during original construction, and then the rate of grade for the entire length of straight and curved track may be taken as the rate on the straight track. If the rate of grade is actually uniform, even through the curves, then the lengths of curved track must be computed separately and on the basis of a rate of grade equal to the actual rate plus an allowance of .035% for each degree of curve. The behavior of a train from starting to stopping must be computed, making due allowance for each change in condition which will affect the hauling power of the locomotive. The locomotive is assumed to be working at the limit of its steaming capacity, except when drifting with steam shut off on a down grade, or when brakes are applied, either to prevent objectionably high velocity on a down grade or to make a stop. The action of brakes during a service stop (as distinguished from an emergency stop), may be considered as a retarding force varying from 10% to 20% of the train weight. Unfortunately brake action is so variable, being directly under the control of the locomotive engineer and varying from zero to the full braking power, that any computation of energy used in operating them or of the effect of the brakes is impracticable except on the basis of arbitrary assumptions such as the requirement that the brakes are used in such a way that a train will be retarded at a specified rate. The performance of the locomotive over the entire division, the total time required, its velocity in critical places, etc., can be computed. In §§ 462 and 463 it was shown that the locomotive considered could haul the particular train considered up a 0.4% grade at a velocity of 29.48 m.p.h. and maintain such speed indefinitely; also that it could haul the same train up a 1.2% grade at 12.21 m.p.h. and maintain its velocity indefinitely. This of course,, means that a much heavier train could be hauled up the 0.4% grade and that a somewhat heavier train could be hauled up the 1.2% grade without being stalled, although the velocities in each case would be reduced. There are an infinite number of combinations, but there are usually some considerations which narrow the choice. Even after construction is complete these tables may be utilized in a study of the most economical combination of type of locomotive and amount of train load for the track conditions as they may exist.

467. Rating of locomotives. The maximum power of a locomotive on any grade at M velocity is measured by its "rating."

Let P = the tractive power of the locomotive, measured at the rim of the drivers;
E = Weight of engine and tender, in pounds;
W = Weight of cars behind tender, in pounds;
r = rate of grade, or the ratio of vertical to horizontal;
a = a constant, which as determined by tests = 2.2 lbs. per ton or .0011 lb. per pound of train;
b = a constant, which as determined by tests = 122 lbs. per ton. a and b are the same constants as are used in § 439.
n = number of cars in train.

Then $P=(E+W)\ (r+a)+bn$.

Transforming,

$$\frac{P}{r+a}-E=W+n\frac{b}{r+a}. \quad . \quad . \quad . \quad . \quad . \quad (122)$$

The right-hand side of this equation is called the "rating," A, and is the weight of the train behind the tender plus the number of cars times a quantity made up of two constants and the rate of grade. This quantity is independent of any special engine or train values and may be tabulated for various rates of grade, as given in Table XL.

Examples. The Mikado locomotive considered in §§ 453, *et seq.*, has a tractive power, measured at the rim of the drivers,

TABLE XL.—LOCOMOTIVE RATING DISCOUNTS.

VALUES OF $b \div (r \times a)$ FOR VARIOUS GRADES.

(In tons per car.)

Grade R (per cent).	Tons per car $b \div (r+a)$.	Grade R (per cent).	Tons per car $b \div (r+a)$.	Grade R (per cent).	Tons per car $b \div (r+a)$.	Grade R (per cent).	Tons per car $b \div (r+a)$.	Grade R (per cent).	Tons per car $b \div (r+a)$.
Level	55	0.5	10.0	1.0	5.5	1.5	3.8	2.0	2.88
0.1	29	0.6	8.5	1.1	5.0	1.6	3.6	2.1	2.75
0.2	20	0.7	7.5	1.2	4.6	1.7	3.4	2.2	2.63
0.3	14	0.8	6.7	1.3	4.3	1.8	3.2	2.3	2.52
0.4	12	0.9	6.0	1.4	4.0	1.9	3.0	2.4	2.42

at M velocity, or 6.167 m.p.h., of $37190-1432=35758$ lbs., which equals P; 1432 is the locomotive resistance between cylinder and rim of drivers, see § 429. The weight of engine and tender is 315000 lbs. What is its rating on a 1.2% grade? The value of r for a 1.2% grade $=.012$; $a=.0011$ lb. per pound. Then

$$A=\frac{P}{r+a}-E=\frac{35758}{.012+.0011}-315000=2{,}414{,}000 \text{ lbs.}=1207 \text{ tons},$$

which is the rating for that locomotive for a 1.2% grade. But this does not mean 1207 tons of cars. Placing this equal to the right-hand side of Eq. 122, we have

$$1207=W+n\frac{b}{r+a}.$$

The value of $\frac{b}{r+a}$ for a 1.2% grade is given in Table XL as 4.6.

Then $$W=1207-4.6n,$$

which shows that the weight of train depends on the number of cars. Assume that $n=16$. Then $W=1133.4$ and the average weight per car is 70.8 tons. Assume that the cars are all "empties," weighing 18 tons each; then $W=18n$, and

$$n=1207 \div (18+4.6)=53.4,$$

which must be interpreted as 53 empty cars.

In the above examples the pulling power P is determined on the basis of the locomotive working at the maximum velocity M at which it can maintain full stroke. See § 455. This represents practically the maximum power of the locomotive. The velocity M is usually from 4 to 7 miles per hour and is as low as should be allowed on maximum grades, since an attempt to utilize a slightly higher tractive force at a somewhat lower velocity would probably result in stalling the train if an unexpected resistance in the track slightly increased the normal resistance.

CHAPTER XIX.

THE PROMOTION OF RAILROAD PROJECTS.

468. Method of formation of railroad corporations. Many business enterprises, especially the smaller ones, are financed entirely by the use of money which is put into them directly in the form of stock or mere partnership interest. A railroad enterprise is frequently floated with a comparatively small financial expenditure on the part of the original promoters. The promoters become convinced that a railroad between *A* and *B*, passing through the intermediate towns of *C* and *D*, with others of less importance, will be a paying investment. They organize a company, have surveys made, obtain a charter, and then, being still better able (on account of the additional information obtained) to exploit the financial advantages of their scheme, they issue a prospectus and invite subscriptions to bonds. Sometimes a portion of these bonds are guaranteed, principal and interest, or perhaps the principal alone, by townships or by the national government. The cost of this preliminary work, although large in gross amount if the road is extensive, is yet but an insignificant proportion of the total amount involved. The proportionate amount that *can* be raised by means of bonds varies with the circumstances. In the early history of railroad building, when a road was projected into a new country where the traffic possibilities were great and there was absolutely no competition, the financial success of the enterprise would seem so assured that no difficulty would be experienced in raising from the sale of bonds all the money necessary to construct and equip the road. But the promoters (or stockholders) must furnish all money for the preliminary expenses, and must make up all deficiencies between the proceeds of the sale of the bonds and the capital needed for construction.

"In theory, stocks represent the property of the responsible owners of the road, and bonds are an encumbrance on that property. According to this theory, a railroad enterprise should begin with an issue of stock somewhere near the value of the property to be created and no more bonds should be issued than are absolutely necessary to complete the enterprise. Now it is not denied that there are instances in which this theory is followed out. In New England, for example, as well as in some of the Southern States, there are a few roads represented wholly by stock or very lightly mortgaged. But this theory does not conform to the general history of railway construction in the United States, nor is it supported by the figures that appear in the summary. The truth is, railroads are built on borrowed capital, and the amount of stock that is issued represents in the majority of cases the difference between the actual cost of the undertaking and the confidence of the public expressed by the amount of bonds it is willing to absorb in the ultimate success of the venture." *

"The same general law obtains and has always obtained throughout the world, that such properties (as railways) are always built on borrowed money up to the limit of what is regarded as the positive and certain minimum value. The risk only—the dubious margin which is dependent upon sagacity, skill, and good management—is assumed and held by the company proper who control and manage the property." †

469. The two classes of financial interests—the security and profits of each. From the above it may be seen that stocks, bonds, car-trust obligations, and even current liabilities represent railroad capital. The issue of the bonds "was one means of collecting the capital necessary to create the property against which the mortgage lies." The variation between these interests lies chiefly in the security and profits of each. The current liabilities are either discharged or, as frequently happens, they accumulate until they are funded and thus become a definite part of the railroad capital.

The growth of this tendency is shown in the following tabular form (see next page):

The bonded interest has greater security than the stock, but less profit. The interest on the bonds must be paid before any money can be disbursed as dividends. If the bond interest

---

* Henry C. Adams, Statistician, U. S. Int. Con. Commission.

† A. M. Wellington, Economic Theory of Railway Location.

Capitalization of Railroads in the United States.	June 30, 1898.		June 30, 1912.		Dec. 31, 1918.	
	Amount, millions.	Per cent.	Amount, millions.	Per cent.	Amount, millions.	Per cent.
Stocks	5311	44.6	8622	43.7	8678	43.2
Funded debt	5510	46.3	11130	56.3	11406	56.8
Current liabilities, etc.	1087	9.1				

is not paid, a receivership, and perhaps a foreclosure and sale of the road, is a probability, and in such case the stockholder's interests are frequently wiped out altogether. The bondholder's real profit is frequently very different from his nominal profit. He sometimes buys the bonds at a very considerable discount, which modifies the rate which the interest received bears to the amount really invested. Even the bondholder's security may suffer if his mortgage is a second (or fifth) mortgage, and the foreclosure sale fails to net sufficient to satisfy all previous claims.

On the other hand, the stockholder, who may have paid in but a small proportion of his subscription, *may*, if the venture is successful, receive a dividend which equals 50 or 100% of the money actually paid in, or, as before stated, his entire holdings may be entirely wiped out by a foreclosure sale. When the road is a great success and the dividends very large, additional issues of stock are generally made, which are distributed to the stockholders in proportion to their holdings, either gratuitously or at rates which give the stockholders a large advantage over outsiders. This is the process known as "watering." While it may sometimes be considered as a legitimate "salting down" of profits, it is frequently a cover for dishonest manipulation of the money market.

For the twelve years between 1887 and 1899 about *two thirds* of all the railroad stock in the United States paid *no* dividends, while of those that paid dividends the average rate varied from 4.96 to 5.74%. The year from June 30, 1898, to June 30, 1899, was the most prosperous year of the group, and yet nearly 60% of all railroad stock paid *no* dividend, and the average rate paid by those which paid at all was 4.96%. The total amount distributed in dividends was greater than ever before, but the average rate is the least of the above group because many roads, which had passed their dividends for many previous years, distinguished themselves by declaring a dividend, even though small. During that same period but 13.35% of the stock paid over 6% interest. The total dividends paid amounted to but 2.01% of all the capital stock, while investments ordinarily are expected to yield from 4 to 6% (or more) according to the risk. Of course the effect of "watering" stock is to decrease the nominal rate of dividends, but there is no dodging the fact that, watered or not, even in that year of "good times," about 60% of all the stock paid *no* dividends. Unfortunately there are no accurate statistics showing how much of the stock of railroads represents actual paid-in capital and how much is "water." The great complication of railroad finances and the dishonest manipulation to which the finances of some railroads have been subjected would render such a computation practically worthless and hopelessly unreliable now.

During the year ending June 30, 1898 (which may in general be considered as a sample), 15.82% of the funded debt paid no interest. About one third of the funded debt paid between 4 and 5% interest, which is about the average which is paid.

The income from railroads (both interest on bonds and dividends on stock) may be shown graphically by diagrams, such as are given in the annual reports of the Interstate Commerce Commission. They show that while railroad investments are occasionally very profitable, the average return is less than that of ordinary investments *to the investors.* The *indirect* value of railroads in building up a section of country is almost incalculable and is worth many times the cost of the roads. It is a discouraging fact that very few railroads (old enough to have a history) have escaped the experience of a receivership, with the usual financial loss to the then stockholders. But there is probably not a railroad in existence which, however much a financial failure in itself, has not profited the community more than its cost.

470. The small margin between profit and loss to projectors. When a railroad is built entirely from the funds furnished by its promoters (or from the sale of stock) it will generally be a paying investment, although the rate of payment may be very small. The percentage of receipts that is demanded for actual operating expenses is usually about 67%. The remainder will usually pay a reasonable interest on the total capital involved. But the operating expenses are frequently 90 and even 100% of the gross receipts. In such cases even the bondholders do not get their due and the stockholders have absolutely nothing. Therefore the stockholder's interest is very speculative. A comparatively small change in the business done (as is illustrated numerically in § 472) will not only wipe out altogether the dividend—taken from the last small percentage of the total receipts and which may equal 50% or more of the capital stock *actually paid in*—but it may even endanger the bondholders' security and cause them to foreclose their mortgage. In such a case the stockholders' interest is usually entirely lost. It does not alter the essential character of the above-stated relations that the stockholders sometimes protect themselves somewhat by buying bonds. By so doing they simply decrease their risk and also decrease the possible profit that might result from the investment of a given total amount of capital.

471. Extent to which a railroad is a monopoly. It is a popular fallacy that a railroad, when not subject to the direct competition of another road, has an absolute monopoly—that it controls "all the traffic there is" and that its income will be practically independent of the facilities afforded to the public. The growth of railroad traffic, like the use of the so-called necessities or luxuries of life, depends entirely on the supply and the cost (in money or effort) to obtain it. A large part of railroad traffic belongs to the unnecessary class—such as traveling for pleasure. Such traffic is very largely affected by mere matters of convenience, such as well-built stations, convenient terminals, smooth track, etc. The freight traffic is very largely dependent on the possibility of delivering manufactured articles or produce at the markets so that the *total* cost of production and transportation shall not exceed the total cost in that same market of similar articles obtained elsewhere. The creation of facilities so that a factory or mine may successfully compete with other factories or mines will develop such traffic. The receipts from such a traffic may render it possible to still further develop facilities which will in return encourage further business. On the other hand, even the partial withdrawal of such facilities may render it impossible for the factory or mine to compete successfully with rivals; the traffic furnished by them is completely cut off and the railroad (and indirectly the whole community) suffers correspondingly. The "strictly necessary" traffic is thus so small that few railroads could pay their operating expenses from it. The dividends of a road come from the last comparatively small percentage of its revenue, and such revenue comes from the "unnecessary" traffic which must be coaxed and which is so easily affected by apparently insignificant "conveniences."

472. Profit resulting from an increase in business done; loss resulting from a decrease. In a subsequent chapter it will be shown that a large portion of the operating expenses are independent of small fluctuations in the business done and that the operating expenses are roughly two thirds of the gross revenue. Assume that by changes in the alinement the business obtained has been increased (or diminished) 10%. Assume for simplicity that the operating expenses on the revised track are the same as on the route originally planned; also that the cost of the track is the same and hence the fixed charges are assumed to be constant for all the cases considered. Assume the fixed charges to be 28%. The additional business, when carried in cars otherwise but partly filled will hardly increase the operating expenses by a measurable amount. When extra cars or extra trains are required, the cost will increase up to about 60% of the average cost per train mile. We may say that 10% increase may in general be carried at a rate of 40% of the average cost of the traffic. A reduction of 10% in traffic may be assumed to reduce expenses a similar amount. The effect of the change in business will therefore be as follows:

	Business increased 10%.	Business decreased 10%.
Operating exp. = 67	67(1 + 10% × 40%) = 69.68	67(1 − 10% × 40%) = 64.32
Fixed charges = 28	.... 28.00	.... 28.00
95	97.68	92.32
Total income.. 100	Income............ 110.00	Income............ 90.00
Available for dividends...... 5	Available for dividends........... 12.32	Deficit............ 2.32

In the one case the increase in business, which may often be obtained by judicious changes in the alinement or even by better management without changing the alinement, more than doubles the amount available for dividends. In the other case the profits are gone, and there is an absolute deficit. The above is a numerical illustration of the argument, previously stated, of the small margin between profit and loss to the original projectors.

473. Estimation of probable volume of traffic and of probable growth. Since traffic and traffic facilities are mutually interdependent and since a large part of the normal traffic is merely potential until the road is built, it follows that the traffic of a road will not attain its normal volume until a considerable time after it is opened for operation. But the estimation even of this normal volume is a very uncertain problem. The estimate may be approached in three ways:

1st. The actual gross revenue derived by all the railroads in that section of the country (as determined by State or U. S. Gov. reports) may be divided by the total population of the section and thus the average annual expenditure per head of population may be determined. A determination of this value for each one of a series of years will give an idea of the normal rate of growth of the traffic. Multiplying this annual contribution by the population which may be considered as tributary gives *a valuation* of the possible traffic. Such an estimate is unreliable (*a*) because the *average* annual contribution may not fit that particular locality, (*b*) because it is very difficult to correctly estimate the number of the true tributary population especially when other railroads encroach more or less into the territory. Since a rough value of this sort may be readily determined, it has its value as a check, if for nothing else.

2d. The actual revenue obtained by some road whose circumstances are as nearly as possible identical with the road to be considered may be computed. The weak point consists in the assumption that the character of the two roads is identical or in incorrectly estimating the allowance to be made for observed differences. The method of course has its value as a check.

3d. A laborious calculation may be made from an actual study of the route—determining the possible output of all factories, mines, etc., the amount of farm produce and of lumber that might be shipped, with an estimate of probable passenger traffic based on that of like towns similarly situated. This method is the best when it is properly done, but there is always the danger of leaving out sources of income—both existent and that to be developed by traffic facilities, or, on the other hand, of overestimating the value of expected traffic. In the following tabular form are shown the population, gross receipts, receipts per head of population, mileage, earnings per mile of line operated, and mileage per 10,000 of population for the whole United States. It should be noted that the values are only *averages*, that individual variations are large, and that only a very rough dependence may be placed on them as applied to any particular case.

Year.	Population (estimated).	Gross receipts.	Receipts per head of population.	Mileage†	Earnings per mile of line operated.	Mileage per 10,000 population.‡
1888...	60,100,000	$910,621,220	$15.15	136,884	$6653	24.94
1889...	61,450,000	964,816,129	15.81	153,385	6290	25.67
1890...	*62,801,571	1051,877,632	16.75	156,404	6725	26.05
1891...	64,150,000	1096,761,395	17.10	161,275	6801	26.28
1892...	65,500,000	1171,407,343	17.89	162,397	7213	26.19
1893...	68,850,000	1220,751,874	18.26	169,780	7190	26.40
1894...	68,200,000	1073,361,797	15.74	175,691	6109	26.20
1895...	69,550,000	1075,371,462	15.46	177,746	6050	25.97
1896...	70,900,000	1150,169,376	16.22	181,983	6320	25.78
1897...	72,350,000	1122,089,773	15.53	183,284	6122	25.53
1898...	73,600,000	1247,325,621	16.95	184,648	6755	25.32
1899...	74,950,000	1313,610,118	17.53	187,535	7005	25.25
1900...	*76,295,220	1487,044,814	19.49	192,556	7722	25.44
1901...	77,863,000	1588,526,037	20.47	195,562	8123	25.52
1902...	79,431,000	1726,380,267	21.88	200,155	8625	25.76
1903...	80,998,000	1900,846,907	23.70	205,314	9258	26.03
1904...	82,566,000	1975,174,091	24.23	212,243	9306	26.34
1905...	84,134,000	2082,482,406	25.15	216,974	9508	26.44
1906...	85,701,000	2325,765,167	27.65	222,340	10460	26.78
1907...	87,279,000	2589,105,578	29.63	227,455	11383	26.38
1908...	88,837,000	2393,805,989	26.95	231,540	10338	26.30
1909...	90,405,000	2418,677,538	26.71	234,800	10301	26.20
1910...	*91,972,266	2750,667,435	29.91	238,609	11528	26.14
1911...	93,572,266	2789,761,669	29.81	244,476	11411	26.10
1912...	95,172,266	2842,695,382	29.87	247,981	11463	25.93

* Actual. † Excludes a small percentage not reporting "gross receipts."
‡ Actual mileage.

The probable growth in traffic, after the traffic has once attained its normal volume, is a small but almost certain quantity. In the above tabular form this is indicated by the gradual growth in "receipts per head of population" from 1897 to 1907. Then the sudden drop due to the panic of 1907 is clearly indicated, and also the gradual growth in the last few years. Even in England, where the population has been nearly stationary for many years, the growth though small is unmistakable. On the other hand the growth in some of the Western States has been very large. For example, the gross earnings per head of population in the State of Iowa increased from $1.42 in 1862 to $10.00 in 1870, and to $19.46 in 1884.

There will seldom be any justification in building to accommodate a larger business than what is "in sight." Even if it could be anticipated with certainty that a large increase in business would come in ten years, there are many reasons why it would be unwise to build on a scale larger than that required for the business to be immediately handled. Even though it may cost more in the future to provide the added accommodations (*e.g.* larger terminals, engine-houses, etc.), the extra expense will be nearly if not quite offset by the interest saved by avoiding the larger outlay for a period of years which may often prove much longer than was expected. A still more important reason is the avoidance of uselessly sinking money at a time when every cent may be needed to insure the success of the enterprise as a whole.

474. Probable number of trains per day. Increase with growth of traffic. The number of passenger trains per day cannot be determined by dividing the total number of passengers estimated to be carried per day by the capacity of the cars that can be hauled by one engine. There are many small railroads, running three or four passenger trains per day each way, which do not carry as many passengers all told as are carried on one heavy train of a trunk line. But because the bulk of the passenger traffic, especially on such light-traffic roads, is "unnecessary" traffic (see § 471) and must be encouraged and coaxed, the trains must be run much more frequently than mere capacity requires. The minimum number of passenger trains per day on even the lightest-traffic road should be two. These need not necessarily be passenger trains exclusively. They may be mixed trains.

The number required for freight service may be kept more nearly according to the actual tonnage to be moved. At least one local freight will be required, and this is apt to be considerably within the capacity of the engine. Some very light-traffic roads have little else than local freight to handle, and on such there is less chance of economical management. Roads with heavy traffic can load up each engine quite accurately according to its hauling capacity and the resulting economy is great. Fluctuations in traffic are readily allowed for by adding on or dropping off one or more trains. Passenger trains must be run on regular schedule, full or empty. Freight trains are run by train-despatcher's orders. A few freight trains per day may be run on a nominal schedule, but all others will be run as extras. The criterion for an increase in the number of passenger trains is impossible to define by set rules. Since it should always come before it is absolutely demanded by the train capacity being overtaxed, it may be said in general terms that a train should be added when it is believed that the consequent increase in facilities will cause an increase in traffic the value of which will equal or exceed the added expense of the extra train.

475. Effect on traffic of an increase in facilities. The term facilities here includes everything which facilitates the transport of articles from the door of the producer to the door of the consumer. As pointed out before, in many cases of freight transport, the reduction of facilities below a certain point will mean the entire loss of such traffic owing to local inability to successfully compete with more favored localities. Sometimes owing to a lack of facilities a railroad company feels compelled to make some concession which is a virtual reduction on what would normally be the freight rate. In competitive freight business such a method of procedure is a virtual necessity in order to retain even a respectable share of the business. Even though the railroad has no direct competitor, it must if possible enable its customers to meet their competitors on even terms. In passenger business the effect of facilities is perhaps even more marked. The pleasure travel will be largely cut down if not destroyed.

476. Loss caused by inconvenient terminals and by stations far removed from business centers. This is but a special case of the subject discussed just in the preceding paragraph. The competition once existing between the West Shore and the New York Central was hopeless for the West Shore from the start. The possession of a terminal at the Grand Central Station gave the New York Central an advantage over the West Shore, with its inconvenient terminal at Weehawken, which could not be compensated by any obtainable advantage by the West Shore. This is especially true of the passenger business. The through freight business passing through or terminating at New York is handled so generally by means of floats that the disadvantage in this respect is not so great. The enormous expenditure (roughly $10,000,000) made by the Pennsylvania R. R., on the Broad Street Station (and its approaches) in Philadelphia, a large part of which was made in crossing the Schuylkill River and running to City Hall Square, rather than retain their terminal in West Philadelphia, is an illustration of the policy of a great road on such a question. The fact that the original plan and expenditure has been very largely increased since the first construction proves that the management has not only approved the original large outlay, but saw the wisdom of making a very large increase in the expenditure.

The construction of great terminals is comparatively infrequent and seldom concerns the majority of engineers. But an engineer has frequently to consider the question of the location of a way station with reference to the business center of the town. The following points may (or may not) have to be considered, and the real question consists in striking a proper balance between conflicting considerations.

(1) During the early history of a railroad enterprise it is especially needful to avoid or at least postpone all expenditures which are not demonstrably justifiable.

(2) The ideal place for a railroad station is a location immediately contiguous to the business center of the town. The location of the station even one fourth of a mile from this may result in a loss of business. Increase this distance to one mile and the loss is very serious. Increase it to five miles and the loss approaches 100%.

(3) The cost of the ideal location and the necessary right of way may be a very large sum of money for the new enterprise. On the other hand the increase in property values and in the general prosperity of the town, caused by the railroad itself, will so enhance the value of a more convenient location that its cost at some future time will generally be extravagant if not absolutely prohibitory. The original location is therefore under ordinary conditions a finality.

(4) To some extent the railroad will cause a movement of the business center toward it, especially in the establishment of new business, factories, etc., but the disadvantages caused to business already established is permanent.

(5) In any attempt to compute the loss resulting from a location at a given distance from the business center it must be

recognized that each problem is distinct in itself and that any change or growth in the business of the town changes the amount of this loss.

The argument for locating the station at some distance from the center of the town may be based on (*a*) the cost of right of way, thus involving the question of a large initial outlay, (*b*) the cost of very expensive construction (*e.g.* bridges), again involving a large initial outlay, (*c*) the avoidance of excessive grade into and out of the town. It sometimes happens that a railroad is following a line which would naturally cause it to pass at a considerable elevation above (rarely below) the town. In this case there is to be considered not only the possible greater initial cost, but the even more important increase in operating cost due to the introduction of a very heavy grade. The loss of business due to inconvenient location can only be guessed at. Wellington says that at a distance of one mile the loss would average 25%, with upper and lower limits of 10 and 40%, depending on the keenness of the competition and other modifying circumstances. For each additional mile reduce 25% of the preceding value. While such estimates are grossly approximate, yet with the aid of sound judgment they are better than nothing and may be used to check gross errors.

477. General principles which should govern the expenditure of money for railroad purposes. It will be shown later that the elimination of grade, curvature, and distance have a positive money value; that the reduction of ruling grade is of far greater value; that the creation of facilities for the handling of a large traffic is of the highest importance and yet the added cost of these improvements is sometimes a large percentage of the cost of *some road* over which it would be physically possible to run trains between the termini.

The subsequent chapters will be largely devoted to a discussion of the value of these details, but the general principles governing the expenditure of money for such purposes may be stated as follows:

1. No money should be spent (beyond the unavoidable minimum) unless it may be shown that the addition is in itself a profitable investment. The additional sum may not wreck the enterprise and it may add something to the value of the road, but unless it adds more than the improvement costs it is not justifiable.

2. If it may be positively demonstrated that an improvement will be more valuable to the road than its cost, it should certainly be made even if the required capital is obtained with difficulty. This is all the more necessary if the neglect to do so will permanently hamper the road with an operating disadvantage which will only grow worse as the traffic increases.

3. This last principle has two exceptions: (*a*) the cost of the improvement may wreck the whole enterprise and cause a total loss to the original investors. For, unless the original promoters can build the road and operate it until its stock has a market value and the road is beyond immediate danger of a receivership, they are apt to lose the most if not all of their investment; (*b*) an improvement which is very costly although unquestionably wise may often be postponed by means of a cheap temporary construction. Cases in point are found at many of the changes of alinement of the Pennsylvania R. R., the N. Y., N. H. & H. R. R., and many others. While some of the cases indicate faulty original construction, at many of the places the original construction was wise, considering the then scanty traffic, and now the improvement is wise considering the great traffic.

478. Study of railroad economics—its nature and limitations. The multiplicity of the elements involved in most problems in railroad construction preclude the possibility of a solution which is demonstrably perfect. Barring out the comparatively few cases in this country where it is difficult to obtain *any* practicable location, it may be said that a comparatively low order of talent will suffice to locate anywhere a railroad over which it is physically possible to run trains. It may be very badly located for obtaining business, the ruling grades may be excessive, the alinement may be very bad, and the road may be a hopeless financial failure, and yet trains can be run. Among the infinite number of possible locations of the road, the engineer must determine the route which will give the best railroad property for the least expenditure of money—the road whose earning capacity is so great that after paying the operating expenses and interest on the bonds the surplus available for dividends or improvements is a maximum.

An unfortunate part of the problem is that even the blunders are not always readily apparent nor their magnitude. A defective dam or bridge will give way and every one realizes the failure, but a badly located railroad affects chiefly the finances of the enterprise by a series of leaks which are only perceptible and demonstrable by an expert, and even he can only say that certain changes would probably have a certain financial value.

479. Outline of the engineer's duties. The engineer must realize at the outset the nature and value of the conflicting interests which are involved in variable amount in each possible route.

(a) **The maximum of business must be obtained,** and yet it *may* happen that some of the business may only be obtained by an extravagant expenditure in building the line or by building a line very expensive to operate.

(b) **The ruling grades should be kept low,** and yet this *may* require a sacrifice in business obtained and also *may* cost more than it is worth.

(c) **The alinement should be made as favorable as possible;** favorable alinement reduces the future operating expenses, but it may require a very large immediate outlay.

(d) **The total cost** must be kept within the amount at which the earnings will make it a profitable investment.

(e) **The road must be completed and operated** until the "normal" traffic is obtained and the road is self-supporting without exhausting the capital obtainable by the projectors; for no matter how valuable the property may ultimately become, the projectors will lose nearly, if not quite, all they have invested if they lose control of the enterprise before it becomes a paying investment.

Each new route suggested makes a new combination of the above conflicting elements. The engineer must select a route by first eliminating all lines which are manifestly impracticable and then gradually narrowing the choice to the best routes whose advantages are so nearly equal that a closer detailed comparison is necessary.

The ruling grade and the details of alinement have a large influence on the operating expenses. A large part of this course of instruction therefore consists of a study of operating expenses under average normal conditions, and then a study of the effect on operating expenses of given changes in the alinement.

CHAPTER XX.

OPERATING EXPENSES.*

480. Distribution of gross revenue. When a railroad comprises but one single property, owned and operated by itself, the distribution of the gross revenue is a comparatively simple matter. The operating expenses then absorb about two thirds of the gross revenue; the fixed charges (chiefly the interest on the bonds) require about 25 or 30% more, leaving perhaps 3 to 8% (more or less) available for dividends. The report on the Fitchburg R. R. for 1898 shows the following:

Operating expenses	$5,083,571	69.1%
Fixed charges	1,567,640	21.3%
Available for dividends, surplus, or permanent improvements	708,259	9.6%
Total revenue	$7,359,470	100.0%

But the financial statements of a large majority of the railroad corporations are by no means so simple. The great consolidations and reorganizations of recent years have been effected by an exceedingly complicated system of leases and sub-leases, purchases, "mergers," etc., whose forms are various. Railroads in their corporate capacity frequently own stocks and bonds of other corporations (railroad properties and otherwise) and receive, as part of their income, the dividends (or bond interest) from the investments.

The Interstate Commerce Commission annually makes a report of the income and profit-and-loss account of all the railroads of the United States, considered as one system. For example, the statement for the year 1912 includes the following items. Operating revenues from rail operations $2,842,695,382; operating expenses due to rail operations $1,972,415,776, which is 69.4%. Interest on funded debt used up 13.9% of the rev-

* The operating expenses of railroads have been utterly abnormal during and since the Great War. The figures of this chapter are not now (1921) applicable to present conditions, but corresponding figures, revised to date, would not be typical. The chapter therefore stands untouched until new figures, representing normal conditions, are available.

enues, and taxes 4.2%. There were other miscellaneous incomes and expenditures which caused a net loss of another 2.0% of revenue, leaving 10.5% or $299,361,208 which were issued as dividends. These dividends are about 3.4% of the outstanding stock. The percentage to the amount of money actually paid for the stock is unknown and unknowable.

481. Operating expenses per train-mile. The uniformity in the average operating expenses per train mile for light-traffic and heavy-traffic roads and for long and short roads is very remarkable. This is illustrated by a comparison of figures for ten heavy traffic roads and ten small roads selected *at random*, except that each had a mileage of less than 100 miles.

OPERATING EXPENSES PER TRAIN-MILE ON LARGE AND SMALL ROADS (1904 AND 1910).

	Mileage.		Operating expenses per train-mile.		Ratio expenses to earnings per cent.	
	1904.	1910.	1904.	1910.	1904.	1910.
Whole United States	220,112	240,439	1.314	1.489	67.79	66.29
Canadian Pacific	8,332	10,271	1.320	1.504	68.72	65.41
C., B. & Q.	8,326	9,040	1.313	1.710	64.35	71.71
Chicago & Northwestern	7,412	7,629	1.136	1.306	66.61	70.31
Southern Railway	7,197	7,050	1.048	1.234	70.30	67.43
C., R. I. & P	6,761	7,396	1.199	1.344	72.90	73.07
Northern Pacific	5,619	6,189	1.392	1.824	52.26	61.71
A., T. & S. F.	5,031	7,460	1.305	1.626	60.05	64.33
Great Northern	4,489	7,147	1.464	1.808	49.72	60.53
Illinois Central	4,374	4,551	1.107	1.409	70.02	74.84
Atlantic Coast Line	4,229	4,491	0.984	1.213	58.95	62.44
Average of ten	......	......	1.227	1.498	63.39	67.18
Montpelier & Wells River	44	50	1.169	1.430	80.73	75.08
Somerset Railway Co.*	42	94	0.802	1.314	59.37	76.65
Huntingdon & Broadtop Mountain	66	70	0.950	2.052	52.10	96.40
Lehigh & New England	96	170	0.793	2.045	69.80	62.84
Ligonier Valley	11	16	1.427	1.480	69.33	49.15
Newburgh, Dutchess & Connecticut †	59	......	0.922	......	85.09	......
Susquehanna & New York	55	80	1.368	1.028	78.47	77.81
Detroit & Charlevoix	51	51	1.424	1.010	67.52	99.53
Harriman & Northeastern *	20	20	2.162	1.733	79.26	63.70
Galveston, Houston & Henderson	50	50	1.556	1.759	47.27	70.37
Average of ten (or nine)	......	......	1.257	1.539	68.89	74.61

* Subsidiary road since 1904.
† Merged since 1904; separate figures not available.

The fluctuations of the average cost per train-mile for several years past may be noted from the following tabular form:

AVERAGE COST PER TRAIN-MILE (FOR WHOLE U. S.) IN CENTS.

Year.	Cents.	Year.	Cents.	Year.	Cents.	Year.	Cents.
1890	96.006	1896	93.838	1902	117.960	1908	147.340
1891	95.707	1897	92.918	1903	126.604	1909	143.370
1892	96.580	1898	95.635	1904	131.375	1910	148.865
1893	97.272	1899	98.390	1905	132.140	1911	154.338
1894	93.478	1900	107.288	1906	137.060	1912	159.077
1895	91.829	1901	112.292	1907	146.993		

The enforced economies after the panic of 1893 are well shown. The reduction generally took the form of a lowering of the standards of maintenance of way and of maintenance of equipment. The marked advance since 1895 is partly due to the necessity for restoring the roads to proper conditions, replenishing worn-out equipment and providing additional equipment to handle the greatly increased volume of business. The recent advance is chiefly due to the increase in wages and the generally increased cost of supplies.

It may be noted from the I. C. C. reports that the cases where the operating expenses per train-mile and the ratio of expenses to earnings vary very greatly from the average are almost invariably those of the very small roads or of "junction roads" where the operating conditions are abnormal. For example, one little road, with a total length of 13 miles and total annual operating expenses of $5342, spent but 22¼c. per train-mile, which precisely exhausted its earnings. This precise equality of earnings and expenses suggests jugglery in the bookkeeping. As another abnormal case, a road 44 miles long spent $3.81 per train-mile, which was nearly *fourteen* times its earnings. In another case a road 13 miles long earned $7.76 per train-mile and spent $6.03 (78%) on operating expenses, but the fixed charges were abnormal and the earnings were less than half the sum of the operating expenses and fixed charges. The *normal* case, even for the small road, is that the cost per train-mile and the ratio of operating expenses to earnings will agree fairly well with the average, and when there is a marked difference it is generally due to some abnormal conditions of expenses or of earning capacity.

482. Reasons for uniformity in expenses per train-mile. The chief reason is that, although on the heavy-traffic road everything is kept up on a finer scale, better roadbed, heavier rails, better rolling stock, more employees, better buildings, stations, and terminals, etc., yet the number of trains is so much greater that the divisor is just enough larger to make the average cost about constant. This is but a general statement of a fact which will be discussed in detail under the different items of expense.

483. Detailed classification of expenses with ratios to the total expense. The Interstate Commerce Commission now publishes each year a classification with detailed summation for the cost of each item. These summations are made up from reports furnished by railroads which have (in the reports recently made) represented over 99% of the total traffic handled. In the annexed tabular form (Table XLI) are shown the percentages which each item bears to the total. The railroads have been divided into two classes, "large" and "small," as indicated below. Large roads report on 116 items which are combined and condensed with 44 items for small roads.

"Large roads" are those with mileage greater than 250 miles, or those with operating revenues greater than $1,000,000. Roads subsidiary to "large roads" are also included in this class.

"Small roads" are those with mileage less than 250 miles and also with operating revenues less than $1,000,000.

484. Amounts and percentages of the various items. The I. C. C. report for the year ending June 30, 1909, was the first to include the distribution of expenses according to the present classification. The items as given are reliable and may be utilized, as far as any such computations are to be depended on, in estimating future expenses. The chief purpose of this discussion is to point out those elements of the cost of operating trains which may be affected by such changes of location as an engineer is able to make. There are some items of expense with which the engineer has not the slightest concern, nor will they be altered by any change in alinement or constructive detail which he may make. In the following discussion such items will be passed over with a brief discussion of the sub-items included.

MAINTENANCE OF WAY AND STRUCTURES.

485. Items 2 to 5. Track material. The relative cost of ballast, ties, rails and other track material, as shown by com-

TABLE XLI.—ANALYSIS OF OPERATING EXPENSES OF ALL "LARGE"* RAILROADS IN THE UNITED STATES FOR YEAR ENDING JUNE 30, 1912, SHOWING PERCENTAGE OF EACH ITEM TO TOTAL AND COST IN CENTS PER TRAIN-MILE.

Item. No.	Account.	Total Amount (thousands)	Per cent of total Expenses	Cents per Train-Mile.
	Maintenance of Way and Structures.			
1	Superintendence	$18,789	0.990	1.58
2	Ballast	7,157	0.377	.60
3	Ties	55,463	2.921	4.65
4	Rails	16,438	.866	1.38
5	Other track material	17,346	.914	1.45
6	Roadway and track	129,397	6.815	10.84
7	Removal of snow, sand, and ice	6,920	.364	.58
8	Tunnels	1,141	.060	.10
9	Bridges, trestles, and culverts	27,712	1.460	2.32
10–12	Crossings, all; fences; snow structures	8,066	.425	.68
13–15	Signals, telegraph, electrical power transmission	13,681	.720	1.14
16, 17	Buildings, grounds, docks, wharves	35,389	1.864	2.96
18	Roadway tools and supplies	4,480	.236	.38
19	Injuries to persons	1,989	.105	.17
20, 21	Stationery, printing and other expenses	1,038	.054	.09
22, 23	Joint tracks, etc. (net balance)	3,463	.182	.29
		$348,471	18.353	29.20
	Maintenance of Equipment.			
24	Superintendence	$13,175	.694	1.10
	Repairs, renewals and depreciation:			
25–30	Locomotives, steam and electric	175,889	9.263	14.74
31–33	Cars, passenger	38,968	2.052	3.26
34–36	Cars, freight	183,968	9.690	15.41
37–39	Equipment, electrical, car	318	.017	.03
40–42	Equipment, floating	1,333	.071	.11
43–45	Equipment, work	6,128	.322	.51
46	Equipment, shop (machinery and tools)	10,418	.548	.87
47	Equipment, power plant	268	.014	.02
48	Injuries to persons	1,818	.096	.15
49, 50	Stationery, printing and other expenses	4,036	.213	.34
51, 52	Joint equipment, at terminals (net balance)	676	.036	.06
		$436,995	23.016	36.61
	Traffic Expenses.			
53–60	Agencies; advertising; fast freight lines; etc.	$59,047	3.110	4.95

* The "large" roads here reported represent 88% of the total mileage.

paring either the gross amounts or the percentages in Table XLI, is suggestive and instructive. The fact that ties cost considerably more than all other track material combined shows

TABLE XLI. (*Continued*).—ANALYSIS OF OPERATING EXPENSES OF ALL "LARGE" RAILROADS IN THE UNITED STATES FOR YEAR ENDING JUNE 30, 1912, SHOWING PERCENTAGE OF EACH ITEM TO TOTAL AND COST IN CENTS PER TRAIN-MILE.

Item No.	Account.	Total Amount (thousands).	Per cent of total expenses.	Cents per train-mile.
	Transportation Expenses.			
61, 62	Superintendence and train dispatching	$40,743	2.146	3.41
63	Station employees	133,877	7.051	11.22
64–66	Weighing; car service association; coal and ore docks	15,949	.839	1.33
67–70	Yards (wages, expenses, supplies)	76,069	4.007	6.37
71–76	Yard locomotives (enginemen, fuel, water, lubricants, supplies)	74,370	3.917	6.23
77, 78 104, 105	Operating joint tracks, terminals, yards, and facilities (net balance)	10,430	.550	.88
79, 80	Motormen and road enginemen	120,966	6.371	10.14
81	Road locomotives, engine-house expenses	33,951	1.788	2.84
82	Road locomotives, fuel	194,142	10.225	16.27
83	Road locomotives, water	12,482	.657	1.04
84, 85	Road locomotives, lubricants and other supplies	7,430	.392	.62
86, 87	Operating power plants, purchased power	1,797	.095	.15
88	Road trainmen	128,339	6.759	10.75
89	Train supplies and expenses	34,462	1.815	2.89
90–92	Interlockers, signals, flagmen, draw-bridges	17,831	.939	1.49
93	Clearing wrecks	5,167	.272	.43
94–98	Telegraph, floating equipment, stationery, miscellaneous	20,009	1.054	1.68
99–103	Loss and damage to property, personal injuries	56,838	2.994	4.76
		$984,852	51.871	82.51
	General Expenses.			
106–116	Salaries of general officers, clerks, etc.; law, insurance, pensions, miscellaneous	69,297	3.650	5.81
	Total operating expenses	$1,898,662	100.000	159.08

the importance of any possible saving in tie renewals. It is also significant that the relative importance of ties has increased in the last few years, and that the relative increase has not been due to a reduction in the cost of other track material. Apparently the lengthening of the average life of ties, due to preservative processes, the use of tie-plates, and greater care to avoid the premature withdrawal from the track of ties which are still serviceable, has not kept pace with the increase in the average cost per tie. The cost of rails has advanced because of (*a*) the very general adoption of heavier rails; (*b*) the almost universal substitution of more expensive open-hearth steel for Bessemer, on account of greater reliability and durability, and (*c*) the increase in cost of all steel products.

486. Item 6. Roadway and track. This item is three-eighths of the total cost of maintenance of way and structures. It consists chiefly of the wages of trackmen. There has been an almost steady increase in the daily wages of section foremen and other trackmen since 1900, as shown below:

	1900	1901	1902	1903	1904	1905	1906
Section foremen......	1.68	1.71	1.72	1.78	1.78	1.79	1.80
Other trackmen......	1.22	1.23	1.25	1.31	1.33	1.32	1.36
No. of trackmen per 100 miles...........	118	122	140	147	136	143	155

	1907	1908	1909	1910	1911	1912
Section foremen......	1.90	1.95	1.96	1.99	2.07	2.09
Other trackmen......	1.46	1.45	1.38	1.47	1.50	1.50
No. of trackmen per 100 miles..........	162	130	136	157	147	143

The average number of section foremen per 100 miles of line has remained almost constant at 18. Although there have been fluctuations in the number of "other trackmen" required per 100 miles of line, there has been in general a very substantial increase. These two causes combined (increased number and increased wages) have had a great influence in producing the regular and steady increase in the average cost of a train-mile, as shown in § 481.

487. Items 8 to 15. Maintenance of track structures. As a matter of economics, the locating engineer has little or no concern with the cost of maintaining track structures. If he is comparing two proposed routes it would be seldom that they would be so different that he would be justified in attempting to compute a train-mile difference in cost of operation, based on differences in these items. Of course, one proposed line might call for one or more tunnels which the alternate line might not have, and the annual cost of maintaining the tunnels would increase the cost of operation. Such a case would justify special consideration. So far as the maintenance of small bridges and culverts are concerned it would usually be sufficiently accurate to consider that a proposed change of line, involving perhaps several miles of road, would require substantially the same number of bridges and culverts, and therefore that the cost of maintaining them would be the same by either line. The error involved in such an assumption would usually be insignificant, unless there was a very large and material difference in the two lines in this respect. Under such conditions special computations should be made. The items total less than 3% for small roads and still less for large roads.

MAINTENANCE OF EQUIPMENT.

488. Items 25 to 27. Repairs, renewals and depreciation of steam and electric locomotives. The item is of interest to the locating engineer because he must appreciate the effect on locomotive repairs and renewals of an addition to distance. A large part of the repairs of locomotives are due to the wear of wheels, which is largely caused by curvature. Therefore the value of any reduction of curvature is a matter of importance, and this will be considered in Chapter XXII. A considerable portion of the deterioration of a locomotive is due to grade, and the economic advantages of reductions of grade will be considered in Chapter XXIII.

This item includes the expenses of work whose effect is supposed to last for an indefinite period. It does *not* include the expense of cleaning out boilers, packing cylinders, etc., which occurs regularly and which is charged to items 72 or 81. It does include all current repairs, general overhauling, and even the replacement of old and worn-out locomotives by new ones to the extent of keeping up the original standard and number. Of course additions beyond this should be considered as so much increase in the original capital investment. As a locomotive becomes older the *annual* repair charge becomes a larger percentage on the first cost, and it may become as much as one-fourth and even one-third of the first cost. When a locomotive is in this condition it is usually consigned to the scrap-pile; the annual cost for maintenance becomes too large an item for its annual mileage. The effect on expenses of increasing the weight of engines is too complicated a problem to be solved accurately, but certain elements of it may be readily computed. While the cost of repairs is greater for the heavier engines, the increase is only about one-half as fast as the increase in weight—some of the subitems not being increased at all.

TRANSPORTATION.

489. Items 71 to 76. Yard-engine expenses. By comparing these items with the corresponding items (80 to 85) for road engines, it may be seen that the total expenses assignable to yard engines are about 20% of those of road engines; the relative fuel charge for 1912 was 15.6%. The number of switching locomotives in the United States in 1912 was 9529 or 15.3% of the total number, 62,262. The relative charge for wages of enginemen was 26.2%. This higher proportionate charge is probably due to the fact that the wages for yard enginemen must necessarily be on a per diem basis, but the wages of road enginemen are generally on a mileage basis, as explained later. On the other hand the mileage of a yard engine is usually comparatively low, and the coal consumed will be correspondingly, although not proportionately, low. It must also be remembered that these figures are exclusive of the work and equipment of switching and terminal companies.

490. Item 80. Road enginemen. This item requires 6% of the total operating expenses. The enginemen are usually paid on a mileage basis, or by the trip, except on very small railroads. On very short roads, where a train crew may make two, three, or even four complete round trips per day, they may readily be paid by the day, so many round trips being considered as a day's work, but on roads of great length, where all trains, and especially freight-trains, are run day and night, weekday and Sunday, all trainmen are necessarily paid by the trip. The pay for a trip is figured on a mileage basis except that a trip is usually considered to have a minimum length of 100 miles or 10 hours of time. Eight hours was fixed as standard by the "Adamson" law, in 1916. All extra time is called "overtime" and is paid for at an extra rate. The basis of train wages is too complicated for any brief discussion. Even the basis is constantly changing, the only uniform feature being a steady increase.

The increase in the average wages paid to enginemen and firemen since 1900 is plainly shown by the following figures:

INCREASE IN DAILY WAGES, FROM 1900 TO 1912.

	1900	1901	1902	1903	1904	1905	1906
	$	$	$	$	$	$	$
Enginemen..........	3.75	3.78	3.84	4.01	4.10	4.12	4.12
Firemen............	2.14	2.16	2.20	2.28	2.35	2.38	2.42

	1907	1908	1909	1910	1911	1912
	$	$	$	$	$	$
Enginemen..........	4.30	4.45	4.44	4.55	4.79	5.00
Firemen............	2.54	2.64	2.67	2.74	2.94	3.02

491. Item 82. Fuel for road locomotives. This item includes every subitem of the entire cost of the fuel until it is placed in the engine-tender. The cost therefore includes not only the first cost at the point of delivery to the road, but also the expense of hauling it over the road from the point of delivery to the various coaling-stations and the cost of operating the coal-pockets from which it is loaded on to the tenders. Even though the cost may be fairly regular for any one road, the cost for different roads is exceedingly variable. There has been an almost steady increase in the *percentage* of the cost of this item per train-mile since 1897. Items 73 and 82 amounted to nearly 12% of the total operating expenses in 1912, and required an actual expenditure of nearly $225,000,000. It is the largest item in the whole cost of railroad operation. Although some roads, which traverse coal-regions and perhaps actually own the coal-mines, are able to obtain their coal for a cost which may be charged up as $1 per ton or less, there are many roads which are far removed from coal-fields which have to pay $3 or $4 per ton, on account of the excessive distance over which the coal must be hauled. Unfortunately the figures published by the Interstate Commerce Commission do not show the variations in the percentage of this item in different localities. A surprisingly large percentage of the fuel consumed is not utilized in drawing a train along the road. A portion of this percentage is used in firing-up. A portion is wasted when the engine is standing still, which is a considerable proportion of the whole time. The policy of banking fires instead of drawing them reduces the injury resulting from great fluctuations in temperature, but in a general way we may say that there is but little, if any, saving in fuel by banking the fires, and therefore we may consider that almost a fire-box full of coal is wasted whether the fires are banked or drawn. As given in § 464, the fuel used by a locomotive in firing-up may be estimated as 510 lbs. per 1000 square feet of heating surface, based on using 12000 B.t.u. coal. But even the amount of coal required to produce the required steam-pressure in the boiler from cold water does not represent the total loss. The train-dispatcher, in his anxiety that engines shall be ready when needed, will sometimes order out the locomotives which remain somewhere in the yard, perhaps exposed to cold weather, and blow off steam for several hours before they make an actual start. This loss has been estimated as 120 lbs. per hour per 1000 square feet of heating surface, but it would evidently be far greater on a windy winter day than on a calm summer day. A freight-train, especially on a single-track road, will usually spend several hours during the day on sidings, and when a single-track road is being run to the limit of its capacity, or when the management is not good, the time will be still greater. It is estimated that the amount lost through a $2\frac{1}{2}$-inch safety-valve in one minute would represent the consumption of 15 pounds of coal, which would be sufficient to haul 100 tons on a mile of track with easy grades. Again we see that the amount thus lost is exceedingly variable and almost non-computable, although as a rough estimate the amount has been placed at from 3 to 6% of the total. Another very large subitem of loss of useful energy is that occasioned by stopping and starting. A train running 30 miles per hour has enough kinetic energy to move it on a straight level track for more than two miles. Therefore, every time a train running at 30 miles per hour is stopped, enough energy is consumed by the brakes to run it about two miles. There is a double loss, not only due to the fact of the loss of energy, but also because the power of the locomotive has been consumed in operating the brakes. When the train is again started, this kinetic energy must be restored to the train in addition to the ordinary resistances which are even greater, on account of the greater resistance at very low velocities. Of course, the proportion of fuel thus consumed depends on the frequency of the stops. It was demonstrated by some tests on the Manhattan Elevated Road in New York City, where the stops average one in every three-eighths of a mile, that this cause alone would account for the consumption of nearly three-fourths of the fuel. On ordinary railroads the proportion, of course, will not be nearly so great, but there is reason to believe that 10 to 20% is not excessive as an average figure.

492. Item 88. Road trainmen. This item includes the wages of conductors and "other trainmen." As in the case of all other employees, the average daily wages have advanced since 1900 as shown below:

AVERAGE DAILY WAGES OF CONDUCTORS AND OTHER TRAINMEN, 1900 TO 1912.

	1900	1901	1902	1903	1904	1905	1906
	$	$	$	$	$	$	$
Conductors..........	3.17	3.17	3.21	3.38	3.50	3.50	3.51
Other trainmen......	1.96	2.00	2.04	2.17	2.27	2.31	2.35

	1907	1908	1909	1910	1911	1912
	$	$	$	$	$	$
Conductors..........	3.69	3.81	3.81	3.91	4.16	4.29
Other trainmen......	2.54	2.60	2.59	2.69	2.88	2.96

These figures are of vital importance from an economic standpoint, since they show a constant tendency to increase and thereby raise the average cost of a train-mile. And as there is no present indication of any limit to this increase, all economic calculations which attempt to predict future expenses, even for a few years in advance, must allow for these and other increased expenses.

493. Item 89. Train supplies and expenses. These items, which average about 1.8%, include the large list of consumable supplies such as lubricating oil, illuminating-oil or gas, ice, fuel for heating, cleaning materials, etc., which are used on the cars and not on the locomotives. The consumption of some of these articles is chiefly a matter of time. In other cases it is a function of mileage. The effect of changes which an engineer may make on this item will be considered when estimating the effect of the changes.

494. Items 93, 99 to 103. Clearing wrecks, loss, damage and injuries to persons and property. These expenses are fortuitous and bear no absolute relation either to the number of miles of road or the number of train-miles. While they depend largely on the standards of discipline on the road, even the best of roads have to pay some small proportion of their earnings to these items. While we might expect that a road with heavy traffic would have a larger proportion of train accidents than a road of light traffic, it is usually true that on the heavy-traffic roads the precautions taken are such that they are usually freer from accidents than the light-traffic roads. During recent years there has been a very perceptible increase in the percentages of these items, particularly in the compensations paid for "injuries to persons." The increase in this item coincides with the increase already noted in the number of passengers killed during recent years. The possible relation between curvature and accidents is discussed in § 507, but otherwise the locating engineer has no concern with these items.

495. Items 104, 105. Operating joint tracks and facilities, Dr. and Cr. A large part of these debit and credit charges are those for car per diem and mileage charges. This is a charge paid by one road to another for the use of cars, which are chiefly freight-cars. To save the rehandling of freight at junctions, the policy of running freight-cars from one road to another is very extensively adopted. Since the foreign road receives its mileage proportion of the freight charge, it justly pays to the road owning the car at a rate which is supposed to represent the value of the use of the freight-car for the number of miles traveled. The foreign road then loads up the freight-car with freight consigned to some point on the home road and sends it back, paying mileage for the distance traveled on the foreign road, a proportional freight charge having been received for that service. All of these movements of freight-cars are reported to a car association, which, by a clearing-house arrangement, settles the debit and credit accounts of the various roads with each other. Such is the simple theory. In practice the cars are not sent back to the home road at once, but wander off according to the local demand. As long as a strict account is kept of the movements of every car, and as long as the home road is paid the charge which really covers the value of lost service, no harm is done to the home road, except that sometimes, when business has suddenly increased, the home road cannot get enough cars to handle its own business. The value of the car is then abnormally above its ordinary value, and the home road suffers for lack of the rolling stock which belongs to it. Formerly such charges were paid strictly according to the mileage. This developed the intolerable condition that loaded cars would be run onto a siding and left there for several days, simply because it was not convenient to the consignee to unload the car immediately. On the mileage basis the car would be earning nothing, and, since the road on which the car then was had no particular interest in the car, the car was allowed to stand to suit the convenience of the consignee. To correct this evil a system of per diem charges has been developed, so that a railroad has to pay a per diem charge for every foreign car on its lines. To reduce this charge as much as possible the railroads compel consignees, under penalty of heavy demurrage charges, to unload cars promptly. The running of freight-cars on foreign lines is now settled almost exclusively on the per diem basis, but the running of passenger-cars over other lines, as is done on account of the advantages of through-car service, as well as the running of Pullmans and other special cars, is still paid for on the mileage basis. To the extent to which this charge is settled on the mileage basis, any change in distance which the engineer may be able to effect in the length of the road will have its influence on this item, but when the freight-car business, which comprises by far the larger part of the running of cars over foreign lines, is settled on the per diem basis no changes in alinement which the engineer may make will affect the item appreciably.

Switching Charges. Where two or more railroads intersect there will be a considerable amount of shifting of cars, chiefly freight-cars, from one road to the other. This shifting at any one junction may be done entirely by the engines of one road or perhaps by those of both roads. A portion of the expense of this work is charged up against the other road by the road which does the work. The total amount of this work is carefully accounted for by a clearing-house arrangement, and the balance is charged up against the road which has done the least work. The item is very small, is fairly uniform year by year, and is seldom, if ever, affected by changes of alinement.

Other Items. All of the remaining items, as stated in Table XLI, are of no concern to the locating engineer. They are either general expenses, such as the salaries of general officers, insurance or law expenses, or are special items, such as advertising or the operation of marine equipment which will not be changed by any variations in distance, curvature, or grades which a locating engineer may make. There is therefore no need for their further discussion here.

CHAPTER XXI.

DISTANCE.

496. Relation of distance to rates and expenses. Rates are usually based on distance traveled, on the apparent hypotheses that each additional mile of distance adds its proportional amount not only to the service rendered but also to the expense of rendering it. Neither hypothesis is true. The value of the service of transporting a passenger or a ton of freight from *A* to *B* is a more or less uncertain gross amount depending on the necessities of the case and independent of the exact distance. Except for that very small part of passenger traffic which is undertaken for the mere pleasure of traveling, the general object to be attained in either passenger or freight traffic is the transportation from *A* to *B*, however it is attained. A mile greater distance does not improve the service rendered; in fact, it consumes valuable time of the passengers and perhaps deteriorates the freight. From the standpoint of service rendered, the railroad which adopts a more costly construction and thereby saves a mile or more in the route between two places is thereby fairly entitled to additional compensation rather than have it cut down as it would be by a strict mileage rate. The actual value of the service rendered may therefore vary from an insignificant amount which is less than any reasonable charge (which therefore discourages such traffic) and its value in cases of necessity—a value which can hardly be measured in money. If the passenger charge between New York and Philadelphia were raised to $5, $10, or even $20, there would still be some passengers who would pay it and go, because *to them* it would be worth $5, $10, or $20, or even more. Therefore, when they pay $2.25 they are not paying what the service is worth to them. The service rendered cannot therefore be made a measure of the charge, nor is the service rendered proportional to the miles of distance.

The idea that the cost of transportation is proportional to the distance is much more prevalent and is in some respects more justifiable, but it is still far from true. This is especially true of passenger service. The extra cost of transporting a single passenger is but little more than the cost of printing his ticket. Once aboard the train, it makes but little difference to the railroad whether he travels one mile or a hundred. Of course there are certain very large expenses due to the passenger traffic which must be paid for by a tariff which is rightfully demanded, but such expenses have but little relation to the cost of an additional mile or so of distance inserted between stations. The same is true to a slightly less degree of the freight traffic. As shown later, the items of expense in the total cost of a train-mile, which are directly affected by a small increase in distance, are but a small proportion of the total cost.

497. The conditions other than distance that affect the cost; reasons why rates are usually based on distance. Curvature and minor grades have a considerable influence on the cost of transportation, as will be shown in detail in succeeding chapters, but they are never considered in making rates. Ruling grades have a very large influence on the cost, but they are likewise disregarded in making rates. An accurate measure of the effect of these elements is difficult and complicated and would not be appreciated by the general public. Mere distance is easily calculated; the public is satisfied with such a method of calculation; and the railroads therefore adopt a tariff which pays expenses and profits even though the charges are not in accordance with the expenses or the service rendered

EFFECT OF DISTANCE ON RECEIPTS.

498. Classification of traffic. There are various methods of classifying traffic, according to the use it is intended to make of the classification. The method here adopted will have reference to its competitive or non-competitive character and also to the method of division of the receipts on through traffic. Traffic may be classified first as "through" and "local"—through traffic being that traveling over two (or more) lines, no matter how short or non-competitive it may be; "local" traffic is that confined entirely to one road. A fivefold classification is however necessary—which is:

A. Non-competitive local—on one road with no choice of routes

B. Non-competitive through—on two (or more) roads, but with no choice.

C. Competitive local—a choice of two (or more) routes, but the entire haul may be made on the home road.

D. Competitive through—direct competition between two or more routes each passing over two or more lines.

E. Semi-competitive through—a non-competitive haul on the home road and a competitive haul on foreign roads.

There are other possible combinations, but they all reduce to one of the above forms so far as their essential effect is concerned.

499. Method of division of through rates between the roads run over. Through rates are divided between the roads run over in proportion to the mileage. There may be terminal charges and possibly other more or less arbitrary deductions to be taken from the total amount received, but when the final division is made the remainder is divided according to the mileage. On account of this method of division and also because non-competitive rates are always fixed according to the distance, there results the unusual feature that, unlike curvature and grade, there is a compensating advantage in increased distance, which applies to all the above kinds of traffic except one (competitive local), and that the compensation is sometimes sufficient to make the added distance an actual source of profit. It has been estimated that the cost of hauling a train an additional mile is only 33 to 49% of the average cost. Therefore in all non-competitive business (local or through) where the rate is according to the distance, there is an actual profit in all such added distance. In competitive local business, in which the rate is fixed by competition and has practically no relation to distance, any additional distance is dead loss. In competitive through business the profit or loss depends on the distances involved. This may best be demonstrated by examples.

500. Effect of a change in the length of the home road on its receipts from through competitive traffic. Suppose the home road is 100 miles long and the foreign road is 150 miles long. Then the home road will receive $\frac{100}{100+150}=40\%$ of the through rate.

Suppose the home road is lengthened 5 miles; then it will receive $\frac{105}{105+150}=41.176\%$ of the through rate. The traffic being competitive, the rate will be a fixed quantity regardless of this change of distance. By the first plan the rate received is 0.4% per mile; adding 5 miles, the rate for the original 100 miles may be considered the same as before; and that the additional 5 miles receive 1.176%, or 0.235% per mile. This is 59% of the original rate per mile, and since this is more than the cost per mile for the additional distance, the added distance is evidently in this case a source of distinct profit. On the other hand, if the line is shortened 5 miles, it may be similarly shown that not only are the receipts lessened, but that the saving in operating expenses by the shorter distance is less than the reduction in receipts.

A second example will be considered to illustrate another phase. Suppose the home road is 200 miles long and the foreign road is 50 miles long. In this case the home road will receive $\frac{200}{200+50}=80\%$ of the through rate. Suppose the home road is lengthened 5 miles; then it will receive $\frac{205}{205+50}=80.392\%$ of the through rate. By the first plan the rate received is 0.400% per mile; adding 5 miles, there is a surplus of 0.392, or 0.0784 per mile, which is but 19.6% of the original rate. At this rate the extra distance evidently is not profitable, although it is not a dead loss—there is some compensation.

501. The most advantageous conditions for roads forming part of a through competitive route. From the above it may be seen that when a road is but a short link in a long competitive through route, an addition to its length will increase its receipts and increase them more than the addition to the operating expenses.

As the proportionate length of the home road increases the less will this advantage become, until at some proportion an increase in distance will just pay for itself. As the proportionate length grows greater the advantage becomes a disadvantage until, when the competitive haul is entirely on the home road, any increase in distance becomes a net loss without any compensation. It is therefore advantageous for a road to be a short link in a long competitive route; an increase in that link will be financially advantageous; if the total length is less than that of the competing line, the advantage is still greater, for then the rate received per mile will be greater.

502. Effect of the variations in the length of haul and the classes of the business actually done. The above distances refer to particular lengths of haul and are not necessarily the total lengths of the road. Each station on the road has traffic relations with an indefinite number of traffic points all over the country. The traffic between each station on the road and any other station in the country between which traffic may pass therefore furnishes a new combination, the effect of which will be an element in the total effect of a change of distance. In consequence of this, any *exact* solution of such a problem becomes impracticable, but a sufficiently accurate solution for all practical purposes is frequently obtainable. For it frequently happens that the great bulk of a road's business is non-competitive, or, on the other hand, it may be competitive-through, and that the proportion of one or more definite kinds of traffic is so large as to overshadow the other miscellaneous traffic. In such cases an approximate but sufficiently accurate solution is possible.

503. General conclusions regarding a change in distance. (a) In *all* non-competitive business (local and through) the added distance is actually profitable. Sometimes practically all of the business of the road is non-competitive; a considerable proportion of it is always non-competitive.

(b) When the competitive local business is very large and the competitive through business has a very large average home haul compared with the foreign haul, the added distance is a source of loss. Such situations are unusual and are generally confined to trunk lines.

(c) The above may be still further condensed to the general conclusion that there is always *some* compensation for the added cost of operating an added length of line and that it frequently is a source of actual profit.

(d) There is, however, a limitation which should not be lost sight of. The above argument may be carried to the logical conclusion that, if added distance is profitable, the engineer should purposely lengthen the line. But added distance means added operating expenses. A sufficient tariff to meet these is a tax on the community—a tax which more or less discourages traffic. It is contrary to public policy to burden a community with an avoidable expense. But, on the other hand, a railroad is not a charitable organization, but a money-making enterprise, and cannot be expected to unduly load up its first cost in order that subsequent operating expenses may be unduly cheapened and the tariff unduly lowered. A common reason for increased distance is the saving of the first cost of a very expensive although shorter line.

(e) Finally, although there is a considerable and uncompensated loss resulting from curvature and grade which will justify a considerable expenditure to avoid them, there is by no means as much justification to incur additional expenditure to avoid distance. Of course needless lengthening should be avoided. A moderate expenditure to shorten the line may be justifiable, but large expenditures to decrease distance are never justifiable except when the great bulk of the traffic is exceedingly heavy and is competitive.

504. Justification of decreasing distance to save time. It should be recalled that the changes which an engineer may make which are physically or financially possible will ordinarily have but little effect on the time required for a trip. The time which can thus be saved will have practically no value for the freight business—at least any value which would justify changing the route. When there is a large directly competitive passenger traffic between two cities (*e.g.* New York to Philadelphia) a difference of even 10 minutes in the time required for a run might have considerable financial importance, but such cases are comparatively rare. It may therefore be concluded that the value of the time saved by shortening distance will not ordinarily be a justification for increased expense to accomplish it.

505. Effect of change of distance on the business done. The above discussion is based on the assumption that the business done is unaffected by any proposed change in distance. If a proposed reduction in distance involves a loss of business obtained, it is almost certainly unwise. But if by increasing the distance the original cost of the road is decreased (because the construction is of less expensive character), and if the receipts are greater, and are increased still more by an increase in business done, then the change is probably wise. While it is almost impossible in a subject of such complexity to give a general rule; the following is generally safe: Adopt a route of such length that the annual traffic per mile of line is a maximum. This statement may be improved by allowing the element of original cost to enter and say, adopt a route of such length that the annual traffic per mile of line divided by the average cost per mile is a maximum. Even in the above the operating cost per mile, as affected by the curvature and grades on the various routes, does not enter, but any attempt to formulate a general rule which would allow for variable operating expenses would evidently be too complicated for practical application.

CHAPTER XXII.

CURVATURE.

506. General objections to curvature. In the popular mind curvature is one of the most objectionable features of railroad alinement. The cause of this is plain. The objectionable qualities are on the surface, and are apparent to the non-technical mind. They may be itemized as follows:

1. Curvature increases operating expenses by increasing (a) the required tractive force, (b) the wear and tear of roadbed and track, (c) the wear and tear of equipment, and (d) the required number of track-walkers and watchmen.

2. It may affect the operation of trains (a) by limiting the length of trains, and (b) by preventing the use of the heaviest types of engines.

3. It may affect travel (a) by the difficulty of making time, (b) on account of rough riding, and (c) on account of the apprehension of danger.

4. There is actually an increased danger of collision, derailment, or other form of accident.

Some of these objections are quite definite and their true value may be computed. Others are more general and vague and are usually exaggerated. These objections will be discussed in inverse order.

507. Financial value of the danger of accident due to curvature. At the outset it should be realized that in general the problem is *not* one of curvature *vs.* no curvature, but simply sharp curvature *vs.* easier curvature (the central angle remaining the same), or a greater or less percentage of elimination of the degrees of central angle. A straight road between termini is in general a financial (if not a physical) impossibility. The practical question is then, how much is the financial value of such diminution of danger that may result from such eliminations of curvature as an engineer is able to make?

In the year 1898 there were 2228 railroad accidents reported by the *Railroad Gazette*, whose lists of all accidents worth reporting are very complete. Of these a very large proportion clearly had no relation whatever to curvature. But suppose we assume that 50% (or 1114 accidents) were directly caused by curvature. Since there are approximately 200,000 curves on the railroads of the country, there was on the average an accident for every 179 curves during the year. Therefore we may say, according to the theory of probabilities, that the chances are even that an accident may happen on any particular curve in 179 years. This assumes all curves to be equally dangerous, which is not true, but we may temporarily consider it to be true. If, at the time of the construction of the road, $1.00 were placed at compound interest at 5% for 179 years, it would produce in that time $620.89 for each dollar saved, wherewith to pay all damages, while the amount necessary to eliminate that curvature, even if it were possible, would probably be several thousand dollars. The number of passengers carried one mile for one killed in 1898–99 was 61,051,580. If a passenger were to ride continuously at the rate of sixty miles per hour, day and night, year after year, he would need to ride for more than 116 years before he had covered such a mileage, and even then the probabilities of his death being due to curvature or to such a reduction of curvature as an engineer might accomplish are very small. Of course particular curves are often, for special reasons, a source of danger and justify the employment of special watchmen. They would also justify very large expenditures for their elimination if possible. But as a general proposition it is evidently impossible to assign a definite money value to the danger of a serious accident happening on a particular curve which has no special elements of danger.

Another element of safety on curved track is that trait of human nature to exercise greater care where the danger is more apparent. Many accidents are on record which have been caused by a carelessness of locomotive engineers on a *straight* track when the extra watchfulness usually observed on a curved track would have avoided them.

508. Effect of curvature on travel. (a) **Difficulty in making time.** The general use of transition curves has largely eliminated the necessity for reducing speed on curves, and even when the speed is reduced it is done so easily and quickly by means of air-brakes that but little time is lost. If two parallel lines were competing sharply for passenger traffic, the handicap of sharp curvature on one road and easy curvature on the other might have a considerable financial value, but ordinarily the *mere reduction* of time due to sharp curvature will not have any computable financial value.

(b) **On account of rough riding.** Again, this is much reduced by the use of transition curves. Some roads suffer from a general reputation for crookedness, but in such cases the excessive curvature is practically unavoidable. This cause probably does have some effect in influencing competitive passenger traffic.

(c) **On account of the apprehension of danger.** This doubtless has its influence in deterring travel. The amount of its influence is hardly computable. When the track is in good condition and transition curves are used so that the riding is smooth, even the apprehension of danger will largely disappear.

Travel is doubtless more or less affected by curvature, but it is impossible to say how much. Nevertheless the engineer should not ordinarily give this item any financial weight whatsoever. Freight traffic (two thirds of the total) is unaffected by it. It chiefly affects that limited class of sharply competitive passenger traffic—a traffic of which most roads have not a trace.

509. Effect on operation of trains. (a) Limiting the length of trains. When curvature actually limits the length of trains, as is sometimes true, the objection is valid and serious. But this can generally be avoided. If a curve occurs on a ruling grade without a reduction of the grade sufficient to compensate for the curvature, then the resistance on that curve will be a maximum and that curve will limit the trains to even a less weight than that which may be hauled on the ruling grade. In such cases the unquestionably correct policy is to "compensate for curvature," as explained later (see §§510, 511), and not allow such an objection to exist. It is *possible* for curvature to limit the length of trains even without the effect of grade. On the Hudson River R. R. the total net fall from Albany to New York is so small that it has practically no influence in determining grade. On the other hand, a considerable portion of the route follows a steep rocky river bank which is so crooked that much curvature is unavoidable and very sharp curvature can only be avoided by very large expenditure. As a consequence sharp curvature has been used and the resistance on the curves is far greater than that of any fluctuations of grade which it was necessary to use. Or, at least, a comparatively small expenditure would suffice to cut down any grade so that its resistance would be less than that of some curve which could not be avoided except at an enormous cost. And as a result, since the length of trains is really limited by curvature, minor grades of 0.3 to 0.5% have been freely introduced which might be removed at comparatively small expense The above case is very unusual. Low grades are usually associated with generally level country where curvature is easily avoided—as in the Camden and Atlantic R. R. Even in the extreme case of the Hudson River road the maximum curvature is only equivalent to a comparatively low ruling grade.

(b) **Preventing the use of the heaviest types of engines.** The validity of this objection depends somewhat on the degree of curvature and the detailed construction of the engine. While some types of engines might have difficulty on curves of extremely short radius, yet the objection is ordinarily invalid. This will best be appreciated when it is recalled that the "Consolidation" type was originally designed for use on the sharp curvature of the mountain divisions of the Lehigh Valley R. R., and that the type has been found so satisfactory that it has been extensively employed elsewhere. It should also be remembered that during the Civil War an immense traffic daily passed over a hastily constructed trestle near Petersburg, Va., the track having a radius of 50 feet. As a result of a test made at Renovo on the Philadelphia and Erie R. R. by Mr. Isaac Dripps, Gen. Mast. Mech., in 1875,* it was claimed that a Consolidation engine encountered less resistance per ton than one of the "American" type. Whether the test was strictly reliable or not, it certainly demonstrated that there was no trouble in using these heavy engines on very sharp curvature, and we may therefore consider that, except in the most extreme cases, this objection has no force whatsoever.

---

* Seventh An. Rep. Am. Mast. Mech. Assn.

COMPENSATION FOR CURVATURE.

510. Reasons for compensation. The effect of curvature on a grade is to increase the resistance by an amount which is equivalent to a material addition to that grade. On minor grades the addition is of little importance, but when the grade is nearly or quite the ruling grade of the road, then the additional resistance induced by a curve will make that curve a place of maximum resistance and the real maximum will be a "virtual grade" somewhat higher than the nominal maximum. If, in Fig. 211,

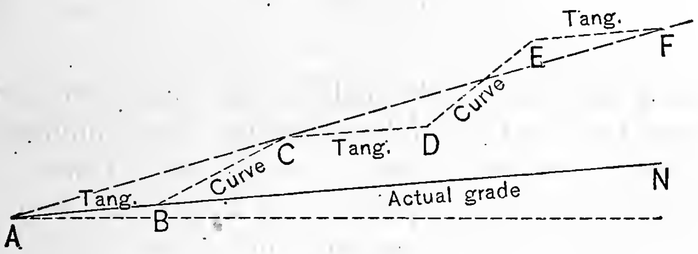


FIG. 211.

AN represents an actual *uniform* grade consisting of tangents and curves, the "virtual grade" on curves at *BC* and *DE* may be represented by *BC* and *DE*. If *BC* and *DE* are very long, or if a stop becomes necessary on the curve, then the full disadvantage of the curve becomes developed. If the whole grade may be operated without stoppage, then, as elaborated further in the next chapter, the whole grade may be operated as if equal to the average grade, *AF*, which is better than *BC*, although much worse than *AN*. The process of "compensation" consists in reducing the grade on every curve by such an amount that the actual resistance on each curve, due to both curvature and grade, shall precisely equal the resistance on the tangent. The practical effect of such reduction is that the "virtual" grade is kept constant, while the nominal grade fluctuates.

One effect of this is that (see Fig. 212) instead of accomplishing the vertical rise from *A* to *G* (i.e., *HG*) in the horizontal distance *AH*, it requires the horizontal distance *AK*. Such an addition to the horizontal distance can usually be obtained by proper development, and it should always be done on a ruling grade. Of course it is possible that it will cost more to accomplish this than it is worth, but the engineer should be sure of this before allowing this virtual increase of the grade.

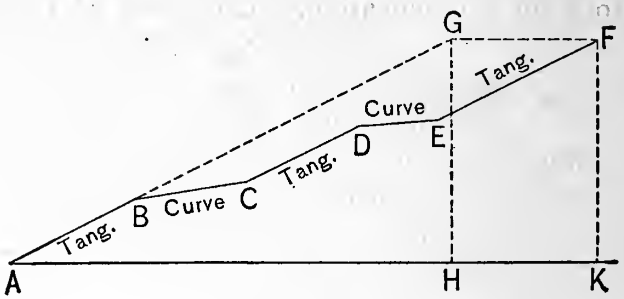


Fig. 212.

European engineers early realized the significance of unreduced curvature and the folly of laying out a uniform ruling grade regardless of the curvature encountered. Curve compensation is now quite generally allowed for in this country, but thousands of miles have been laid out without any compensation. A very common limitation of curvature and grade has been the alliterative figures 6° curvature and 60 feet per mile of grade, either singly or in combination. Assuming that the resistance on a 6° curve is equivalent to a 0.3% grade (15.84 feet per mile), then a 6° curve occurring on a 60-foot grade would develop more resistance than a 75-foot grade on a tangent. The "mountain cut-off" of the Lehigh Valley Railroad near Wilkesbarre is a fine example of a heavy grade compensated for curvature, and yet so laid out that the virtual grade is uniform from bottom to top, a distance of several miles.

511. The proper rate of compensation. This evidently is the rate of grade of which the resistance just equals the resistance due to the curve. But such resistance is variable. It is greater as the velocity is lower; it is generally about 2 lbs. per ton (equivalent to a 0.1% grade) per degree of curve when starting a train. On this account, the compensation for a curve which occurs at a known stopping-place for the heaviest trains should be 0.1% per degree of curve. The resistance is not even strictly proportional to the degree of curvature, although it is usually considered to be so. In fact most formulæ for curve resistance are based on such a relation. But if the experimentally determined resistances for low curvatures are applied to the excessive curvature of the New York Elevated road, for example, the rules become ridiculous. On this account the compensation *per degree of curve* may be made less on a sharp curve than on an easy curve. The compensation actually required for very fast trains is less than for slow trains, say 0.02 or 0.03% per degree of curve; but since the comparatively slow and heavy freight trains are the trains which are chiefly limited by ruling grade, the compensation must be made with respect to those trains. From 0.04 to 0.05% per degree is the rate of compensation most usually employed for average conditions. Curves which occur *below* a known stopping-place for *all* trains need not be compensated, for the extra resistance of the curve will be simply utilized in place of brakes to stop the train. If a curve occurs just *above* a stopping-place, it is very serious and should be amply compensated. Of course the down-grade traffic need not be considered.

It sometimes happens that the ordinary rate of compensation will consume so much of the vertical height (especially if the curvature is excessive) that a steeper through grade must be adopted than was first computed, and then the trains might stall on the tangents rather than on the curves. In such cases a slight reduction in the rate of compensation might be justifiable.

The following rules have been approved by the Amer. Rwy. Eng. Assoc.

1. Compensate .03% per degree (*a*) when the length of curve is less than half the length of the longest train; (*b*) when a curve occurs within the first 20 feet of rise of a grade; (*c*) when curvature is in no sense limiting.

2. Compensate .035% per degree (*a*) when curves are between one-half and three-quarters as long as the longest train; (*b*) when the curve occurs between 20 feet and 40 feet of rise from the bottom of the grade.

3. Compensate .04% per degree (*a*) where the curve is habitually operated at low speed; (*b*) where the length of the curve is longer than three-quarters of the length of the longest train; (*c*) where elevation is excessive for freight trains; (*d*) at all places where curvature is likely to be limiting.

4. Compensate .05% per degree wherever the loss of elevation can be spared.

512. The limitations of maximum curvature. What is the maximum degree of curvature which should be allowed on any road? It has been shown that sharp curvature does not prevent the use of the heaviest types of engines, and although a sharp curve unquestionably increases operating expenses, the increase is but one of degree with hardly any definite limit. The general character of the country and the gross capital available (or the probable earnings) are generally the true criterions.

A portion of the road from Denver to Leadville, Col., is an example of the necessity of considering sharp curvature. The traffic that might be expected on the line was so meagre and yet the general character of the country was so forbidding that a road built according to the usual standards would have cost very much more than the traffic could possibly pay for. The line as adopted cost about $20,000 per mile, and yet in a stretch of 11.2 miles there are about 127 curves. One is a 25° 20′ curve, twenty-four are 24° curves, twenty-five are 20° curves, and seventy-two are sharper than 10°. If 10° had been made the limit (a rather high limit according to usual ideas), it is probable that the line would have been found impracticable (except with prohibitive grades) unless four or five times as much per mile had been spent on it, and this would have ruined the project financially.

For many years the main-line traffic of the Baltimore and Ohio R. R. has passed over a 300-foot curve (19° 10′) and a 400-foot curve (14° 22′) at Harper's Ferry. A few years ago some reduction was made in this by means of a tunnel, but the fact that such a road thought it wise to construct and operate such curves (and such illustrations on the heaviest-traffic roads are quite common) shows how foolish it is for an engineer to sacrifice money or (which is much more common) sacrifice gradients in order to reduce the *rate* of curvature on a road which at its best is but a second- or third-class road.

Of course such belittling of the effects of curvature may be (and sometimes is) carried to an extreme and cause an engineer to fail to give to curvature its due consideration. Degrees of central angle should always be reduced by all the ingenuity of the engineer, and should only be limited by the general relation between the financial and topographical conditions of the problem. Easy curvature is in general better than sharp curvature and should be adopted when it may be done at a small financial sacrifice, especially since it reduces distance generally and may even cut down the initial cost of that section of the road. But large financial expenditures are rarely, if ever, justifiable where the net result is a mere increase in radius without a reduction in central angle. An analysis of the changes which have been so extensively made during late years on the Penn. R. R. and the N. Y., N. H. & H. R. R. will show invariably a reduction of distance, or of central angle, or both, and perhaps incidentally an increase in radius of curvature. There are but few, if any, cases where the sole object to be attained by the improvement is a mere increase in radius.

The requirements of standard M. C. B. car-couplers have virtually placed a limitation on the radius on account of the corners of adjacent cars striking each other on very sharp curves. This limitation has been crystallized into a rule on the P. R. R. that no curve, even that of a siding, can have a less radius than 175 feet, which is nearly the radius of a 33° curve. Of course only the most peremptory requirements of yard work would justify the employment of such a radius.

CHAPTER XXIII.

GRADE.

513. Two distinct effects of grade. The effects of grade on train expenses are of two distinct kinds; one possible effect is very costly and should be limited even at considerable expenditure; the other is of comparatively little importance, its cost being slight. As long as the length of the train is not limited, the occurrence of a grade on a road simply means that the engine is required to develop so many foot-pounds of work in raising the train so many feet of vertical height. For example, if a freight train weighing 600 tons (1,200,000 lbs.) climbs a hill 50 feet high, the engine performs an *additional* work of creating 60,000,000 foot-pounds of potential energy. If this height is surmounted in 2 miles and in 6 minutes of actual time (20 miles per hour), the *extra* work is 10,000,000 foot-pounds per minute, or about 303 horse-power. But the disadvantages of such a rise are always largely compensated. Except for the fact that one terminus of a road is generally higher than the other, every up grade is followed, more or less directly, by a down grade which is operated partly by the potential energy acquired during the previous climb. But when we consider the trains running in both directions even the difference of elevation of the termini is largely neutralized. If we could eliminate frictional resistances and particularly the use of brakes, the *net* effect of minor grades on the operation of minor grades in both directions would be zero. Whatever was lost on any up grade would be regained on a succeeding down grade, or at any rate on the return trip. On the very lowest grades (the limits of which are defined later) we may consider this to be literally true, viz., that nothing is lost by their presence; whatever is temporarily lost in climbing them is either immediately regained on a subsequent light down grade or is regained on the return trip. If a stop is required at the bottom of a sag, there is a net and uncompensated loss of energy.

On the other hand, if the length of trains is limited by the grade, it will require more trains to handle a given traffic. The receipts from the traffic are a definite sum. The cost of handling it will be nearly in proportion to the number of trains. Assume that by lowering the rate of ruling grade it becomes possible to handle such an increased number of cars with one engine that four engines can haul as many cars on the reduced grade as five engines could haul on the higher grade and at a cost but slightly more than four-fifths as much. The effect of this on dividends may readily be imagined.

514. Application to the movement of trains of the laws of accelerated motion. When a train starts from rest and acquires its normal velocity, it overcomes not only the usual tangent resistances (and perhaps curve and grade resistances), but it also performs work in storing into the train a vast fund of kinetic energy. This work is not lost, for every foot-pound of such energy may later be utilized in overcoming resistances, provided it is not wasted by the action of train-brakes. If for a moment we consider that a train runs without any friction, then, when running at a velocity of v feet per second, it possesses a kinetic energy which would raise it to a height h feet, when $h=\frac{v^2}{2g}$, in which g is the acceleration of gravity $=32.16$. Assuming that the engine is exerting just enough energy to overcome the frictional resistances, the train would climb a grade until the train was raised h feet above the point where its velocity was v. When it had climbed a height h' (less than h) it would have a velocity $v_1=\sqrt{2g(h-h')}$. As a numerical illustration, assume $v=30$ miles per hour $=44$ feet per second. Then $h=\frac{v^2}{2g}=30.1$ feet, and assuming that the engine was exerting just enough force to overcome the rolling resistances on a level, the kinetic energy in the train would carry it for two miles up a grade of 15 feet per mile, or half a mile up a grade of 60 feet per mile. When the train had climbed 20 feet, there would still be 10.1 feet left and its velocity would be $v_1=\sqrt{2g(10.1)}=25.49$ feet per second $=17.4$ miles per hour. These figures, however, must be slightly modified on account of the weight and the revolving action of the wheels, which form a considerable percentage of the total weight of the train. When train velocity is being acquired, part of the work done is spent in imparting the energy of rotation to the driving-wheels and various truck-wheels of the train. Since these wheels run on the rails and must turn as the train moves, their rotative kinetic energy is just as effective—as far as it goes—in becoming transformed back into useful work. The proportion of this energy to the total kinetic energy has already been demonstrated (see Chapter XVI, § 435). The value of this correction is variable, but an average value of 5% has been adopted for use in the accompanying tabular form (Table XLII), in which is given the corrected "velocity head" corresponding to various velocities in miles per hour. The table is computed from the following formula:

$$\text{Velocity head} = \frac{v^2 \text{ in ft. per sec.}}{64.32} = \frac{2.151\,V^2 \text{ in m. per h.}}{64.32} = 0.03344\,V^2$$

adding 5% for the rotative kinetic energy of the wheels, $0.00167\,V^2$

The corrected velocity head therefore equals $0.03511\,V^2$

Part of the figures of Table XLII were obtained by interpolation and the final *hundredth* may be in error by one unit; but it may readily be shown that the final hundredth is of no practical importance. It is also true that the chief use made of this table is with velocities much less than 45 miles per hour. Corresponding figures may be obtained for higher velocities, if desired, by multiplying the figure for *half* the velocity by *four*.

515. Construction of a virtual profile. The following simple demonstration will be made on the basis that the ordinary tractive resistances and also the tractive force of the locomotive are independent of velocity. For a considerable range of velocity which includes the most common freight-train velocities the first assumption is practically true; the second assumption is so nearly true under certain possible operative conditions that it may serve as a preliminary to the more accurate solution. It may best be illustrated by considering a simple numerical example.

Assume that Fig. 213 shows the profile of a section of road and that the grade of *AE* is 0.40%, which is 21.12 feet per mile. Assume also that a freight engine is climbing up the grade at a uniform velocity of 20 miles per hour. But since the train is moving at 20 miles per hour it has a kinetic energy corresponding to a velocity of 14.05 feet (see Table XLII). At *A* it encounters a down-grade of 0.20 per cent, which is 1500 feet long. Although

AB has a down-grade of only 0.20%, its grade with respect to the up-grade of AE (0.40%) is 0.60%. Therefore B is 9.00 feet below B'. Since the work done by the engine would have carried the train up to the point B' with a velocity of 20 miles per hour, the *virtual* drop of 9 feet will increase the velocity head from 14.05 feet to 23.05 feet, which corresponds to the velocity of 25.6 miles per hour, and this will actually be the velocity of the train at the point B. At B the grade changes to a 1.0% up-grade for a distance of 2300 feet.

The approach of the grade BC to the grade $B'C$ is at the rate of $1.0-0.4=0.6\%$ and therefore, the point C will be reached in 1500 feet. In the remaining 800 feet the line will climb to D, which is 4.8 feet above D'. Although at B the train is moving at the rate of 25.6 miles per hour and the engine is working at such a rate that it will carry the train up a 0.4% grade, yet when climbing up a 1.0% grade it consumes its kinetic energy in overcoming the additional grade. When it reaches C, it has lost the additional kinetic energy which it gained from A to B, and as it continues it loses even more. When it reaches D, it has lost 4.8 feet more and its velocity head is reduced to $14.05-4.8=9.25$ ft., which corresponds to a velocity of 16.2 miles per hour. At D the grade changes to $+0.1\%$.

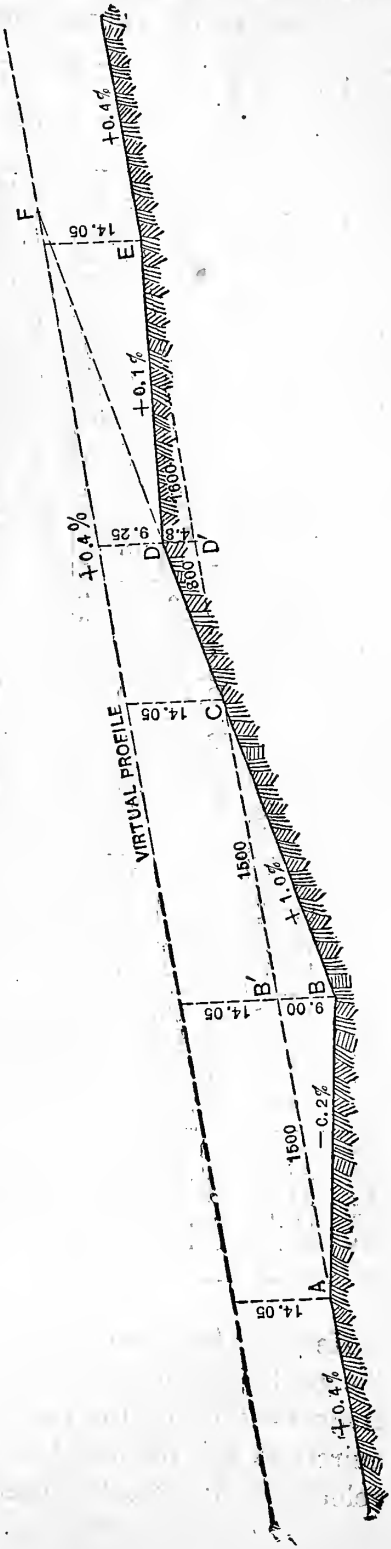


Fig. 213.—Typical Profile of Road Section.

TABLE XLII—VELOCITY HEAD (REPRESENTING THE KINETIC ENERGY) OF TRAINS MOVING AT VARIOUS VELOCITIES.

Vel. mi. hr.	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
5	0.88	0.91	0.95	0.99	1.02	1.06	1.10	1.14	1.18	1.22
6	1.26	1.31	1.35	1.40	1.44	1.48	1.53	1.58	1.62	1.67
7	1.72	1.77	1.82	1.87	1.92	1.97	2.03	2.08	2.14	2.19
8	2.25	2.30	2.36	2.42	2.48	2.54	2.60	2.66	2.72	2.78
9	2.85	2.91	2.97	3.04	3.10	3.17	3.24	3.30	3.37	3.44
10	3.51	3.58	3.65	3.72	3.79	3.87	3.95	4.02	4.10	4.17
11	4.25	4.33	4.41	4.49	4.57	4.65	4.73	4.81	4.89	4.97
12	5.06	5.15	5.23	5.32	5.41	5.50	5.58	5.67	5.75	5.84
13	5.93	6.02	6.12	6.21	6.31	6.40	6.50	6.59	6.69	6.78
14	6.88	6.98	7.08	7.19	7.29	7.39	7.49	7.60	7.70	7.80
15	7.90	8.00	8.11	8.22	8.33	8.44	8.55	8.66	8.77	8.88
16	8.99	9.10	9.21	9.32	9.43	9.55	9.67	9.79	9.91	10.03
17	10.15	10.27	10.39	10.51	10.63	10.75	10.87	10.99	11.12	11.25
18	11.38	11.50	11.63	11.76	11.89	12.02	12.15	12.28	12.41	12.55
19	12.68	12.81	12.95	13.08	13.22	13.35	13.49	13.63	13.77	13.91
20	14.05	14.19	14.33	14.47	14.61	14.75	14.89	15.04	15.19	15.34
21	15.49	15.64	15.79	15.94	16.09	16.24	16.39	16.54	16.69	16.84
22	17.00	17.15	17.30	17.46	17.62	17.78	17.94	18.10	18.26	18.42
23	18.58	18.74	18.90	19.06	19.22	19.38	19.55	19.72	19.89	20.06
24	20.23	20.40	20.57	20.74	20.91	21.08	21.25	21.42	21.59	21.77
25	21.95	22.12	22.30	22.48	22.66	22.84	23.02	23.20	23.38	23.56
26	23.74	23.92	24.10	24.28	24.46	24.65	24.84	25.03	25.22	25.41
27	25.60	25.79	25.98	26.17	26.36	26.55	26.74	26.93	27.13	27.33
28	27.53	27.73	27.93	28.13	28.33	28.53	28.73	28.93	29.13	29.33
29	29.53	29.73	29.93	30.13	30.34	30.55	30.76	30.97	31.18	31.39
30	31.60	31.81	32.02	32.23	32.44	32.65	32.86	33.08	33.30	33.52
31	33.74	33.96	34.18	34.40	34.62	34.84	35.06	35.28	35.50	35.72
32	35.95	36.17	36.39	36.62	36.85	37.08	37.31	37.54	37.77	38.00
33	38.23	38.46	38.69	38.92	39.15	39.38	39.62	39.86	40.10	40.34
34	40.58	40.82	41.06	41.30	41.54	41.78	42.02	42.26	42.51	42.76
35	43.01	43.26	43.51	43.76	44.01	44.26	44.51	44.76	45.01	45.26
36	45.51	45.76	46.01	46.26	46.52	46.78	47.04	47.30	47.56	47.82
37	48.08	48.34	48.60	48.86	49.12	49.38	49.64	49.91	50.18	50.45
38	50.72	50.99	51.26	51.53	51.80	52.07	52.34	52.61	52.88	53.15
39	53.42	53.69	53.96	54.23	54.51	54.79	55.07	55.35	55.63	55.91
40	56.19	56.47	56.75	57.03	57.31	57.59	57.87	58.16	58.45	58.74
41	59.03	59.32	59.61	59.90	60.19	60.48	60.77	61.06	61.35	61.64
42	61.94	62.23	62.52	62.82	63.12	63.42	63.72	64.02	64.32	64.62
43	64.92	65.22	65.52	65.82	66.12	66.43	66.74	67.05	67.36	67.67
44	67.98	68.29	68.60	68.91	69.22	69.53	69.84	70.15	70.46	70.78

Here we have the rather surprising condition that, although the grade is actually rising, it is virtually a down-grade under the given conditions, for the engine is working harder than is required to run up merely a 0.1% grade and hence will gain in velocity. At *E*, a distance of 1600 feet from *D*, it reaches what would have been a uniform 0.4% grade from A to E and the grade continues at that rate. Although the train has actually climbed 1.6 feet from D to E, it has virtually fallen the 4.8 feet between D and D', and the velocity head has increased from its value of 9.25 feet at D to 14.05 feet, and its velocity is again 20 miles per hour. The upper line represents the "virtual profile," which may always be drawn by measuring off to the proper scale at every point an ordinate which is the velocity head at that point. Since the engine is working uniformly, the virtual profile is in this case a straight line.

As another case, assume that a train is climbing the grade AE and exerting a pull just sufficient to maintain a constant velocity up that grade. Then $A'B'$ (parallel to AB) is the virtual profile, AA' representing the velocity head. A stop being required at C, steam is shut off and brakes are applied at B, and the velocity head BB' reduces to zero at C. The train starts from C, and at D attains a velocity corresponding to the ordinate DD'. At D the throttle may be slightly closed so that the velocity will be uniform and the virtual grade is $D'E'$, parallel to DE.

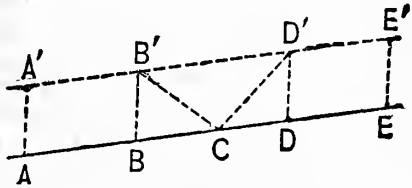


FIG. 214.

From the above it may be seen that a virtual profile has the following properties:

(*a*) When the velocity is *uniform*, the virtual profile is parallel with the actual.

(*b*) When the velocity is increasing the profiles are separating; when decreasing the profiles are approaching.

(*c*) When the velocity is zero the profiles coincide.

(*d*) The virtual grade at any place is a measure of the work required of the engine beyond that required to overcome merely the tractive resistances. If it is horizontal it shows that the engine is doing nothing besides overcoming the tractive resistances. If it is upward and is uniform, as in Fig. 213, it shows that it is working uniformly and is storing in the train "potential" energy which may be utilized on the return trip if it is not utilized to overcome tractive resistance in moving down a succeeding down-grade. If it is downward, as from B' to C, Fig. 214, it shows that the train is giving up kinetic energy, probably consuming most of it in brakes, but utilizing some of it to furnish the tractive power to run from B to C and also to overcome the grade from B to C.

516. Variation in draw-bar pull. The above demonstration has been made on the basis that the draw-bar pull is constant throughout. It is shown in Chapter XVIII that, when the engine is working at its full capacity the draw-bar pull decreases as the velocity increases, which is chiefly due to the fact that if we attempt to use full stroke at 2 M or 3 M velocity the steam will be so rapidly exhausted from the boiler that the pressure will fall. Therefore the valves are set to cut off so as to use the steam expansively but as this reduces the average pressure in the cylinder, then (see Eq. 103), the tractive power must be less. The reduction of tractive power for several multiples of M is shown in Table XXXIX. For example, in the numerical problem given above, and assuming the use of the Mikado engine whose characteristics have already been computed, the velocity at $A = 20 \div 6.167 = 3.25\ M$ and the tractive power at this velocity is 49.23% of its power at M velocity. From the tabular form in § 460 the draw-bar pull at 3.25 M-velocity may be found by interpolation to be 16587 lbs. Similarly at B the velocity is *expected* to be 25.6 m.p.h. $= 4.15\ M$, and then the tractive power is 38.48% and the draw-bar pull only 12484 lbs., about 75% of the pull at A. But since the draw-bar pull is so much reduced the velocity evidently would not be increased the theoretical amount due to the virtual drop BB'. On the other hand, when the train reaches D, where the velocity is *supposed* to be 16.2 m.p.h. $= 2.62\ M$, the draw-bar pull would be 20144, which is over 121% of the normal pull at 3.25 M velocity. The average pull between B and D is 16314 or within 2 % of the normal 16587. The average between A and E, assuming that the theoretical velocities at B and D were actually realized, would be about 2% below the assumed pull at A. The 3000-foot sag ABC will be passed in 90 seconds and no very great reduction in boiler power could take place in that time, especially if the fireman used extra care to maintain the pressure. Investigators have declared that tests of trains, with a dynamometer car between the tender and cars, have shown a practically uniform draw-bar pull, with an unchanged throttle and with velocities varying substantially on the principles indicated above. If the sag ABC is excessively long or deep the reduction of tractive force with increased velocity would be so great that the error of the method would be too great for practical use. But experience has proven that for ordinary cases the method can be used with substantial accuracy.

517. Use, value, and possible misuse. The essential feature respecting grades is the demand on the locomotive. From the foregoing it may readily be seen that the ruling grade of a road is not necessarily the steepest nominal grade. When a grade may be operated by momentum, i.e., when every train has an opportunity to take "a run at the hill," it may become a very harmless grade and not limit the length of trains, while another grade, actually much less, which occurs at a stopping-place for the heaviest trains, will require such extra exertion to get trains started that it may be the worst place on the road. Therefore the true way to consider the value of the grade at any critical place on the road is to construct a virtual profile for that section of the road. The required length of such a profile is variable, but in general may be said to be limited by points on each side of the critical section at which the velocity is definite, as at a stopping-place (velocity zero), or a long heavy grade where it is the minimum permissible, say M miles per hour.

Since the velocities of different trains vary, each train will have its own virtual profile at any particular place. Fast passenger trains are less affected than slow freight trains. The requirement of high average speed necessitates the use of powerful engines, and grades which would stall a heavy freight will only cause a momentary and harmless reduction of speed of the fast passenger train.

A possible misuse of virtual profiles lies in the chance that a station or railroad grade crossing may be subsequently located on a heavy grade that was designed to be operated by momentum. But this should not be used as an argument against the employment of a virtual profile. The virtual profile shows the *actual state of the case* and only points out the necessity, if an unexpected requirement for a full stoppage of trains at a critical point has developed, of changing the location (if a station), or of changing the grade by regrading or by using an overhead crossing.

518. Undulatory grades. Advantages. Money can generally be saved by adopting an actual profile which is not strictly uniform—the matter of compensation for curvature being here ignored. Its effect on the operation of trains is harmless provided the sag or hump is not too great. In Fig. 215 the undulatory grade may actually be operated as a uniform grade *AG*. The sag at *C* must be considered as a sag, even though *BC* is actually an up grade. But the engine is supposed to be working hard enough to carry a train at uniform velocity up a grade *AG*. Therefore it *gains* in velocity from *B* to *C*, and from *C* to *D* loses an equal amount. It may even be proven that the *time* re-

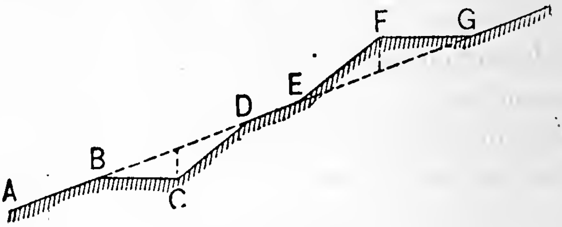


Fig. 215.

quired to pass the sag will be slightly less than the time required to run the uniform grade.

Disadvantages. The hump at *F* is dangerous in that, if the velocity at *E* is not equal to that corresponding to the extra velocity-head ordinate at *F*, the train will be stalled before reaching *F*. In practice there should be considerable margin. Any train should have a velocity of at least *M* (see § 455) in passing any summit. An extra heavy head wind, slippery rails, etc., may use up any smaller margin and stall the train. If the grade *AG* is a ruling grade, then *no* bump should be allowed under any circumstances. For the heaviest trains are supposed to be so made up that the engine will *just* haul them up the ruling grades—of course with some margin for safety. Any increase of this grade, however short, would probably stall the train.

Safe limits. Since over 99.4% of all freight cars are now equipped with train brakes and automatic couplers, there is not now the limitation which formerly existed about operating freight trains at high speeds, but it may frequently happen that it would be undesirable to run a freight train through a deep sag at such a velocity as would result from a free run and it would therefore become necessary to use brakes, which will add a distinct element of cost.

The term "safe limits" as used here, refers to the limits within which a freight train may be safely operated without the application of brakes or varying the work of the engine. Of course much greater undulations are frequently necessary and are safely operated, but it should be remembered that they add a distinct element to the cost of operating trains and that they must not be considered as harmless or that they should be introduced unless really necessary.

RULING GRADES.

519. Definition. Ruling grades are those which limit the weight of the train of cars which may be hauled by one engine. The subject of "pusher grades" will be considered later. For the present it will suffice to say that on all well-designed roads the large majority of the grades on any one division are kept below some limit which is considered the ruling grade. If a heavier grade is absolutely necessary no special expense will be made to keep it below a rate where the resistance is twice (or possibly three times) the resistance on the ruling grade, and then the trains can be hauled unbroken up these few special grades with the help of one (or two) pusher engines. So far as limitation of train length is concerned, these pusher grades are no worse than the regular ruling grades and, except for the expense of operating the pusher engines (which is a separate matter), they are not appreciably more expensive than any ruling grade. As before stated, the engineer cannot alter very greatly the ruling grade of the road when the general route has been decided on. He may remove sags or humps, or he may lower the natural grade of the route by development in order to bring the grade within the adopted limit of ruling grade.

520. Choice of ruling grade. It is of course impracticable for an engine to drop off or pick up cars according to the grades which may be encountered along the line. A train load is made up at one terminus of a division and must run to the other terminus. Excluding from consideration any short but steep grades which may *always* be operated by momentum, and also all pusher grades, the maximum grade on that division is the ruling grade.

It will evidently be economy to reduce the few grades which naturally would be a little higher than the great majority of others until such a large amount of grade is at some uniform limit that a reduction at all these places would cost more than it is worth. The precise determination of this limit is practically impossible, but an approximate value may be at once determined from a general survey of the route. The distance apart of consecutive control points (see § 18) into their difference of elevation is a first trial figure for the rate of the grade. If a grade even approximately uniform is impossible owing to the elevation of intervening ground, the worst place may be selected and the natural grade of that part of the route determined. If this grade is much steeper than the general run of the natural grades, it may be policy to reduce it by development or to boldly plan to operate that place as a pusher grade. The choice of possible grades thus has large limitations, and it justifies very close study to determine the best combination of grades and pusher grades. When the choice has narrowed down to two limits, the lower of which may be obtained by the expenditure of a definite extra sum, the choice may be readily computed, as will be developed.

521. Maximum train load on any grade. The Mikado locomotive, whose characteristics were analyzed in Chapter XVIII, has a net pulling power at the rim of the drivers, at M velocity, of 35758 lbs. which is 23.3% of 153,200, the weight on the drivers. This percentage is slightly over $\frac{9}{40}$. Increasing the percentage 6% on account of increased power at starting we have 24.7% or nearly $\frac{1}{4}$. On the other hand, wet, slippery rails may render the adhesion as low as $\frac{1}{5}$ and thus limit the actual drawing power. Although the real power of a locomotive depends on the velocity at which it seems desirable to run, the maximum tractive power at "M" velocity can always be approximately estimated as $\frac{1}{4}$ of the weight on the drivers. In Table XLIII are given the weights of several types of locomotives together with their tractive powers at three ratios of adhesion. These values are useful when the more elaborate method detailed in Chapter XVIII is not considered necessary.

The maximum train load on any grade depends on the character and number of the cars, as well as on their gross weight. The approximate resistance of cars is given by Eq. 121 as $R=2.2\,t+122\,n$. Applying this to a steel box-car weighing 24 tons net and loaded with 100,000 lbs., the resistance would be 285 lbs. or 3.85 lbs. per ton. Empty, the resistance would be 7.28 lbs. per

TABLE XLIII.—TRACTIVE POWER OF VARIOUS TYPES OF STANDARD-GAUGE LOCOMOTIVE AT VARIOUS RATES OF ADHESION.

Type of locomotive.	Total weight of engine and tender.		Weight of engine only.	Weight on the drivers.	Tractive power when ratio of adhesion is		
	Lbs.	Tons.			$\frac{1}{4}$	$\frac{9}{40}$	$\frac{1}{5}$
Atlantic, 4–4–2.....	340,000	170.0	199,400	105,540	26,385	23,740	21,100
Atlantic, 4–4–2, four cylinder compound	368,800	184.4	206,000	115,000	28,750	25,875	23,000
Pacific, 4–6–2......	343,600	171.8	218,000	142,000	35,500	31,950	28,400
Pacific, 4–6–2......	403,780	201.9	226,700	151,900	37,975	34,180	30,380
Ten-wheel, 4–6–0...	321,000	160.5	201,000	154,000	38,500	34,650	30,800
Prairie, 2–6–2......	366,500	183.2	212,500	154,000	38,500	34,650	30,800
Consolidation, 2–8–0	214,000	107.0	120,000	106,000	26,500	23,850	21,200
Consolidation, 2–8–0	366,700	183.3	221,500	197,500	49,375	44,440	39,500
Mikado, 2–8–2.....	405,500	202.7	259,000	196,000	49,000	44,100	39,200
Mikado, 2–8–2.....	315,000	157.5	196,100	153,200	38,300	34,470	30,640

ton. Applying the formula to a wooden box-car weighing 15 tons net and carrying 60,000 lbs., the resistances for the car full and empty would be 4.9 and 10.3 lbs. per ton, respectively. Three and 10 pounds per ton are the ordinary extremes. Although resistances of less than 3 lbs. per ton have been measured for whole trains of heavy-loaded coal cars, there are usually enough light-weight cars and empties in a train to increase the average per ton resistance to perhaps 6 lbs. per ton.

The Mikado locomotive, referred to above, had a draw-bar pull on a level at M velocity (6.167 m.p.h.) of 35,419 lbs. How much of a load could it draw up a 1.2% grade at M velocity? Assume that the cars have a weight and character such that the average resistance would be 6 lbs. per ton. The grade resistance of the locomotive is $315{,}000 \times .012 = 3780$, which subtracted from 35,419 leaves 31,639, the pull available for the cars. Then, calling T the tons weight of cars

$$31{,}639 = 6T + (20 \times 1.2 \times T) = 30T, \text{ and } T = 1054.$$

It should be noted that this computed tonnage is on the basis of an assumed tractive resistance of 6 lbs. per ton. In § 467 the tractive power of this same locomotive, on the same grade, is computed, by the regular rating formula, to be 16 fully loaded cars, weighing 70.8 tons per car, a total load of 1133 tons, *or* 53 empties, weighing 18 tons per car, a total load of 954 tons. The above value of T is approximately the mean of these two extremes. For general computations, when the character of the train load is unknowable, some such average value, as used above, is probably as accurate as it is possible to utilize it.

522. Proportion of the traffic affected by the ruling grade. Some very light traffic roads are not so fortunate as to have a traffic which will be largely affected by the rate of the ruling grade. When passenger traffic is light, and when, for the sake of encouraging traffic, more frequent trains are run than are required from the standpoint of engine capacity, it may happen that no passenger trains are really limited by any grade on the road—i.e., an extra passenger car *could* be added if needed. The maximum grade then has no worse effect (for passenger trains) than to cause a harmless reduction of speed at a few points. The local freight business is frequently affected in practically the same way. All coal, mineral, or timber roads are affected by the rate of ruling grade as far as such traffic is concerned. Likewise the through business in general merchandise, especially of the heavy traffic roads, will generally be affected by the rate of ruling grade. Therefore in computing the effect of ruling grade, the total number of trains on the road should not ordinarily be considered, but only the trains to which cars are added, until the limit of the hauling power of the engine on the ruling grades is reached.

PUSHER GRADES.

523. General principles underlying the use of pusher engines. On nearly all roads there are some grades which are greatly in excess of the general average rate of grade, and these heavy grades cannot usually be materially reduced without an expenditure which is excessive and beyond the financial capacity of the road. If no pusher engines are used, the length of all heavy trains is limited by these grades. The financial value of the reduction of such ruling grades has already been shown. But in the operation of pusher grades there is incurred the additional cost of pusher-engine service, for a pusher engine must run *twice* over the grade for each train which is assisted. It is possible for this additional expense to equal or even exceed the advantage to be gained. In any case it means the adoption of the lesser of two evils, or the adoption of the more economical method. The work of overcoming the normal resistances of so many loaded cars over so many miles of track and of lifting so many tons up the gross differences of elevation of predetermined points of the line is approximately the same whatever the exact route, and if the grades are so made that fewer engines working more constantly can accomplish the work as well as more engines which are not hard worked for a considerable proportion of the time, the economy is very apparent and unquestionable. Wellington expresses it concisely: "It is a truth of the first importance that the objection to high gradients is not the work which the engines have to do on them, but it is the work which they do *not* do when they thunder over the track with a light train behind them, from end to end of a division, in order that the needed power may be at hand at a few scattered points where alone it is needed."

524. Balance of grades for pusher service. Assume that both pusher and through engines are the Mikado engine with dimensions already given (§ 453), and that they will be operated at their most effective velocity, $M = 6.167$ m.p.h., and that the effective draw-bar pull of each is $37190 - 1771 = 35419$ lbs., less the locomotive grade resistance, which on a 1.9% grade is $20 \times 1.9 \times 157.5 = 5985$ lbs. The net draw-bar pull on this grade for each engine is, therefore, 29434 lbs. Assume that the train considered is made up of coal cars weighing 40000 lbs. net and carrying 100,000 lbs. each; also a caboose weighing 12 tons. Utilizing Eq. 121, the tractive resistance of a loaded coal car will be $2.2 \times 70 + 122 = 276$, and the grade resistance $20 \times 1.9 \times 70 = 2660$, making a total of 2936. The total for the caboose is $148 + 456 = 604$. The two engines have a net draw-bar pull of $2 \times 29434 = 58868$ lbs. Subtracting 604 for the caboose, there is left 58264 for coal cars. $58264 \div 2936 = 19.84$, the number of cars. Although the number of cars must, of course, be a whole number, the computation of the relative through and pusher grades requires that we use the fractional number. The tractive resistance of the 19.84 cars and caboose is $2.2\,[(19.84 \times 70) + 12] + (122 \times 20.84) = 5624$. The force available for grade is $35419 - 5624 = 29795$. The tonnage on the single engine grade is 157.5 (engine) plus $19.84 \times 70 = 1388.8$ (coal cars), plus 12 (caboose), or 1558.3 tons. $29795 \div 1558.3 = 19.12$ lbs. per ton, which is the grade resistance for a 0.956% grade. This means that the through grade can be made 0.956% and the corresponding pusher grade may be 1.9%. If the same problem is worked out on the basis of some other type of engine, which, perhaps, weighs considerably less, very nearly the same through grade to correspond with the pusher grade will be obtained. The above combination of unit car weights must be worked as 19 coal cars and a caboose and have a considerable margin of unused power. A different combination of car weights would use up the power with less or no margin, but in any case the computation of the corresponding lower grade, or the computation of an allowable pusher grade on the basis of a given through grade, should be made by using a fractional number of cars.

Since the pusher engine service is intermittent, and since it is working at full power for much less than half the time, it is practicable for the fireman to feed coal faster than the standard of 4000 lbs. of coal per hour while going up the pusher grade. The above computation was made on the basis of power production at the 4000-lb. rate. In § 457, it is shown that increasing the rate of coal consumption increases the value of M, and conversely when the locomotive is run at a velocity less than M the tractive power is increased, although the increase is disproportionately small. Increasing the tractive power of the pusher engine will increase the number of cars, although probably not as much as one car. Then the increase in car number will increase the computed resistance and *decrease* the amount available for grade. This decreased amount is divided by an increased number of tons and the amount of available for grade per ton is less and the computed through grade is less. Considering the very slight and disproportionate difference made by increasing the rate of coal consumption beyond the 4000-lb. standard, it is, perhaps, wisest to make the ratio of the grades on the basis of engines of equal power.

525. Two-pusher grades. It may happen, although rarely, that three systems of ruling grades may be necessary on one division, which may be so balanced that one unbroken train is handled with equal facility on through grades with one engine, on one-pusher grades with two engines and on two-pusher grades with three engines. The relation of these three grades may be computed on the same principles as are used above.

526. Operation of pusher engines. The maximum efficiency in operating pusher engines is obtained when the pusher engine is kept constantly at work, and this is facilitated when the pusher grade is as long as possible, i.e., when the heavy grades and the great bulk of the difference of elevation to be surmounted is at one place. For example, a pusher grade of three miles followed by a comparatively level stretch of three miles and then by another pusher grade of two miles cannot all be operated as cheaply as a continuous pusher grade of five miles. Either the two grades must be operated as a continuous grade of eight miles (sixteen pusher miles per trip) or else as two short pusher grades, in which case there would be a very great loss of time and a difficulty in so arranging the schedules that a train need not wait for a pusher or the pushers need not waste too much time in idleness waiting for trains. If the level stretch were imperative, the two grades would probably be operated as one, but an effort should be made to bring the grades together. It is not necessary to bring the trains to a stop to uncouple the pusher engine, but a stop is generally made for coupling on, and the actual cost in loss of energy and in wear and tear of stopping and starting a heavy train is as great as the cost of running an engine light for several miles.

There are two ways in which it is *possible* to economize in the use of pusher engines. (*a*) When the traffic of a road is so very light that a pusher engine will not be kept reasonably busy on the pusher grade it *may* be worth while to place a siding long enough for the longest trains both at top and bottom of the pusher grade and then take up the train in sections. Perhaps the worst objection to this method is the time lost while the engine runs the extra mileage, but with such very light traffic roads a little time more or less is of small consequence. On light traffic roads this method of surmounting a heavy grade will be occasionally adopted even if pushers are never used. If the traffic is fluctuating, the method has the advantage of only requiring such operation when it is needed and avoiding the purchase and operation of a pusher engine which has but little to do and which might be idle for a considerable proportion of the year. (*b*) The second possible method of economizing is only practicable when a pusher grade begins or ends at or near a station yard where switching-engines are required. In such cases there is a possible economy in utilizing the switching-engines as pushers, especially when the work in each class is small, and thus obtain a greater useful mileage. But such cases are special and generally imply small traffic.

A telegraph-station at top and bottom of a pusher grade is generally indispensable to effective and safe operation.

527. Length of a pusher grade. The virtual length of the pusher grade, as indicated by the mileage of the pusher engine, is always somewhat in excess of the true length of the grade as shown on the profile, and sometimes the excess length is very great. If a station is located on a lower grade within a mile or so of the top or bottom of a pusher grade, it will ordinarily be advisable to couple or uncouple at or near the station, since the telegraph-station, switching, and signaling may be more economically operated at a regular station. If the extra engine is coupled on ahead of the through engine (as is sometimes required by law for passenger trains) the uncoupling at the top of the grade may be accomplished by running the assistant engine ahead at greater speed after it is uncoupled, and, after running it on a siding, clearing the track for the train. But this requires considerable extra track at the top of the grade. Therefore, when estimating the length of the pusher grade, the most desirable position for the terminal sidings must be studied and the length determined accordingly rather than by measuring the mere length of the grade on the profile. Of course these odd distances are always *excess*; the coupling or uncoupling should not be done while on the grade.

528. The cost of pusher-engine service. When we analyze the elements of cost, we will find that many of them are dependent only on time, while others are dependent upon mileage. Still others are dependent on both. Very much will depend on the constancy of the service, and this in turn depends on the train schedule and on a variety of local conditions which must be considered for each particular case. The effect of a pusher-engine on maintenance of way may be considered on the basis that an engine is responsible for one-half of the deterioration of maintenance of way and structures, and, therefore, one-half of the percentage of the first 19 items in Table XLI or 9.06% of the average cost of a train-mile will be considered as chargeable for each mile of pusher engine service. Although the cost of repairs and renewals of engines is evidently a function of the mileage, and would therefore be somewhat less for a pusher-engine which did little work than for an engine which was worked to the limit of its capacity, yet it is only safe to make the same allowance as for other engines. Other items of maintenance of equipment are evidently to be ignored. The item of wages of enginemen will evidently depend upon the system employed on the particular road. Whatever the precise system

TABLE XLIV.—COST FOR EACH MILE OF PUSHER-ENGINE SERVICE.

Item number.	Item (abbreviated).	Normal average.	Per cent affected.	Cost per engine mile, per cent.
1–19	Track material, labor, bridges....	18.12%	50	9.06
25–27	Steam locomotives..............	9.24	100	9.24
80, 81	Road enginemen and engine-house expenses.....................	8.12	100	8.12
82–85	Fuel and other engine supplies....	11.27	100	11.27
90, 91, 94	Signaling, flagmen, and telegraph..	1.21	100	1.21
		....	....	38.90

the general result is to pay the enginemen as much in wages as the average payment for regular service, and therefore the full allowance for Item 80 will be made. Similarly we must allow the full cost of the items for engine supplies. While the engine is doing its heavy work in climbing up the grade, the consumption of fuel and water is certainly greater than the average; but, on the other hand, on the return trip, when the engine is running light, it probably runs for a considerable portion of the distance actually without steam, and therefore the consumption of fuel and water will nearly, if not quite, average the consumption for an engine running up and down grade along the whole line. That portion of fuel consumption which is due to radiation, blowing-off steam, and the many other causes previously enumerated, will be the same regardless of the work done. We therefore allow 100% for all of these items of engine supplies. In general we must add 100% for Items 90, 91, and 94, the cost of switchmen and telegraphic service. While there might be cases where there would be no actual addition to the pay-rolls or the operating expenses on account of these items, we are not justified in general in neglecting to add the full quota for such service. Collecting these items we will have 38.90% of the average cost of a train-mile for the cost of each mile run by the pusher engine. On the basis that the average cost of a train mile is $1.60, the cost of one mile of pusher engine service would be .3890×$1.60=62.24 cents. Assume that the pusher engine grade is five miles long but that the engine actually runs 11 miles on a round trip and that it makes 5 round trips or 55 miles per day. Then the daily cost would be .6224×55= $34.23 per day. Probably $25 to $30 per day should be charged up even if the mileage did not amount to as much, since many of the items in the cost of service are largely independent of mileage. On the other hand the pusher engine service renders unnecessary the extra trains which would have been required to handle the traffic with one engine over the steeper grades. The cost of these must be computed for each particular case.

BALANCE OF GRADES FOR UNEQUAL TRAFFIC.

529. Nature of the subject. It sometimes happens, as when a road runs into a mountainous country for the purpose of hauling therefrom the natural products of lumber or minerals, that the heavy grades are all in one direction—that the whole line consists of a more or less unbroken climb having perhaps a few comparatively level stretches, but no down grade (except possibly a slight sag) in the direction of the general up grade. With such lines this present topic has no concern. But the majority of railroads have termini at nearly the same level (500 feet in 500 miles has no practical effect on grade) and consist of up and down grades in nearly equal amounts and rates. The general rate of ruling grade is determined by the character of the country and the character and financial backing of the road to be built. It is always possible to reduce the grade at some point by "development" or in general by the expenditure of more money. It has been tacitly assumed in the previous discussions that when the ruling grade has been determined all grades in either direction are cut down to that limit. If the traffic in both directions were the same this would be the proper policy and sometimes is so. But it has developed, especially on the great east and west trunk lines, that the *weight* of the eastbound freight traffic is enormously greater than that of the westbound—that westbound trains consist very largely of "empties" and that an engine which could haul twenty loaded cars up a given grade in eastbound traffic could haul the same cars empty up a much higher grade when running west. As an illustration of the large disproportion which may exist, the eastbound ton-mileage on the P. R. R. between the years 1851 and 1885 was 3.7 times the westbound ton-mileage. Between the years 1876 and 1880 the ratio rose to more than 4.5 to 1. On such a basis it is as important and necessary to obtain, say, a 0.6% ruling grade against the eastbound traffic as to have, say, a 1.0% grade against the westbound traffic. This is the basis of the following discussion. It now remains to estimate the probable ratio of the traffic in the two directions and from that to determine the proper "balance" of the opposite ruling grades.

530. Computation of the theoretical balance. Assume first, for simplicity, that the exact business in either direction is accurately known. A little thought will show the truth of the following statements.

1. The locomotive and passenger-car traffic in both directions is equal.

2. Except as a road may carry emigrants, the passenger traffic in both directions is equal. Of course there are innumerable individual instances in which the return trip is made by another route, but it is seldom if ever that there is any marked tendency to uniformity in this. Considering that a car load of, say, 50 passengers at 150 pounds apiece weigh but 7500 pounds, which is $\frac{1}{10}$ of the 75000 pounds which the car may weigh, even a considerable variation in the number of passengers will not appreciably affect the hauling of cars on grades. On parlor-cars and sleepers the ratio of live load to dead load (say 20 passengers, 3000 pounds, and the car, 125000 pounds) is even more insignificant. The effect of passenger traffic on balance of grades may therefore be disregarded.

3. Empty cars have a greater resistance *per ton* than loaded cars. Therefore in computing the hauling capacity of a locomotive hauling so many tons of "empties," a larger figure must be used for the ordinary tractive resistances—say four pounds per ton greater.

4. Owing to greater or less imperfections of management a small percentage of cars will run empty or but partly full in the direction of greatest traffic.

5. Freight having great bulk and weight (such as grain, lumber, coal, etc.) is run from the rural districts toward the cities and manufacturing districts.

6. The return traffic—manufactured products—although worth as much or more, do not weigh as much.

As a simple numerical illustration assume that the weight of the cars is $\frac{1}{3}$ and the live load $\frac{2}{3}$ of the total load when the cars are "full"—although not loaded to their absolute limit of capacity. Assume that the relative weight of live load to be hauled in the other direction is but $\frac{1}{3}$; assume that the grade against the heaviest traffic is 0.9%. Since the tractive resistance per ton is considerably greater in the case of unloaded cars than it is in the case of loaded cars, allowance must be made for this in calculating the train resistance. Assuming the use of the Mikado locomotive described in § 453, its rating on a 0.9% grade, see § 467, equals

$$A=\frac{35758}{.009+.0011}-315,000=3,230,000=1615 \text{ tons, the "rating."}$$

Call W_E the total weight, live and dead, of the cars in an *east-bound* train, and W_W the corresponding weight for a west-bound train. F_E and F_W are the weights of live freight; w the dead weight of a car, which for simplicity is considered in this case to be uniformly a 100,000-lb. capacity car, weighing 20 tons or 40,000 lbs. The problem assumes that $F_W=\frac{1}{3}F_E$. Then $W_W=\frac{1}{3}F_E+nw$.

$$W_E=1615-6.0\,n \quad \text{(for a 0.9\% grade—see Table XL, § 467).}$$

By trial, it is found that for $n=24$, $W_E=1615-144=1471$, which means a total weight of 61.3 tons per car, or a net load of 41.3 tons or 82,600 lbs. live load per car. This fulfils the condition that the live load is $\frac{2}{3}$ of the total load as nearly as possible for an even number of car loads. $\frac{1}{3}$ of 41.3 tons, or 13.8 tons, plus 20 tons, gives an average load of 33.8 tons per car for west-bound trains, and for a train of 24 cars = 811.2 tons per train, or 1,622,400 lbs. Substituting in Eq. 122, § 467,

$$\frac{35758}{r+.0011}-315,000=1,622,400+24\frac{122}{r+.0011}.$$

Solving, $r=.0169$, or a 1.69% grade, which, *under the above assumptions and conditions*, is the grade on which the given type of locomotive could handle one-third of the live load which could be hauled up a 0.9% grade, in the same number of cars, by that same locomotive. It is interesting to note that the solution of this problem, given in a previous edition, using a more approximate method, and based on the use of a much lighter consolidation locomotive, weighing only 107 tons, gave 1.60% as the grade corresponding to 0.9% against east bound traffic. This substantial agreement, in spite of the difference in operating conditions, shows the substantial accuracy of the method for the solution of a problem for which the varying conditions of traffic in the two directions render useless any very precise solution.

Of course the actual traffic in the two directions, and their ratio, will vary from time to time, and the actual operation of trains will vary accordingly, and therefore the relation of ruling grades in the two directions, for maximum efficiency of operation, will fluctuate accordingly, while the ruling grades, once established, are practically finalities. Therefore any close precision in the computation of these relative grades is useless. Nevertheless the above calculation shows unmistakably that under the given conditions, a very considerable variation in the rate of grade in opposite directions is not only justifiable, but a neglect to allow for it would be a great economic error.

531. Computation of relative traffic. Some of the principal elements have already been referred to, but in addition the following facts should be considered.

(*a*) The greatest disparity in traffic occurs through the handling of large amounts of coal, lumber, iron ore, grain, etc. On roads which handle but little of these articles or on which for local reasons coal is hauled one way and large shipments of grain the other way the disparity will be less and will perhaps be insignificant.

(*b*) A marked change in the development of the country may, and often does, cause a marked difference in the disparity of traffic. The heaviest traffic (in mere weight) is always toward manufacturing regions and away from agricultural regions. But when a region, from being purely agricultural or mineral, becomes largely manufacturing, or when a manufacturing region develops an industry which will cause a growth of heavy freight traffic from it, a marked change in the relative freight movement will be the result.

(*c*) Very great fluctuations in the relative traffic may be expected for prolonged intervals.

(*d*) An estimate of the relative traffic may be formed by the same general method used in computing the total traffic of the road (see § 473, Chapter XIX) or by noting the relative traffic on existing roads which may be assumed to have practically the same traffic as the proposed road will obtain.

CHAPTER XXIV.

THE IMPROVEMENT OF OLD LINES.

532. Classification of improvements. The improvements here considered are only those of alignment—horizontal and vertical. Strictly there is no definite limit, either in kind or magnitude, to the improvements which may be made. But since a railroad cannot ordinarily obtain money, even for improvements, to an amount greater than some small proportion of the previously invested capital, it becomes doubly necessary to expend such money to the greatest possible advantage. It has been previously shown that securing additional business and increasing the train load are the two most important factors in increasing dividends. After these, and of far less importance, come reductions of curvature, reductions of distance (frequently of doubtful policy, see Chap. XXI, § 503), and elimination of sags and humps. These various improvements will be briefly discussed.

(a) **Securing additional business.** It is not often possible by any small modification of alignment to materially increase the business of a road. The cases which do occur are usually those in which a gross error of judgment was committed during the original construction. For instance, in the early history of railroad construction many roads were largely aided by the towns through which the road passed, part of the money necessary for construction being raised by the sale of bonds, which were assumed or guaranteed and subsequently paid by the towns. Such aid was often demanded and exacted by the promoters. Instances are not unknown where a failure to come to an agreement has caused the promoters to deliberately pass by the town at a distance of some miles, to the mutual disadvantage of the road and the town. If the town subsequently grew in spite of this disadvantage, the *annual* loss of business might readily amount to more than the original sum in dispute.

Such an instance would be a legitimate opportunity for study of the advisability of re-location.

As another instance (the original location being justifiable) a railroad might have been located along the bank of a considerable river too wide to be crossed except at considerable expense. When originally constructed the enterprise would not justify the two extra bridges needed to reach the town. A growth in prosperity and in the business obtainable might subsequently make such extra expense a profitable investment.

(b) **Increasing the train load.** On account of its importance this will be separately considered in § 535 *et seq.*

(c) **Reduction in curvature and distance and the elimination of sags and humps.** Such improvements are constantly being made by all progressive roads. The need for such changes occurs in some cases because the original location was very faulty, the revised location being no more expensive than the original, and in other cases because the original location was the best that was then financially possible and because the present expanded business will justify a change.

(d) **Changing the location of stations or of passing sidings.** The station may sometimes be re-located so as to bring it nearer to the business center and thus increase the business done. But the principal reasons for re-locating stations or passing sidings is that starting trains may have an easier grade on which to overcome the additional resistances of starting. Such changes will be discussed in detail in § 537.

533. Advantages of re-locations. There are certain undoubted advantages possessed by the engineer who is endeavoring to improve an old line.

(*a*) The gross traffic to be handled is definitely known.

(*b*) The actual cost per train-mile for that road (which *may* differ very greatly from the average) is also known, and therefore the value of the proposed improvement can be more accurately determined.

(*c*) The actual performance of such locomotives as are used on the road may be studied at leisure and more reliable data may be obtained for the computations.

534. Disadvantages of re-locations. The disadvantages are generally more apparent and frequently appear practically insuperable—more so than they prove to be on closer inspection (*a*) It frequently means the abandonment of a greater or less length of old line and the construction of new line. At first thought it might seem as if a change of line such as would permit an increase of train-load of 50 or perhaps 100% could never be obtained, or at least that it could not be done except at an impracticable expense. On the contrary a change of 10% of the old line is frequently all that is necessary to reduce the grades so that the train-loads hauled by one engine may be nearly if not quite doubled. And when it is considered that the cost of a road to sub-grade is generally not more than one-third of the total cost of construction and equipment per mile, it becomes plain that an expenditure of but a small percentage of the original outlay, expended where it will do the most good, will often suffice to increase enormously the earning capacity.

(*b*) One of the most difficult matters is to convince the financial backers of the road that the proposed improvement will be justifiable. The cause is simple. The disadvantages of the original construction lie in the large increase of certain items of expense which are necessary to handle a given traffic. And yet the fact that the expenditures are larger than they need be are only apparent to the expert, and the fact that a saving may be made is considered to be largely a matter of opinion until it is demonstrated by actual trial. On the other hand the cost of the proposed changes is definite, and the very fact that the road has been uneconomically worked and is in a poor financial condition makes it difficult to obtain money for improvements.

(*c*) The legal right to abandon a section of operated line and thus reduce the value of some adjoining property has sometimes been successfully attacked. A common instance would be that of a factory which was located adjoining the right of way for convenience of transportation facilities. The abandonment of that section of the right of way would probably be fatal to the successful operation of the factory. The objection may be largely eliminated by the maintenance of the old right of way as a long siding (although the business of the factory might not be worth it), but it is not always so easy of solution, and this phase of the question must always be considered.

REDUCTION OF VIRTUAL GRADE.

535. Obtaining data for computations. As developed in the last chapter (§§ 515–517) the real object to be attained is the reduction of the *virtual grade.* The method of comparing grades under various assumed conditions was there discussed. When the road is still "on paper" some such method is all that is possible; but when the road is in actual operation the virtual grade of the road at various critical points, with the rolling stock actually in use, may be determined by a simple test and the effect of a proposed change may be reliably computed. Bearing in mind the general principle that the virtual grade line is the locus of points determined by adding to the actual grade profile ordinates equal to the velocity head of the train, it only becomes necessary to measure the velocity at various points. Since the velocity is *not* usually uniform, its precise determination at any instant is almost impossible, but it will generally be found to be sufficiently precise to assume the velocity to be uniform for a short distance, and then observe the time required to pass that short space. Suppose that an ordinary watch is used and the time taken to the nearest second. At 30 miles per hour, the velocity is 44 feet per second. To obtain the time to within 1%, the time would need to be 100 seconds and the space 4400 feet. But with variable velocity there would be too great error in assuming the velocity as uniform for 4400 feet or for the time of 100 seconds. Using a stop-watch registering fifths of a second, a 1% accuracy would require but 20 seconds and a space of 880 feet, at 30 miles per hour. Wellington suggests that the space be made 293 feet 4 inches, or $\frac{1}{18}$ of a mile; then the speed in miles per hour equals $200 \div s$, in which s is the time in seconds required to traverse the 293′ 4″. For instance, suppose the time required to pass the interval is 12.5 seconds. $\frac{1}{18}$ mile in 12.5 seconds = one mile in 225 seconds, or 16 miles per hour. But likewise $200 \div 12.5 = 16$, the required velocity. The following features should be noted when obtaining data for the computations:

(*a*) All critical grades on the road should be located and their profiles obtained—by a survey if necessary.

(*b*) At the bottom and top of all long grades (and perhaps at intermediate points if the grades are very long) spaces of known length (preferably $293\frac{1}{3}$ feet) should be measured off and marked by flags, painted boards, or any other serviceable targets.

(*c*) Provided with a stop-watch marking fifths of seconds the observer should ride on the trains affected by these grades and note the exact interval of time required to pass these spaces. If the space is $293\frac{1}{3}$ feet, the velocity in miles per hour $= 200 \div$ interval in seconds. In general, the velocity in miles per hour,

$$V = \frac{\text{distance in feet} \times 3600}{\text{time in seconds} \times 5280}.$$

(*d*) Since these critical grades are those which require the greatest tax on the power of the locomotive, the conditions under which the locomotive is working must be known—i.e., the steam pressure, point of cut-off, and position of the throttle. Economy of coal consumption as well as efficient working at high speeds requires that steam be used expansively (using an early cut-off), and even that the throttle be partly closed; but when an engine is slowly climbing up a maximum grade with a full load it is not exerting its maximum tractive power unless it has its maximum steam pressure, wide-open throttle, and is cutting off nearly at full stroke. These data must therefore be obtained so as to know whether the engine is developing at a critical place all the tractive force of which it is capable. The condition of the track (wet and slippery or dry) and the approximate direction and force of the wind should be noted with sufficient accuracy to judge whether the test has been made under ordinary conditions rather than under conditions which are exceptionally favorable or unfavorable.

(*e*) The train-loading should be obtained as closely as possible. Of course the dead weight of the cars is easily found, and the records of the freight department will usually give the live load with all sufficient accuracy.

536. Use of the data obtained. A very brief inspection of the results, freed from refined calculations or uncertainties, will demonstrate the following truths:

(*a*) If, on a uniform grade, the velocity increases, it shows that, under those conditions of engine working, the load is less than the engine can handle on that grade.

(*b*) If the velocity decreases, it shows that the load is greater than the engine can handle on an indefinite length of such grade. It shows that such a grade is being operated by momentum. From the rate of decrease of velocity the maximum practicable length of such a grade (starting with a given velocity) may be easily computed.

(*c*) By combining results under different conditions of grade but with practically the same engine working, the tractive power of the engine may be determined (according to the principles previously demonstrated) for any grade and velocity. For example: On an examination of the profile of a division of a road the maximum grade was found to be 1.62% (85.54 feet per mile). At the bottom and near the top of this grade two lengths of 293′ 4″ are laid off. The distance between the centers of these lengths is 6000 feet. A freight train moving up the grade is timed at $9\frac{2}{5}$ seconds on the lower stretch and $7\frac{3}{5}$ seconds on the upper. These times correspond to $\frac{200}{9.4}$ and $\frac{200}{7.6}$ or 21.3 and 26.3 miles per hour respectively. It is at once observed that the velocity has increased and that the engine could draw even a heavier load up such a grade for an indefinite distance. How much heavier might the load be?

For simplicity we will assume that the conditions were normal, neither exceptionally favorable nor unfavorable, and that the engine was worked to its maximum capacity. The engine is a "consolidation" weighing 128700 pounds, with 112600 pounds on the drivers. The train-load behind the engine consists of ten loaded cars weighing 465 tons and eleven empties weighing 183 tons, thus making a total train-weight of 712 tons. Applying Eq. 106, we find that the *additional* force which the engine has actually exerted per ton in increasing the velocity from 21.3 to 26.3 miles per hour in a distance of 6000 feet is

$$P = \frac{70}{6000}(26.3^2 - 21.3^2) = 2.78 \text{ pounds } \textit{per ton.}$$

The grade resistance on a 1.62% grade is 32.4 pounds per ton. The average train resistance may be computed from §§ 429 and 439.

Engine resistance, at say 8 m.p.h. (§ 429)	=1615 lbs.
Cars resistance, $(648 \times 2.2) + (21 \times 122)$	=3988 lbs.
Total tractive resistance on level	=5603 lbs.

The average tractive resistance is therefore $5603 \div 712 = 7.87$ pounds per ton. Adding the grade resistance (32.4) we have a total train resistance of 40.27 pounds per ton. But, computing from the increase in velocity, the locomotive is evidently exerting a pull of 2.78 pounds per ton in excess of the computed required pull on that grade, or a total pull of 43.05 pounds per ton. Therefore the train load might have been increased proportionately and might have been made

$$712 \times \frac{2.78 + 40.27}{40.27} = 761 \text{ tons.}$$

This shows that 49 tons additional might have been loaded on to the train, or say, three more empties or one additional loaded car.

A pull of 43.05 pounds per ton means a total adhesion at the drivers of 30,652 pounds, which is about 27% of the weight on the drivers—112,600 pounds. This indicates average conditions as to traction, and as good as can be depended on for regular service.

The above calculation should of course be considered simply as a "single observation." The performance of the same engine on the same grade (as well as on many other grades) on succeeding days should also be noted. It may readily happen that variations in the condition of the track or of the handling of the engine may make considerable variation in the results of the several calculations, but when the work is properly done it is always possible to draw definite and very positive deductions.

537. Reducing the starting grade at stations. The resistance to starting a train is augmented from two causes: (*a*) the tractive resistances are usually about 20 pounds per ton instead of, say, 6 pounds, and (*b*) the inertia resistance must be overcome. The inertia resistance of a freight train (see § 435) which is expected to attain a velocity of 15 miles per hour in a distance of 1000 feet is (see Eq. 140)

$$P = \frac{70}{1000}(15^2 - 0) = 15.8 \text{ pounds per ton,}$$

which is the equivalent of a 0.79% grade. Adding this to a grade which nearly or quite equals the ruling grade, it virtually creates a new and higher ruling grade. Of course that additional force can be greatly reduced at the expense of slower acceleration, but even this cannot be done indefinitely, and an acceleration to only 15 miles per hour in 1000 feet is as slow as should be allowed for. With perhaps 14 pounds per ton additional tractive resistance, we have about 30 pounds per ton additional—equivalent to a 1.5% grade. Instances are known where it has proven wise to create a *hump* (in what was otherwise a uniform grade) at a station. The effect of this on high-speed passenger trains moving *up* the grade would be merely to reduce their speed very slightly. No harm is done to trains moving *down* the grade. Freight trains moving *up* the grade and intending to stop at the station will merely have their velocity reduced as they approach the station and will actually save part of the wear and tear otherwise resulting from applying brakes. When the trains start they are assisted by the short down grade, just where they need assistance most. Even if the grade *CD* is still an up grade, the pull required at starting is *less* than that required on the uniform grade by an amount equal to 20 times the difference of the grade in per cent.

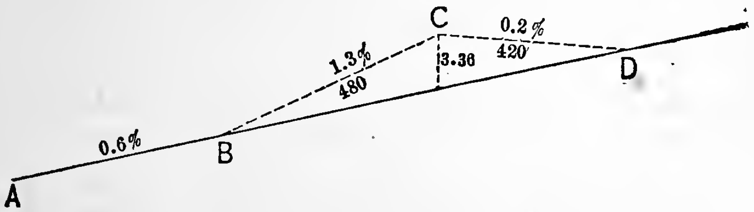


FIG. 216.

CHAPTER XXV.

STRESSES IN TRACK.

538. Nature of the subject. The character and amount of the stresses in the rails, rail fastenings and ties, which make up the track, and the intensity and distribution of the pressure which is transmitted by the ties through the ballast and embankment to the subsoil, have long been a subject of investigation by railroad engineers. The complexity of the subject is too great for a dependence on mere theoretical analysis. Even experimental work must be so elaborate that no one person or single individual railroad have hitherto obtained conclusive results, except upon isolated details.

In 1913, a committee was appointed by the Amer. Rwy. Eng. Assoc. who cooperated with a similar committee appointed by the Amer. Soc. of Civil Engineers. Both societies appropriated money for the large expenses involved. Several railroads cooperated by furnishing facilities for experimental work. Several steel-rail corporations contributed funds. Special instruments were designed for experimental use. After five years of work, a progress report, covering 184 pages, was made to the 1918 convention of the Amer. Rwy. Eng. Assoc. The second progress report (170 pp.) was made to the 1920 convention. The investigation is not yet (1921) complete. But from these two voluminous reports, which indicate the magnitude of the problem, the following very condensed summary has been compiled. The thoroughness of the investigation is indicated by the fact that the number of observations for rail strain only, made, read, recorded and reduced, and on which the first progress report was partly based, is more than 250,000. The conclusions, which can be drawn from the tests made, have already had their effect in modifying track construction, and will probably have still greater effect when the principles underlying the stresses in track, due to rapidly moving and very heavy rolling-stock, are more thoroughly comprehended and when these principles have crystallized into definite rules of practice.

539. Action of track as an elastic structure. Wheel loads bear vertically, but usually with some horizontal component, on a rail. The rails are flexible beams, supported by flexible ties, which are supported by a more or less yielding but elastic ballast, which rests on a more or less yielding subsoil. For convenience, the term **modulus of elasticity of rail support** is used as a measure of the vertical stiffness of the rail support, and is defined as "the pressure per unit of length of each rail required to depress the track one unit." For example, a series of wheel loads, equivalent to 10,000 pounds per tie for each rail, depress the track an average of 0.3 inch. Then, on the basis of proportionality of depression to pressure, 33,333 lbs. would produce one inch of depression, which for a tie spacing of 22 inches would require a pressure of 33,333 ÷ 22 = 1515 lbs. per inch of length of rail per inch of depression. The elasticity and flexibility of these various materials affects the stresses to which they are subject. The spacing of wheels along a rail also affects very greatly the intensity and character of the stresses produced in the rails and ties. Although a purely theoretical solution is unsatisfactory and inadequate, a theoretical study makes it possible to limit the scope of the necessary experimental work. Theoretical analysis shows that the bending moment of a rail will be comparatively large for a single concentrated load with no appreciable loads sufficiently near to hold the rail down and produce a negative bending moment at an adjacent point, thus reducing the positive moment immediately under the concentrated load. But railroad loadings are always in groups. A heavy driver-load is almost invariably preceded and followed by a comparatively light truck-wheel load, if not by another driver. The variation in operating conditions as to spacing and intensity of wheel loads limits the use of precise calculations for purposes of generalization, but analysis (which is substantially confirmed by experimental tests) shows that "the assumption of a continuous elastic support under the rail is by far the most convenient, most easily applied and most comprehensive in its application to the questions involved in the work of the committee."

540. Typical track depression profile for static load on one or two axles. See Fig. 217. Note that the depression for one axle extends for about ten tie spaces and that the rail is somewhat raised *above* the normal height beyond a distance of about

5 tie spaces from the load even if there is a comparatively light wheel load on the rail at that point. The deflection is of course maximum directly under the load and it makes almost

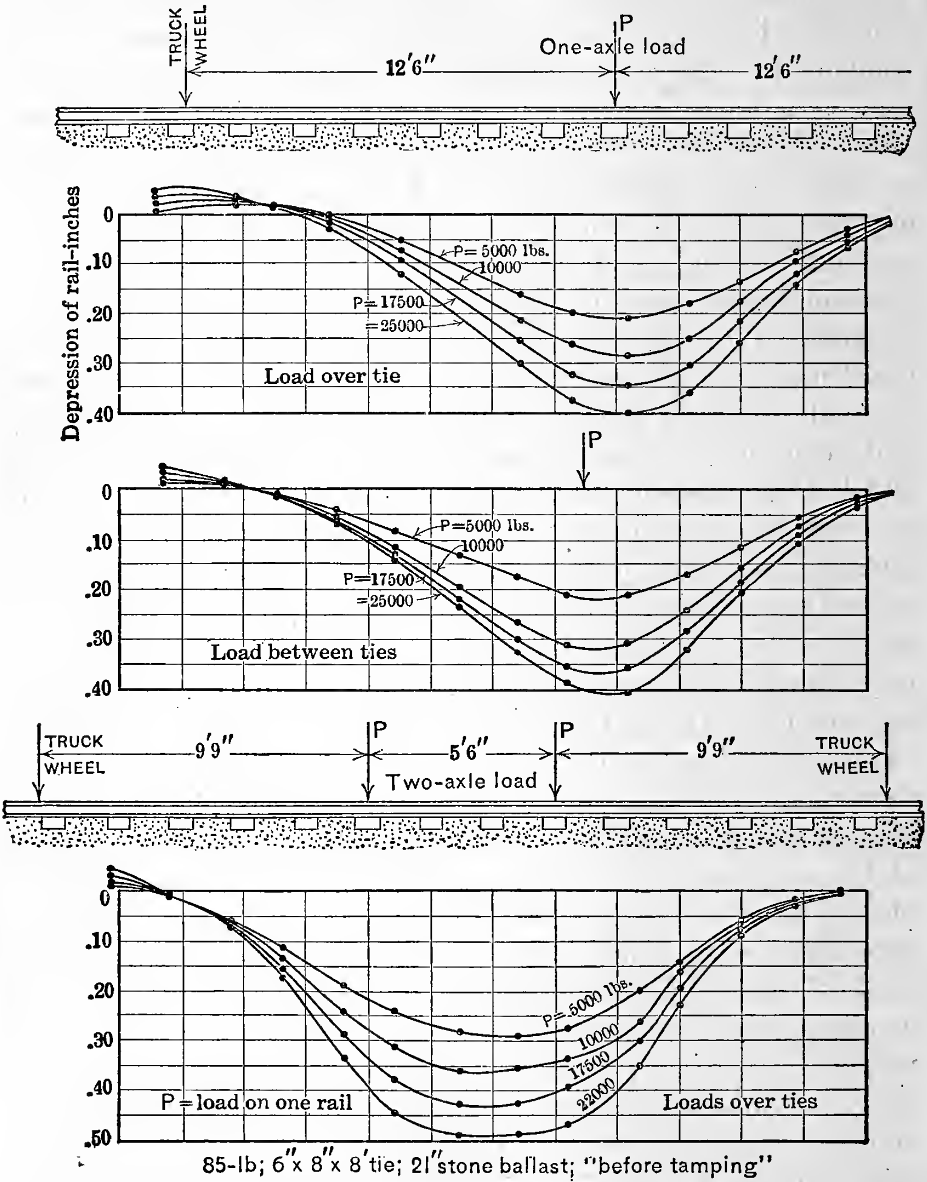


FIG. 217.—TRACK DEPRESSION PROFILES, STATIC LOAD ON ONE AND TWO AXLES.

no difference whether the load is directly above a tie or between two ties. The curves are substantially identical, merely moved along as the load moves. The amount of the depression for a given load varies with the character of the ballast and the tamping, whether recent or old, as was shown by the numerous other similar profiles given in the report. The effect of recent tamping was investigated and it was shown that the depression under a load on recently tamped track is nearly proportional to the loading, which implies a nearly constant "modulus of elasticity of rail support." On the other hand, if track has not been tamped for several months, there is a comparatively deep depression for the first 5000 lbs., proportionately less for the next additional

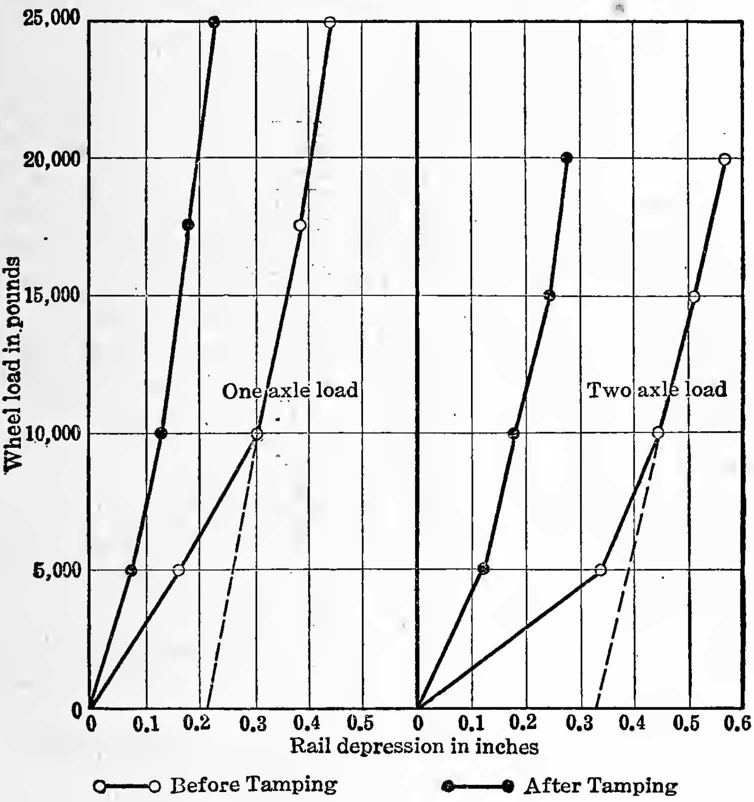


FIG. 218.—TIE DEPRESSION DIAGRAM, STATIC LOADS.

5000 lbs., and perhaps still less for additional increments. This is also shown by Fig. 218, which shows the "after tamping" curve to be nearly a straight line; the "before tamping" curve is much more curved. It should be noted that the "before tamping" depression line is nearly a straight line *after* it is loaded to about 10,000 lbs. In later investigations this fact was utilized by producing this nearly straight line back to the line of zero pressure, as shown by the dotted line. The intercept on the line of zero wheel-load is a measure of the depression of the tie before it has its full bearing on the ballast. As a part of the investigation on the stresses and the elastic curve of a tie under load, the depression of a tie was very accurately measured at several points along the tie and for a regular series of light to heavy loads. For all cases where the tamping had not been recent (or "before tamping") a curve, similar to those of Fig. 218, was drawn for each point along the tie. Producing the depression line backward to the point of zero loading gives an intercept which is called "the initial position of the ballast bed with respect to the bottom of the tie for the compact condition of ballast existing in the track." Of course this does not mean that there is such an actual gap between the under side of the tie and the ballast, but such gap as may exist at some points along the tie will make up a large part of this initial depression. A comparison of similar curves for light and heavy rails proves what might have been predicted, that the depression under a heavy rail for a given load is less than that under a light load. The heavy rail, by its extra stiffness, distributes the loading over a greater number of ties and the one or two ties nearly under the load do not need to carry such a large proportion of the total.

A broad general idea of the depressions due to track loading and of the proportions of the total depression due to rail, tie, ballast and sub-soil, may be obtained from the following figures, which, however, must be considered as very approximate and subject to great variation.

Division of depressions of track under drivers of Mikado locomotive:

1. Compression of tie under rail, plus effect of bending of tie to bring it to full bearing on the ballast along its length	0.05 in.
2. Compression of 24″ of stone ballast immediately under the rail	0.15 in.
3. Compression of roadway immediately under the rail	0.15 in.
	0.35 in.

Bending of 85-lb. rail between ties spaced 22″ c.c. by a Mikado locomotive not more than 0.01.″

541. Bending moment and depression in a rail due to a group of loads. Fig. 219 shows graphically the relative bending moments under each wheel of a Mikado locomotive. The light lines show the curves of moments due to each wheel; the heavier lines give the algebraic summation of the effects of all the wheels. Note (*a*) that the effect of each wheel is maximum directly under that wheel but the effect continues even beyond adjacent wheels; (*b*) a wheel usually develops a *negative* moment under an adjacent wheel, which reduces the positive moment developed by the adjacent wheel; (*c*) as an example, calling the moment developed by the second driver (counting

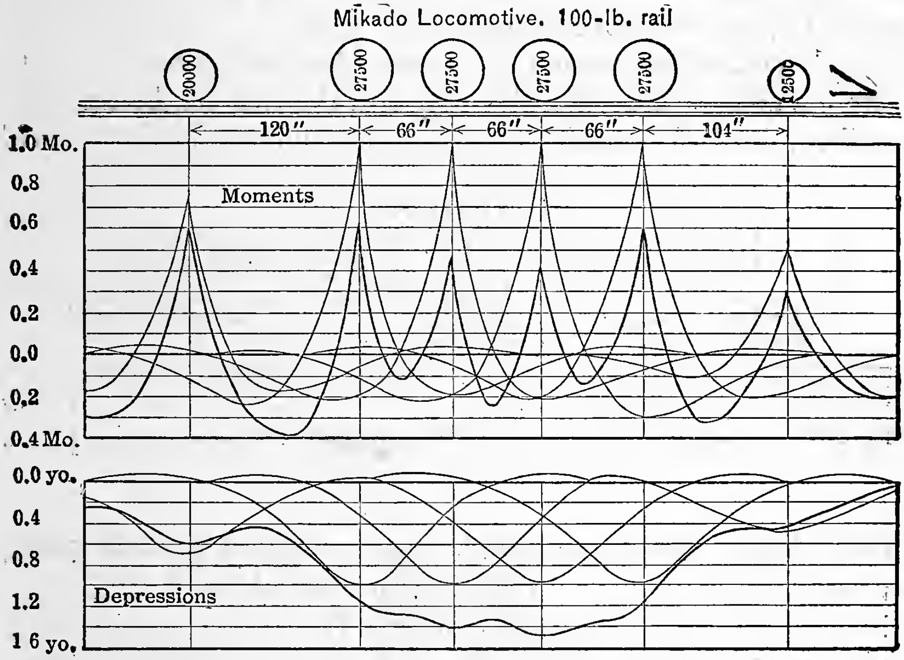


FIG. 219.—BENDING MOMENTS AND DEPRESSIONS. COMBINATION OF LOADS.

from right to left) under the second driver $= +1.00$, the effect of the first driver is -0.20; the effect of the third driver is -0.20; that of the fourth driver is -0.05; the effect of the pilot is zero and likewise the effect of the trailer. The net effect is that the combination of wheels develops a moment under the second driver of only 55% of that due to the second driver if it acted alone. Similarly the *depression* of rail produced by a wheel is maximum under that wheel, but it develops an upward force which may reduce the depression under some other wheel, although probably not the adjacent wheel. For example, calling the depression produced by the first driver $= +1.00$, the effect of the second driver is to cause a further depression under the first driver equal to +0.23; the third driver has an added effect of − 0.04; the effect of the pilot truck is negligible. The net effect is a depression under the first driver which is 1.19 times the depression which the first driver alone would cause. Note that, although there is depression under all the wheels, the depression between the fourth driver and the trailer is less than that under the trailer. Between the two trucks of a car, the depression is usually negative, i.e., the rails are curved upward *above* their normal position.

542. Special instruments and devices for making tests. Tests were made to measure the depression of the rail, tie, ballast and roadbed, both for static loads and for moving loads. Static

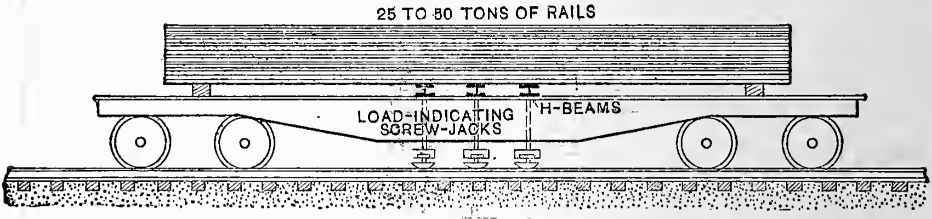


FIG. 220.—LOADING DEVICE FOR PRODUCING ANY DESIRED ONE-AXLE OR TWO-AXLE LOADS.

loads of any desired magnitude were produced by spotting a carload of 25 to 50 tons of rails over the track to be tested. Two H-beams (for two-axle loads) or one H-beam (for single-axle loads) were placed under the load of rails, each H-beam being supported by two struts having load-indicating screw jacks, which were carried on curved bearing blocks, placed on the track rails, the blocks having the same radius as car wheels but without coning. Since the bearing blocks were under the center of the car and were 12 to 15 feet in either direction from the car wheels, the effect of the car wheels was nearly negligible and was so considered.

Unit rail stress. The stretching of the base of the rail under a static load was measured with a Berry **strain gage** just as any such stress in metal is measured in a testing laboratory. The Berry strain gage is not applicable for observing the rapidly changing stresses due to moving loads, which therefore require the use of a **stremmatograph.** The form used will record at any instant, on a revolving disk any minute variation in the distance apart of a pair of gage points drilled in the base of the rail exactly 4″ apart.

Unit pressures. The unit pressure exerted at any depth of the ballast was measured by a **pressure capsule.** As shown in Fig. 221, the ballast bears on a circular bearing plate, having an area of 5 sq. in., which transmits the pressure to a thin

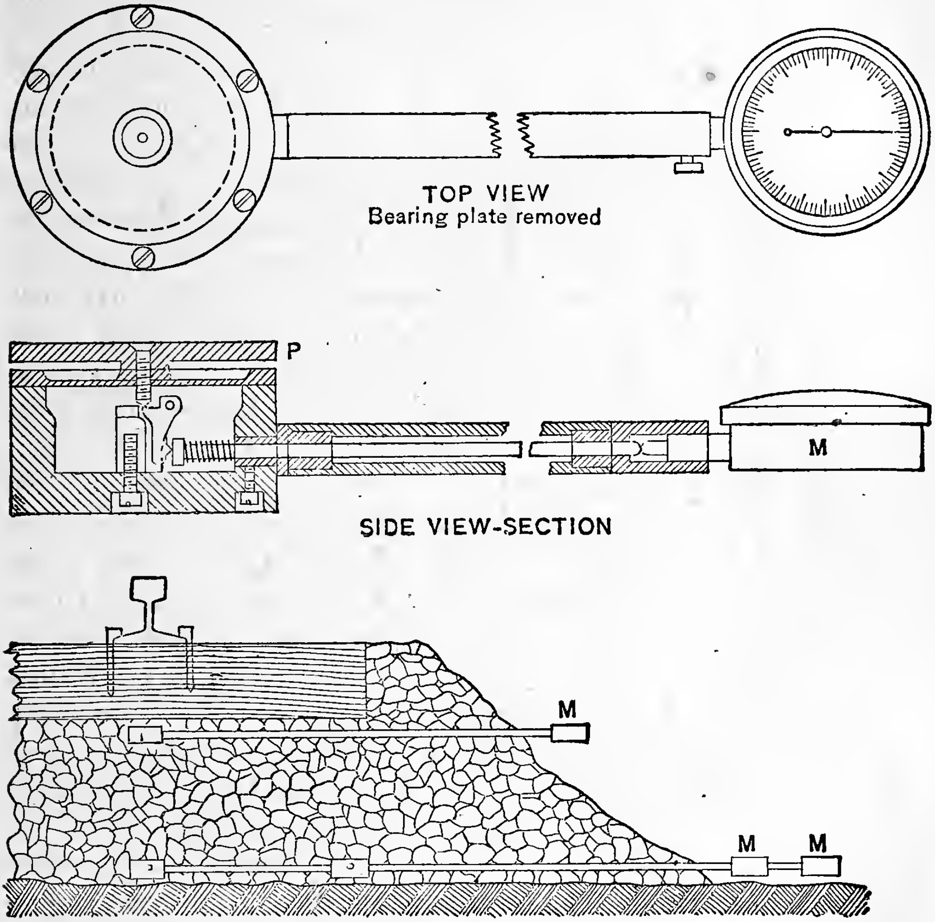


FIG. 221.—PRESSURE CAPSULES.

steel diaphragm. The movement of the diaphragm actuates a simple mechanism which pushes a rod enclosed in a pipe leading to a dial located outside the ballast. The mechanism is calibrated by observing the readings for known pressures. Several of these capsules are inserted in the ballast almost immediately under the tie, and also at the bottom of the ballast just above sub-grade, as shown in Fig. 221. The simple dial form is used to measure the pressure produced by static loads.

For moving loads, the mechanism operates a stylus which makes a record on a revolving disk.

Depression plugs. The actual depression of the ballast at any depth, or of the sub-soil at subgrade, was measured by locating a horizontal plate at the desired point. A vertical $\frac{1}{2}''$ tube, enclosing a $\frac{5}{16}''$ rod, with a set screw for adjustment, (see Fig. 222) is attached to this plate. To avoid any binding action of the ballast through which it passes, the vertical rod and tube is surrounded by another $\frac{3}{4}''$ tube. The top of the rod is adjusted to be above the ballast and at a convenient height for comparison of elevation with a fixed reference plug. Of course the plate will follow the strata in which it is placed in any change of elevation which may occur. The fixed plugs were located in the ground far enough away from the track so that they would not be appreciably influenced by track depression, and at nearly the same elevation as the tops of the vertical rods. The relative elevations were observed very accurately by means of a **level-bar**, a metal bar provided with a level bubble and a micrometer adjusting screw. Then, after the track had been loaded, minute changes of elevation, due to pressure, were observed. For measuring depressions directly under a tie, a double plug, having two vertical rods which would straddle a tie, were used, and the average reading of the two rods was taken. The level bar was used to observe depressions of rail, tie, ballast or subsoil, but only as to the effect of static loading. The depression of the rail under moving load was measured by a double exposure photograph. Pieces of black paper, with white crosses on them, having one line vertical, were pasted on the web of the rail. A camera was focused on the rail about 10 feet away. An initial exposure was taken of the unloaded rail. Then, without disturbance of the camera, the desired train load was run over the track at the desired speed. When the train (or locomotive) was at the desired point, it closed an electric circuit which operated

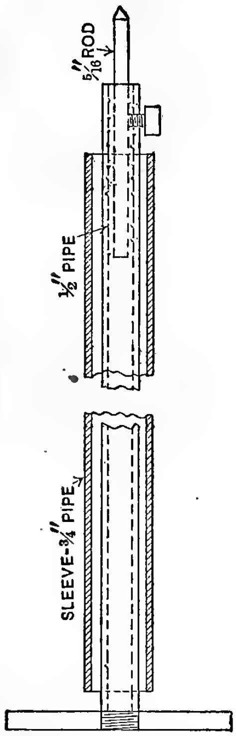


Fig. 222.—Depression Plug.

the shutter for a .001 second exposure. The resultant photograph showed for each cross a double cross with one vertical and two horizontal lines whose distance apart represented, after suitable reduction, the depression of the rail. Using a magnifying micrometer microscope, and a computed constant multiplier, it was possible to measure from the photographic plate the actual deflection of the rail with a precision of about 0.01 inch.

543. Pressure transmitted from tie to ballast. This subject was investigated both theoretically and experimentally. The

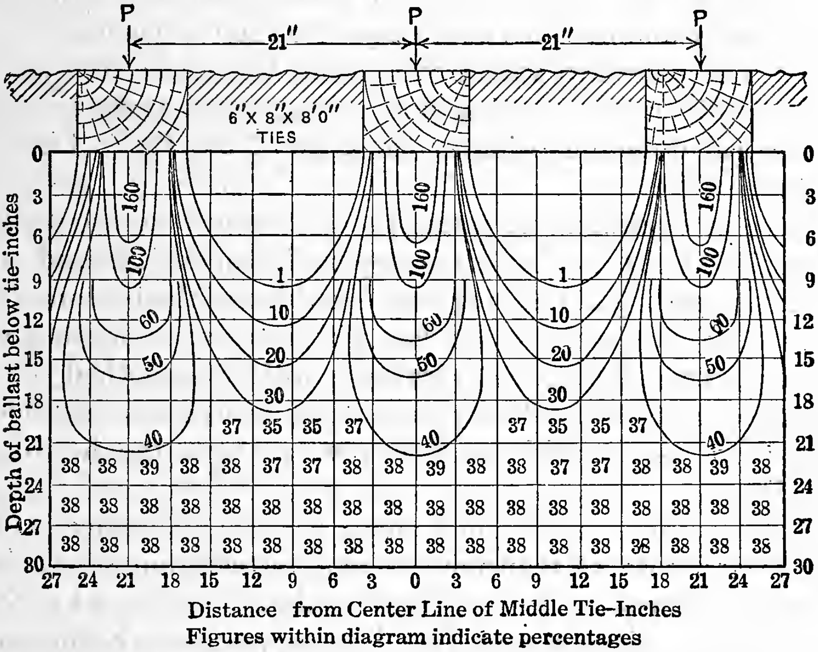


FIG. 223.—LINES OF EQUAL VERTICAL PRESSURE IN BALLAST FOR EQUAL LOADS ON TIES, SPACED 21″ C.C.

experimental work included not only track tests but also an extensive series of laboratory tests using sand ballast, pebbles, and broken stone. If ballast consists of absolutely clean spheres of perfectly elastic material, whose mutual actions and reactions are only pressure without friction, a definite theoretical solution as to distribution of pressure is possible, although complicated. The equation of pressure is a logarithmic equation which is chiefly useful in interpreting experimental results. Both theory and experimental tests demonstrate that:

(*a*) "The bearing pressure of the tie varies in intensity from its edge to its middle line." This is shown in Fig. 223, where the numbers within the diagram give *percentages* of the *average* tie pressure. The figure also shows that if the ballast is only 6 inches thick the entire pressure on the subsoil is concentrated on a comparatively narrow area under the tie and that a considerable part of the subsoil between the ties carries but little pressure. The ballast must be nearly 24 inches deep (if the ties are spaced 21″) before the load is distributed with substantial uniformity. If the ties are spaced further apart, the depth for uniform pressure must be still greater. In a very approximate way, it may be said that the pressure becomes substantially uniform at a depth equal to the tie spacing.

(*b*) "The pressures which react from the lower face of the tie act in other than vertical lines, the greatest variation from the vertical direction being at the edge of the tie." Fig. 223 also shows this.

(*c*) "The variation in intensity of pressure in the ballast lengthwise of the tie (which is dependent upon size and stiffness of tie, quality of tamping, and condition of the bed on which the tie rests) becomes less and less with increase in depth and it may be expected that the variations will be smoothed out at a depth equal to the ordinary tie spacing, or a few inches below, where there will be fairly uniform pressure over the horizontal plane."

(*d*) "For quiescent loading there is little difference in the manner and rate of transmission and distribution of pressure for broken stone, pebbles, and sand ballasts; that is, at a given depth the intensities of pressure will be approximately the same, provided, of course, the ultimate carrying capacity of the ballast is not exceeded; and this conclusion may properly be extended to other non-cohesive materials. It will require less load to force the tie into sand ballast than into broken stone; the ultimate carrying capacity of the broken stone ballast under tie pressure is much greater than that of the sand ballast—the particles of sand ballast are more easily moved and rearrange themselves under lighter loads. For the different kinds of ballast there are great differences in the ultimate load which can be carried on a tie before ballast movement begins. The ultimate carrying capacity depends upon size of particle, smoothness of surface and degree of angularity. A material whose mobility under pressure is increased by the action of water or by mixture with other materials may thereby have its carrying capacity decreased. For heavy loading the ultimate carrying capacity of a ballast material is especially important."

(*e*) For quiescent loads the presence of ballast above the level of the bottom of the tie has little or no effect in increasing the maximum load which can be carried without forcing the ballast from under the tie and allowing the tie to settle. For moving loads which produce vibration, the presence of ballast up to the top of the tie, and particularly at the tie ends, increases considerably the resistance to lateral displacement. The greater the velocity of trains, the greater the necessity for such lateral reinforcement.

544. Transverse stresses in the tie. The character and distribution of transverse stresses in the tie depend very largely on the tamping. If the tamping were absolutely uniform throughout the length of the tie, the upward pressure would be uniform and there would be a maximum positive moment under each rail, a maximum negative moment in the center of the tie, and points of inflection between the center and each rail. If the tie is very strongly tamped under the center and tamped very little if at all under the ends, making it "center-bound," there will be a severe negative moment in the center, and little or none under the rails. Concentrating the tamping for a short space on each side of each rail, and leaving the center almost clear of ballast, relieves the center of any transverse stress and even minimizes that under the rails. From the standpoint of stress in the tie, it is desirable, but it makes an undesirable concentration of pressure on the ballast and roadbed. Probably the ballast would soon crush down under such a concentrated pressure. The best method of tamping is that which makes the tamping firmest on either side of each rail, with enough tamping in the center to give good support and yet not so much that a negative moment would be developed which would be in excess of the positive moment under the rail. Since the amounts of these moments depend on the tamping and since the effect of the tamping may be more or less altered with the passage of each train, due to a slight settlement of the ballast, any attempt at precise quantitative computation of moment is fruitless. Nevertheless tests were made to determine the moments under a variety of conditions (center-bound ties, end-bound ties, etc.) so as to determine maximum and minimum values for the moments under the rails and in the center. Fig.

224 is a composite of the deflections of three ties on Class A track on the Ch. M. & St. P. Rwy. The vertical scale is 500 times the horizontal scale. The curve represents the depression of the tie and may also be considered to represent the deformed neutral axis and that the curvature indicates the character of the bending. The curve shows the usual case of a negative moment in the center and positive moments under each rail. Static tests under a truck load of 100,000 lbs., on poorly ballasted track, showed a negative bending moment in the center of as much as $-4.5\ W$ inch-pounds, in which W = the load in pounds carried by one tie. This was observed to be about 15,000 lbs. $4.5 \times 15{,}000 = 67{,}500$ in. lbs. For a $6'' \times 8''$ tie, a moment of 67,500 in. lbs. means a maximum unit stress

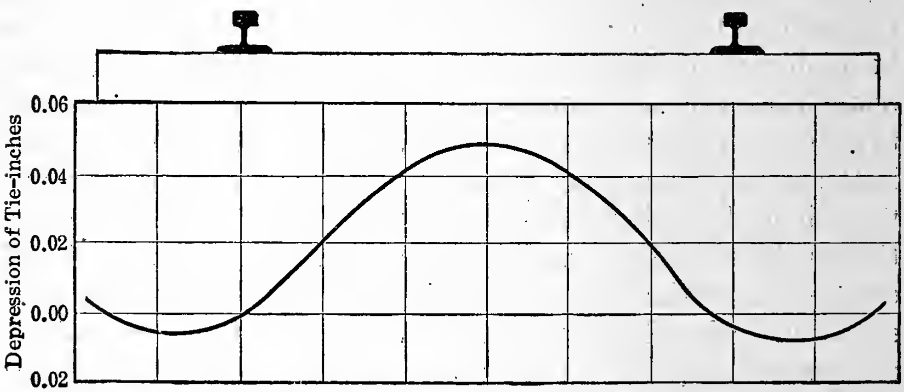


FIG. 224.—COMPOSITE DIAGRAM OF TIE FLEXURE.

of 1406 lbs. per sq. in. But this stress was produced by a static load. The effect of speed and dynamic augment (see § 413) would largely increase this figure and perhaps make it exceed the safe working stress for even an oak tie. On the other hand, for track in good condition, a negative bending moment of $-2.0\ W$ in the center is as much as should be expected.

545. Effect of counterbalancing. In § 413 there is given an elementary explanation of the necessity for counterbalancing and some of the rules for accomplishing it. It was also explained that perfect counterbalancing is necessarily impossible and that there is always an unbalanced dynamic augment which produces an increased pressure on the rails at some part of the revolution of the driver, or a racking of the locomotive frame at each half-stroke of each piston. The dynamic augment increases as the square of the velocity, and its effect is therefore very great and serious at high speeds. It is sometimes found impracticable to make the counterweight on the main driver sufficiently large and heavy to balance the effect of the very great weight of the side rods, main rod, etc., of a very heavy locomotive. In such a case, the driver is said to be **under-balanced** and then the greatest stress in the rail may occur when the counterweight is up rather than when it is down. The underbalance of the main driver is made up by overbalancing

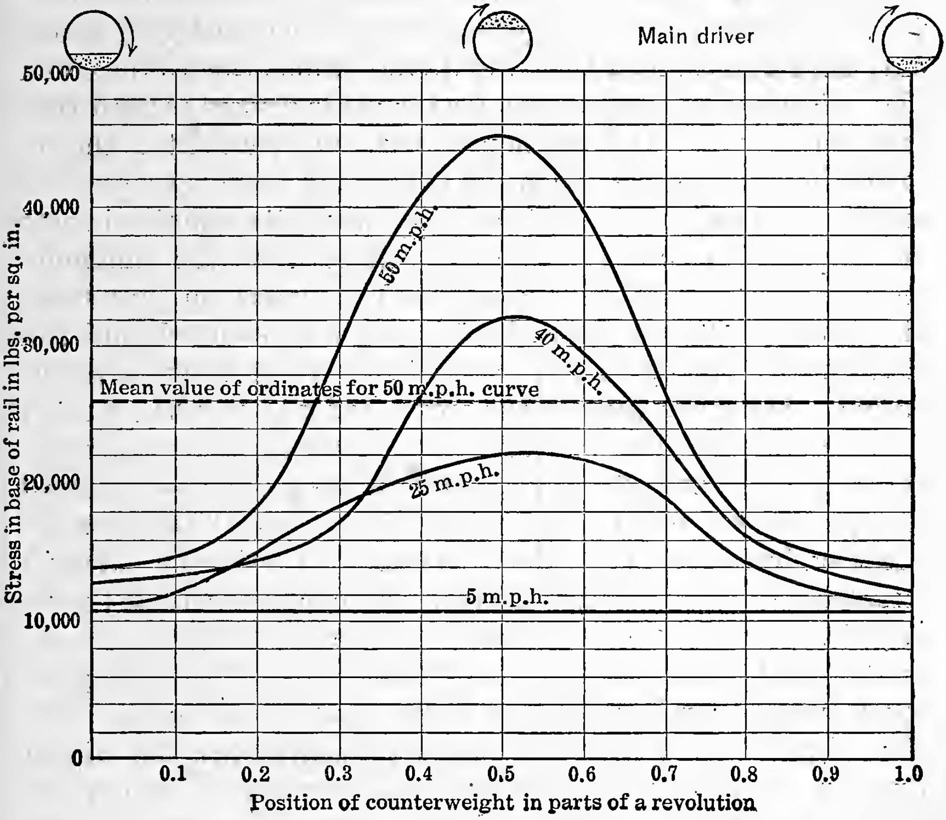


FIG. 225.—COUNTERBALANCING STRESS IN RAIL, UNDER MAIN DRIVER, DURING ONE REVOLUTION.

the other drivers, and this increases the pressure under them when the counterweight is down. Although the dynamic augment may be computed numerically, as illustrated in § 413, its real effect on the rail is modified by the action of the equalizing levers and also by the effect that a change of pressure by the other drivers has on the rail and on the reaction of the rail on the driver considered.

Another item which increases the pressure exerted by the main driver on the rail is the vertical component of the pull (or push) of the main rod. This component acts downward both when the crank pin is up and when it is down. For one case this was computed to be about 12% of the cylinder pressure at mid-stroke. This is a very significant addition to the rail pressure. It was not included in the figures observed in the tests since steam was shut off when the locomotive passed over the test track.

In Fig. 225 are shown plotted results of tests with a locomotive of the Santa Fé type (2-10-2). The diagram shows only the stresses under the main driver—which carries the crank pin. Corresponding diagrams for the other drivers showed very different results. The position of the counterweight is shown, indicating that, since the main driver was *underbalanced*, the maximum stress in the rail occurred when the crank pin was down and the counterweight up. Note that the minimum stress in the base of the rail was 14,000 lbs. per sq. in. for a speed of 50 m.p.h. The pressures for 5 m.p.h. were so nearly uniform that a mean average line to represent them was drawn at about 10,700. The mean value of the ordinates for 50 m.p.h. indicated a mean stress of about 26,000 lbs. per sq. in. The difference between 10,700 and 26,000, or 15,300 lbs. per sq. in., is considered to represent the mean value of the effect of speed alone, or the effect of increasing the velocity from 5 to 50 m.p.h. without reference to counter-weight effects. Similar tests with a Pacific type locomotive (4-6-2) showed that the effect of speed is to increase the rail stress 1.95 and 2.25 times by increasing the speed from 5 m.p.h. to 45 and to 60 m.p.h. respectively. But these figures are of academic interest chiefly, since the critical figure is the maximum actual stress in the rail at high speed. The average maximum shown by the tests was 44,700 lbs. per sq. in. during each revolution of the drivers. One observed stress was as high as 52,000 lbs. per sq. in.

It should also be noted that, for the type of rail used in this test, the maximum stress in the head of the rail is about 10% greater than that in the base for vertical loads. In these tests the strain measurements were taken in the base of the rail since the lateral stresses are greater there than in the head and are " great enough to be significant."

Trailer. These tests developed some very unexpected results with respect to the stresses under the trailers—the comparatively small loose wheels under the firebox and next behind the drivers. These wheels are presumably perfectly balanced and normally carry a definite proportion of the load of the engine. It might have been expected that the rail pressure would be substantially uniform and that any variation in pressure would be due to some accidental unevenness in the track. On the contrary the variations were quite marked, especially at high speeds, and the positions of maximum stress seem to bear a definite relation to the position of the counterweight on the drivers. If this relation were constant for all locomotives, its analysis would be simplified. For a locomotive of the Santa Fé type, the maximum stress occurred when the counterweight was at a position from 0.6 to 0.8 of a revolution after the low position. For a locomotive of the Pacific type, the maximum effect occurred at about 0.4 of a revolution after the low position. In each case the various observations of the tests were so consistent that the conclusions are indisputable. The differences in results for different locomotives shows that it depends on the relative weights on the wheels and on the equalizer system. The systematic variation from uniformity shows the effect of variable pressure of adjacent drivers, acting through the equalizing levers, and also through the rails, to modify what would otherwise be a uniform pressure. It also helps to explain certain apparent inconsistencies in the results for the driver pressures. Evidently there is a large field for future investigation, and it is to be expected that succeeding reports from this committee will throw more light on this phase of the subject.

APPENDIX.

THE ADJUSTMENTS OF INSTRUMENTS.

THE accuracy of instrumental work may be vitiated by any one of a large number of inaccuracies in the geometrical relations of the parts of the instruments. Some of these relations are so apt to be altered by ordinary usage of the instrument that the makers have provided adjusting-screws so that the inaccuracies may be readily corrected. There are other possible defects, which, however, will seldom be found to exist, provided the instrument was properly made and has never been subjected to treatment sufficiently rough to distort it. Such defects, when found, can only be corrected by a competent instrument-maker or repairer.

A WARNING is necessary to those who would test the accuracy of instruments, and especially to those whose experience in such work is small. Lack of skill in handling an instrument will often indicate an apparent error of adjustment when the real error is very different or perhaps non-existent. It is always a safe plan when testing an adjustment to note the amount of the apparent error; then, beginning anew, make another independent determination of the amount of the error. When two or more *perfectly independent* determinations of such an error are made it will generally be found that they differ by an appreciable amount. The *differences* may be due in variable measure to careless inaccurate manipulation and to instrumental *defects* which are wholly independent of the particular test being made. Such careful determinations of the amounts of the errors are generally advisable in view of the next paragraph.

DO NOT DISTURB THE ADJUSTING-SCREWS ANY MORE THAN NECESSARY. Although metals are apparently rigid, they are really elastic and yielding. If some parts of a complicated mechanism, which is held together largely by friction, are subjected to greater internal stresses than other parts of the mechanism, the jarring resulting from handling will frequently cause a slight readjustment in the parts which will tend to more nearly equalize the internal stresses. Such action frequently occurs with the adjusting mechanism of instruments. One screw may be strained more than others. The friction of parts may prevent the opposing screw from *immediately* taking up an equal stress. Perhaps the adjustment appears perfect under these conditions Jarring diminishes the friction between the parts, and the unequal stresses tend to equalize. A motion takes place which, although microscopically minute, is sufficient to indicate an error of adjustment. A readjustment made by unskillful hands may not make the final adjustment any more perfect. The frequent shifting of adjusting-screws wears them badly, and when the screws are worn it is still more difficult to keep them from moving enough to vitiate the adjustments. It is therefore preferable in many cases to refrain from disturbing the adjusting-screws, especially as the accuracy of the work done is not *necessarily* affected by errors of adjustment, as may be illustrated:

(*a*) Certain operations are *absolutely* unaffected by certain errors of adjustment.

(*b*) Certain operations are so slightly affected by certain *small* errors of adjustment that their effect may properly be neglected.

(*c*) Certain errors of adjustment may be readily allowed for and neutralized so that no error results from the use of the unadjusted instrument. Illustrations of all these cases will be given under their proper heads.

ADJUSTMENTS OF THE TRANSIT.

1. *To have the plate-bubbles in the center of the tubes when the axis is vertical.* Clamp the upper plate and, with the lower clamp loose, swing the instrument so that the plate-bubbles are parallel to the lines of opposite leveling-screws. Level up until both bubbles are central. Swing the instrument 180°. If the bubbles again settle at the center, the adjustment is perfect. If either bubble does not settle in the center, move the leveling-screws until the bubble is *half-way* back to the center. Then, before touching the adjusting-screws, note carefully the position of the bubbles and observe whether the bubbles always settle at the *same* place in the tube, no matter to what position the in-

strument may be rotated. When the instrument is so leveled, the axis is truly vertical and the discrepancies between this constant position of the bubbles and the centers of the tubes measure the errors of adjustment. By means of the adjusting-screws bring each bubble to the center of the tube. If this is done so skillfully that the true level of the instrument is not disturbed, the bubbles should settle in the center for all positions of the instrument. Under unskillful hands, two or more such trials may be necessary.

When the plates are not horizontal, the measured angle is greater than the true horizontal angle by the difference between the measured angle and its projection on a horizontal plane. When this angle of inclination is small, the difference is insignificant. Therefore when the plate-bubbles are *very nearly* in adjustment, the error of measurement of horizontal angles may be far within the lowest unit of measurement used. A *small* error of adjustment of the plate-bubble *perpendicular* to the telescope will affect the horizontal angles by only a small proportion of the error, which will be perhaps imperceptible. Vertical angles will be affected by the same insignificant amount. A *small* error of adjustment of the plate-bubble *parallel* to the telescope will affect horizontal angles very slightly, but will affect vertical angles by the full amount of the error.

All error due to unadjusted plate-bubbles may be avoided by noting in what positions in the tubes the bubbles will remain fixed for all positions of azimuth and then keeping the bubbles adjusted to these positions, for the axis is then truly vertical. It will often save time to work in this way temporarily rather than to stop to make the adjustments. This should especially be done when accurate vertical angles are required.

When the bubbles are truly adjusted, they should remain stationary regardless of whether the telescope is revolved with the upper plate loose and the lower plate clamped or whether the whole instrument is revolved, the plates being clamped together. If there is any appreciable difference, it shows that the two vertical axes or "centers" of the plates are not concentric. This may be due to cheap and faulty construction or to the excessive wear that may be sometimes observed in an old instrument originally well made. In either case it can only be corrected by a maker.

2. *To make the revolving axis of the telescope perpendicular to the vertical axis of the instrument.* This is best tested by using a long plumb-line, so placed that the telescope must be pointed upward at an angle of about 45° to sight at the top of the plumb-line and downward about the same amount, if possible, to sight at the lower end. The vertical axis of the transit must be made truly vertical. Sight at the upper part of the line, clamping the horizontal plates. Swing the telescope down and see if the cross-wire again bisects the cord. If so, the adjustment is *probably* perfect (a conceivable exception will be

noted later); if not, raise or lower one end of the axis by means of the adjusting-screws, placed at the top of one of the standards, until the cross-wire will bisect the cord both at top and bottom. The plumb-bob may be steadied, if necessary, by hanging it in a pail of water. As many telescopes cannot be focused on an object nearer than 6 or 8 feet from the telescope, this method requires a long plumb-line swung from a high point, which may be inconvenient.

Another method is to set up the instrument about 10 feet from a high wall. After leveling, sight at some convenient mark high up on the wall. Swing the telescope down and make a mark (when working alone some convenient natural mark may generally be found) low down on the wall. Plunge the telescope and revolve the instrument about its vertical axis and again sight at the upper mark. Swing down to the lower mark. If the wire again bisects it, the adjustment is perfect. If not, fix a point *half-way* between the two positions of the lower mark. The plane of this point, the upper point, and the center of the instrument is truly vertical. Adjust the axis to these upper and lower points as when using the plumb-line.

3. *To make the line of collimation perpendicular to the revolving axis of the telescope.* With the instrument level and the telescope nearly horizontal point at some well-defined point at a distance of 200 feet or more. Plunge the telescope and establish a point in the opposite direction. Turn the whole instrument about the vertical axis until it again points at the first mark. Again plunge to "direct position" (*i.e.*, with the level-tube *under* the telescope). If the vertical cross-wire again points at the second mark, the adjustment is perfect. If not, the error is *one-fourth* of the distance between the two positions of the second mark. Loosen the capstan screw on one side of the telescope and tighten it on the other side until the vertical wire is set at the one-fourth mark. Turn the whole instrument by means of the tangent screw until the vertical wire is *midway* between the two positions of the second mark. Plunge the telescope. If the adjusting has been skillfully done, the cross-wire should come exactly to the first mark. As an "erecting eyepiece" reinverts an image already inverted, the ring carrying the cross-wires must be moved in the *same* direction as the *apparent* error in order to correct that error.

The necessity for the third adjustment lies principally in the practice of producing a line by plunging the telescope, but when this is required to be done with great accuracy it is always better to obtain the forward point by reversion (as described above for making the test) and take the *mean* of the two forward points. Horizontal and vertical angles are practically unaffected by *small* errors of this adjustment, unless, in the case of horizontal angles, the vertical angles to the points observed are very different.

Unnecessary motion of the adjusting-screws may sometimes be avoided by carefully establishing the forward point on line by repeated reversions of the instrument, and thus determining by repeated trials the exact amount of the error. *Differences* in the amount of error determined would be evidence of inaccuracy in manipulating the instrument, and would show that an adjustment based on the first trial would *probably* prove unsatisfactory.

The 2d and 3d adjustments are mutually dependent. If either adjustment is badly out, the other adjustment cannot be made except as follows:

(*a*) The second adjustment can be made regardless of the third when the lines to the high point and the low point make *equal* angles with the horizontal.

(*b*) The third adjustment can be made regardless of the second when the front and rear points are *on a level* with the instrument.

When both of these requirements are *nearly* fulfilled, and especially when the error of either adjustment is small, no trouble will be found in perfecting either adjustment on account of a small error in the other adjustment.

If the test for the second adjustment is made by means of the plumb-line and the vertical cross-wire intersects the line at all points as the telescope is raised or lowered, it not only demonstrates at once the accuracy of that adjustment, but also shows that the third adjustment is either perfect or has so small an error that it does not affect the second.

4. *To have the bubble of the telescope-level in the center of the tube when the line of collimation is horizontal.* The line of collimation should coincide with the optical axis of the telescope. If the object-glass and eyepiece have been properly centered, the previous adjustment will have brought the vertical cross-wire to the center of the field of view. The horizontal cross-wire should also be brought to the center of the field of view, and the bubble should be adjusted to it.

a. Peg method. Set up the transit at one end of a nearly level stretch of about 300 feet. Clamp the telescope with its bubble in the center. Drive a stake vertically under the eyepiece of the transit, and another about 300 feet away. Observe the height of the center of the eyepiece (the telescope being level) above the stake (calling it *a*); observe the reading of the rod when held on the other stake (calling it *b*); take the instrument to the other stake and set it up so that the eyepiece is vertically over the stake, observing the height, c; take a reading on the first stake, calling it d. If this adjustment is perfect, then

$$a-d=b-c,$$

$$\text{or} \quad (a-d)-(b-c)=0.$$

$$\text{Call} \quad (a-d)-(b-c)=2m.$$

When m is positive, the line points downward;
" m " negative, " " " upward.

To adjust: if the line points *up*, sight the horizontal cross-wire (by moving the vertical tangent screw) at a point which is m lower, then adjust the bubble so that it is in the center.

By taking several independent values for a, b, c, and d, a mean value for m is obtained, which is more reliable and which may save much unnecessary working of the adjusting-screws.

b. Using an auxiliary level. When a carefully adjusted level is at hand, this adjustment may sometimes be more easily made by setting up the transit and level, so that their lines of collimation are as nearly as possible at the same height. If a point may be found which is half a mile or more away and which is on the horizontal cross-wire of the level, the horizontal cross-wire of the transit may be pointed directly at it, and the bubble adjusted accordingly. Any slight difference in the heights of the lines of collimation of the transit and level (say $\frac{1}{4}''$) may almost be disregarded at a distance of $\frac{1}{2}$ mile or more, or, if the difference of level would have an appreciable effect, even this may be practically eliminated by making an estimated allowance when sighting at the distant point. Or, if a distant point is not available, a level-rod with target may be used at a distance of (say) 300 feet, making allowance for the carefully determined difference of elevation of the two lines of collimation.

5. *Zero of vertical circle.* When the line of collimation is truly horizontal and the vertical axis is truly vertical, the reading of the vertical circle should be 0°. If the arc is adjustable, it should be brought to 0°. If it is not adjustable, the *index error* should be observed, so that it may be applied to all readings of vertical angles.

ADJUSTMENTS OF THE WYE LEVEL.

1. *To make the line of collimation coincide with the center of the rings.* Point the intersection of the cross-wires at some

well-defined point which is at a considerable distance. The instrument need not be level, which allows much greater liberty in choosing a convenient point. The vertical axis should be clamped, and the clips over the wyes should be loosened and raised. Rotate the telescope in the wyes. The intersection of the cross-wires should be continually on the point. If it is not, it requires adjustment. Rotate the telescope 180° and adjust *one-half* of the error by means of the capstan-headed screws that move the cross-wire ring. It should be remembered that, with an erecting telescope, on account of the inversion of the image, the ring should be moved in the direction of the *apparent* error. Adjust the other half of the error with the leveling-screws. Then rotate the telescope 90° from its usual position, sight accurately at the point, and then rotate 180° from that position and adjust any error as before. It may require several trials, but it is necessary to adjust the ring until the intersection of the cross-wires will remain on the point for any position of rotation.

If such a test is made on a very distant point and again on a point only 10 or 15 feet from the instrument, the adjustment may be found correct for one point and incorrect for the other. This indicates that the object-slide is improperly centered. Usually this defect can only be corrected by an instrument-maker. If the difference is very small it may be ignored, but the adjustment should then be made on a point which is at about the mean distance for usual practice—say 150 feet.

If the whole image appears to shift as the telescope is rotated, it indicates that the eyepiece is improperly adjusted. This defect is likewise usually corrected only by the maker. It does not interfere with instrumental accuracy, but it usually causes the intersection of the cross-wires to be eccentric with the field of view.

2. *To make the axis of the level-tube parallel to the line of collimation.* Raise the clips as far as possible. Swing the level so that it is parallel to a pair of opposite leveling-screws and clamp it. Bring the bubble to the middle of the tube by means of the leveling-screws. Take the telescope out of the wyes and replace it end for end, using *extreme care* that the wyes are not jarred by the action. If the bubble does not come to the center, correct *one-half* of the error by the vertical adjusting-screws at one end of the bubble. Correct the other half by the leveling-screws. Test the work by again changing the telescope end for end in the wyes.

Care should be taken while making this adjustment to see that the level-tube is vertically under the telescope. With the bubble in the center of the tube, rotate the telescope in the wyes for a considerable angle each side of the vertical. If the first half of the adjustment has been made and the bubble moves, it shows that the axis of the wyes and the axis of the level-tube are not in the same vertical plane although both have been made horizontal. By moving one end of the level-tube *sidewise* by means of the horizontal screws at one end of the tube, the two axes may be brought into the same plane. As this adjustment is liable to disturb the other, both should be alternately tested until both requirements are complied with.

By these methods the axis of the bubble is made parallel to the axis of the wyes; and as this has been made parallel to the lines of collimation by means of the previous adjustment, the axis of the bubble is therefore parallel to the line of collimation.

3. *To make the line of collimation perpendicular to the vertical axis.* Level up so that the instrument is approximately level over both sets of leveling-screws. Then, after leveling carefully over one pair of screws, revolve the telescope 180°. If it is not level, adjust half of the error by means of the capstan-headed screw under one of the wyes, and the other half by the leveling-screws. Reverse again as a test.

When the first two adjustments have been accurately made, good leveling may always be done by bringing the bubble to the center by means of the leveling-screws, at every sight if necessary, even if the third adjustment is not made. Of course this third adjustment should be made as a matter of convenience, so that the line of collimation may be always level no matter in what direction it may be pointed, but it is not *necessary* to stop work to make this adjustment every time it is found to be defective.

ADJUSTMENTS OF THE DUMPY LEVEL.

1. *To make the axis of the level-tube perpendicular to the vertical axis.* Level up so that the instrument is approximately level over both sets of leveling-screws. Then, after leveling carefully over one pair of screws, revolve the telescope 180°. If it is not level, adjust *one-half* of the error by means of the adjusting-screws at one end of the bubble, and the other half by means of the leveling-screws. Reverse again as a test.

2. *To make the line of collimation perpendicular to the vertical axis.* The method of adjustment is identical with that for the transit (No. 4, pl. 505) except that the cross-wire must be

adjusted to agree with the level-bubble rather than *vice versa*, as is the case with the corresponding adjustment of the transit; i.e., with the level-bubble in the center, raise or lower the horizontal cross-wire until it points at the mark known to be on a level with the center of the instrument.

If the instrument has been well made and has not been distorted by rough usage, the cross-wires will intersect at the center of the field of view when adjusted as described. If they do not, it indicates an error which ordinarily can only be corrected by an instrument-maker. The error may be due to any one of several causes, which are

(*a*) faulty centering of object-slide;

(*b*) faulty centering of eyepiece;

(*c*) distortion of instrument so that the geometric axis of the telescope is not perpendicular to the vertical axis. If the error is only just perceptible, it will not probably cause any error in the work.

AZIMUTH.

The azimuth of a line on the surface of the earth is its angle with a true meridian through a point on the line. It is the **true bearing** as distinguished from "magnetic bearing." Federal law requires that all surveys of government lands shall be made by "Solar Observations" (rather than with the magnetic needle) so as to obtain true bearings.

Solar Azimuth may be obtained in two general ways, (*a*) by direct observation on the sun with an ordinary "complete" transit, provided with a colored glass shade, and (*b*) by the use of a "solar attachment" or a solar compass. The first method only requires as special equipment a colored glass shade costing but a few dollars, but it requires the separate solution of a formula for each observation made. Even the colored glass shade is not always necessary—as when the disc of the sun is just seen through thin clouds and is not too bright to be observed with the naked eye. The "colored glass shade" may be merely a piece of colored glass fitted over the eye-piece, or the glass may be set into a frame very similar to the object glass cover and readily taken off and put on. In the latter case the glass must be "optically perfect," i.e., with the sides perfectly plane and parallel, so that there shall be no refraction of the image, or such glass as is used for the sun shade of a sextant.

The second method (*b*) does not require any calculation of a formula; the true meridian is given directly but it requires the use of a special instrument, whose adjustments must be made with great care or the resulting azimuth will often be in error by a *much larger* amount than the error in the adjustment. A proper appreciation of either method requires an understanding of certain astronomical relations.

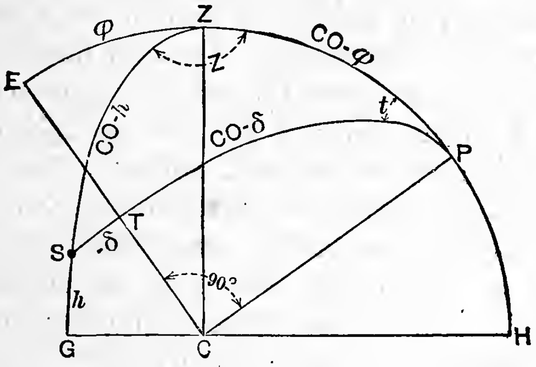


FIG. 1.

Fig. 1 represents the orthographic projection of the celestial sphere, projected on the plane of the meridian of the observer.

$HPZE$ represents the meridian of the observer.

Z = the zenith.

CP = the polar axis of the earth.

CE = the plane of the equator.

S = the position of the sun.

EZ = the latitude of the observer = ϕ.

$ZP = 90° - \phi = \text{co}\ \phi$.

SG = the true altitude of the sun = h.

$SZ = 90° - h = \text{co}\ h$.

ST = the declination of the sun, north or south of the equator = δ.

$SP = 90° - \delta = \text{co}\ \delta$, also called p = polar distance.

The essential sign of δ must be considered. If the sun is south of the equator (as it is from about September 21 to March 21), δ is negative and if the declination is (say) S 20°, $\delta = -20°$. Then co $\delta = 90° - \delta = 90° - (-20°) = 110°$.

Z = the angle from the position of the sun to the true north = the spherical angle SZP. A is its supplement $= 180° - Z$.

Of several possible formulae, the U. S. Coast and Geodetic Survey prefer the following:

$$\text{Cot } \tfrac{1}{2} A = \sqrt{\frac{\sin (S-\phi) \sin (S-h)}{\cos S \cos (S-p)}},$$

in which $S = \frac{1}{2}(\phi + h + p)$.

The sun describes each day a path which is approximately parallel with the equator, the change in declination being very small during June and December and fastest when the sun is crossing the equator in March and September, the greatest rate of change being about 59 seconds of arc per hour. The declination of the sun must be known for the time of observation. This is obtainable from the Nautical Almanac or Ephemeris.

Example.—Declination for Philadelphia, Feb. 20, 1914, at 8:10 A. M., standard time, 75th meridian. Since "standard time" is a definite time interval from Greenwich mean local time, we may use it here regardless of precise longitude or mean local time, 8:10 A. M. on the 75° meridian is 1:10 P. M. mean time, at Greenwich. $1.17h \times 53''.64 = 62''.58 = 1'\ 2''.6$ and $-11°\ 7'\ 1''.1 + 0°\ 1'\ 2''.6 = -11°\ 5'\ 58''.5$ which is **south** declination.

Refraction. Refraction causes the sun to appear higher than it actually is. Therefore when the **altitude** of the sun is observed, the computed refraction should be **subtracted** from the **apparent** altitude to obtain the **true** altitude. The amount of the refraction is a very complicated function of the temperature and of the barometric pressure. For refined astronomical work, large refraction tables should be used, making due allowance for temperature and pressure, but for such work as may be done with an ordinary transit the values given in the following table will suffice.

Angular diameter of sun. The sun's angular diameter is about 0° 32′. With the comparatively high power telescopes now generally used on transits, this fills a large part of the field of view and it is impossible to accurately bisect such a large

MEAN REFRACTIONS—[BESSEL] TRUE FOR BAROMETER AT 29″.6, TEMP. 48° F.

Alt.	Refr.	Alt.	Refr.	Alt.	Refr.
0° 0′	34′ 54″	1° 30′	20′ 51″	5° 0′	9′ 46″
10	32 49	40	19 52	30	9 02
20	30 52	50	18 58	6 0	8 23
30	29 03	2 0	18 09	30	7 49
40	27 23	30	16 01	7 0	7 20
50	25 50	3 0	14 15	30	6 53
1° 0	24 25	30	12 48	8 0	6 30
10	23 07	4 0	11 39	30	6 08
20	21 56	30	10 40	9 0	5 49

Alt.	Refr.	Alt.	Refr.	Alt.	Refr.
9° 30′	5′ 32″	18°	2′ 56″	30°	1′ 40″
10 0	5 16	19	2 46	35	1 22
11 0	4 48	20	2 37	40	1 09
12 0	4 25	21	2 29	45	0 58
13 0	4 05	22	2 22	50	0 48
14 0	3 47	23	2 15	60	0 33
15 0	3 32	24	2 09	70	0 21
16 0	3 19	26	1 58	80	0 10
17 0	3 07	28	1 48	90	0 0

angular width especially as the apparent motion of the sun across the field of view is very rapid. It therefore becomes advisable (when sighting directly at the sun with the transit telescope) to sight the cross wires on the edges of the sun, as shown in Fig. 2, and make due allowance for the semi-diameter of the sun. The effect of this is to obtain an altitude which differs from the true altitude by the angular value of the semi-diameter. The observed azimuth differs from the true azimuth by the semi-diameter ÷ cos h. When the sun is at the horizon, cos $h = 1$, and the allowance equals the semi-diameter both for altitude and azimuth. For higher altitudes the allowance for azimuth is much larger than the semi-diameter, since the divisor (cos h) is small. If several observations are taken within a short interval, the *change* in this allowance for azimuth during this short interval may be too small for notice and one value may be sufficiently accurate for all the observations.

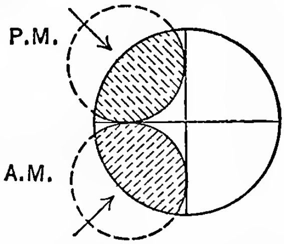


FIG. 2.

There is a slight variation in the semi-diameter as is shown in the accompanying tabular form, giving average values, which may be used by interpolation, if a closer value than the nearest minute is desired.

Time.	Semi-diam. of the Sun in minutes of arc.
Jan. 1....	16′.30 (max)
April 1...	16 .03
July 1....	15 .76 (min)
Oct. 1....	16 .01

Latitude. If the latitude of the place of observation is not known to the nearest minute, it may readily be obtained by observing the altitude of the sun at culmination at noon. The horizontal cross wire should be sighted at the upper (or the lower) edge of the disc of the sun.

If d = angular diameter of sun; r = refraction
ϕ = latitude; δ = declination
h' = observed angle of elevation

$$\text{then } \phi = 90° - [h' - r - \delta \pm \tfrac{1}{2}d]$$

in which $\frac{1}{2}d$ is + for an observation on the lower edge,
and $\frac{1}{2}d$ is − for an observation on the upper edge.

Set up the transit several minutes before noon, taking sufficient time to level up with the utmost care. Set the horizontal cross wire on the upper (or lower) edge of the sun and with the tangent screw follow the motion of the sun. As the required angle is found at **culmination**, the motion of the telescope should cease when the highest altitude is obtained and the sun begins to descend.

Azimuth by an Observation with the transit telescope. Set up the transit at a convenient station from which an unobstructed view of the sun may be obtained at all times and from which a convenient permanent azimuth mark (e.g., a distant steeple or chimney) may be observed. Point at the azimuth mark with the horizontal plates reading zero. With the upper plate loose, point at the sun observing the time, altitude and the horizontal angle from the azimuth mark. Three or more such observations are generally advisable, especially as they are so easily and quickly taken and are such a valuable check on each other. A single observation may be vitiated by some inaccuracy or blunder in manipulation or reading which would not be discovered unless more than one observation is taken, in which case the error would hardly be precisely repeated both in nature and amount. Finally, point at the azimuth mark to test whether the lower plate has slipped. The reading on the azimuth mark should be 0°.

Reducing the Observations. Compute the declinations for the given times of observation. If several observations are taken, it is generally best to compute the declinations for the times of the first and last observations and interpolate for the others. The observations may most readily be reduced by using a regular form as given below. The six observations quoted were taken in 15 minutes by one of the author's students.

Time	Apparent Altitude	α	h	δ	Z	$\frac{\text{Semi-diam.}}{\text{cos.ap. alt.}}$	True Azi. of Mark.
4:50	22° 48′.5	237° 41′	22° 30′.3	14° 45′.6	89° 16′.6	17′.2	213° 19′.6
4:53	22 12 .5	238 11	21 54 .3	45 .6	88 46 .6	17 .2	19 .6
4:55	21 44 .5	238 34	21 26 .2	45 .6	88 23 .3	17 .1	19 .8
4:58	21 19 .0	238 55	21 0 .7	45 .7	88 02 .4	17 .1	19 .7
5:00	20 49 .5	239 19 .5	20 31 .1	45 .7	87 38 .0	17 .0	19 .5
5:03	20 28 .0	239 38 .0	20 9 .5	14 45 .7	87 19 .9	17 .0	213 19 .1

Mean = 213°19′.55.

Observations taken Apr. 29, 1897: Semi-diam. of Sun 15′.9.
Sun observed in lower left-hand corner.

α = horizontal angle to azimuth mark, the angle being measured to the right.

h = app. alt. − refraction − semi-diam. of sun; semi-diam. is + when sun is **above** hor. cross wire, − when below.

δ = declination, and Z = computed angle (as illustrated below).

$$\text{True azimuth of mark} = 540° \pm \frac{\text{Semi-diam.}}{\text{cos. app. alt.}} \pm Z - \alpha, \text{ in which}$$

Z is + for A. M. and − for P. M. and the $\frac{\text{Semi-diam.}}{\text{cos. app. alt.}}$ is + when the sun is on the **left** of the middle wire (as above); $\frac{\text{Semi-diam.}}{\text{cos. app. alt.}}$ is − when the sun is on the **right** of the middle wire.

As a numerical specimen of the reduction:—App. decl. Greenwich mean noon Apr. 29, 1897, 14° 38′.0; hourly change +0′77; diff. of time between Greenwich and Philadelphia 5.0 hours; 5 P. M. at Philadelphia = 10 P. M. at Greenwich; therefore δ for 5 P. M. at Philadelphia = 14° 38′.0 + 10 × 0′.77 = 14° 45′.7. Using the equation

$$\cot \tfrac{1}{2}A = \sqrt{\frac{\sin (S-\phi) \sin (S-h)}{\cos S \cos (S-p)}},$$

in which $S = \frac{1}{2}(\phi + h + p)$.

$$\begin{array}{llll}
\phi = 39° \ 58'.0 & s-\phi = 28° \ 53'.3, & & \sin = 9.68404 \\
h = 22° \ 30'.3 & s-h = 46° \ 21'.0, & & \sin = 9.85948 \\
p = 75° \ 14'.3 & s-p = -\ 6° \ 23'.0, & & \overline{\ 9.54352} \\
\overline{\ \ 137° \ 42'.6} & & & \\
s = 68° \ 51'.3 & \cos 68° \ 51'.3 = 9.55718 & & \\
 & \cos - 6° \ 23'.0 = 9.99730 & & \\
 & \overline{\qquad 9.55448} & & 9.55448 \\
\tfrac{1}{2}A = 45° \ 21'.7 & & & 2 \,|\, 9.98904 \\
A = 90° \ 43'.4 & & & 9.99452 = \cot 45° \ 21'.6 \\
Z = 89° \ 16'.6 & & &
\end{array}$$

$$\frac{\text{Semi-diam. Sun}}{\text{cos. app. alt.}} = \frac{15.9}{\cos 22° \ 48'} = 17'.2$$

$$\begin{array}{rr}
540° + 17'.2 = & 540° \ 17'.2 \\
-Z - \alpha = -89° \ 16'.6 - 237° \ 41' = & -326° \ 57'.6 \\
\hline
& 213° \ 19'.6 = \text{true azimuth of mark.}
\end{array}$$

The instrument used had a vertical circle reading 30″ directly and could be estimated to 15″.

EXPLANATORY NOTE ON THE USE OF THE TABLES.

The logarithms here given are "five-place," but the last figure sometimes has a special mark over it (*e.g.*, $\bar{6}$) which indicates that one-half a unit in the last place should be *added*. For example

the value	includes all values between
·69586	·6958575000 + and ·6958624999...
$\cdot 6958\bar{6}$	·6958625000 + and ·6958674999...

The maximum error in any one value therefore does not exceed one-quarter of a fifth-place unit.

When adding or subtracting such logarithms allow a half-unit for such a sign. For example

·69586	·69586	$\cdot 6958\bar{6}$
·10841	$\cdot 1084\bar{1}$	$\cdot 1084\bar{1}$
$\cdot 1294\bar{7}$	$\cdot 1294\bar{7}$	$\cdot 1294\bar{7}$
$\cdot 9337\bar{4}$	·93375	$\cdot 9337\bar{5}$

All other logarithmic operations are performed as usual and are supposed to be understood by the student.

Deg	0°		1°		2°		3°		Deg
Min	Radius.	Log *R*	Radius.	Log *R*	Radius.	Log *R*	Radius.	Log *R*	Min
0	∞	∞	5729·6	3·75813	2864·9	3·45711	1910·1	3·28105	0
1	343775	5·53627	5635·7	·75095	2841·3	·45351	1899·5	·27864	1
2	171887	5·23524	5544·8	·74389	2818·0	·44993	1889·1	·27625	2
3	114592	5·05915	5456·8	·73694	2795·1	·44639	1878·8	·27387	3
4	85944	4·93421	5371·6	·73010	2772·5	·44287	1868·6	·27151	4
5	68755	4·83730	5288·9	·72336	2750·4	·43939	1858·5	·26915	5
6	57296	4·75812	5208·8	3·71673	2728·5	3·43593	1848·5	3·26681	6
7	49111	·69117	5131·0	·71020	2707·0	·43249	1838·6	·26448	7
8	42972	·63318	5055·6	·70377	2685·9	·42909	1828·8	·26217	8
9	38197	·58203	4982·3	·69743	2665·1	·42571	1819·1	·25986	9
10	34377	·53627	4911·2	·69118	2644·6	·42235	1809·6	·25757	10
11	31252	4·49488	4842·0	3·68502	2624·4	3·41903	1800·1	3·25529	11
12	28648	·45709	4774·7	·67895	2604·5	·41572	1790·7	·25303	12
13	26444	·42233	4709·3	·67296	2584·9	·41245	1781·5	·25077	13
14	24555	·39014	4645·7	·66705	2565·6	·40919	1772·3	·24853	14
15	22918	·36018	4583·8	·66122	2546·6	·40597	1763·2	·24629	15
16	21486	4·33215	4523·4	3·65547	2527·9	3·40276	1754·2	3·24407	16
17	20222	·30582	4464·7	·64979	2509·5	·39958	1745·3	·24186	17
18	19099	·28100	4407·5	·64419	2491·3	·39642	1736·5	·23967	18
19	18093	·25752	4351·7	·63865	2473·4	·39329	1727·8	·23748	19
20	17189	·23524	4297·3	·63319	2455·7	·39017	1719·1	·23530	20
21	16370	4·21405	4244·2	3·62780	2438·3	3·38708	1710·6	3·23314	21
22	15626	·19385	4192·5	·62247	2421·1	·38401	1702·1	·23098	22
23	14947	·17454	4142·0	·61720	2404·2	·38097	1693·7	·22884	23
24	14324	·15606	4092·7	·61200	2387·5	·37794	1685·4	·22670	24
25	13751	·13833	4044·5	·60686	2371·0	·37494	1677·2	·22458	25
26	13222	4·12130	3997·5	3·60178	2354·8	3·37195	1669·1	3·22247	26
27	12732	·10491	3951·5	·59676	2338·8	·36899	1661·0	·22037	27
28	12278	·08911	3906·6	·59180	2323·0	·36604	1653·0	·21827	28
29	11854	·07387	3862·7	·58689	2307·4	·36312	1645·1	·21619	29
30	11459	·05915	3819·8	·58204	2292·0	·36021	1637·3	·21412	30
31	11090	4·04491	3777·9	3·57724	2276·8	3·35733	1629·5	3·21206	31
32	10743	·03112	3736·8	·57250	2261·9	·35446	1621·8	·21000	32
33	10417	·01776	3696·6	·56780	2247·1	·35162	1614·2	·20796	33
34	10111	4·00479	3657·3	·56316	2232·5	·34879	1606·7	·20593	34
35	9822·2	3·99221	3618·8	·55856	2218·1	·34598	1599·2	·20390	35
36	9549·3	3·97997	3581·1	3·55401	2203·9	3·34318	1591·8	3·20189	36
37	9291·3	·96807	3544·2	·54951	2189·8	·34041	1584·5	·19988	37
38	9046·7	·95649	3508·0	·54506	2176·0	·33765	1577·2	·19789	38
39	8814·8	·94521	3472·6	·54065	2162·3	·33491	1570·0	·19590	39
40	8594·4	·93421	3437·9	·53629	2148·8	·33219	1562·9	·19392	40
41	8384·8	3·92349	3403·8	3·53197	2135·4	3·32949	1555·8	3·19195	41
42	8185·2	·91302	3370·5	·52769	2122·3	·32680	1548·8	·18999	42
43	7994·8	·90281	3337·7	·52345	2109·2	·32412	1541·9	·18804	43
44	7813·1	·89282	3305·7	·51925	2096·4	·32147	1535·0	·18610	44
45	7639·5	·88306	3274·2	·51510	2083·7	·31883	1528·2	·18417	45
46	7473·4	3·87352	3243·3	3·51098	2071·1	3·31621	1521·4	3·18224	46
47	7314·4	·86418	3213·0	·50691	2058·7	·31360	1514·7	·18032	47
48	7162·0	·85503	3183·2	·50287	2046·5	·31101	1508·1	·17842	48
49	7015·9	·84608	3154·0	·49883	2034·4	·30843	1501·5	·17652	49
50	6875·6	·83731	3125·4	·49490	2022·4	·30587	1495·0	·17462	50
51	6740·7	3·82871	3097·2	3·49097	2010·6	3·30332	1488·5	3·17274	51
52	6611·1	·82027	3069·6	·48707	1998·9	·30079	1482·1	·17087	52
53	6486·4	·81200	3042·4	·48321	1987·3	·29827	1475·7	·16900	53
54	6366·3	·80388	3015·7	·47939	1975·9	·29577	1469·4	·16714	54
55	6250·5	·79591	2989·5	·47559	1964·6	·29328	1463·2	·16529	55
56	6138·9	3·78809	2963·7	3·47183	1953·5	3·29081	1457·0	3·16344	56
57	6031·2	·78040	2938·4	·46811	1942·4	·28835	1450·8	·16161	57
58	5927·2	·77285	2913·5	·46441	1931·5	·28590	1444·7	·15978	58
59	5826·8	·76542	2889·0	·46075	1920·7	·28347	1438·7	·15796	59
60	5729·6	·75813	2864·9	·45711	1910·1	·28105	1432·7	·15615	60

Deg	4°		5°		6°		7°		Deg
Min	Radius.	Log R	Radius.	Log R	Radius.	Log R	Radius.	Log R	Min
0	1432.7	3.15615	1146.3	3.05929	955.37	2.98017	819.02	2.91329	0
1	1426.7	.15434	1142.5	.05784	952.72	.97896	817.08	.91226	1
2	1420.8	.15255	1138.7	.05640	950.09	.97776	815.14	.91123	2
3	1415.0	.15076	1134.9	.05497	947.48	.97657	813.22	.91021	3
4	1409.2	.14897	1131.2	.05354	944.88	.97537	811.30	.90918	4
5	1403.5	.14720	1127.5	.05211	942.29	.97418	809.40	.90816	5
6	1397.8	3.14543	1123.8	3.05069	939.72	2.97300	807.50	2.90714	6
7	1392.1	.14367	1120.2	.04928	937.16	.97181	805.61	.90612	7
8	1386.5	.14191	1116.5	.04787	934.62	.97063	803.73	.90511	8
9	1380.9	.14017	1112.9	.04646	932.09	.96945	801.86	.90410	9
10	1375.4	.13843	1109.3	.04506	929.57	.96828	800.00	.90309	10
11	1369.9	3.13669	1105.8	3.04366	927.07	2.96711	798.14	2.90208	11
12	1364.5	.13497	1102.2	.04227	924.58	.96594	796.30	.90107	12
13	1359.1	.13325	1098.7	.04088	922.10	.96478	794.46	.90007	13
14	1353.8	.13154	1095.2	.03949	919.64	.96361	792.63	.89907	14
15	1348.4	.12983	1091.7	.03811	917.19	.96246	790.81	.89807	15
16	1343.2	3.12813	1088.3	3.03674	914.75	2.96130	789.00	2.89708	16
17	1338.0	.12644	1084.8	.03537	912.33	.96015	787.20	.89608	17
18	1332.8	.12475	1081.4	.03400	909.92	.95900	785.41	.89509	18
19	1327.6	.12307	1078.1	.03264	907.52	.95785	783.62	.89410	19
20	1322.5	.12140	1074.7	.03128	905.13	.95671	781.84	.89312	20
21	1317.5	3.11974	1071.3	3.02992	902.76	2.95557	780.07	2.89213	21
22	1312.4	.11808	1068.0	.02857	900.40	.95443	778.31	.89115	22
23	1307.4	.11642	1064.7	.02723	898.05	.95330	776.55	.89017	23
24	1302.5	.11477	1061.4	.02589	895.71	.95217	774.81	.88919	24
25	1297.6	.11313	1058.2	.02455	893.39	.95104	773.07	.88821	25
26	1292.7	3.11150	1054.9	3.02322	891.08	2.94991	771.34	2.88724	26
27	1287.9	.10987	1051.7	.02189	888.78	.94879	769.61	.88627	27
28	1283.1	.10825	1048.5	.02056	886.49	.94767	767.90	.88530	28
29	1278.3	.10663	1045.3	.01924	884.21	.94655	766.19	.88433	29
30	1273.6	.10502	1042.1	.01792	881.95	.94544	764.49	.88337	30
31	1268.9	3.10341	1039.0	3.01661	879.69	2.94433	762.80	2.88241	31
32	1264.2	.10182	1035.9	.01530	877.45	.94322	761.11	.88145	32
33	1259.6	.10022	1032.8	.01400	875.22	.94212	759.43	.88049	33
34	1255.0	.09864	1029.7	.01270	873.00	.94101	757.76	.87953	34
35	1250.4	.09705	1026.6	.01140	870.80	.93991	756.10	.87858	35
36	1245.9	3.09548	1023.5	3.01010	868.60	2.93882	754.44	2.87762	36
37	1241.4	.09391	1020.5	.00882	866.41	.93772	752.80	.87668	37
38	1236.9	.09234	1017.5	.00753	864.24	.93663	751.16	.87573	38
39	1232.5	.09079	1014.5	.00625	862.07	.93554	749.52	.87478	39
40	1228.1	.08923	1011.5	.00497	859.92	.93446	747.89	.87384	40
41	1223.7	3.08769	1008.6	3.00370	857.78	2.93337	746.27	2.87290	41
42	1219.4	.08614	1005.6	.00242	855.65	.93229	744.66	.87196	42
43	1215.1	.08461	1002.7	3.00116	853.53	.93122	743.06	.87102	43
44	1210.8	.08308	999.76	2.99989	851.42	.93014	741.46	.87008	44
45	1206.6	.08155	996.87	.99863	849.32	.92907	739.86	.86915	45
46	1202.4	3.08003	993.99	2.99738	847.23	2.92800	738.28	2.86822	46
47	1198.2	.07852	991.13	.99613	845.15	.92693	736.70	.86729	47
48	1194.0	.07701	988.28	.99488	843.08	.92587	735.13	.86636	48
49	1189.9	.07550	985.45	.99363	841.02	.92480	733.56	.86544	49
50	1185.8	.07400	982.64	.99239	838.97	.92374	732.01	.86451	50
51	1181.7	3.07251	979.84	2.99115	836.93	2.92269	730.45	2.86359	51
52	1177.7	.07102	977.06	.98992	834.90	.92163	728.91	.86267	52
53	1173.6	.06954	974.29	.98869	832.89	.92058	727.37	.86175	53
54	1169.7	.06806	971.54	.98746	830.88	.91953	725.84	.86084	54
55	1165.7	.06658	968.81	.98624	828.88	.91849	724.31	.85992	55
56	1161.8	3.06511	966.09	2.98501	826.89	2.91744	722.79	2.85901	56
57	1157.9	.06365	963.39	.98380	824.91	.91640	721.28	.85810	57
58	1154.0	.06219	960.70	.98258	822.93	.91536	719.77	.85719	58
59	1150.1	.06074	958.03	.98137	820.97	.91433	718.27	.85629	59
60	1146.3	.05929	955.37	.98017	819.02	.91329	716.78	.85538	60

Deg.	8°		9°		10°		11°		Deg
Min.	Radius.	Log *R*	Radius.	Log *R*	Radius.	Log *R*	Radius.	Log *R*	Min
0	716·78	2·85538	637·27	2·80432	573·69	2·75867	521·67	2·71739	0
1	715·29	·85448	636·10	·80352	572·73	·75795	520·88	·71674	1
2	713·81	·85358	634·93	·80272	571·78	·75723	520·10	·71608	2
3	712·34	·85268	633·76	·80192	570·84	·75651	519·32	·71543	3
4	710·87	·85178	632·60	·80113	569·90	·75579	518·54	·71478	4
5	709·40	·85089	631·44	·80033	568·96	·75508	517·76	·71413	5
6	707·95	2·85000	630·29	2·79954	568·02	2·75436	516·99	2·71348	6
7	706·49	·84911	629·14	·79874	567·09	·75365	516·21	·71283	7
8	705·05	·84822	627·99	·79795	566·16	·75293	515·44	·71218	8
9	703·61	·84733	626·85	·79716	565·23	·75222	514·68	·71153	9
10	702·17	·84644	625·71	·79637	564·31	·75151	513·91	·71088	10
11	700·75	2·84556	624·58	2·79558	563·38	2·75080	513·15	2·71024	11
12	699·33	·84468	623·45	·79480	562·47	·75009	512·38	·70959	12
13	697·91	·84380	622·32	·79401	561·55	·74939	511·63	·70895	13
14	696·50	·84292	621·20	·79323	560·64	·74868	510·87	·70831	14
15	695·09	·84204	620·09	·79245	559·73	·74798	510·11	·70767	15
16	693·70	2·84117	618·97	2·79167	558·82	2·74727	509·36	2·70702	16
17	692·30	·84029	617·87	·79089	557·92	·74657	508·61	·70638	17
18	690·91	·83942	616·76	·79011	557·02	·74587	507·86	·70575	18
19	689·53	·83855	615·66	·78934	556·12	·74517	507·12	·70511	19
20	688·16	·83768	614·56	·78856	555·23	·74447	506·38	·70447	20
21	686·78	2·83682	613·47	2·78779	554·34	2·74377	505·64	2·70383	21
22	685·42	·83595	612·38	·78702	553·45	·74307	504·90	·70320	22
23	684·06	·83509	611·30	·78625	552·56	·74238	504·16	·70257	23
24	682·70	·83423	610·21	·78548	551·68	·74168	503·42	·70193	24
25	681·35	·83337	609·14	·78471	550·80	·74099	502·69	·70130	25
26	680·01	2·83251	608·06	2·78395	549·92	2·74030	501·96	2·70067	26
27	678·67	·83166	606·99	·78318	549·05	·73961	501·23	·70004	27
28	677·34	·83080	605·93	·78242	548·17	·73892	500·51	·69941	28
29	676·01	·82995	604·86	·78165	547·30	·73823	499·78	·69878	29
30	674·69	·82910	603·80	·78089	546·44	·73754	499·06	·69815	30
31	673·37	2·82825	602·75	2·78013	545·57	2·73685	498·34	2·69752	31
32	672·06	·82740	601·70	·77938	544·71	·73617	497·62	·69690	32
33	670·75	·82656	600·65	·77862	543·86	·73548	496·91	·69627	33
34	669·45	·82571	599·61	·77786	543·00	·73480	496·19	·69565	34
35	668·15	·82487	598·57	·77711	542·15	·73412	495·48	·69503	35
36	666·86	2·82403	597·53	2·77636	541·30	2·73343	494·77	2·69440	36
37	665·57	·82319	596·50	·77561	540·45	·73275	494·07	·69378	37
38	664·29	·82235	595·47	·77486	539·61	·73207	493·36	·69316	38
39	663·01	·82152	594·44	·77411	538·76	·73140	492·66	·69254	39
40	661·74	·82068	593·42	·77336	537·92	·73072	491·96	·69192	40
41	660·47	2·81985	592·40	2·77261	537·09	2·73004	491·26	2·69131	41
42	659·21	·81902	591·38	·77187	536·25	·72937	490·56	·69069	42
43	657·95	·81819	590·37	·77112	535·42	·72869	489·86	·69007	43
44	656·69	·81736	589·36	·77038	534·59	·72802	489·17	·68946	44
45	655·45	·81653	588·36	·76964	533·77	·72735	488·48	·68884	45
46	654·20	2·81571	587·36	2·76890	532·94	2·72668	487·79	2·68823	46
47	652·96	·81489	586·36	·76816	532·12	·72601	487·10	·68762	47
48	651·73	·81406	585·36	·76742	531·30	·72534	486·42	·68701	48
49	650·50	·81324	584·37	·76669	530·49	·72467	485·73	·68640	49
50	649·27	·81243	583·38	·76595	529·67	·72401	485·05	·68579	50
51	648·05	2·81161	582·40	2·76522	528·86	2·72334	484·37	2·68518	51
52	646·84	·81079	581·42	·76449	528·05	·72267	483·69	·68457	52
53	645·63	·80998	580·44	·76376	527·25	·72201	483·02	·68396	53
54	644·42	·80917	579·47	·76303	526·44	·72135	482·34	·68335	54
55	643·22	·80836	578·49	·76230	525·64	·72069	481·67	·68275	55
56	642·02	2·80755	577·53	2·76157	524·84	2·72003	481·00	2·68214	56
57	640·83	·80674	576·56	·76084	524·05	·71937	480·33	·68154	57
58	639·64	·80593	575·60	·76012	523·25	·71871	479·67	·68094	58
59	638·45	·80513	574·64	·75939	522·46	·71805	479·00	·68033	59
60	637·27	·80432	573·69	·75867	521·67	·71739	478·34	·67973	60

Deg.	Radius.	Log R
12°	478.34	2.67973
2	477.02	.67853
4	475.71	.67734
6	474.40	.67614
8	473.10	.67495
10	471.81	2.67376
12	470.53	.67258
14	469.25	.67140
16	467.98	.67022
18	466.72	.66905
20	465.46	2.66788
22	464.21	.66671
24	462.97	.66555
26	461.73	.66439
28	460.50	.66323
30	459.28	2.66207
32	458.06	.66092
34	456.85	.65977
36	455.65	.65863
38	454.45	.65748
40	453.26	2.65634
42	452.07	.65521
44	450.89	.65407
46	449.72	.65294
48	448.56	.65181
50	447.40	2.65069
52	446.24	.64957
54	445.09	.64845
56	443.95	.64733
58	442.81	.64622
13°	441.68	2.64511
2	440.56	.64400
4	439.44	.64290
6	438.33	.64180
8	437.22	.64070
10	436.12	2.63960
12	435.02	.63851
14	433.93	.63742
16	432.84	.63633
18	431.76	.63524
20	430.69	2.63416
22	429.62	.63308
24	428.56	.63201
26	427.50	.63093
28	426.44	.62936
30	425.40	2.62879
32	424.35	.62773
34	423.32	.62666
36	422.28	.62560
38	421.26	.62454
40	420.23	2.62349
42	419.22	.62243
44	418.20	.62138
46	417.19	.62034
48	416.19	.61929
50	415.19	2.61825
52	414.20	.61721
54	413.21	.61617
56	412.23	.61514
58	411.25	.61410
14°	410.28	2.61307

Deg.	Radius.	Log R
14°	410.28	2.61307
2	409.31	.61205
4	408.34	.61102
6	407.38	.61000
8	406.42	.60898
10	405.47	2.60796
12	404.53	.60694
14	403.58	.60593
16	402.65	.60492
18	401.71	.60391
20	400.78	2.60291
22	399.86	.60190
24	398.94	.60090
26	398.02	.59990
28	397.11	.59891
30	396.20	2.59791
32	395.30	.59692
34	394.40	.59593
36	393.50	.59494
38	392.61	.59396
40	391.72	2.59298
42	390.84	.59199
44	389.96	.59102
46	389.08	.59004
48	388.21	.58907
50	387.34	2.58809
52	386.48	.58713
54	385.62	.58616
56	384.77	.58519
58	383.91	.58423
15°	383.06	2.58327
2	382.22	.58231
4	381.38	.58135
6	380.54	.58040
8	379.71	.57945
10	378.88	2.57850
12	378.05	.57755
14	377.23	.57661
16	376.41	.57566
18	375.60	.57472
20	374.79	2.57378
22	373.98	.57284
24	373.17	.57191
26	372.37	.57097
28	371.57	.57004
30	370.78	2.56911
32	369.99	.56819
34	369.20	.56726
36	368.42	.56634
38	367.64	.56542
40	366.86	2.56450
42	366.09	.56358
44	365.31	.56266
46	364.55	.56175
48	363.78	.56084
50	363.02	2.55993
52	362.26	.55902
54	361.51	.55812
56	360.76	.55721
58	360.01	.55631
16°	359.26	2.55541

Deg.	Radius.	Log R
16°	359.26	2.55541
5	357.42	.55317
10	355.59	.55094
15	353.77	.54872
20	351.98	.54652
25	350.21	.54432
30	348.45	2.54214
35	346.71	.53997
40	344.99	.53780
45	343.29	.53565
50	341.60	.53351
55	339.93	.53138
17°	338.27	2.52927
5	336.64	.52716
10	335.01	.52506
15	333.41	.52297
20	331.82	.52090
25	330.24	.51883
30	328.68	2.51677
35	327.13	.51472
40	325.60	.51269
45	324.09	.51066
50	322.59	.50864
55	321.10	.50663
18°	319.62	2.50464
5	318.16	.50265
10	316.71	.50067
15	315.28	.49869
20	313.86	.49673
25	312.45	.49478
30	311.06	2.49284
35	309.67	.49090
40	308.30	.48898
45	306.95	.48706
50	305.60	.48515
55	304.27	.48325
19°	302.94	2.48136
5	301.63	.47948
10	300.33	.47760
15	299.04	.47573
20	297.77	.47388
25	296.50	.47203
30	295.25	2.47018
35	294.00	.46835
40	292.77	.46652
45	291.55	.46471
50	290.33	.46289
55	289.13	.46109
20°	287.94	2.45930
5	286.76	.45751
10	285.58	.45573
15	284.42	.45396
20	283.27	.45219
25	282.12	.45044
30	280.99	2.44869
35	279.86	.44694
40	278.75	.44521
45	277.64	.44348
50	276.54	.44176
55	275.45	.44004
21°	274.37	2.43833

Deg.	Radius	Log R
21°	274.37	2.43833
10	272.23	.43494
20	270.13	.43157
30	268.06	.42823
40	266.02	.42492
50	264.02	.42163
22°	262.04	2.41837
10	260.10	.41513
20	258.18	.41192
30	256.29	.40873
40	254.43	.40557
50	252.60	.40243
23°	250.79	2.39931
10	249.01	.39622
20	247.26	.39315
30	245.53	.39010
40	243.82	.38707
50	242.14	.38407
24°	240.49	2.38109
10	238.85	.37813
20	237.24	.37519
30	235.65	.37227
40	234.08	.36937
50	232.54	.36649
25°	231.01	2.36363
30	226.55	.35517
26°	222.27	.34688
30	218.15	.33875
27°	214.18	2.33078
30	210.36	.32296
28°	206.68	.31529
30	203.13	.30776
29°	199.70	2.30037
30	196.38	.29310
30°	193.19	.28597
30	190.09	.27896
31°	187.10	2.27207
32	181.40	.25863
33	176.05	.24563
34	171.02	.23303
35	166.28	.22083
36	161.80	2.20899
37	157.58	.19749
38	153.58	.18633
39	149.79	.17547
40	146.19	.16492
41	142.77	2.15464
42	139.52	.14464
43	136.43	.13489
44	133.47	.12539
45	130.66	.11613
46	127.97	2.10709
47	125.39	.09827
48	122.93	.08965
49	120.57	.08124
50	118.31	.07302
52	114.06	2.05713
54	110.13	.04192
56	106.50	.02736
58	103.13	.01340
60	100.00	2.00000

TABLE II.—TANGENTS, EXTERNAL DISTANCES, AND LONG CHORDS FOR A 1° CURVE.

Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*	Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*	Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*
1°	50.00	0.218	100.00	**11°**	551.70	26.500	1098.3	**21°**	1061.9	97.58	2088.3
10′	58.34	0.297	116.67	10	560.11	27.313	1114.9	10	1070.6	99.15	2104.7
20	66.67	0.388	133.33	20	568.53	28.137	1131.5	20	1079.2	100.75	2121.1
30	75.01	0.491	150.00	30	576.95	28.974	1148.1	30	1087.8	102.35	2137.4
40	83.34	0.606	166.66	40	585.36	29.824	1164.7	40	1096.4	103.97	2153.8
50	91.68	0.733	183.33	50	593.79	30.686	1181.2	50	1105.1	105.60	2170.2
2°	100.01	0.873	199.99	**12°**	602.21	31.561	1197.8	**22°**	1113.7	107.24	2186.5
10	108.35	1.024	216.66	10	610.64	32.447	1214.4	10	1122.4	108.90	2202.9
20	116.68	1.188	233.32	20	619.07	33.347	1231.0	20	1131.0	110.57	2219.2
30	125.02	1.364	249.98	30	627.50	34.259	1247.5	30	1139.7	112.25	2235.6
40	133.36	1.552	266.65	40	635.93	35.183	1264.1	40	1148.4	113.95	2251.9
50	141.70	1.752	283.31	50	644.37	36.120	1280.7	50	1157.0	115.66	2268.3
3°	150.04	1.964	299.97	**13°**	652.81	37.069	1297.2	**23°**	1165.7	117.38	2284.6
10	158.38	2.188	316.63	10	661.25	38.031	1313.8	10	1174.4	119.12	2301.0
20	166.72	2.425	333.29	20	669.70	39.006	1330.3	20	1183.1	120.87	2317.3
30	175.06	2.674	349.95	30	678.15	39.993	1346.9	30	1191.8	122.63	2333.6
40	183.40	2.934	366.61	40	686.60	40.992	1363.4	40	1200.5	124.41	2349.9
50	191.74	3.207	383.27	50	695.06	42.004	1380.0	50	1209.2	126.20	2366.2
4°	200.08	3.492	399.92	**14°**	703.51	43.029	1396.5	**24°**	1217.9	128.00	2382.5
10	208.43	3.790	416.58	10	711.97	44.066	1413.1	10	1226.6	129.82	2398.8
20	216.77	4.099	433.24	20	720.44	45.116	1429.6	20	1235.3	131.65	2415.1
30	225.12	4.421	449.89	30	728.90	46.178	1446.2	30	1244.0	133.50	2431.4
40	233.47	4.755	466.54	40	737.37	47.253	1462.7	40	1252.8	135.36	2447.7
50	241.81	5.100	483.20	50	745.85	48.341	1479.2	50	1261.5	137.23	2464.0
5°	250.16	5.459	499.85	**15°**	754.32	49.441	1495.7	**25°**	1270.2	139.11	2480.2
10	258.51	5.829	516.50	10	762.80	50.554	1512.3	10	1279.0	141.01	2496.5
20	266.86	6.211	533.15	20	771.29	51.679	1528.8	20	1287.7	142.93	2512.8
30	275.21	6.606	549.80	30	779.77	52.818	1545.3	30	1296.5	144.85	2529.0
40	283.57	7.013	566.44	40	788.26	53.969	1561.8	40	1305.3	146.79	2545.3
50	291.92	7.432	583.09	50	796.75	55.132	1578.3	50	1314.0	148.75	2561.5
6°	300.28	7.863	599.73	**16°**	805.25	56.309	1594.8	**26°**	1322.8	150.71	2577.8
10	308.64	8.307	616.38	10	813.75	57.498	1611.3	10	1331.6	152.69	2594.0
20	316.99	8.762	633.02	20	822.25	58.699	1627.8	20	1340.4	154.69	2610.3
30	325.35	9.230	649.66	30	830.76	59.914	1644.3	30	1349.2	156.70	2626.5
40	333.71	9.710	666.30	40	839.27	61.141	1660.8	40	1358.0	158.72	2642.7
50	342.08	10.202	682.94	50	847.78	62.381	1677.3	50	1366.8	160.76	2658.9
7°	350.44	10.707	699.57	**17°**	856.30	63.634	1693.8	**27°**	1375.6	162.81	2675.1
10	358.81	11.224	716.21	10	864.82	64.900	1710.3	10	1384.4	164.87	2691.3
20	367.17	11.753	732.84	20	873.35	66.178	1726.8	20	1393.2	166.95	2707.5
30	375.54	12.294	749.47	30	881.88	67.470	1743.2	30	1402.0	169.04	2723.7
40	383.91	12.847	766.10	40	890.41	68.774	1759.7	40	1410.9	171.15	2739.9
50	392.28	13.413	782.73	50	898.95	70.091	1776.2	50	1419.7	173.27	2756.1
8°	400.66	13.991	799.36	**18°**	907.49	71.421	1792.6	**28°**	1428.6	175.41	2772.3
10	409.03	14.582	815.99	10	916.03	72.764	1809.1	10	1437.4	177.55	2788.4
20	417.41	15.184	832.61	20	924.58	74.119	1825.5	20	1446.3	179.72	2804.6
30	425.79	15.799	849.23	30	933.13	75.488	1842.0	30	1455.1	181.89	2820.7
40	434.17	16.426	865.85	40	941.69	76.869	1858.4	40	1464.0	184.08	2836.9
50	442.55	17.066	882.47	50	950.25	78.264	1874.9	50	1472.9	186.29	2853.0
9°	450.93	17.717	899.09	**19°**	958.81	79.671	1891.3	**29°**	1481.8	188.51	2869.2
10	459.32	18.381	915.70	10	967.38	81.092	1907.8	10	1490.7	190.74	2885.3
20	467.71	19.058	932.31	20	975.96	82.525	1924.2	20	1499.6	192.99	2901.4
30	476.10	19.746	948.92	30	984.53	83.972	1940.6	30	1508.5	195.25	2917.6
40	484.49	20.447	965.53	40	993.12	85.431	1957.1	40	1517.4	197.53	2933.7
50	492.88	21.161	982.14	50	1001.70	86.904	1973.5	50	1526.3	199.82	2949.8
10°	501.28	21.886	998.74	**20°**	1010.29	88.389	1989.9	**30°**	1535.3	202.12	2965.9
10	509.68	22.624	1015.35	10	1018.89	89.888	2006.3	10	1544.2	204.44	2982.0
20	518.08	23.375	1031.95	20	1027.49	91.399	2022.7	20	1553.1	206.77	2998.1
30	526.48	24.138	1048.54	30	1036.09	92.924	2039.1	30	1562.1	209.12	3014.2
40	534.89	24.913	1065.14	40	1044.70	94.462	2055.5	40	1571.0	211.48	3030.2
50	543.29	25.700	1081.73	50	1053.31	96.013	2071.9	50	1580.0	213.86	3046.3
11°	551.70	26.500	1098.33	**21°**	1061.93	97.577	2088.3	**31°**	1589.0	216.25	3062.4

TABLE II.—TANGENTS, EXTERNAL DISTANCES, AND LONG CHORDS FOR A 1° CURVE.

Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*	Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*	Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*
31°	1589.0	216.25	3062.4	**41°**	2142.2	387.38	4013.1	**51°**	2732.9	618.39	4933.4
10	1598.0	218.66	3078.4	10	2151.7	390.71	4028.7	10	2743.1	622.81	4948.4
20	1606.9	221.08	3094.5	20	2161.2	394.06	4044.3	20	2753.4	627.24	4963.4
30	1615.9	223.51	3110.5	30	2170.8	397.43	4059.9	30	2763.7	631.69	4978.4
40	1624.9	225.96	3126.6	40	2180.3	400.82	4075.5	40	2773.9	636.16	4993.4
50	1633.9	228.42	3142.6	50	2189.9	404.22	4091.1	50	2784.2	640.66	5008.4
32°	1643.0	230.90	3158.6	**42°**	2199.4	407.64	4106.6	**52°**	2794.5	645.17	5023.4
10	1652.0	233.39	3174.6	10	2209.0	411.07	4122.2	10	2804.9	649.70	5038.4
20	1661.0	235.90	3190.6	20	2218.6	414.52	4137.7	20	2815.2	654.25	5053.4
30	1670.0	238.43	3206.6	30	2228.1	417.99	4153.3	30	2825.6	658.83	5068.3
40	1679.1	240.96	3222.6	40	2237.7	421.48	4168.8	40	2835.9	663.42	5083.3
50	1688.1	243.52	3238.6	50	2247.3	424.98	4184.3	50	2846.3	668.03	5098.2
33°	1697.2	246.08	3254.6	**43°**	2257.0	428.50	4199.8	**53°**	2856.7	672.66	5113.1
10	1706.3	248.66	3270.6	10	2266.6	432.04	4215.3	10	2867.1	677.32	5128.0
20	1715.3	251.26	3286.6	20	2276.2	435.59	4230.8	20	2877.5	681.99	5142.9
30	1724.4	253.87	3302.5	30	2285.9	439.16	4246.3	30	2888.0	686.68	5157.8
40	1733.5	256.50	3318.5	40	2295.6	442.75	4261.8	40	2898.4	691.40	5172.7
50	1742.6	259.14	3334.4	50	2305.2	446.35	4277.3	50	2908.9	696.13	5187.6
34°	1751.7	261.80	3350.4	**44°**	2314.9	449.98	4292.7	**54°**	2919.4	700.89	5202.4
10	1760.8	264.47	3366.3	10	2324.6	453.62	4308.2	10	2929.9	705.66	5217.3
20	1770.0	267.16	3382.2	20	2334.3	457.27	4323.6	20	2940.4	710.46	5232.1
30	1779.1	269.86	3398.2	30	2344.1	460.95	4339.0	30	2951.0	715.28	5246.9
40	1788.2	272.58	3414.1	40	2353.8	464.64	4354.5	40	2961.5	720.11	5261.7
50	1797.4	275.31	3430.0	50	2363.5	468.35	4369.9	50	2972.1	724.97	5276.5
35°	1806.6	278.05	3445.9	**45°**	2373.3	472.08	4385.3	**55°**	2982.7	729.85	5291.3
10	1815.7	280.82	3461.8	10	2383.1	475.82	4400.7	10	2993.3	734.76	5306.1
20	1824.9	283.60	3477.7	20	2392.8	479.59	4416.1	20	3003.9	739.68	5320.9
30	1834.1	286.39	3493.5	30	2402.6	483.37	4431.4	30	3014.5	744.62	5335.6
40	1843.3	289.20	3509.4	40	2412.4	487.16	4446.8	40	3025.2	749.59	5350.4
50	1852.5	292.02	3525.3	50	2422.3	490.98	4462.2	50	3035.8	754.57	5365.1
36°	1861.7	294.86	3541.1	**46°**	2432.1	494.82	4477.5	**56°**	3046.5	759.58	5379.8
10	1870.9	297.72	3557.0	10	2441.9	498.67	4492.8	10	3057.2	764.61	5394.5
20	1880.1	300.59	3572.8	20	2451.8	502.54	4508.2	20	3067.9	769.66	5409.2
30	1889.4	303.47	3588.6	30	2461.7	506.42	4523.5	30	3078.7	774.73	5423.9
40	1898.6	306.37	3604.5	40	2471.5	510.33	4538.8	40	3089.4	779.83	5438.6
50	1907.9	309.29	3620.3	50	2481.4	514.25	4554.1	50	3100.2	784.94	5453.3
37°	1917.1	312.22	3636.1	**47°**	2491.3	518.20	4569.4	**57°**	3110.9	790.08	5467.9
10	1926.4	315.17	3651.9	10	2501.2	522.16	4584.7	10	3121.7	795.24	5482.5
20	1935.7	318.13	3667.7	20	2511.2	526.13	4599.9	20	3132.6	800.42	5497.2
30	1945.0	321.11	3683.5	30	2521.1	530.13	4615.2	30	3143.4	805.62	5511.8
40	1954.3	324.11	3699.3	40	2531.1	534.15	4630.4	40	3154.2	810.85	5526.4
50	1963.6	327.12	3715.0	50	2541.0	538.18	4645.7	50	3165.1	816.10	5541.0
38°	1972.9	330.15	3730.8	**48°**	2551.0	542.23	4660.9	**58°**	3176.0	821.37	5555.6
10	1982.2	333.19	3746.5	10	2561.0	546.30	4676.1	10	3186.9	826.66	5570.2
20	1991.[illegible]	336.25	3762.3	20	2571.0	550.39	4691.3	20	3197.8	831.98	5584.7
30	2000.9	339.32	3778.0	30	2581.0	554.50	4706.5	30	3208.8	837.31	5599.3
40	2010.2	342.41	3793.8	40	2591.1	558.63	4721.7	40	3219.7	842.67	5613.8
50	2019.6	345.52	3809.5	50	2601.1	562.77	4736.9	50	3230.7	848.06	5628.3
39°	2029.0	348.64	3825.2	**49°**	2611.2	566.94	4752.1	**59°**	3241.7	853.46	5642.8
10	2038.4	351.78	3840.9	10	2621.2	571.12	4767.3	10	3252.7	858.89	5657.3
20	2047.8	354.94	3856.6	20	2631.3	575.32	4782.4	20	3263.7	864.34	5671.8
30	2057.2	358.11	3872.3	30	2641.4	579.54	4797.5	30	3274.8	869.82	5686.3
40	2066.6	361.29	3888.0	40	2651.5	583.78	4812.7	40	3285.8	875.32	5700.8
50	2076.0	364.50	3903.6	50	2661.6	588.04	4827.8	50	3296.9	880.84	5715.2
40°	2085.4	367.72	3919.3	**50°**	2671.8	592.32	4842.9	**60°**	3308.0	886.38	5729.7
10	2094.9	370.95	3935.0	10	2681.9	596.62	4858.0	10	3319.1	891.95	5744.1
20	2104.3	374.20	3950.6	20	2692.1	600.93	4873.1	20	3330.3	897.54	5758.5
30	2113.8	377.47	3966.3	30	2702.3	605.27	4888.2	30	3341.4	903.15	5772.9
40	2123.3	380.76	3981.9	40	2712.5	609.62	4903.2	40	3352.6	908.79	5787.3
50	2132.7	384.06	3997.5	50	2722.7	614.00	4918.3	50	3363.8	914.45	5801.7
41°	2142.2	387.38	4013.1	**51°**	2732.9	618.39	4933.4	**61°**	3375.0	920.14	5816.0

TABLE II.—TANGENTS, EXTERNAL DISTANCES, AND LONG CHORDS FOR A 1° CURVE.

Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*	Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*	Δ	Tang. *T.*	Ext. Dist. *E.*	Long Chord *LC.*
61°	3375.0	920.14	5816.0	**68°**	3864.7	1181.6	6408.0	**75°**	4396.5	1492.4	6976.0
10′	3386.3	925.85	5830.4	10′	3876.8	1188.4	6421.8	10′	4409.8	1500.5	6989.2
20	3397.5	931.58	5844.7	20	3889.0	1195.2	6435.6	20	4423.1	1508.6	7002.4
30	3408.8	937.34	5859.1	30	3901.2	1202.0	6449.4	30	4436.4	1516.7	7015.6
40	3420.1	943.12	5873.4	40	3913.4	1208.9	6463.1	40	4449.7	1524.9	7028.8
50	3431.4	948.92	5887.7	50	3925.6	1215.8	6476.9	50	4463.1	1533.1	7041.9
62°	3442.7	954.75	5902.0	**69°**	3937.9	1222.7	6490.6	**76°**	4476.5	1541.4	7055.0
10	3454.1	960.60	5916.3	10	3950.2	1229.7	6504.4	10	4489.9	1549.7	7068.2
20	3465.4	966.48	5930.5	20	3962.5	1236.7	6518.1	20	4503.4	1558.0	7081.3
30	3476.8	972.39	5944.8	30	3974.8	1243.7	6531.8	20	4516.9	1566.3	7094.4
40	3488.2	978.31	5959.0	40	3987.2	1250.8	6545.5	40	4530.4	1574.7	7107.5
50	3499.7	984.27	5973.3	50	3999.5	1257.9	6559.1	50	4544.0	1583.1	7120.5
63°	3511.1	990.24	5987.5	**70°**	4011.9	1265.0	6572.8	**77°**	4557.6	1591.6	7133.6
10	3522.6	996.24	6001.7	10	4024.4	1272.1	6586.4	10	4571.2	1600.1	7146.6
20	3534.1	1002.3	6015.9	20	4036.8	1279.3	6600.1	20	4584.8	1608.6	7159.6
30	3545.6	1008.3	6030.0	30	4049.3	1286.5	6613.7	30	4598.5	1617.1	7172.6
40	3557.2	1014.4	6044.2	40	4061.8	1293.7	6627.3	40	4612.2	1625.7	7185.6
50	3568.7	1020.5	6058.4	50	4074.4	1300.9	6640.9	50	4626.0	1634.4	7198.6
64°	3580.3	1026.6	6072.5	**71°**	4086.9	1308.2	6654.4	**78°**	4639.8	1643.0	7211.6
10	3591.9	1032.8	6086.6	10	4099.5	1315.5	6668.0	10	4653.6	1651.7	7224.5
20	3603.5	1039.0	6100.7	20	4112.1	1322.9	6681.6	20	4667.4	1660.5	7237.4
30	3615.1	1045.2	6114.8	30	4124.8	1330.3	6695.1	30	4681.3	1669.2	7250.4
40	3626.8	1051.4	6128.9	40	4137.4	1337.7	6708.6	40	4695.2	1678.1	7263.3
50	3638.5	1057.7	6143.0	50	4150.1	1345.1	6722.1	50	4709.2	1686.9	7276.1
65°	3650.2	1063.9	6157.1	**72°**	4162.8	1352.6	6735.6	**79°**	4723.2	1695.8	7289.0
10	3661.9	1070.2	6171.1	10	4175.6	1360.1	6749.1	10	4737.2	1704.7	7301.9
20	3673.7	1076.6	6185.2	20	4188.4	1367.6	6762.5	20	4751.2	1713.7	7314.7
30	3685.4	1082.9	6199.2	30	4201.2	1375.2	6776.0	30	4765.3	1722.7	7327.5
40	3697.2	1089.3	6213.2	40	4214.0	1382.8	6789.4	40	4779.4	1731.7	7340.3
50	3709.0	1095.7	6227.2	50	4226.8	1390.4	6802.8	50	4793.6	1740.8	7353.1
66°	3720.9	1102.2	6241.2	**73°**	4239.7	1398.0	6816.3	**80°**	4807.7	1749.9	7365.9
10	3732.7	1108.6	6255.2	10	4252.6	1405.7	6829.6	10	4822.0	1759.0	7378.7
20	3744.6	1115.1	6269.1	20	4265.6	1413.5	6843.0	20	4836.2	1768.2	7391.4
30	3756.5	1121.7	6283.1	30	4278.5	1421.2	6856.4	30	4850.5	1777.4	7404.1
40	3768.5	1128.2	6297.0	40	4291.5	1429.0	6869.7	40	4864.8	1786.7	7416.8
50	3780.4	1134.8	5310.9	50	4304.6	1436.8	6883.1	50	4879.2	1796.0	7429.5
67°	3792.4	1141.4	6324.8	**74°**	4317.6	1444.6	6896.4	**81°**	4893.6	1805.3	7442.2
10	3804.4	1148.0	6338.7	10	4330.7	1452.5	6909.7	10	4908.0	1814.7	7454.9
20	3816.4	1154.7	6352.6	20	4343.8	1460.4	6923.0	20	4922.5	1824.1	7467.5
30	3828.4	1161.3	6366.4	30	4356.9	1468.4	6936.2	30	4937.0	1833.6	7480.2
40	3840.5	1168.1	6380.3	40	4370.1	1476.4	6949.5	40	4951.5	1843.1	7492.8
50	3852.6	1174.8	6394.1	50	4383.3	1484.4	6962.8	50	4966.1	1852.6	7505.4
68°	3864.7	1181.6	6408.0	**75°**	4396.5	1492.4	6976.0	**82°**	4980.7	1862.2	7518.0

Correction Table (always additive)

Δ	Degree of curve. 5°			10°			15°			20°		
	T	E	LC	T	E	LC	T	E	LC	T	E	LC
10°	.03	.001	.06	.06	.003	.13	.10	.004	.17	.13	.006	.25
20	.06	.005	.12	.13	.011	.25	.19	.017	.38	.26	.022	.51
30	.09	.012	.18	.19	.025	.37	.29	.038	.56	.39	.051	.75
40	.13	.022	.24	.26	.046	.49	.40	.070	.74	.53	.093	1.00
50	.16	.036	.30	.34	.075	.61	.51	.112	.92	.68	.151	1.23
60	.20	.054	.35	.42	.111	.72	.63	.168	1.09	.84	.225	1.46
70	.24	.077	.40	.50	.159	.83	.76	.240	1.25	1.02	.321	1.67
80	.29	.107	.45	.60	.220	.93	.91	.332	1.40	1.22	.455	1.87
90	.35	.145	.49	.72	.298	1.02	1.09	.451	1.54	1.46	.603	2.06

Degree of Curve	Nominal length of sub chord.														
	10	20	30	40	45	50	55	60	65	70	75	80	85	90	95
5	.003	.006	.009	.011	.011	.012	.012	.012	.012	.011	.010	.009	.007	.005	.003
6	.005	.009	.012	.015	.016	.017	.018	.018	.017	.016	.015	.013	.011	.008	.004
7	.006	.012	.017	.021	.022	.023	.024	.024	.023	.022	.020	.018	.015	.011	.006
8	.008	.016	.022	.027	.029	.030	.031	.031	.030	.029	.027	.023	.019	.014	.008
9	.010	.020	.028	.035	.037	.038	.039	.039	.039	.037	.034	.030	.024	.018	.010
10	.013	.024	.035	.043	.046	.048	.049	.049	.048	.045	.042	.037	.030	.022	.012
11	.015	.029	.042	.052	.055	.058	.059	.059	.058	.055	.051	.044	.036	.026	.014
12	.018	.035	.050	.062	.066	.069	.070	.070	.069	.066	.060	.053	.043	.031	.017
13	.021	.041	.059	.072	.077	.080	.082	.083	.081	.077	.071	.062	.051	.037	.020
14	.025	.048	.068	.084	.090	.094	.096	.096	.094	.089	.082	.072	.059	.043	.023
15	.028	.055	.079	.097	.103	.108	.110	.110	.108	.103	.094	.083	.068	.049	.027
16	.032	.063	.089	.109	.117	.122	.125	.125	.122	.116	.107	.094	.077	.056	.030
17	.036	.071	.100	.123	.132	.138	.141	.141	.138	.131	.120	.106	.087	.063	.034
18	.041	.079	.113	.139	.148	.155	.158	.158	.155	.147	.135	.119	.097	.070	.038
19	.045	.088	.125	.154	.165	.172	.176	.177	.172	.164	.151	.132	.108	.079	.043
20	.050	.098	.139	.171	.183	.191	.195	.196	.191	.182	.167	.147	.120	.087	.047
21	.056	.108	.153	.189	.202	.211	.215	.216	.211	.200	.184	.162	.132	.096	.052
22	.061	.118	.168	.207	.221	.231	.237	.237	.231	.220	.202	.177	.145	.105	.057
23	.067	.129	.184	.226	.242	.253	.259	.259	.253	.241	.221	.194	.159	.115	.062
24	.073	.141	.201	.247	.264	.275	.282	.282	.276	.262	.241	.211	.173	.125	.068
25	.079	.153	.218	.268	.286	.299	.306	.306	.299	.284	.261	.229	.188	.136	.074
26	.085	.166	.236	.290	.310	.324	.331	.331	.324	.308	.283	.248	.203	.147	.080
27	.092	.179	.254	.313	.334	.349	.357	.357	.349	.332	.305	.268	.219	.159	.086
28	.099	.192	.273	.337	.359	.375	.384	.384	.376	.357	.328	.288	.236	.171	.093
29	.107	.207	.293	.361	.386	.403	.412	.412	.403	.383	.352	.309	.253	.183	.099
30	.114	.221	.314	.387	.413	.431	.441	.442	.432	.410	.377	.331	.271	.196	.109

TABLE III.—SWITCH LEADS AND DISTANCES.

A. TRIGONOMETRICAL FUNCTIONS OF THE FROG ANGLES.

Frog No. (n)	Frog Angle (F).	Nat. sin F.	Nat. cos F.	Log sin F.	Log cos F.	Log cot F.	Log vers F.	Frog No. (n)
5	11° 25′ 16″	.19802	.98020	9.2967$\overline{0}$	9.9913$\overline{1}$	10.69461	8.2967$\overline{0}$	5
6	9 31 38	.16552	.98621	.21884	.99397	.77513	.13966	6
7	8 10 16	.14213	.98985	.1526$\overline{8}$	.99557	.8428$\overline{8}$	8.0065$\overline{5}$	7
8	7 09 10	.12452	.99222	.0952$\overline{2}$	.9966$\overline{0}$	.9013$\overline{8}$	7.8911$\overline{0}$	8
9	6 21 35	.11077	.99385	9.04442	.99732	.95289	.78915	9
10	5 43 29	.09975	.99501	8.99891	.99783	10.99892	.69787	10
11	5 12 18	.09072	.99588	.95770	.9982$\overline{0}$	11.0405$\overline{0}$	.61527	11
12	4 46 19	.08319	.99653	.92007	.99849	.07842	.53986	12
14	4 05 27	.07134	.99745	.8533$\overline{1}$	.99889	.14557	.40616	14
15	3 49 06	.06659	.99778	.82343	.9990$\overline{3}$	.1756$\overline{0}$	.34631	15
16	3 34 47	.06244	.99805	.7954$\overline{3}$	.99915	.2037$\overline{0}$	.29028	16
18	3 10 56	.05551	.99846	.7443$\overline{8}$	.99933	.2549$\overline{4}$	.1880$\overline{7}$	18
20	2° 51′ 51″	.04997	.99875	8.6986$\overline{9}$	9.9994$\overline{5}$	11.30076	7.09663	20

B. THEORETICAL LEADS, USING STRAIGHT POINT-RAILS AND STRAIGHT FROG RAILS; GAUGE 4′ 8½″. See §§ **305** and **313**.

Frog No. (*n*)	Frog bluntness.	Frog: Toe length to theoret. pt. of frog. (*W*)		Frog: Heel to theoret. pt. of frog. (*K*)		Switch Rail: Length. (*S*)		Switch Rail: Angle. (*α*)			Switch Dimensions: Radius. (*r*)	Switch Dimensions: Degree of lead curve. (*D*)			Switch Dimensions: Ac. pt. of sw. rail to ac. pt. frog. (*L′*)
	ft.	ft.	in.	ft.	in.	ft.	in.	°	′	″	ft.	°	′	″	ft.
5	0.21	3	4	5	8	11	0	2	36	19	185.59	31	15	28	43.15
6	0.25	3	6	6	6	11	0	2	36	19	280.48	20	32	14	48.66
7	0.29	4	5	7	7	16	6	1	44	11	364.88	15	47	19	62.23
8	0.33	4	9	8	3	16	6	1	44	11	488.71	11	44	40	67.80
9	0.37	6	0	10	0	16	6	1	44	11	616.27	9	18	27	72.61
10	0.42	6	0	10	6	16	6	1	44	11	790.25	7	15	18	77.93
11	0.46	6	0	11	0	22	0	1	18	08	940.21	6	05	48	92.52
12	0.50	6	5	12	1	22	0	1	18	08	1136.34	5	02	38	97.75
14	0.58	7	3	14	3	22	0	1	18	08	1600.73	3	34	48	107.74
15	0.62	7	8	14	10	30	0	0	57	18	1764.69	3	14	50	126.49
16	0.67	8	0	16	0	30	0	0	57	18	2032.74	2	49	08	131.82
18	0.75	8	10	17	8	30	0	0	57	18	2632.76	2	10	35	141.93
20	0.83	9	8	19	4	30	0	0	57	18	3334.16	1	43	06	151.60

C. PRACTICAL LEADS, USING STRAIGHT POINT-RAILS AND STRAIGHT FROG RAILS; GAUGE 4′ 8½″. See §§ **305–307**.

Frog No. (*n*)	Radius of center line. (*r*)	Degree of lead curve. (*D*)			Tangent adjacent to switch rail. (T_s)	Tangent adjacent to toe of frog. (T_f)	Actual point of switch rail to act. pt. of frog. (*L′*)	Closure for straight rail.		Closure for curved rail.	
	ft.	°	′	″	ft.	ft.	ft.				
5	175.40	33	07	28	0.00	0.97	42.54		1–28.0		1–28.31
6	254.00	22	42	20	0.00	2.00	47.50		1–32.75	1–33	
7	361.69	15	53	30	0.00	0.22	62.08	1–26	1–14.87	1–26	1–15.12
8	487.37	11	46	36	0.32	0.00	68.00	1–30	1–16.42	1–30	1–16.58
9	605.18	9	28	42	0.00	0.57	72.28	1–33	1–16.41	1–33	1–16.59
10	779.82	7	21	08	1.56	0.00	78.75	1–28	1–27.83	2–28	
11	922.65	6	12	47	2.99	0.00	94.31	1–33	1–32.85	2–33	
12	1098.73	5	12	59	5.33	0.00	100.80	2–24	1–23.88	3–24	
14	1512.14	3	47	23	0.00	2.84	106.27	2–30	1–16.44	2–30	1–16.56
15	1748.29	3	16	40	0.00	0.51	126.19	2–30	1–27.90	2–30	1–28
16	2019.18	2	50	16	0.00	0.40	131.56	2–30	1–32.90	2–30	1–33
18	2380.47	2	24	26	0.00	6.38	138.50	2–33	1–32.92	3–33	
20	3322.13	1	43	29	0.00	0.27	151.46	2–33	1–30	2–33	1–30
									1–14.96		1–15.02

The lengths of switch rail used with each frog are the same as those specified for theoretical leads.

PART A.—Coefficients of a_1 for deflection angles to chord points.

Deflection angle to chord-point number.	Transit at chord-point number.										
	0 T. S.	1	2	3	4	5	6	7	8	9	10 S. C.
0 T. S.	0	2	8	18	32	50	72	98	128	162	200
1	1	0	5	14	27	44	65	90	119	152	189
2	4	4	0	8	20	36	56	80	108	140	176
3	9	10	7	0	11	26	45	68	95	126	161
4	16	18	16	10	0	14	32	54	80	110	144
5	25	28	27	22	13	0	17	38	63	92	125
6	36	40	40	36	28	16	0	20	44	72	104
7	49	54	55	52	45	34	19	0	23	50	81
8	64	70	72	70	64	54	40	22	0	26	56
9	81	88	91	90	85	76	63	46	25	0	29
10 S. C.	100	108	112	112	108	100	88	72	52	28	0

PART B.—Values of $\frac{U}{L}$ and $\frac{V}{L}$.

ϕ	$\frac{U}{L}$	$\frac{V}{L}$	ϕ	$\frac{U}{L}$	$\frac{V}{L}$
0°	.666 667	.333 333	23°	.672 423	.338 586
1	.666 678	.333 343	24	.672 943	.339 061
2	.666 710	.333 372	25	.673 486	.339 559
3	.666 763	.333 421	26	.674 054	.340 078
4	.666 838	.333 490	27	.674 645	.340 619
5	.666 935	.333 578	28	.675 261	.341 183
6	.667 053	.333 685	29	.675 901	.341 769
7	.667 193	.333 812	30	.676 566	.342 378
8	.667 354	.333 959	31	.677 256	.343 011
9	.667 537	.334 126	32	.677 971	.343 667
10	.667 742	.334 313	33	.678 712	.344 346
11	.667 968	.334 519	34	.679 478	.345 050
12	.668 216	.334 746	35	.680 270	.345 777
13	.668 487	.334 992	36	.681 089	.346 529
14	.668 779	.335 259	37	.681 935	.347 307
15	.669 094	.335 546	38	.682 808	.348 109
16	.669 431	.335 853	39	.683 708	.348 937
17	.669 790	.336 181	40	.684 636	.349 791
18	.670 172	.336 529	41	.685 592	.350 671
19	.670 576	.336 899	42	.686 577	.351 578
20	.671 003	.337 289	43	.687 590	.352 513
21	.671 453	.337 700	44	.688 633	.353 474
22	.671 926	.338 132	45	.689 706	.354 464

Table IV, of which Part C is condensed, was computed by the Track Committee of the American Railway Engineering Association and is taken from the Proceedings of the Association.

PART C.

Total spiral angle, ϕ	A	$\frac{C}{L}$	$\frac{X}{L}$	$\frac{Y}{L}$
0° 0′	0° 00′ 00″	1.000 000	1.000 000	.000 000
30	0 10 00	.999 997	.999 993	.002 909
1 0	0 20 00	.999 987	.999 970	.005 818
30	0 30 00	.999 970	.999 932	.008 726
2 0	0 40 00	.999 947	.999 879	.011 635
30	0 50 00	.999 916	.999 811	.014 542
3 0	1 00 00	.999 880	.999 727	.017 450
30	1 10 00	.999 836	.999 629	.020 357
4 00	1 20 00	.999 786	.999 515	.023 263
30	1 30 00	.999 729	.999 387	.026 169
5 00	1 40 00	.999 666	.999 243	.029 073
30	1 50 00	.999 596	.999 084	.031 977
6 00	1 59 59	.999 519	.998 910	.034 880
30	2 09 59	.999 435	.998 721	.037 781
7 00	2 19 59	.999 345	.998 517	.040 681
30	2 29 59	.999 248	.998 298	.043 581
8 00	2 39 58	.999 145	.998 063	.046 478
30	2 49 58	.999 035	.997 814	.049 374
9 00	2 59 58	.998 918	.997 549	.052 269
30	3 09 57	.998 794	.997 270	.055 162
10 00	3 19 57	.998 664	.996 975	.058 053
30	3 29 57	.998 527	.996 666	.060 942
11 00	3 39 56	.998 384	.996 341	.063 829
30	3 49 55	.998 233	.996 002	.066 714
12 00	3 59 55	.998 077	.995 647	.069 598
30	4 09 54	.997 913	.995 278	.072 478
13 00	4 19 53	.997 743	.994 893	.075 357
30	4 29 53	.997 566	.994 494	.078 233
14 00	4 39 52	.997 383	.994 079	.081 106
30	4 49 51	.997 192	.993 650	.083 977
15 00	4 59 50	.996 996	.993 206	.086 846
30	5 09 49	.996 792	.992 747	.089 711
16 00	5 19 48	.996 582	.992 273	.092 574
30	5 29 47	.996 366	.991 785	.095 433
17 00	5 39 45	.996 142	.991 281	.098 290
30	5 49 44	.995 912	.990 763	.101 143
18 00	5 59 43	.995 676	.990 230	.103 993
30	6 09 41	.995 432	.989 682	.106 840
19 00	6 19 40	.995 183	.989 120	.109 683
30	6 29 36	.994 926	.988 543	.112 523
20 00	6 39 36	.994 663	.987 951	.115 360
30	6 49 34	.994 393	.987 344	.118 192
21 00	6 59 32	.994 117	.986 723	.121 021
30	7 09 30	.993 834	.986 088	.123 846
22 00	7 19 28	.993 545	.985 437	.126 667
22° 30′	7° 29′ 26″	.993 248	.984 772	.129 483

PART C.—*Con.*

Total spiral angle, ϕ	A	$\frac{C}{L}$	$\frac{X}{L}$	$\frac{Y}{L}$
22° 30′	7° 29′ 26″	.993 248	.984 772	.129 483
23 00	7 39 24	.992 946	.984 093	.132 296
30	7 49 21	.992 636	.983 399	.135 105
24 00	7 59 19	.992 321	.982 691	.137 909
30	8 09 16	.991 998	.981 968	.140 708
25 00	8 19 14	.991 669	.981 231	.143 504
30	8 29 11	.991 333	.980 479	.146 294
26 00	8 39 08	.990 991	.979 714	.149 080
30	8 49 05	.990 642	.978 933	.151 861
27 00	8 59 02	.990 287	.978 139	.154 638
30	9 08 58	.989 925	.977 330	.157 409
28 00	9 18 55	.989 557	.976 508	.160 176
30	9 28 51	.989 182	.975 670	.162 937
29 00	9 38 48	.988 800	.974 819	.165 693
30	9 48 44	.988 412	.973 954	.168 444
30 00	9 58 40	.988 018	.973 074	.171 189
30	10 08 36	.987 617	.972 181	.173 929
31 00	10 18 32	.987 209	.971 273	.176 664
30	10 28 27	.986 795	.970 352	.179 392
32 00	10 38 23	.986 375	.969 417	.182 116
30	10 48 18	.985 948	.968 468	.184 833
33 00	10 58 13	.985 514	.967 504	.187 544
30	11 08 08	.985 074	.966 528	.190 250
34 00	11 18 03	.984 627	.965 537	.192 949
30	11 27 58	.984 174	.964 532	.195 643
35 00	11 37 53	.983 715	.963 515	.198 330
30	11 47 47	.983 249	.962 483	.201 010
36 00	11 57 41	.982 777	.961 438	.203 685
30	12 07 36	.982 298	.960 379	.206 353
37 00	12 17 30	.981 813	.959 306	.209 014
30	12 27 23	.981 321	.958 221	.211 669
38 00	12 37 17	.980 823	.957 121	.214 317
30	12 47 11	.980 318	.956 009	.216 959
39 00	12 57 04	.979 807	.954 883	.219 593
30	13 06 57	.979 290	.953 744	.222 221
40 00	13 16 50	.978 766	.952 591	.224 841
30	13 26 43	.978 236	.951 426	.227 455
41 00	13 36 35	.977 700	.950 247	.230 061
30	13 46 28	.977 157	.949 055	.232 660
42 00	13 56 20	.976 608	.947 850	.235 252
30	14 06 12	.976 053	.946 632	.237 836
43 00	14 16 04	.975 491	.945 402	.240 413
30	14 25 56	.974 923	.944 158	.242 982
44 00	14 35 47	.974 348	.942 901	.245 544
30	14 45 38	.973 768	.941 632	.248 098
45° 00′	14° 55′ 29″	.973 181	.940 350	.250 644

N.	0	1	2	3	4	5	6	7	8	9	P. P.
100	00 000	043	087	130	173	216	260	303	346	389	43 43 42 41
101	432	475	518	561	604	646	689	732	775	817	.1 4.3 4.3 4.2 4.1
102	860	902	945	987	*030	*072	*114	*157	*199	*241	.2 8.7 8.6 8.4 8.2
103	01 283	326	368	410	452	494	536	578	619	661	.3 13.0 12.9 12.6 12.3
104	703	745	787	828	870	911	953	994	*036	*077	.4 17.4 17.2 16.8 16.4
105	02 119	160	201	243	284	325	366	407	448	489	.5 21.7 21.5 21.0 20.5
106	530	571	612	653	694	735	775	816	857	898	.6 26.1 25.8 25.2 24.6
107	938	979	*019	*060	*100	*141	*181	*221	*262	*302	.7 30.4 30.1 29.4 28.7
108	03 342	382	422	463	503	543	583	623	663	703	.8 34.8 34.4 33.6 32.8
109	742	782	822	862	901	941	981	*020	*060	*100	.9 39.1 38.7 37.8 36.9
110	04 139	178	218	257	297	336	375	415	454	493	40 40 39 38
111	532	571	610	649	688	727	766	805	844	883	.1 4.0 4.0 3.9 3.8
112	922	960	999	*038	*076	*115	*154	*192	*231	*269	.2 8.1 8.0 7.8 7.6
113	05 308	346	384	423	461	499	538	576	614	652	.3 12.1 12.0 11.7 11.4
114	690	728	766	804	842	880	918	956	994	*032	.4 16.2 16.0 15.6 15.2
115	06 070	107	145	183	220	258	296	333	371	408	.5 20.2 20.0 19.5 19.0
116	446	483	520	558	595	632	670	707	744	781	.6 24.3 24.0 23.4 22.8
117	818	855	893	930	967	*004	*040	*077	*114	*151	.7 28.3 28.0 27.3 26.6
118	07 188	225	261	298	335	372	408	445	481	518	.8 32.4 32.0 31.2 30.4
119	554	591	627	664	700	737	773	809	845	882	.9 36.4 36.0 35.1 34.2
120	918	954	990	*026	*062	*098	*134	*170	*206	*242	37 37 36 35
121	08 278	314	350	386	422	457	493	529	564	600	.1 3.7 3.7 3.6 3.5
122	636	671	707	742	778	813	849	884	920	955	.2 7.5 7.4 7.2 7.0
123	990	*026	*061	*096	*131	*166	*202	*237	*272	*307	.3 11.2 11.1 10.8 10.5
124	09 342	377	412	447	482	517	552	586	621	656	.4 15.0 14.8 14.4 14.0
125	691	725	760	795	830	864	899	933	968	*002	.5 18.7 18.5 18.0 17.5
126	10 037	071	106	140	174	209	243	277	312	346	.6 22.5 22.2 21.6 21.0
127	380	414	448	483	517	551	585	619	653	687	.7 26.2 25.9 25.2 24.5
128	721	755	789	822	856	890	924	958	991	*025	.8 30.0 29.6 28.8 28.0
129	11 059	092	126	160	193	227	260	294	327	361	.9 33.7 33.3 32.4 31.5
130	394	427	461	494	528	561	594	627	661	694	34 34 33 32
131	727	760	793	826	859	892	925	958	991	*024	.1 3.4 3.4 3.3 3.2
132	12 057	090	123	156	189	221	254	287	320	352	.2 6.9 6.8 6.6 6.4
133	385	418	450	483	515	548	580	613	645	678	.3 10.3 10.2 9.9 9.6
134	710	743	775	807	840	872	904	937	969	*001	.4 13.8 13.6 13.2 12.8
135	13 033	065	097	130	162	194	226	258	290	322	.5 17.2 17.0 16.5 16.0
136	354	386	417	449	481	513	545	577	608	640	.6 20.7 20.4 19.8 19.2
137	672	703	735	767	798	830	862	893	925	956	.7 24.1 23.8 23.1 22.4
138	988	*019	*051	*082	*113	*145	*176	*207	*239	*270	.8 27.6 27.2 26.4 25.6
139	14 301	332	364	395	426	457	488	519	550	582	.9 31.0 30.6 29.7 28.8
140	613	644	675	706	736	767	798	829	860	891	31 31 30 29
141	922	952	983	*014	*045	*075	*106	*137	*167	*198	.1 3.1 3.1 3.0 2.9
142	15 229	259	290	320	351	381	412	442	473	503	.2 6.3 6.2 6.0 5.8
143	533	564	594	624	655	685	715	745	776	806	.3 9.4 9.3 9.0 8.7
144	836	866	896	926	956	987	*017	*047	*077	*107	.4 12.6 12.4 12.0 11.6
145	16 137	166	196	226	256	286	316	346	376	405	.5 15.7 15.5 15.0 14.5
146	435	465	494	524	554	584	613	643	672	702	.6 18.9 18.6 18.0 17.4
147	731	761	791	820	849	879	908	938	967	997	.7 22.0 21.7 21.0 20.3
148	17 026	055	085	114	143	172	202	231	260	289	.8 25.2 24.8 24.0 23.2
149	318	348	377	406	435	464	493	522	551	580	.9 28.3 27.9 27.0 26.1
150	609	638	667	696	725	753	782	811	840	869	
N.	0	1	2	3	4	5	6	7	8	9	P. P.

N.	0	1	2	3	4	5	6	7	8	9
150	17 609	638	667	696	725	753	782	811	840	869
151	897	926	955	984	*012	*041	*070	*098	*127	*156
152	18 184	213	241	270	298	327	355	384	412	440
153	469	497	526	554	582	611	639	667	695	724
154	752	780	808	836	864	893	921	949	977	*005
155	19 033	061	089	117	145	173	201	229	256	284
156	312	340	368	396	423	451	479	507	534	562
157	590	617	645	673	700	728	755	783	810	838
158	865	893	920	948	975	*003	*030	*057	*085	*112
159	20 139	167	194	221	249	276	303	330	357	385
160	412	439	466	493	520	547	574	601	628	655
161	682	709	736	763	790	817	844	871	898	924
162	951	978	*005	*032	*058	*085	*112	*139	*165	*192
163	21 219	245	272	298	325	352	378	405	431	458
164	484	511	537	564	590	616	643	669	695	722
165	748	774	801	827	853	880	906	932	958	984
166	22 011	037	063	089	115	141	167	193	219	245
167	271	297	323	349	375	401	427	453	479	505
168	531	557	582	608	634	660	686	711	737	763
169	788	814	840	865	891	917	942	968	994	*019
170	23 045	070	096	121	147	172	198	223	249	274
171	299	325	350	375	401	426	451	477	502	527
172	553	578	603	628	653	679	704	729	754	779
173	804	829	855	880	905	930	955	980	*005	*030
174	24 055	080	105	129	154	179	204	229	254	279
175	304	328	353	378	403	427	452	477	502	526
176	551	576	600	625	650	674	699	723	748	773
177	797	822	846	871	895	920	944	968	993	*017
178	25 042	066	091	115	139	164	188	212	237	261
179	285	309	334	358	382	406	430	455	479	503
180	527	551	575	599	623	647	672	696	720	744
181	768	792	816	840	863	887	911	935	959	983
182	26 007	031	055	078	102	126	150	174	197	221
183	245	269	292	316	340	363	387	411	434	458
184	482	505	529	552	576	599	623	646	670	693
185	717	740	764	787	811	834	858	881	904	928
186	951	974	998	*021	*044	*068	*091	*114	*137	*161
187	27 184	207	230	254	277	300	323	346	369	392
188	416	439	462	485	508	531	554	577	600	623
189	646	669	692	715	738	761	784	806	829	852
190	875	898	921	944	966	989	*012	*035	*058	*080
191	28 103	126	149	171	194	217	239	262	285	307
192	330	352	375	398	420	443	465	488	510	533
193	555	578	600	623	645	668	690	713	735	758
194	780	802	825	847	869	892	914	936	959	981
195	29 003	025	048	070	092	114	137	159	181	203
196	225	248	270	292	314	336	358	380	402	424
197	446	468	490	512	534	556	578	600	622	644
198	666	688	710	732	754	776	798	820	841	863
199	885	907	929	950	972	994	*016	*038	*059	*081
200	30 103	124	146	168	190	211	233	254	276	298
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	29	28	27
.1	2.9	2.8	2.7
.2	5.8	5.6	5.4
.3	8.7	8.4	8.1
.4	11.6	11.2	10.8
.5	14.5	14.0	13.5
.6	17.4	16.8	16.2
.7	20.3	19.6	18.9
.8	23.2	22.4	21.6
.9	26.1	25.2	24.3

	$\overline{26}$	26
.1	2.6	2.6
.2	5.3	5.2
.3	7.9	7.8
.4	10.6	10.4
.5	13.2	13.0
.6	15.9	15.6
.7	18.5	18.2
.8	21.2	20.8
.9	23.8	23.4

	$\overline{25}$	25	24
.1	2.5	2.5	2.4
.2	5.1	5.0	4.8
.3	7.6	7.5	7.2
.4	10.2	10.0	9.6
.5	12.7	12.5	12.0
.6	15.3	15.0	14.4
.7	17.8	17.5	16.8
.8	20.4	20.0	19.2
.9	22.9	22.5	21.6

	$\overline{23}$	23
.1	2.3	2.3
.2	4.7	4.6
.3	7.0	6.9
.4	9.4	9.2
.5	11.7	11.5
.6	14.1	13.8
.7	16.4	16.1
.8	18.8	18.4
.9	21.1	20.7

	$\overline{22}$	22	$\overline{21}$
.1	2.2	2.2	2.1
.2	4.5	4.4	4.3
.3	6.7	6.6	6.4
.4	9.0	8.8	8.6
.5	11.2	11.0	10.7
.6	13.5	13.2	12.9
.7	15.7	15.4	15.0
.8	18.0	17.6	17.2
.9	20.2	19.8	19.3

N.		0	1	2	3	4	5	6	7	8	9
200	30	103	124	146	168	190	211	233	254	276	298
201		319	341	363	384	406	427	449	470	492	513
202		535	556	578	599	621	642	664	685	707	728
203		749	771	792	813	835	856	878	899	920	941
204		963	984	*005	*027	*048	*069	*090	*112	*133	*154
205	31	175	196	217	239	260	281	302	323	344	365
206		386	408	429	450	471	492	513	534	555	576
207		597	618	639	660	681	702	722	743	764	785
208		806	827	848	869	890	910	931	952	973	994
209	32	014	035	056	077	097	118	139	160	180	201
210		222	242	263	284	304	325	346	366	387	407
211		428	449	469	490	510	531	551	572	592	613
212		633	654	674	695	715	736	756	776	797	817
213		838	858	878	899	919	940	960	980	*001	*021
214	33	041	061	082	102	122	142	163	183	203	223
215		244	264	284	304	324	344	365	385	405	425
216		445	465	485	505	525	546	566	586	606	626
217		646	666	686	706	726	746	766	786	806	825
218		845	865	885	905	925	945	965	985	*004	*024
219	34	044	064	084	104	123	143	163	183	203	222
220		242	262	281	301	321	341	360	380	400	419
221		439	459	478	498	518	537	557	576	596	615
222		635	655	674	694	713	733	752	772	791	811
223		830	850	869	889	908	928	947	966	986	*005
224	35	025	044	063	083	102	121	141	160	179	199
225		218	237	257	276	295	314	334	353	372	391
226		411	430	449	468	487	507	526	545	564	583
227		602	621	641	660	679	698	717	736	755	774
228		793	812	831	850	869	888	907	926	945	964
229		983	*002	*021	*040	*059	*078	*097	*116	*135	*154
230	36	173	191	210	229	248	267	286	305	323	342
231		361	380	399	417	436	455	474	492	511	530
232		549	567	586	605	623	642	661	679	698	717
233		735	754	773	791	810	828	847	866	884	903
234		921	940	958	977	996	*014	*033	*051	*070	*088
235	37	107	125	143	162	180	199	217	236	254	273
236		291	309	328	346	364	383	401	420	438	456
237		475	493	511	530	548	566	584	603	621	639
238		657	676	694	712	730	749	767	785	803	821
239		840	858	876	894	912	930	948	967	985	*003
240	38	021	039	057	075	093	111	129	147	165	183
241		201	219	237	255	273	291	309	327	345	363
242		381	399	417	435	453	471	489	507	525	543
243		560	578	596	614	632	650	667	685	703	721
244		739	757	774	792	810	828	845	863	881	899
245		916	934	952	970	987	*005	*023	*040	*058	*076
246	39	093	111	129	146	164	181	199	217	234	252
247		269	287	305	322	340	357	375	392	410	427
248		445	462	480	497	515	532	550	567	585	602
249		620	637	655	672	689	707	724	742	759	776
250		794	811	828	846	863	881	898	915	933	950
N.		0	1	2	3	4	5	6	7	8	9

P. P.

	22	21
.1	2.2	2.1
.2	4.4	4.2
.3	6.6	6.3
.4	8.8	8.4
.5	11.0	10.5
.6	13.2	12.6
.7	15.4	14.7
.8	17.6	16.8
.9	19.8	18.9

	20	20
.1	2.0	2.0
.2	4.1	4.0
.3	6.1	6.0
.4	8.2	8.0
.5	10.2	10.0
.6	12.3	12.0
.7	14.3	14.0
.8	16.4	16.0
.9	18.4	18.0

	19	19
.1	1.9	1.9
.2	3.9	3.8
.3	5.8	5.7
.4	7.8	7.6
.5	9.7	9.5
.6	11.7	11.4
.7	13.6	13.3
.8	15.6	15.2
.9	17.5	17.1

	18	18
.1	1.8	1.8
.2	3.7	3.6
.3	5.5	5.4
.4	7.4	7.2
.5	9.2	9.0
.6	11.1	10.8
.7	12.9	12.6
.8	14.8	14.4
.9	16.6	16.2

	17	17
.1	1.7	1.7
.2	3.5	3.4
.3	5.2	5.1
.4	7.0	6.8
.5	8.7	8.5
.6	10.5	10.2
.7	12.2	11.9
.8	14.0	13.6
.9	15.7	15.3

N.	0	1	2	3	4	5	6	7	8	9
250	39 794	811	828	846	863	881	898	915	933	950
251	967	984	*002	*019	*036	*054	*071	*088	*105	*123
252	40 140	157	174	191	209	226	243	260	277	295
253	312	329	346	363	380	398	415	432	449	466
254	483	500	517	534	551	569	586	603	620	637
255	654	671	688	705	722	739	756	773	790	807
256	824	841	858	875	892	908	925	942	959	976
257	993	*010	*027	*044	*061	*077	*094	*111	*128	*145
258	41 162	179	195	212	229	246	263	279	296	313
259	330	346	363	380	397	413	430	447	464	480
260	497	514	530	547	564	581	597	614	631	647
261	664	680	697	714	730	747	764	780	797	813
262	830	846	863	880	896	913	929	946	962	979
263	995	*012	*028	*045	*061	*078	*094	*111	*127	*144
264	42 160	177	193	209	226	242	259	275	292	308
265	324	341	357	373	390	406	423	439	455	472
266	488	504	521	537	553	569	586	602	618	635
267	651	667	683	700	716	732	748	765	781	797
268	813	829	846	862	878	894	910	927	943	959
269	975	991	*007	*023	*040	*056	*072	*088	*104	*120
270	43 136	152	168	184	200	216	233	249	265	281
271	297	313	329	345	361	377	393	409	425	441
272	457	473	489	505	520	536	552	568	584	600
273	616	632	648	664	680	695	711	727	743	759
274	775	791	806	822	838	854	870	886	901	917
275	933	949	965	980	996	*012	*028	*043	*059	*075
276	44 091	106	122	138	154	169	185	201	216	232
277	248	263	279	295	310	326	342	357	373	389
278	404	420	435	451	467	482	498	513	529	545
279	560	576	591	607	622	638	653	669	685	700
280	716	731	747	762	778	793	809	824	839	855
281	870	886	901	917	932	948	963	978	994	*009
282	45 025	040	055	071	086	102	117	132	148	163
283	178	194	209	224	240	255	270	286	301	316
284	332	347	362	377	393	408	423	438	454	469
285	484	499	515	530	545	560	576	591	606	621
286	636	652	667	682	697	712	727	743	758	773
287	788	803	818	833	848	864	879	894	909	924
288	939	954	969	984	999	*014	*029	*044	*059	*075
289	46 090	105	120	135	150	165	180	195	210	225
290	240	255	269	284	299	314	329	344	359	374
291	389	404	419	434	449	464	479	493	508	523
292	538	553	568	583	597	612	627	642	657	672
293	687	701	716	731	746	761	775	790	805	820
294	834	849	864	879	894	908	923	938	952	967
295	982	997	*011	*026	*041	*055	*070	*085	*100	*114
296	47 129	144	158	173	188	202	217	232	246	261
297	275	290	305	319	334	348	363	378	392	407
298	421	436	451	465	480	494	509	523	538	552
299	567	581	596	610	625	639	654	668	683	697
300	712	726	741	755	770	784	799	813	828	842
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	$\overline{17}$	17
·1	1·7	1·7
·2	3·5	3·4
·3	5·2	5·1
·4	7·0	6·8
·5	8·7	8·5
·6	10·5	10·2
·7	12·2	11·9
·8	14·0	13·6
·9	15·7	15·3

	$\overline{16}$	16
·1	1·6	1·6
·2	3·3	3·2
·3	4·9	4·8
·4	6·6	6·4
·5	8·2	8·0
·6	9·9	9·6
·7	11·5	11·2
·8	13·2	12·8
·9	14·8	14·4

	$\overline{15}$	15
·1	1·5	1·5
·2	3·1	3·0
·3	4·6	4·5
·4	6·2	6·0
·5	7·7	7·5
·6	9·3	9·0
·7	10·8	10·5
·8	12·4	12·0
·9	13·9	13·5

	$\overline{14}$	14
·1	1·4	1·4
·2	2·9	2·8
·3	4·3	4·2
·4	5·8	5·6
·5	7·2	7·0
·6	8·7	8·4
·7	10·1	9·8
·8	11·6	11·2
·9	13·0	12·6

P. P.

N.	0	1	2	3	4	5	6	7	8	9
300	47 712	726	741	755	770	784	799	813	828	842
301	856	871	885	900	914	928	943	957	972	986
302	48 000	015	029	044	058	072	087	101	115	130
303	144	158	173	187	201	216	230	244	259	273
304	287	301	316	330	344	358	373	387	401	415
305	430	444	458	472	487	501	515	529	543	558
306	572	586	600	614	629	643	657	671	685	699
307	714	728	742	756	770	784	798	812	827	841
308	855	869	883	897	911	925	939	953	967	982
309	996	*010	*024	*038	*052	*066	*080	*094	*108	*122
310	49 136	150	164	178	192	206	220	234	248	262
311	276	290	304	318	332	346	359	373	387	401
312	415	429	443	457	471	485	499	513	526	540
313	554	568	582	596	610	624	637	651	665	679
314	693	707	720	734	748	762	776	789	803	817
315	831	845	858	872	886	900	913	927	941	955
316	968	982	996	*010	*023	*037	*051	*065	*078	*092
317	50 106	119	133	147	160	174	188	201	215	229
318	242	256	270	283	297	311	324	338	352	365
319	379	392	406	420	433	447	460	474	488	501
320	515	528	542	555	569	583	596	610	623	637
321	650	664	677	691	704	718	731	745	758	772
322	785	799	812	826	839	853	866	880	893	907
323	920	933	947	960	974	987	*001	*014	*027	*041
324	51 054	068	081	094	108	121	135	148	161	175
325	188	201	215	228	242	255	268	282	295	308
326	322	335	348	361	375	388	401	415	428	441
327	455	468	481	494	508	521	534	547	561	574
328	587	600	614	627	640	653	667	680	693	706
329	719	733	746	759	772	785	798	812	825	838
330	851	864	877	891	904	917	930	943	956	969
331	983	996	*009	*022	*035	*048	*061	*074	*087	*100
332	52 114	127	140	153	166	179	192	205	218	231
333	244	257	270	283	296	309	322	335	348	361
334	374	387	400	413	426	439	452	465	478	491
335	504	517	530	543	556	569	582	595	608	621
336	634	647	660	672	685	698	711	724	737	750
337	763	776	789	801	814	827	840	853	866	879
338	891	904	917	930	943	956	968	981	994	*007
339	53 020	033	045	058	071	084	097	109	122	135
340	148	160	173	186	199	211	224	237	250	262
341	275	288	301	313	326	339	352	364	377	390
342	402	415	428	440	453	466	478	491	504	516
343	529	542	554	567	580	592	605	618	630	643
344	656	668	681	693	706	719	731	744	756	769
345	782	794	807	819	832	845	857	870	882	895
346	907	920	932	945	958	970	983	995	*008	*020
347	54 033	045	058	070	083	095	108	120	133	145
348	158	170	183	195	208	220	232	245	257	270
349	282	295	307	320	332	344	357	369	382	394
350	407	419	431	444	456	469	481	493	506	518
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	14	14
.1	1.4	1.4
.2	2.9	2.8
.3	4.3	4.2
.4	5.8	5.6
.5	7.2	7.0
.6	8.7	8.4
.7	10.1	9.8
.8	11.6	11.2
.9	13.0	12.6

	13	13
.1	1.3	1.3
.2	2.7	2.6
.3	4.0	3.9
.4	5.4	5.2
.5	6.7	6.5
.6	8.1	7.8
.7	9.4	9.1
.8	10.8	10.4
.9	12.1	11.7

	12	12
.1	1.2	1.2
.2	2.5	2.4
.3	3.7	3.6
.4	5.0	4.8
.5	6.2	6.0
.6	7.5	7.2
.7	8.7	8.4
.8	10.0	9.6
.9	11.2	10.8

P. P.

N.	0	1	2	3	4	5	6	7	8	9	P. P.
350	54 407	419	431	444	456	469	481	493	506	518	12
351	530	543	555	568	580	592	605	617	629	642	.1 1.2
352	654	666	679	691	703	716	728	740	753	765	.2 2.5
353	777	790	802	814	826	839	851	863	876	888	.3 3.7
354	900	912	925	937	949	961	974	986	998	*010	.4 5.0
355	55 023	035	047	059	071	084	096	108	120	133	.5 6.2
356	145	157	169	181	194	206	218	230	242	254	.6 7.5
357	267	279	291	303	315	327	340	352	364	376	.7 8.7
358	388	400	412	424	437	449	461	473	485	497	.8 10.0
359	509	521	533	545	558	570	582	594	606	618	.9 11.2
360	630	642	654	666	678	690	702	714	726	738	12
361	750	762	775	787	799	811	823	835	847	859	.1 1.2
362	871	883	895	907	919	931	943	955	966	978	.2 2.4
363	990	*002	*014	*026	*038	*050	*062	*074	*086	*098	.3 3.6
364	56 110	122	134	146	158	170	181	193	205	217	.4 4.8
365	229	241	253	265	277	288	300	312	324	336	.5 6.0
366	348	360	372	383	395	407	419	431	443	455	.6 7.2
367	466	478	490	502	514	525	537	549	561	573	.7 8.4
368	585	596	608	620	632	643	655	667	679	691	.8 9.6
369	702	714	726	738	749	761	773	785	796	808	.9 10.8
370	820	832	843	855	867	879	890	902	914	925	11
371	937	949	961	972	984	996	*007	*019	*031	*042	.1 1.1
372	57 054	066	077	089	101	112	124	136	147	159	.2 2.3
373	171	182	194	206	217	229	240	252	264	275	.3 3.4
374	287	299	310	322	333	345	357	368	380	391	.4 4.6
375	403	414	426	438	449	461	472	484	495	507	.5 5.7
376	519	530	542	553	565	576	588	599	611	622	.6 6.9
377	634	645	657	668	680	691	703	714	726	737	.7 8.0
378	749	760	772	783	795	806	818	829	841	852	.8 9.2
379	864	875	887	898	909	921	932	944	955	967	.9 10.3
380	978	990	*001	*012	*024	*035	*047	*058	*069	*081	11
381	58 092	104	115	126	138	149	161	172	183	195	.1 1.1
382	206	217	229	240	252	263	274	286	297	308	.2 2.2
383	320	331	342	354	365	376	388	399	410	422	.3 3.3
384	433	444	455	467	478	489	501	512	523	535	.4 4.4
385	546	557	568	580	591	602	613	625	636	647	.5 5.5
386	658	670	681	692	703	715	726	737	748	760	.6 6.6
387	771	782	793	804	816	827	838	849	861	872	.7 7.7
388	883	894	905	916	928	939	950	961	972	984	.8 8.8
389	995	*006	*017	*028	*039	*050	*062	*073	*084	*095	.9 9.9
390	59 106	117	128	140	151	162	173	184	195	206	10
391	217	229	240	251	262	273	284	295	306	317	.1 1.0
392	328	339	351	362	373	384	395	406	417	428	.2 2.1
393	439	450	461	472	483	494	505	516	527	538	.3 3.1
394	549	560	571	582	593	604	615	626	637	648	.4 4.2
395	659	670	681	692	703	714	725	736	747	758	.5 5.2
396	769	780	791	802	813	824	835	846	857	868	.6 6.3
397	879	890	901	912	923	933	944	955	966	977	.7 7.3
398	988	999	*010	*021	*032	*043	*053	*064	*075	*086	.8 8.4
399	60 097	108	119	130	141	151	162	173	184	195	.9 9.4
400	206	217	227	238	249	260	271	282	293	303	
N.	0	1	2	3	4	5	6	7	8	9	P. P.

N.	0	1	2	3	4	5	6	7	8	9
400	60 206	217	227	238	249	260	271	282	293	303
401	314	325	336	347	357	368	379	390	401	412
402	422	433	444	455	466	476	487	498	509	519
403	530	541	552	563	573	584	595	606	616	627
404	638	649	659	670	681	692	702	713	724	735
405	745	756	767	777	788	799	810	820	831	842
406	852	863	874	884	895	906	916	927	938	949
407	959	970	981	991	*002	*013	*023	*034	*044	*055
408	61 066	076	087	098	108	119	130	140	151	161
409	172	183	193	204	215	225	236	246	257	268
410	278	289	299	310	320	331	342	352	363	373
411	384	394	405	416	426	437	447	458	468	479
412	489	500	511	521	532	542	553	563	574	584
413	595	605	616	626	637	647	658	668	679	689
414	700	710	721	731	742	752	763	773	784	794
415	805	815	825	836	846	857	867	878	888	899
416	909	920	930	940	951	961	972	982	993	*003
417	62 013	024	034	045	055	065	076	086	097	107
418	117	128	138	149	159	169	180	190	200	211
419	221	232	242	252	263	273	283	294	304	314
420	325	335	345	356	366	376	387	397	407	418
421	428	438	449	459	469	480	490	500	510	521
422	531	541	552	562	572	582	593	603	613	624
423	634	644	654	665	675	685	695	706	716	726
424	736	747	757	767	777	788	798	808	818	828
425	839	849	859	869	879	890	900	910	920	931
426	941	951	961	971	981	992	*002	*012	*022	*032
427	63 043	053	063	073	083	093	104	114	124	134
428	144	154	164	175	185	195	205	215	225	235
429	245	256	266	276	286	296	306	316	326	336
430	347	357	367	377	387	397	407	417	427	437
431	447	458	468	478	488	498	508	518	528	538
432	548	558	568	578	588	598	608	618	628	639
433	649	659	669	679	689	699	709	719	729	739
434	749	759	769	779	789	799	809	819	829	839
435	849	859	869	879	889	899	909	919	928	938
436	948	958	968	978	988	998	*008	*018	*028	*038
437	64 048	058	068	078	088	098	107	117	127	137
438	147	157	167	177	187	197	207	217	226	236
439	246	256	266	276	286	296	306	315	325	335
440	345	355	365	375	384	394	404	414	424	434
441	444	453	463	473	483	493	503	512	522	532
442	542	552	562	571	581	591	601	611	621	630
443	640	650	660	670	679	689	699	709	718	728
444	738	748	758	767	777	787	797	806	816	826
445	836	846	855	865	875	885	894	904	914	923
446	933	943	953	962	972	982	992	*001	*011	*021
447	65 031	040	050	060	069	079	089	098	108	118
448	128	137	147	157	166	176	186	195	205	215
449	224	234	244	253	263	273	282	292	302	311
450	321	331	340	350	360	369	379	389	398	408
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	11	10̄	10	9̄
.1	1.1	1.0	1.0	0.9
.2	2.2	2.1	2.0	1.9
.3	3.3	3.1	3.0	2.8
.4	4.4	4.2	4.0	3.8
.5	5.5	5.2	5.0	4.7
.6	6.6	6.3	6.0	5.7
.7	7.7	7.3	7.0	6.6
.8	8.8	8.4	8.0	7.6
.9	9.9	9.4	9.0	8.5

N.		0	1	2	3	4	5	6	7	8	9
450	65	321	331	340	350	360	369	379	389	398	408
451		417	427	437	446	456	466	475	485	494	504
452		514	523	533	542	552	562	571	581	590	600
453		610	619	629	638	648	657	667	677	686	696
454		705	715	724	734	744	753	763	772	782	791
455		801	810	820	830	839	849	858	868	877	887
456		896	906	915	925	934	944	953	963	972	982
457		991	*001	*010	*020	*029	*039	*048	*058	*067	*077
458	66	086	096	105	115	124	134	143	153	162	172
459		181	190	200	209	219	228	238	247	257	266
460		276	285	294	304	313	323	332	342	351	360
461		370	379	389	398	408	417	426	436	445	455
462		464	473	483	492	502	511	520	530	539	548
463		558	567	577	586	595	605	614	623	633	642
464		652	661	670	680	689	698	708	717	726	736
465		745	754	764	773	782	792	801	810	820	829
466		838	848	857	866	876	885	894	904	913	922
467		931	941	950	959	969	978	987	996	*006	*015
468	67	024	034	043	052	061	071	080	089	099	108
469		117	126	136	145	154	163	173	182	191	200
470		210	219	228	237	246	256	265	274	283	293
471		302	311	320	329	339	348	357	366	376	385
472		394	403	412	422	431	440	449	458	467	477
473		486	495	504	513	523	532	541	550	559	568
474		578	587	596	605	614	623	633	642	651	660
475		669	678	687	697	706	715	724	733	742	751
476		760	770	779	788	797	806	815	824	833	842
477		852	861	870	879	888	897	906	915	924	933
478		943	952	961	970	979	988	997	*006	*015	*024
479	68	033	042	051	060	070	079	088	097	106	115
480		124	133	142	151	160	169	178	187	196	205
481		214	223	232	241	250	259	268	277	286	295
482		304	313	322	331	340	349	358	367	376	385
483		394	403	412	421	430	439	448	457	466	475
484		484	493	502	511	520	529	538	547	556	565
485		574	583	592	601	610	619	628	637	646	654
486		663	672	681	690	699	708	717	726	735	744
487		753	762	770	779	788	797	806	815	824	833
488		842	851	860	868	877	886	895	904	913	922
489		931	940	948	957	966	975	984	993	*002	*010
490	69	019	028	037	046	055	064	073	081	090	099
491		108	117	126	134	143	152	161	170	179	187
492		196	205	214	223	232	240	249	258	267	276
493		284	293	302	311	320	328	337	346	355	364
494		372	381	390	399	408	416	425	434	443	451
495		460	469	478	487	495	504	513	522	530	539
496		548	557	565	574	583	592	600	609	618	627
497		635	644	653	662	670	679	688	697	705	714
498		723	731	740	749	758	766	775	784	792	801
499		810	819	827	836	845	853	862	871	879	888
500		897	905	914	923	931	940	949	958	966	975
N.		0	1	2	3	4	5	6	7	8	9

P. P.

	10
·1	1·0
·2	2·0
·3	3·0
·4	4·0
·5	5·0
·6	6·0
·7	7·0
·8	8·0
·9	9·0

	9
·1	0·9
·2	1·9
·3	2·8
·4	3·8
·5	4·7
·6	5·7
·7	6·6
·8	7·6
·9	8·5

	9
·1	0·9
·2	1·8
·3	2·7
·4	3·6
·5	4·5
·6	5·4
·7	6·3
·8	7·2
·9	8·1

	8
·1	0·8
·2	1·7
·3	2·5
·4	3·4
·5	4·2
·6	5·1
·7	5·9
·8	6·8
·9	7·6

N.		0	1	2	3	4	5	6	7	8	9
500	69	897	905	914	923	931	940	949	958	966	975
501		984	992	*001	*010	*018	*027	*036	*044	*053	*061
502	70	070	079	087	096	105	113	122	131	139	148
503		157	165	174	182	191	200	208	217	226	234
504		243	251	260	269	277	286	294	303	312	320
505		329	337	346	355	363	372	380	389	398	406
506		415	423	432	441	449	458	466	475	483	492
507		501	509	518	526	535	543	552	560	569	578
508		586	595	603	612	620	629	637	646	654	663
509		672	680	689	697	706	714	723	731	740	748
510		757	765	774	782	791	799	808	816	825	833
511		842	850	859	867	876	884	893	901	910	918
512		927	935	944	952	961	969	978	986	995	*003
513	71	011	020	028	037	045	054	062	071	079	088
514		096	105	113	121	130	138	147	155	164	172
515		180	189	197	206	214	223	231	239	248	256
516		265	273	282	290	298	307	315	324	332	340
517		349	357	366	374	382	391	399	408	416	424
518		433	441	449	458	466	475	483	491	500	508
519		516	525	533	542	550	558	567	575	583	592
520		600	608	617	625	633	642	650	659	667	675
521		684	692	700	709	717	725	734	742	750	758
522		767	775	783	792	800	808	817	825	833	842
523		850	858	867	875	883	891	900	908	916	925
524		933	941	949	958	966	974	983	991	999	*007
525	72	016	024	032	040	049	057	065	074	082	090
526		098	107	115	123	131	140	148	156	164	173
527		181	189	197	206	214	222	230	238	247	255
528		263	271	280	288	296	304	312	321	329	337
529		345	354	362	370	378	386	395	403	411	419
530		427	436	444	452	460	468	476	485	493	501
531		509	517	526	534	542	550	558	566	575	583
532		591	599	607	615	624	632	640	648	656	664
533		672	681	689	697	705	713	721	729	738	746
534		754	762	770	778	786	795	803	811	819	827
535		835	843	851	859	868	876	884	892	900	908
536		916	924	932	941	949	957	965	973	981	989
537		997	*005	*013	*021	*030	*038	*046	*054	*062	*070
538	73	078	086	094	102	110	118	126	134	143	151
539		159	167	175	183	191	199	207	215	223	231
540		239	247	255	263	271	279	287	295	303	311
541		319	328	336	344	352	360	368	376	384	392
542		400	408	416	424	432	440	448	456	464	472
543		480	488	496	504	512	520	528	536	544	552
544		560	568	576	584	592	600	608	615	623	631
545		639	647	655	663	671	679	687	695	703	711
546		719	727	735	743	751	759	767	775	783	791
547		798	806	814	822	830	838	846	854	862	870
548		878	886	894	902	909	917	925	933	941	949
549		957	965	973	981	989	997	*004	*012	*020	*028
550	74	036	044	052	060	068	075	083	091	099	107
N.		0	1	2	3	4	5	6	7	8	9

P. P.

	9
.1	0.9
.2	1.8
.3	2.7
.4	3.6
.5	4.5
.6	5.4
.7	6.3
.8	7.2
.9	8.1

	$\bar{8}$
.1	0.8
.2	1.7
.3	2.5
.4	3.4
.5	4.2
.6	5.1
.7	5.9
.8	6.8
.9	7.6

	8
.1	0.8
.2	1.6
.3	2.4
.4	3.2
.5	4.0
.6	4.8
.7	5.6
.8	6.4
.9	7.2

	$\bar{7}$
.1	0.7
.2	1.5
.3	2.2
.4	3.0
.5	3.7
.6	4.5
.7	5.2
.8	6.0
.9	6.7

N.	0	1	2	3	4	5	6	7	8	9
550	74 036	044	052	060	068	075	083	091	099	107
551	115	123	131	139	146	154	162	170	178	186
552	194	202	209	217	225	233	241	249	257	264
553	272	280	288	296	304	312	319	327	335	343
554	351	359	366	374	382	390	398	406	413	421
555	429	437	445	453	460	468	476	484	492	499
556	507	515	523	531	538	546	554	562	570	577
557	585	593	601	609	616	624	632	640	648	655
558	663	671	679	687	694	702	710	718	725	733
559	741	749	756	764	772	780	788	795	803	811
560	819	826	834	842	850	857	865	873	881	888
561	896	904	912	919	927	935	942	950	958	966
562	973	981	989	997	*004	*012	*020	*027	*035	*043
563	75 051	058	066	074	081	089	097	105	112	120
564	128	135	143	151	158	166	174	182	189	197
565	205	212	220	228	235	243	251	258	266	274
566	281	289	297	304	312	320	327	335	343	350
567	358	366	373	381	389	396	404	412	419	427
568	435	442	450	458	465	473	480	488	496	503
569	511	519	526	534	541	549	557	564	572	580
570	587	595	602	610	618	625	633	641	648	656
571	663	671	679	686	694	701	709	717	724	732
572	739	747	755	762	770	777	785	792	800	808
573	815	823	830	838	846	853	861	868	876	883
574	891	899	906	914	921	929	936	944	951	959
575	967	974	982	989	997	*004	*012	*019	*027	*034
576	76 042	050	057	065	072	080	087	095	102	110
577	117	125	132	140	147	155	162	170	178	185
578	193	200	208	215	223	230	238	245	253	260
579	268	275	283	290	298	305	313	320	328	335
580	343	350	358	365	372	380	387	395	402	410
581	417	425	432	440	447	455	462	470	477	485
582	492	500	507	514	522	529	537	544	552	559
583	567	574	582	589	596	604	611	619	626	634
584	641	648	656	663	671	678	686	693	700	708
585	715	723	730	738	745	752	760	767	775	782
586	790	797	804	812	819	827	834	841	849	856
587	864	871	878	886	893	901	908	915	923	930
588	937	945	952	960	967	974	982	989	997	*004
589	77 011	019	026	033	041	048	055	063	070	078
590	085	092	100	107	114	122	129	136	144	151
591	158	166	173	181	188	195	203	210	217	225
592	232	239	247	254	261	269	276	283	291	298
593	305	313	320	327	335	342	349	356	364	371
594	378	386	393	400	408	415	422	430	437	444
595	451	459	466	473	481	488	495	503	510	517
596	524	532	539	546	554	561	568	575	583	590
597	597	604	612	619	626	634	641	648	655	663
598	670	677	684	692	699	706	713	721	728	735
599	742	750	757	764	771	779	786	793	800	808
600	815	822	829	837	844	851	859	866	873	880
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	8
·1	0·8
·2	1·6
·3	2·4
·4	3·2
·5	4·0
·6	4·8
·7	5·6
·8	6·4
·9	7·2

	7
·1	0·7
·2	1·5
·3	2·2
·4	3·0
·5	3·7
·6	4·5
·7	5·2
·8	6·0
·9	6·7

	7
·1	0·7
·2	1·4
·3	2·1
·4	2·8
·5	3·5
·6	4·2
·7	4·9
·8	5·6
·9	6·3

P. P.

N.	0	1	2	3	4	5	6	7	8	9
600	77 815	82$\bar{2}$	82$\bar{9}$	837	844	85$\bar{1}$	85$\bar{8}$	866	873	880
601	88$\bar{7}$	89$\bar{4}$	902	909	91$\bar{6}$	92$\bar{3}$	931	938	945	95$\bar{2}$
602	95$\bar{9}$	967	974	98$\bar{1}$	98$\bar{8}$	99$\bar{5}$	*003	*010	*01$\bar{7}$	*02$\bar{4}$
603	78 03$\bar{1}$	039	046	05$\bar{3}$	06$\bar{0}$	06$\bar{7}$	075	082	08$\bar{9}$	09$\bar{6}$
604	10$\bar{3}$	111	118	12$\bar{5}$	13$\bar{2}$	13$\bar{9}$	147	154	161	16$\bar{8}$
605	17$\bar{5}$	18$\bar{2}$	190	197	204	21$\bar{1}$	21$\bar{8}$	226	233	240
606	24$\bar{7}$	25$\bar{4}$	26$\bar{1}$	269	276	28$\bar{3}$	290	29$\bar{7}$	30$\bar{4}$	31$\bar{1}$
607	319	326	333	34$\bar{0}$	34$\bar{7}$	35$\bar{4}$	362	369	376	383
608	39$\bar{0}$	39$\bar{7}$	40$\bar{4}$	412	419	426	433	44$\bar{0}$	44$\bar{7}$	45$\bar{4}$
609	46$\bar{1}$	469	476	483	490	49$\bar{7}$	50$\bar{4}$	51$\bar{1}$	51$\bar{8}$	526
610	533	540	547	55$\bar{4}$	56$\bar{1}$	56$\bar{8}$	57$\bar{5}$	583	590	597
611	604	611	61$\bar{8}$	62$\bar{5}$	63$\bar{2}$	63$\bar{9}$	64$\bar{6}$	654	661	668
612	675	682	68$\bar{9}$	69$\bar{6}$	70$\bar{3}$	71$\bar{0}$	71$\bar{7}$	725	732	739
613	746	753	760	76$\bar{7}$	77$\bar{4}$	78$\bar{1}$	78$\bar{8}$	79$\bar{5}$	80$\bar{2}$	810
614	817	824	831	838	845	852	85$\bar{9}$	86$\bar{6}$	87$\bar{3}$	88$\bar{0}$
615	88$\bar{7}$	89$\bar{4}$	90$\bar{1}$	90$\bar{8}$	91$\bar{5}$	923	930	937	944	951
616	958	965	972	979	98$\bar{6}$	99$\bar{3}$	*00$\bar{0}$	*00$\bar{7}$	*01$\bar{4}$	*02$\bar{1}$
617	79 02$\bar{8}$	03$\bar{5}$	04$\bar{2}$	04$\bar{9}$	05$\bar{6}$	06$\bar{3}$	07$\bar{0}$	078	085	092
618	099	106	113	120	127	134	141	148	155	162
619	169	176	183	190	197	204	211	218	225	232
620	239	246	253	260	267	274	281	288	295	302
621	309	316	323	330	337	344	351	358	365	372
622	379	386	393	400	407	414	421	428	435	442
623	449	456	46$\bar{2}$	46$\bar{9}$	47$\bar{6}$	48$\bar{3}$	49$\bar{0}$	49$\bar{7}$	50$\bar{4}$	51$\bar{1}$
624	51$\bar{8}$	52$\bar{5}$	53$\bar{2}$	53$\bar{9}$	54$\bar{6}$	553	560	567	574	581
625	588	595	602	609	616	62$\bar{2}$	62$\bar{9}$	63$\bar{6}$	64$\bar{3}$	65$\bar{0}$
626	65$\bar{7}$	66$\bar{4}$	67$\bar{1}$	678	685	692	699	706	713	720
627	727	73$\bar{3}$	74$\bar{0}$	74$\bar{7}$	75$\bar{4}$	76$\bar{1}$	76$\bar{8}$	775	782	789
628	796	803	810	81$\bar{6}$	82$\bar{3}$	83$\bar{0}$	83$\bar{7}$	84$\bar{4}$	85$\bar{1}$	858
629	865	872	879	886	89$\bar{2}$	89$\bar{9}$	90$\bar{6}$	91$\bar{3}$	92$\bar{0}$	927
630	934	941	948	95$\bar{4}$	96$\bar{1}$	96$\bar{8}$	97$\bar{5}$	98$\bar{2}$	989	996
631	80 003	010	01$\bar{6}$	02$\bar{3}$	03$\bar{0}$	03$\bar{7}$	044	051	058	065
632	07$\bar{1}$	07$\bar{8}$	08$\bar{5}$	09$\bar{2}$	099	106	113	120	12$\bar{6}$	13$\bar{3}$
633	14$\bar{0}$	147	154	161	168	17$\bar{4}$	18$\bar{1}$	18$\bar{8}$	195	202
634	209	216	22$\bar{2}$	22$\bar{9}$	23$\bar{6}$	243	250	257	26$\bar{3}$	27$\bar{0}$
635	27$\bar{7}$	284	291	298	30$\bar{4}$	31$\bar{1}$	31$\bar{8}$	325	332	339
636	34$\bar{5}$	35$\bar{2}$	35$\bar{9}$	366	373	380	38$\bar{6}$	39$\bar{3}$	40$\bar{0}$	407
637	414	421	42$\bar{7}$	43$\bar{4}$	441	448	455	46$\bar{1}$	46$\bar{8}$	47$\bar{5}$
638	482	489	49$\bar{5}$	50$\bar{2}$	50$\bar{9}$	516	523	52$\bar{9}$	53$\bar{6}$	54$\bar{3}$
639	550	557	56$\bar{3}$	57$\bar{0}$	57$\bar{7}$	584	591	59$\bar{7}$	60$\bar{4}$	611
640	618	625	63$\bar{1}$	63$\bar{8}$	645	652	65$\bar{8}$	66$\bar{5}$	67$\bar{2}$	679
641	686	69$\bar{2}$	69$\bar{9}$	706	713	71$\bar{9}$	72$\bar{6}$	733	740	74$\bar{6}$
642	75$\bar{3}$	76$\bar{0}$	767	774	78$\bar{0}$	78$\bar{7}$	794	801	80$\bar{7}$	81$\bar{4}$
643	821	828	83$\bar{4}$	84$\bar{1}$	848	855	86$\bar{1}$	86$\bar{8}$	875	882
644	88$\bar{8}$	89$\bar{5}$	902	909	91$\bar{5}$	92$\bar{2}$	929	936	94$\bar{2}$	949
645	956	96$\bar{2}$	96$\bar{9}$	976	983	98$\bar{9}$	99$\bar{6}$	*003	*010	*01$\bar{6}$
646	81 02$\bar{3}$	030	03$\bar{6}$	04$\bar{3}$	050	057	06$\bar{3}$	07$\bar{0}$	077	08$\bar{3}$
647	09$\bar{0}$	097	104	11$\bar{0}$	11$\bar{7}$	124	13$\bar{0}$	13$\bar{7}$	144	151
648	15$\bar{7}$	164	171	17$\bar{7}$	13$\bar{4}$	191	19$\bar{7}$	20$\bar{4}$	211	218
649	22$\bar{4}$	231	238	24$\bar{4}$	251	258	26$\bar{4}$	27$\bar{1}$	278	28$\bar{4}$
650	29$\bar{1}$	298	30$\bar{4}$	31$\bar{1}$	318	32$\bar{4}$	33$\bar{1}$	338	345	35$\bar{1}$
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	$\bar{7}$
.1	0·$\bar{7}$
.2	1·5
.3	2·$\bar{2}$
.4	3·0
.5	3·$\bar{7}$
.6	4·5
.7	5·$\bar{2}$
.8	6·0
.9	6·$\bar{7}$

	7
.1	0·7
.2	1·4
.3	2·1
.4	2·8
.5	3·5
.6	4·2
.7	4·9
.8	5·6
.9	6·3

	$\bar{6}$
.1	0·$\bar{6}$
.2	1·3
.3	1·$\bar{9}$
.4	2·6
.5	3·$\bar{2}$
.6	3·9
.7	4·$\bar{5}$
.8	5·2
.9	5·$\bar{8}$

P. P.

N.		0	1	2	3	4	5	6	7	8	9
650	81	291	298	304	311	318	324	331	338	345	351
651		358	365	371	378	385	391	398	405	411	418
652		425	431	438	444	451	458	464	471	478	484
653		491	498	504	511	518	524	531	538	544	551
654		558	564	571	577	584	591	597	604	611	617
655		624	631	637	644	650	657	664	670	677	684
656		690	697	703	710	717	723	730	736	743	750
657		756	763	770	776	783	789	796	803	809	816
658		822	829	836	842	849	855	862	869	875	882
659		888	895	901	908	915	921	928	934	941	948
660		954	961	967	974	980	987	994	*000	*007	*013
661	82	020	026	033	040	046	053	059	066	072	079
662		086	092	099	105	112	118	125	131	138	145
663		151	158	164	171	177	184	190	197	203	210
664		217	223	230	236	243	249	256	262	269	275
665		282	288	295	302	308	315	321	328	334	341
666		347	354	360	367	373	380	386	393	399	406
667		412	419	425	432	438	445	451	458	464	471
668		477	484	490	497	503	510	516	523	529	536
669		542	549	555	562	568	575	581	588	594	601
670		607	614	620	627	633	640	646	653	659	666
671		672	678	685	691	698	704	711	717	724	730
672		737	743	750	756	763	769	775	782	788	795
673		801	808	814	821	827	834	840	846	853	859
674		866	872	879	885	892	898	904	911	917	924
675		930	937	943	949	956	962	969	975	982	988
676		994	*001	*007	*014	*020	*027	*033	*039	*046	*052
677	83	059	065	071	078	084	091	097	103	110	116
678		123	129	136	142	148	155	161	168	174	180
679		187	193	200	206	212	219	225	231	238	244
680		251	257	263	270	276	283	289	295	302	308
681		314	321	327	334	340	346	353	359	365	372
682		378	385	391	397	404	410	416	423	429	435
683		442	448	455	461	467	474	480	486	493	499
684		505	512	518	524	531	537	543	550	556	562
685		569	575	581	588	594	600	607	613	619	626
686		632	638	645	651	657	664	670	676	683	689
687		695	702	708	714	721	727	733	740	746	752
688		759	765	771	778	784	790	796	803	809	815
689		822	828	834	841	847	853	859	866	872	878
690		885	891	897	904	910	916	922	929	935	941
691		948	954	960	966	973	979	985	992	998	*004
692	84	010	017	023	029	035	042	048	054	061	067
693		073	079	086	092	098	104	111	117	123	129
694		136	142	148	154	161	167	173	179	186	192
695		198	204	211	217	223	229	236	242	248	254
696		261	267	273	279	286	292	298	304	311	317
697		323	329	335	342	348	354	360	367	373	379
698		385	392	398	404	410	416	423	429	435	441
699		447	454	460	466	472	479	485	491	497	503
700		510	516	522	528	534	541	547	553	559	565
N.		0	1	2	3	4	5	6	7	8	9

P. P.

	7
·1	0·7
·2	1·4
·3	2·1
·4	2·8
·5	3·5
·6	4·2
·7	4·9
·8	5·6
·9	6·3

	6̄
·1	0·6̄
·2	1·3
·3	1·9̄
·4	2·6̄
·5	3·2̄
·6	3·9
·7	4·5̄
·8	5·2
·9	5·8

	6
·1	0·6
·2	1·2
·3	1·8
·4	2·4
·5	3·0
·6	3·6
·7	4·2
·8	4·8
·9	5·4

P. P.

N.	0	1	2	3	4	5	6	7	8	9
700	84 510	516	522	528	534	541	547	553	559	565
701	572	578	584	590	596	603	609	615	621	627
702	633	640	646	652	658	664	671	677	683	689
703	695	701	708	714	720	726	732	739	745	751
704	757	763	769	776	782	788	794	800	806	813
705	819	825	831	837	843	849	856	862	868	874
706	880	886	893	899	905	911	917	923	929	936
707	942	948	954	960	966	972	979	985	991	997
708	85 003	009	015	021	028	034	040	046	052	058
709	064	070	077	083	089	095	101	107	113	119
710	126	132	138	144	150	156	162	168	174	181
711	187	193	199	205	211	217	223	229	236	242
712	248	254	260	266	272	278	284	290	297	303
713	309	315	321	327	333	339	345	351	357	363
714	370	376	382	388	394	400	406	412	418	424
715	430	436	443	449	455	461	467	473	479	485
716	491	497	503	509	515	521	527	533	540	546
717	552	558	564	570	576	582	588	594	600	606
718	612	618	624	630	636	642	648	655	661	667
719	673	679	685	691	697	703	709	715	721	727
720	733	739	745	751	757	763	769	775	781	787
721	793	799	805	811	817	823	829	835	841	847
722	853	859	865	872	878	884	890	896	902	908
723	914	920	926	932	938	944	950	956	962	968
724	974	980	986	992	998	*004	*010	*016	*022	*028
725	86 034	040	046	052	058	063	069	075	081	087
726	093	099	105	111	117	123	129	135	141	147
727	153	159	165	171	177	183	189	195	201	207
728	213	219	225	231	237	243	249	255	261	267
729	273	278	284	290	296	302	308	314	320	326
730	332	338	344	350	356	362	368	374	380	386
731	391	397	403	409	415	421	427	433	439	445
732	451	457	463	469	475	481	486	492	498	504
733	510	516	522	528	534	540	546	552	558	563
734	569	575	581	587	593	599	605	611	617	623
735	628	634	640	646	652	658	664	670	676	682
736	688	693	699	705	711	717	723	729	735	741
737	746	752	758	764	770	776	782	788	794	800
738	805	811	817	823	829	835	841	847	852	858
739	864	870	876	882	888	894	899	905	911	917
740	923	929	935	941	946	952	958	964	970	976
741	982	987	993	999	*005	*011	*017	*023	*028	*034
742	87 040	046	052	058	064	069	075	081	087	093
743	099	104	110	116	122	128	134	140	145	151
744	157	163	169	175	180	186	192	198	204	210
745	215	221	227	233	239	245	250	256	262	268
746	274	279	285	291	297	303	309	314	320	326
747	332	338	343	349	355	361	367	372	378	384
748	390	396	402	407	413	419	425	431	436	442
749	448	454	460	465	471	477	483	489	494	500
750	506	512	517	523	529	535	541	546	552	558
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	$\bar{6}$
.1	0.6
.2	1.3
.3	1.9
.4	2.6
.5	3.2
.6	3.9
.7	4.5
.8	5.2
.9	5.8

	6
.1	0.6
.2	1.2
.3	1.8
.4	2.4
.5	3.0
.6	3.6
.7	4.2
.8	4.8
.9	5.4

	$\bar{5}$
.1	0.5
.2	1.1
.3	1.6
.4	2.2
.5	2.7
.6	3.3
.7	3.8
.8	4.4
.9	4.9

N.	0	1	2	3	4	5	6	7	8	9
750	87 506	512	517̅	523̅	529̅	535	541	546̅	552̅	558
751	564	570	575̅	581̅	587	593	598̅	604̅	610	616
752	622	627̅	633̅	639	645	650̅	656̅	662	668	673̅
753	679̅	685̅	691	697	702̅	708̅	714	720	725̅	731̅
754	737	743	748̅	754̅	760	766	771̅	777̅	783	789
755	794̅	800̅	806	812	817̅	823̅	829	835	840̅	846̅
756	852	858	863̅	869̅	875	881	886̅	892̅	898	904
757	909̅	915̅	921	927	932̅	938̅	944	949̅	955̅	961
758	967	972̅	978̅	984	990	995̅	*001̅	*007	*012̅	*018̅
759	88 024	030	035̅	041̅	047	053	058̅	064	070	075̅
760	081̅	087	093	098̅	104	110	115̅	121̅	127	133
761	138̅	144	150	155̅	161̅	167	172̅	178̅	184	190
762	195̅	201	207	212̅	218̅	224	229̅	235̅	241	247
763	252̅	258	264	269̅	275	281	286̅	292̅	298	303̅
764	309̅	315	320̅	326̅	332	337̅	343̅	349	355	360̅
765	366	372	377̅	383	389	394̅	400	406	411̅	417
766	423	428̅	434	440	445̅	451	457	462̅	468	474
767	479̅	485	491	496̅	502	508	513̅	519	525	530̅
768	536	542	547̅	553	558̅	564̅	570	575̅	581̅	587
769	592̅	598̅	604	609̅	615	621	626̅	632	638	643̅
770	649	654̅	660̅	666	671̅	677̅	683	688̅	694	700
771	705̅	711	716̅	722̅	728	733̅	739	745	750̅	756
772	761̅	767̅	773	778̅	784	790	795̅	801	806̅	812̅
773	818	823̅	829	835	840̅	846	851̅	857̅	863	868̅
774	874	879̅	885̅	891	896̅	902	907̅	913̅	919	924̅
775	930	936	941̅	947	952̅	958	964	969̅	975	980̅
776	986	992	997̅	*003	*008̅	*014	*019̅	*025̅	*031	*036̅
777	89 042	047̅	053̅	059	064̅	070	075̅	081	087	092̅
778	098	103̅	109	114̅	120̅	126	131̅	137	142̅	148
779	153̅	159̅	165	170̅	176	181̅	187	193	198	204
780	209̅	215	220̅	226	231̅	237̅	243	248̅	254	259̅
781	265	270̅	276	282	287̅	293	298̅	304	309̅	315
782	320̅	326	332	337̅	343	348̅	354	359̅	365	370̅
783	376	381̅	387̅	393	398̅	404	409̅	415	420̅	426
784	431̅	437	442̅	448	454	459̅	465	470̅	476	481̅
785	487	492̅	498	503̅	509	514̅	520	525̅	531	536̅
786	542̅	548	553̅	559	564̅	570	575̅	581	586̅	592
787	597̅	603	608̅	614	619̅	625	630̅	636	641̅	647
788	652̅	658	663̅	669	674̅	680	685̅	691	696̅	702
789	707̅	713	718̅	724	729̅	735	740̅	746	751̅	757
790	762̅	768	773̅	779	784̅	790	795̅	801	806̅	812
791	817̅	823	828̅	834	839̅	845	850̅	856	861̅	867
792	872̅	878	883̅	889	894̅	900	905̅	911	916̅	922
793	927	933	938̅	943̅	949	954̅	960	965̅	971	976̅
794	982	987̅	993	998	*004	*009̅	*015	*020̅	*026	*031
795	90 036̅	042	047̅	053	058̅	064	069̅	075	080̅	086
796	091̅	097	102	107̅	113	118̅	124	129̅	135	140̅
797	146	151̅	156̅	162	167̅	173	178̅	184	189̅	195
798	200̅	205̅	211	216̅	222	227	233	238̅	244	249
799	254̅	260	265̅	271	276̅	282	287̅	292̅	298	303̅
800	309	314̅	320	325̅	330̅	336	341̅	347	352̅	358
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	6
.1	0.6
.2	1.2
.3	1.8
.4	2.4
.5	3.0
.6	3.6
.7	4.2
.8	4.8
.9	5.4

	5̅
.1	0.5̅
.2	1.1
.3	1.6̅
.4	2.2
.5	2.7̅
.6	3.3
.7	3.8̅
.8	4.4
.9	4.9̅

	5
.1	0.5
.2	1.0
.3	1.5
.4	2.0
.5	2.5
.6	3.0
.7	3.5
.8	4.0
.9	4.5

P. P.

N.	0	1	2	3	4	5	6	7	8	9	P. P.
800	90 309	314	320	325	330	336	341	347	352	358	
801	363	368	374	379	385	390	396	401	406	412	
802	417	423	428	433	439	444	450	455	460	466	
803	471	477	482	488	493	498	504	509	515	520	
804	525	531	536	542	547	552	558	563	569	574	
805	579	585	590	596	601	606	612	617	622	628	
806	633	639	644	649	655	660	666	671	676	682	
807	687	692	698	703	709	714	719	725	730	736	
808	741	746	752	757	762	768	773	778	784	789	
809	795	800	805	811	816	821	827	832	838	843	
810	848	854	859	864	870	875	880	886	891	896	5
811	902	907	913	918	923	929	934	939	945	950	·1 0·5
812	955	961	966	971	977	982	987	993	998	*003	·2 1·1
813	91 009	014	019	025	030	036	041	046	052	057	·3 1·6
814	062	068	073	078	084	089	094	100	105	110	·4 2·2
815	116	121	126	131	137	142	147	153	158	163	·5 2·7
816	169	174	179	185	190	195	201	206	211	217	·6 3·3
817	222	227	233	238	243	249	254	259	264	270	·7 3·8
318	275	280	286	291	296	302	307	312	318	323	·8 4·4
819	328	333	339	344	349	355	360	365	371	376	·9 4·9
820	381	386	392	397	402	408	413	418	423	429	
821	434	439	445	450	455	461	466	471	476	482	
822	487	492	497	503	508	513	519	524	529	534	
823	540	545	550	556	561	566	571	577	582	587	
824	592	598	603	608	614	619	624	629	635	640	
825	645	650	656	661	666	671	677	682	687	692	
826	698	703	708	714	719	724	729	735	740	745	
827	750	756	761	766	771	777	782	787	792	798	
828	803	808	813	819	824	829	834	839	845	850	
829	855	860	866	871	876	881	887	892	897	902	
830	908	913	918	923	928	934	939	944	949	955	5
831	960	965	970	976	981	986	991	996	*002	*007	·1 0·5
832	92 012	017	023	028	033	038	043	049	054	059	·2 1·0
833	064	069	075	080	085	090	096	101	106	111	·3 1·5
834	116	122	127	132	137	142	148	153	158	163	·4 2·0
835	168	174	179	184	189	194	200	205	210	215	·5 2·5
836	220	226	231	236	241	246	252	257	262	267	·6 3·0
837	272	277	283	288	293	298	303	309	314	319	·7 3·5
838	324	329	335	340	345	350	355	360	366	371	·8 4·0
839	376	381	386	391	397	402	407	412	417	423	·9 4·5
840	428	433	438	443	448	454	459	464	469	474	
841	479	485	490	495	500	505	510	515	521	526	
842	531	536	541	546	552	557	562	567	572	577	
843	583	588	593	598	603	608	613	619	624	629	
844	634	639	644	649	655	660	665	670	675	680	
845	685	691	696	701	706	711	716	721	727	732	
846	737	742	747	752	757	762	768	773	778	783	
847	788	793	798	803	809	814	819	824	829	834	
848	839	844	850	855	860	865	870	875	880	885	
849	891	896	901	906	911	916	921	926	931	937	
850	942	947	952	957	962	967	972	977	982	988	
N.	0	1	2	3	4	5	6	7	8	9	P. P.

N.	0	1	2	3	4	5	6	7	8	9
850	92 942	947	952	957	962	967	972	977	982	988
851	993	998	*003	*008	*013	*018	*023	*028	*034	*039
852	93 044	049	054	059	064	069	074	079	084	090
853	095	100	105	110	115	120	125	130	135	140
854	146	151	156	161	166	171	176	181	186	191
855	196	201	207	212	217	222	227	232	237	242
856	247	252	257	262	267	272	278	283	288	293
857	298	303	308	313	318	323	328	333	338	343
858	348	354	359	364	369	374	379	384	389	394
859	399	404	409	414	419	424	429	434	439	445
860	450	455	460	465	470	475	480	485	490	495
861	500	505	510	515	520	525	530	535	540	545
862	550	556	561	566	571	576	581	586	591	596
863	601	606	611	616	621	626	631	636	641	646
864	651	656	661	666	671	676	681	686	691	696
865	701	706	711	716	721	726	731	736	742	747
866	752	757	762	767	772	777	782	787	792	797
867	802	807	812	817	822	827	832	837	842	847
868	852	857	862	867	872	877	882	887	892	897
869	902	907	912	917	922	927	932	937	942	947
870	952	957	962	967	972	977	982	987	992	997
871	94 002	007	012	017	022	026	031	036	041	046
872	051	056	061	066	071	076	081	086	091	096
873	101	106	111	116	121	126	131	136	141	146
874	151	156	161	166	171	176	181	186	191	196
875	201	206	210	215	220	225	230	235	240	245
876	250	255	260	265	270	275	280	285	290	295
877	300	305	310	315	320	324	329	334	339	344
878	349	354	359	364	369	374	379	384	389	394
879	399	404	409	413	418	423	428	433	438	443
880	448	453	458	463	468	473	478	483	487	492
881	497	502	507	512	517	522	527	532	537	542
882	547	552	556	561	566	571	576	581	586	591
883	596	601	606	611	615	620	625	630	635	640
884	645	650	655	660	665	670	674	679	684	689
885	694	699	704	709	714	719	724	728	733	738
886	743	748	753	758	763	768	773	777	782	787
887	792	797	802	807	812	817	821	826	831	836
888	841	846	851	856	861	865	870	875	880	885
889	890	895	900	905	909	914	919	924	929	934
890	939	944	949	953	958	963	968	973	978	983
891	988	992	997	*002	*007	*012	*017	*022	*026	031
892	95 036	041	046	051	056	061	065	070	075	080
893	085	090	095	099	104	109	114	119	124	129
894	134	138	143	148	153	158	163	167	172	177
895	182	187	192	197	201	206	211	216	221	226
896	231	235	240	245	250	255	260	264	269	274
897	279	284	289	294	298	303	308	313	318	323
898	327	332	337	342	347	352	356	361	366	371
899	376	381	385	390	395	400	405	410	414	419
900	424	429	434	438	443	448	453	458	463	467
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	5̄
.1	0.5
.2	1.1
.3	1.6
.4	2.2
.5	2.7
.6	3.3
.7	3.8
.8	4.4
.9	4.9

	5
.1	0.5
.2	1.0
.3	1.5
.4	2.0
.5	2.5
.6	3.0
.7	3.5
.8	4.0
.9	4.5

	4̄
.1	0.4
.2	0.9
.3	1.3
.4	1.8
.5	2.2
.6	2.7
.7	3.1
.8	3.6
.9	4.0

N.		0	1	2	3	4	5	6	7	8	9
900	95	42$\bar{4}$	429	434	43$\bar{8}$	44$\bar{3}$	44$\bar{8}$	453	458	463	46$\bar{7}$
901		47$\underline{2}$	47$\bar{7}$	48$\underline{2}$	487	492	49$\bar{6}$	50$\bar{1}$	50$\underline{6}$	511	516
902		52$\bar{0}$	52$\underline{5}$	53$\bar{0}$	535	540	54$\bar{4}$	54$\underline{9}$	55$\underline{4}$	559	564
903		569	57$\bar{3}$	57$\bar{8}$	58$\underline{3}$	588	593	59$\bar{7}$	60$\bar{2}$	60$\underline{7}$	612
904		617	62$\bar{1}$	62$\bar{6}$	63$\bar{1}$	636	641	64$\underline{5}$	65$\bar{0}$	65$\bar{5}$	660
905		665	66$\underline{9}$	67$\underline{4}$	67$\bar{9}$	684	689	69$\underline{3}$	69$\bar{8}$	703	708
906		71$\underline{3}$	71$\bar{7}$	72$\bar{2}$	727	732	73$\underline{7}$	74$\underline{1}$	74$\bar{6}$	751	756
907		76$\bar{0}$	76$\bar{5}$	77$\bar{0}$	775	78$\underline{0}$	78$\underline{4}$	78$\underline{9}$	794	799	80$\underline{4}$
908		80$\bar{8}$	81$\bar{3}$	818	82$\underline{3}$	82$\bar{7}$	83$\bar{2}$	83$\bar{7}$	842	84$\underline{7}$	85$\underline{1}$
909		85$\bar{6}$	861	866	87$\bar{0}$	87$\bar{5}$	88$\bar{0}$	885	890	89$\bar{4}$	89$\bar{9}$
910		904	909	91$\bar{3}$	91$\bar{8}$	923	928	933	93$\bar{7}$	94$\bar{2}$	947
911		95$\underline{2}$	95$\bar{6}$	96$\bar{1}$	966	97$\underline{1}$	97$\bar{5}$	98$\bar{0}$	985	99$\underline{0}$	99$\bar{4}$
912		99$\bar{9}$	*004	*00$\underline{9}$	*01$\underline{4}$	*01$\bar{8}$	*02$\bar{3}$	*02$\underline{8}$	*03$\underline{3}$	*03$\bar{7}$	*04$\bar{2}$
913	96	04$\underline{7}$	05$\underline{2}$	05$\bar{6}$	06$\bar{1}$	06$\underline{6}$	07$\underline{1}$	07$\bar{5}$	08$\bar{0}$	08$\underline{5}$	09$\underline{0}$
914		09$\bar{4}$	09$\bar{9}$	10$\underline{4}$	10$\underline{9}$	11$\bar{3}$	11$\bar{8}$	12$\underline{3}$	12$\underline{8}$	13$\bar{2}$	13$\bar{7}$
915		14$\underline{2}$	14$\underline{7}$	15$\bar{1}$	15$\bar{6}$	16$\underline{1}$	166	17$\bar{0}$	17$\underline{5}$	18$\underline{0}$	185
916		18$\bar{9}$	19$\underline{4}$	19$\underline{9}$	204	20$\bar{8}$	21$\underline{3}$	21$\underline{8}$	22$\bar{2}$	22$\bar{7}$	23$\underline{2}$
917		23$\underline{7}$	24$\bar{1}$	24$\bar{6}$	25$\underline{1}$	256	26$\bar{0}$	26$\underline{5}$	27$\underline{0}$	275	27$\bar{9}$
918		28$\underline{4}$	28$\underline{9}$	29$\bar{3}$	29$\bar{8}$	30$\underline{3}$	308	31$\bar{2}$	31$\underline{7}$	32$\underline{2}$	327
919		33$\bar{1}$	33$\bar{6}$	341	34$\bar{5}$	35$\bar{0}$	355	360	36$\bar{4}$	36$\bar{9}$	374
920		379	38$\bar{3}$	388	393	39$\bar{7}$	40$\bar{2}$	407	412	41$\bar{6}$	421
921		426	43$\bar{0}$	43$\underline{5}$	440	445	44$\underline{9}$	45$\underline{4}$	459	46$\bar{3}$	46$\underline{8}$
922		473	478	48$\underline{2}$	48$\underline{7}$	492	49$\underline{6}$	50$\underline{1}$	506	511	51$\underline{5}$
923		520	525	52$\bar{9}$	53$\underline{4}$	539	54$\underline{3}$	54$\underline{8}$	553	558	56$\bar{2}$
924		567	572	57$\bar{6}$	58$\underline{1}$	586	59$\bar{0}$	59$\underline{5}$	600	60$\underline{5}$	60$\bar{9}$
925		614	619	62$\bar{3}$	62$\bar{8}$	633	63$\underline{7}$	64$\bar{2}$	647	65$\underline{1}$	65$\bar{6}$
926		661	66$\underline{6}$	67$\bar{0}$	675	68$\underline{0}$	68$\underline{4}$	689	694	69$\bar{8}$	70$\bar{3}$
927		708	71$\bar{2}$	71$\bar{7}$	722	72$\bar{6}$	73$\bar{1}$	736	74$\underline{1}$	74$\bar{5}$	750
928		75$\underline{5}$	75$\bar{9}$	764	76$\underline{9}$	77$\bar{3}$	778	78$\underline{3}$	78$\underline{7}$	792	79$\underline{7}$
929		80$\bar{1}$	806	811	81$\bar{5}$	82$\bar{0}$	825	82$\bar{9}$	83$\bar{4}$	839	84$\bar{3}$
930		84$\bar{8}$	853	85$\bar{7}$	86$\bar{2}$	867	87$\bar{1}$	87$\bar{6}$	881	88$\bar{5}$	89$\bar{0}$
931		89$\underline{5}$	89$\bar{9}$	90$\bar{4}$	90$\underline{9}$	91$\bar{3}$	91$\bar{8}$	92$\underline{3}$	92$\bar{7}$	93$\bar{2}$	93$\underline{7}$
932		94$\bar{1}$	94$\bar{6}$	95$\underline{1}$	95$\bar{5}$	960	96$\underline{5}$	96$\bar{9}$	97$\underline{4}$	97$\underline{9}$	98$\bar{3}$
933		98$\underline{8}$	99$\underline{3}$	99$\bar{7}$	*00$\underline{2}$	*00$\underline{7}$	*01$\bar{1}$	*01$\underline{6}$	*02$\bar{0}$	*02$\bar{5}$	*03$\underline{0}$
934	97	03$\bar{4}$	03$\bar{9}$	04$\underline{4}$	04$\bar{8}$	05$\underline{3}$	05$\underline{8}$	06$\bar{2}$	06$\underline{7}$	07$\underline{2}$	07$\bar{6}$
935		08$\underline{1}$	086	09$\bar{0}$	09$\underline{5}$	09$\bar{9}$	10$\bar{4}$	10$\underline{9}$	11$\bar{3}$	11$\underline{8}$	12$\underline{3}$
936		12$\bar{7}$	13$\underline{2}$	137	14$\bar{1}$	14$\underline{6}$	151	15$\bar{5}$	16$\underline{0}$	16$\bar{4}$	16$\underline{9}$
937		17$\underline{4}$	178	18$\underline{3}$	188	19$\bar{2}$	19$\underline{7}$	202	20$\bar{6}$	21$\underline{1}$	21$\bar{5}$
938		22$\underline{0}$	225	22$\bar{9}$	23$\underline{4}$	239	24$\underline{3}$	24$\underline{8}$	25$\bar{2}$	25$\underline{7}$	262
939		26$\bar{6}$	271	276	28$\bar{0}$	285	28$\bar{9}$	29$\bar{4}$	299	30$\bar{3}$	308
940		313	31$\bar{7}$	322	32$\bar{6}$	33$\bar{1}$	336	34$\bar{0}$	345	34$\bar{9}$	35$\bar{4}$
941		359	36$\underline{3}$	36$\underline{8}$	373	37$\underline{7}$	382	38$\underline{6}$	39$\bar{1}$	396	40$\underline{0}$
942		405	40$\bar{9}$	41$\underline{4}$	419	42$\underline{3}$	428	43$\bar{2}$	43$\underline{7}$	442	44$\underline{6}$
943		451	456	46$\underline{0}$	465	46$\bar{9}$	474	479	48$\underline{3}$	488	49$\underline{2}$
944		497	502	50$\underline{6}$	511	51$\bar{5}$	520	52$\underline{5}$	52$\underline{9}$	534	53$\underline{8}$
945		543	54$\underline{8}$	55$\underline{2}$	557	56$\underline{1}$	566	57$\underline{0}$	57$\bar{5}$	580	58$\underline{4}$
946		589	59$\underline{3}$	59$\bar{8}$	603	60$\underline{7}$	612	61$\underline{6}$	621	62$\underline{6}$	63$\bar{0}$
947		635	63$\underline{9}$	644	64$\underline{9}$	65$\bar{3}$	65$\underline{8}$	66$\underline{2}$	667	67$\underline{1}$	67$\bar{6}$
948		68$\underline{1}$	68$\bar{5}$	690	69$\underline{4}$	699	70$\underline{3}$	70$\bar{8}$	71$\underline{3}$	71$\bar{7}$	722
949		72$\bar{6}$	731	736	74$\bar{0}$	745	74$\bar{9}$	754	75$\bar{8}$	763	768
950		77$\bar{2}$	777	78$\bar{1}$	786	79$\bar{0}$	795	800	80$\bar{4}$	809	81$\bar{3}$
N.		0	1	2	3	4	5	6	7	8	9

P. P.

	5
.1	0.5
.2	1.0
.3	1.5
.4	2.0
.5	2.5
.6	3.0
.7	3.5
.8	4.0
.9	4.5

	$\bar{4}$
.1	0.4
.2	0.$\underline{9}$
.3	1.$\bar{3}$
.4	1.$\underline{8}$
.5	2.$\bar{2}$
.6	2.$\underline{7}$
.7	3.$\bar{1}$
.8	3.$\underline{6}$
.9	4.$\bar{0}$

P. P.

N.	0	1	2	3	4	5	6	7	8	9
950	97 772	777	781	786	790	795	800	804	809	813
951	818	822	827	831	836	841	845	850	854	859
952	863	868	873	877	882	886	891	895	900	904
953	909	914	918	923	927	932	936	941	945	950
954	955	959	964	968	973	977	982	986	991	996
955	98 000	005	009	014	018	023	027	032	036	041
956	046	050	055	059	064	068	073	077	082	086
957	091	095	100	105	109	114	118	123	127	132
958	136	141	145	150	154	159	163	168	173	177
959	182	186	191	195	200	204	209	213	218	222
960	227	231	236	240	245	249	254	259	263	268
961	272	277	281	286	290	295	299	304	308	313
962	317	322	326	331	335	340	344	349	353	358
963	362	367	371	376	380	385	389	394	398	403
964	407	412	416	421	425	430	434	439	443	448
965	452	457	461	466	470	475	479	484	488	493
966	497	502	506	511	515	520	524	529	533	538
967	542	547	551	556	560	565	569	574	578	583
968	587	592	596	601	605	610	614	619	623	628
969	632	637	641	646	650	655	659	663	668	672
970	677	681	686	690	695	699	704	708	713	717
971	722	726	731	735	740	744	749	753	757	762
972	766	771	775	780	784	789	793	798	802	807
973	811	815	820	824	829	833	838	842	847	851
974	856	860	865	869	873	878	882	887	891	896
975	900	905	909	914	918	922	927	931	936	940
976	945	949	954	958	963	967	971	976	980	985
977	989	994	998	*003	*007	*011	*016	*020	*025	*029
978	99 034	038	043	047	051	056	060	065	069	074
979	078	082	087	091	096	100	105	109	113	118
980	122	127	131	136	140	145	149	153	158	162
981	167	171	176	180	184	189	193	198	202	206
982	211	215	220	224	229	233	237	242	246	251
983	255	260	264	268	273	277	282	286	290	295
984	299	304	308	312	317	321	326	330	335	339
985	343	348	352	357	361	365	370	374	379	383
986	387	392	396	401	405	409	414	418	423	427
987	431	436	440	445	449	453	458	462	467	471
988	475	480	484	489	493	497	502	506	511	515
989	519	524	528	533	537	541	546	550	554	559
990	563	568	572	576	581	585	590	594	598	603
991	607	611	616	620	625	629	633	638	642	647
992	651	655	660	664	668	673	677	682	686	690
993	695	699	703	708	712	717	721	725	730	734
994	738	743	747	751	756	760	765	769	773	778
995	782	786	791	795	800	804	808	813	817	821
996	826	830	834	839	843	847	852	856	861	865
997	869	874	878	882	887	891	895	900	904	908
998	913	917	922	926	930	935	939	943	948	952
999	956	961	965	969	974	978	982	987	991	995
1000	00 000	004	008	013	017	021	026	030	034	039
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	5
.1	0.5
.2	1.0
.3	1.5
.4	2.0
.5	2.5
.6	3.0
.7	3.5
.8	4.0
.9	4.5

	4
.1	0.4
.2	0.9
.3	1.3
.4	1.8
.5	2.2
.6	2.7
.7	3.1
.8	3.6
.9	4.0

	4
.1	0.4
.2	0.8
.3	1.2
.4	1.6
.5	2.0
.6	2.4
.7	2.8
.8	3.2
.9	3.6

N.	0	1	2	3	4	5	6	7	8	9
1000	000 000	043	087	130	173	217	260	304	347	390
01	434	477	521	564	607	651	694	737	781	824
02	867	911	954	997	*041	*084	*127	*171	*214	*257
03	001 301	344	387	431	474	517	560	604	647	690
04	733	777	820	863	906	950	993	*036	*079	*123
05	002 166	209	252	295	339	382	425	468	511	555
06	598	641	684	727	770	814	857	900	943	986
07	003 029	072	115	159	202	245	288	331	374	417
08	460	503	546	590	633	676	719	762	805	848
09	891	934	977	*020	*063	*106	*149	*192	*235	*278
1010	004 321	364	407	450	493	536	579	622	665	708
11	751	794	837	880	923	966	*009	*051	*094	*137
12	005 180	223	266	309	352	395	438	481	523	566
13	609	652	695	738	781	824	866	909	952	995
14	006 038	081	123	166	209	252	295	337	380	423
15	466	509	551	594	637	680	722	765	808	851
16	893	936	979	*022	*064	*107	*150	*193	*235	*278
17	007 321	363	406	449	491	534	577	620	662	705
18	748	790	833	875	918	961	*003	*046	*089	131
19	008 174	217	259	302	344	387	430	472	515	557
1020	600	642	685	728	770	813	855	898	940	983
21	009 025	068	111	153	196	238	281	323	366	408
22	451	493	536	578	621	663	706	748	790	833
23	875	918	960	*003	*045	*088	*130	*172	*215	*257
24	010 300	342	385	427	469	512	554	596	639	681
25	724	766	808	851	893	935	978	*020	*062	*105
26	011 147	189	232	274	316	359	401	443	486	528
27	570	612	655	697	739	782	824	866	908	951
28	993	*035	*077	*120	*162	*204	*246	*288	*331	*373
29	012 415	457	500	542	584	626	668	710	753	795
1030	837	879	921	963	*006	*048	*090	*132	174	216
31	013 258	301	343	385	427	469	511	553	595	637
32	679	722	764	806	848	890	932	974	*016	*058
33	014 100	142	184	226	268	310	352	394	436	478
34	520	562	604	646	688	730	772	814	856	898
35	940	982	*024	*066	*108	*150	*192	*234	*276	*318
36	015 360	401	443	485	527	569	611	653	695	737
37	779	820	862	904	946	988	*030	*072	*113	155
38	016 197	239	281	323	364	406	448	490	532	573
39	615	657	699	741	782	824	866	908	950	991
1040	017 033	075	117	158	200	242	284	325	367	409
41	450	492	534	576	617	659	701	742	784	826
42	867	909	951	992	*034	*076	*117	*159	*201	*242
43	018 284	326	367	409	451	492	534	575	617	659
44	700	742	783	825	867	908	950	991	*033	*074
45	019 116	158	199	241	282	324	365	407	448	490
46	531	573	614	656	697	739	780	822	863	905
47	946	988	*029	*071	*112	*154	*195	*237	*278	*320
48	020 361	402	444	485	527	568	610	651	692	734
49	775	817	858	899	941	982	*024	*065	*106	*148
1050	021 189	230	272	313	354	396	437	478	520	561
N.	0	1	2	3	4	5	6	7	8	9

P. P.

	$\overline{43}$	43
.1	4.3	4.3
.2	8.7	8.6
.3	13.0	12.9
.4	17.4	17.2
.5	21.7	21.5
.6	26.1	25.8
.7	30.4	30.1
.8	34.8	34.4
.9	39.1	38.7

	$\overline{42}$	42
.1	4.2	4.2
.2	8.5	8.4
.3	12.7	12.6
.4	17.0	16.8
.5	21.2	21.0
.6	25.5	25.2
.7	29.7	29.4
.8	34.0	33.6
.9	38.2	37.8

	$\overline{41}$	41
.1	4.1	4.1
.2	8.3	8.2
.3	12.4	12.3
.4	16.6	16.4
.5	20.7	20.5
.6	24.9	24.6
.7	29.0	28.7
.8	33.2	32.8
.9	37.3	36.9

P. P.

N.		0	1	2	3	4	5	6	7	8	9	P. P.	
1050	021	189	230	272	313	354	396	437	478	520	561		41
51		602	644	685	726	768	809	850	892	933	974	.1	4.1
52	022	015	057	098	139	181	222	263	304	346	387	.2	8.3
53		428	469	511	552	593	634	676	717	758	799	.3	12.4
54		840	882	923	964	*005	*046	*088	*129	*170	*211	.4	16.6
55	023	252	293	335	376	417	458	499	540	581	623	.5	20.7
56		664	705	746	787	828	869	910	951	993	*034	.6	24.9
57	024	075	116	157	198	239	280	321	362	403	444	.7	29.0
58		485	526	568	609	650	691	732	773	814	855	.8	33.2
59		896	937	978	*019	*060	*101	*142	*183	*224	*265	.9	37.3
1060	025	306	347	388	429	469	510	551	592	633	674		41
61		715	756	797	838	879	920	961	*002	*042	*083	.1	4.1
62	026	124	165	206	247	288	329	370	410	451	492	.2	8.2
63		533	574	615	656	696	737	778	819	860	901	.3	12.3
64		941	982	*023	*064	*105	*145	*186	*227	*268	*309	.4	16.4
65	027	349	390	431	472	512	553	594	635	675	716	.5	20.5
66		757	798	838	879	920	961	*001	*042	*083	*123	.6	24.6
67	028	164	205	246	286	327	368	408	449	490	530	.7	28.7
68		571	612	652	693	734	774	815	856	896	937	.8	32.8
69		977	*018	*059	*099	*140	*181	*221	*262	*302	*343	.9	36.9
1070	029	384	424	465	505	546	586	627	668	708	749		40
71		789	830	870	911	951	992	*032	*073	*114	*154	.1	4.0
72	030	195	235	276	316	357	397	438	478	519	559	.2	8.1
73		599	640	680	721	761	802	842	883	923	964	.3	12.1
74	031	004	044	085	125	166	206	247	287	327	368	.4	16.2
75		408	449	489	529	570	610	651	691	731	772	.5	20.2
76		812	852	893	933	973	*014	*054	*094	*135	*175	.6	24.3
77	032	215	256	296	336	377	417	457	498	538	578	.7	28.3
78		619	659	699	739	780	820	860	900	941	981	.8	32.4
79	033	021	061	102	142	182	222	263	303	343	383	.9	36.4
1080		424	464	504	544	584	625	665	705	745	785		40
81		825	866	906	946	986	*026	*066	*107	147	187	.1	4.0
82	034	227	267	307	347	388	428	468	508	548	588	.2	8.0
83		628	668	708	748	789	829	869	909	949	989	.3	12.0
84	035	029	069	109	149	189	229	269	309	349	389	.4	16.0
85		429	470	510	550	590	630	670	710	750	790	.5	20.0
86		830	870	910	950	990	*029	*069	*109	*149	*189	.6	24.0
87	036	229	269	309	349	389	429	469	509	549	589	.7	28.0
88		629	669	708	748	788	828	868	908	948	988	.8	32.0
89	037	028	068	107	147	187	227	267	307	347	386	.9	36.0
1090		426	466	506	546	586	625	665	705	745	785		39
91		825	864	904	944	984	*023	*063	*103	143	183	.1	3.9
92	038	222	262	302	342	381	421	461	501	540	580	.2	7.9
93		620	660	699	739	779	819	858	898	938	977	.3	11.8
94	039	017	057	096	136	176	216	255	295	335	374	.4	15.8
95		414	454	493	533	572	612	652	691	731	771	.5	19.7
96		810	850	890	929	969	*008	*048	*088	*127	*167	.6	23.7
97	040	206	246	286	325	365	404	444	483	523	563	.7	27.6
98		602	642	681	721	760	800	839	879	918	958	.8	31.6
99		997	*037	*076	*116	*155	*195	*234	*274	*313	*353	.9	35.5
1100	041	392	432	471	511	550	590	629	669	708	748		
N.		0	1	2	3	4	5	6	7	8	9	P. P.	

Log sin ϕ = log ϕ'' + S.
Log tan ϕ = log ϕ'' + T.

0°

log ϕ'' = log sin ϕ + S'.
log ϕ'' = log tan ϕ + T'.

″	′	S	T	Log. Sin.	S′	T′	Log. Tan.
0	0	4.685 57	57	— ∞	5.314 42	42	— ∞
60	1	57	57	6.46 372	42	42	6.46 372
120	2	57	57	.76 475	42	42	.76 475
180	3	57	57	.94 084	42	42	.94 084
240	4	57	57	7.06 578	42	42	7.06 578
300	5	4.685 57	57	7.16 269	5.314 42	42	7.16 269
360	6	57	57	.24 187	42	42	.24 188
420	7	57	57	.30 882	42	42	.30 882
480	8	57	57	.36 681	42	42	.36 681
540	9	57	57	.41 797	42	42	.41 797
600	10	4.685 57	57	7.46 372	5.314 42	42	7.46 372
660	11	57	57	.50 512	42	42	.50 512
720	12	57	57	.54 290	42	42	.54 291
780	13	57	57	.57 767	42	42	.57 767
840	14	57	57	.60 985	42	42	.60 985
900	15	4.685 57	58	7.63 981	5.314 42	42	7.63 982
960	16	57	58	.66 784	42	42	.66 785
1020	17	57	58	.69 417	42	42	.69 418
1080	18	57	58	.71 899	42	42	.71 900
1140	19	57	58	.74 248	42	42	.74 248
1200	20	4.685 57	58	7.76 475	5.314 43	42	7.76 476
1260	21	57	58	.78 594	43	42	.78 595
1320	22	57	58	.80 614	43	42	.80 615
1380	23	57	58	.82 545	43	42	.82 546
1440	24	57	58	.84 393	43	42	.84 394
1500	25	4.685 57	58	7.86 166	5.314 43	41	7.86 167
1560	26	57	58	.87 869	43	41	.87 871
1620	27	57	58	.89 508	43	41	.89 510
1680	28	57	58	.91 088	43	41	.91 089
1740	29	57	58	.92 612	43	41	.92 613
1800	30	4.685 57	58	7.94 084	5.314 43	41	7.94 086
1860	31	57	58	.95 508	43	41	.95 510
1920	32	57	58	.96 887	43	41	.96 889
1980	33	57	59	.98 223	43	41	.98 225
2040	34	57	59	.99 520	43	41	.99 522
2100	35	4.685 56	59	8.00 778	5.314 43	41	8.00 781
2160	36	56	59	.02 002	43	41	.02 004
2220	37	56	59	.03 192	43	41	.03 194
2280	38	56	59	.04 350	43	40	.04 352
2340	39	56	59	.05 478	43	40	.05 481
2400	40	4.685 56	59	8.06 577	5.314 43	40	8.06 580
2460	41	56	59	.07 650	43	40	.07 653
2520	42	56	59	.08 696	43	40	.08 699
2580	43	56	60	.09 718	43	40	.09 721
2640	44	56	60	.10 716	43	40	.10 720
2700	45	4.685 56	60	8.11 692	5.314 44	40	8.11 696
2760	46	56	60	.12 647	44	40	.12 651
2820	47	56	60	.13 581	44	40	.13 585
2880	48	56	60	.14 495	44	39	.14 499
2940	49	56	60	.15 390	44	39	.15 395
3000	50	4.685 56	60	8.16 268	5.314 44	39	8.16 272
3060	51	56	60	.17 128	44	39	.17 133
3120	52	56	61	.17 971	44	39	.17 976
3180	53	56	61	.18 798	44	39	.18 803
3240	54	55	61	.19 610	44	39	.19 615
3300	55	4.685 55	61	8.20 407	5.314 44	39	8.20 412
3360	56	55	61	.21 189	44	38	.21 195
3420	57	55	61	.21 958	44	38	.21 964
3480	58	55	61	.22 713	44	38	.22 719
3540	59	55	62	.23 455	44	38	.23 462

Log sin ϕ = log ϕ'' + S.
Log tan ϕ = log ϕ'' + T.

1°

log ϕ'' = log sin ϕ + S'.
log ϕ'' = log tan ϕ + T'.

″	′	S	T	Log. Sin.	S′	T′	Log. Tan.
3600	0	4.685 5$\bar{5}$	62	8.24 18$\bar{5}$	5.314 4$\bar{4}$	38	8.24 192
3660	1	55	62	.24 90$\bar{3}$	45	38	.24 910
3720	2	55	62	.25 60$\bar{9}$	45	38	.25 61$\bar{6}$
3780	3	55	6$\bar{2}$	.26 304	45	3$\bar{7}$	.26 31$\bar{1}$
3840	4	55	6$\bar{2}$	.26 988	45	3$\bar{7}$	.26 99$\bar{5}$
3900	5	4.685 55	6$\bar{2}$	8.27 66$\bar{1}$	5.314 45	3$\bar{7}$	8.27 669
3960	6	55	63	.28 32$\bar{4}$	45	37	.28 33$\bar{2}$
4020	7	5$\bar{4}$	63	.28 97$\bar{7}$	4$\bar{5}$	37	.28 98$\bar{5}$
4080	8	5$\bar{4}$	63	.29 62$\bar{0}$	4$\bar{5}$	37	.29 629
4140	9	5$\bar{4}$	6$\bar{3}$	.30 25$\bar{4}$	4$\bar{5}$	3$\bar{6}$	.30 26$\bar{3}$
4200	10	4.685 5$\bar{4}$	6$\bar{3}$	8.30 87$\bar{9}$	5.314 4$\bar{5}$	3$\bar{6}$	8.30 88$\bar{8}$
4260	11	5$\bar{4}$	6$\bar{3}$	.31 49$\bar{5}$	4$\bar{5}$	3$\bar{6}$	.31 50$\bar{4}$
4320	12	54	64	.32 10$\bar{2}$	45	36	.32 112
4380	13	54	64	.32 70$\bar{1}$	46	36	.32 71$\bar{1}$
4440	14	54	64	.33 29$\bar{2}$	46	36	.33 30$\bar{2}$
4500	15	4.685 54	6$\bar{4}$	8.33 87$\bar{5}$	5.314 46	3$\bar{5}$	8.33 88$\bar{5}$
4560	16	54	6$\bar{4}$	.34 45$\bar{0}$	46	3$\bar{5}$	.34 461
4620	17	54	65	.35 018	46	35	.35 029
4680	18	5$\bar{4}$	65	.35 57$\bar{8}$	46	35	.35 58$\bar{9}$
4740	19	5$\bar{3}$	65	.36 13$\bar{1}$	4$\bar{6}$	35	.36 143
4800	20	4.685 5$\bar{3}$	6$\bar{5}$	8.36 67$\bar{7}$	5.314 4$\bar{6}$	3$\bar{4}$	8.36 689
4860	21	5$\bar{3}$	6$\bar{5}$	.37 217	4$\bar{6}$	3$\bar{4}$	.37 229
4920	22	5$\bar{3}$	65	.37 750	4$\bar{6}$	3$\bar{4}$	.37 762
4980	23	5$\bar{3}$	66	.38 276	4$\bar{6}$	34	.38 289
5040	24	53	66	.38 796	47	34	.38 809
5100	25	4.685 53	6$\bar{6}$	8.39 310	5.314 47	3$\bar{3}$	8.39 32$\bar{3}$
5160	26	53	6$\bar{6}$	.39 818	47	3$\bar{3}$	.39 83$\bar{1}$
5220	27	5$\bar{3}$	67	.40 320	4$\bar{7}$	33	.40 33$\bar{4}$
5280	28	5$\bar{2}$	67	.40 816	4$\bar{7}$	33	.40 83$\bar{0}$
5340	29	5$\bar{2}$	67	.41 307	4$\bar{7}$	33	.41 32$\bar{1}$
5400	30	4.685 5$\bar{2}$	6$\bar{7}$	8.41 792	5.314 4$\bar{7}$	3$\bar{2}$	8.41 807
5460	31	5$\bar{2}$	6$\bar{7}$	.42 27$\bar{1}$	4$\bar{7}$	3$\bar{2}$	.42 287
5520	32	5$\bar{2}$	68	.42 74$\bar{6}$	4$\bar{7}$	32	.42 76$\bar{2}$
5580	33	52	6$\bar{8}$	.43 21$\bar{5}$	48	3$\bar{2}$	.43 23$\bar{1}$
5640	34	52	6$\bar{8}$	.43 680	48	3$\bar{1}$	.43 696
5700	35	4.685 52	6$\bar{8}$	8.44 13$\bar{9}$	5.314 48	3$\bar{1}$	8.44 156
5760	36	5$\bar{2}$	69	.44 594	4$\bar{8}$	3$\bar{1}$	.44 61$\bar{1}$
5820	37	5$\bar{1}$	69	.45 044	4$\bar{8}$	3$\bar{1}$	.45 06$\bar{1}$
5880	38	5$\bar{1}$	6$\bar{9}$	.45 48$\bar{9}$	4$\bar{8}$	3$\bar{0}$	.45 507
5940	39	5$\bar{1}$	6$\bar{9}$	.45 930	4$\bar{8}$	3$\bar{0}$	.45 948
6000	40	4.685 5$\bar{1}$	6$\bar{9}$	8.46 36$\bar{6}$	5.314 4$\bar{8}$	3$\bar{0}$	8.46 385
6060	41	51	70	.46 79$\bar{8}$	49	30	.46 81$\bar{7}$
6120	42	51	7$\bar{0}$	.47 22$\bar{6}$	49	3$\bar{0}$	.47 24$\bar{5}$
6180	43	51	7$\bar{0}$	.47 65$\bar{0}$	49	2$\bar{9}$	.47 669
6240	44	51	7$\bar{0}$	.48 06$\bar{9}$	49	2$\bar{9}$	.48 089
6300	45	4.685 5$\bar{0}$	7$\bar{1}$	8.48 485	5.314 4$\bar{9}$	2$\bar{9}$	8.48 505
6360	46	5$\bar{0}$	7$\bar{1}$	.48 89$\bar{6}$	4$\bar{9}$	2$\bar{8}$	.48 917
6420	47	5$\bar{0}$	7$\bar{1}$	.49 304	4$\bar{9}$	2$\bar{8}$	.49 32$\bar{5}$
6480	48	5$\bar{0}$	72	.49 708	4$\bar{9}$	28	.49 72$\bar{9}$
6540	49	50	72	.50 108	50	28	.50 130
6600	50	4.685 50	7$\bar{2}$	8.50 50$\bar{4}$	5.314 50	2$\bar{7}$	8.50 52$\bar{6}$
6660	51	50	7$\bar{2}$	.50 89$\bar{7}$	50	2$\bar{7}$	.50 920
6720	52	5$\bar{0}$	73	.51 28$\bar{6}$	5$\bar{0}$	27	.51 310
6780	53	4$\bar{9}$	73	.51 672	5$\bar{0}$	2$\bar{7}$	.51 696
6840	54	4$\bar{9}$	7$\bar{3}$	.52 055	5$\bar{0}$	2$\bar{6}$	.52 079
6900	55	4.685 4$\bar{9}$	7$\bar{3}$	8.52 43$\bar{4}$	5.314 5$\bar{0}$	2$\bar{6}$	8.52 45$\bar{8}$
6960	56	49	7$\bar{4}$	.52 810	51	2$\bar{6}$	.52 835
7020	57	49	7$\bar{4}$	.53 18$\bar{3}$	51	2$\bar{5}$	.53 208
7080	58	49	7$\bar{4}$	.53 55$\bar{2}$	51	2$\bar{5}$	.53 57$\bar{9}$
7140	59	49	75	.53 91$\bar{8}$	51	25	.53 94$\bar{4}$

Log sin ϕ = log ϕ'' + S.
Log tan ϕ = log ϕ'' + T.

2°

log ϕ'' = log sin ϕ + S'
log ϕ'' = log tan ϕ + T'

″	′	S	T	Log. Sin.	S′	T′	Log. Tan.
7200	0	4.685 48	75	8.54 282	5.314 51	25	8.54 308
7260	1	48	75	.54 642	51	24	.54 669
7320	2	48	75	.54 999	51	24	.55 027
7380	3	48	76	.55 354	52	24	.55 381
7440	4	48	76	.55 705	52	23	.55 733
7500	5	4.685 48	76	8.56 054	5.314 52	23	8.56 083
7560	6	48	77	.56 400	52	23	.56 429
7620	7	47	77	.56 743	52	22	.56 772
7680	8	47	77	.57 083	52	22	.57 113
7740	9	47	78	.57 421	52	22	.57 452
7800	10	4.685 47	78	8.57 756	5.314 53	22	8.57 787
7860	11	47	78	.58 089	53	21	.58 121
7920	12	47	79	.58 419	53	21	.58 451
7980	13	46	79	.58 747	53	21	.58 779
8040	14	46	79	.59 072	53	20	.59 105
8100	15	4.685 46	80	8.59 395	5.314 53	20	8.59 428
8160	16	46	80	.59 715	54	20	.59 749
8220	17	46	80	.60 033	54	19	.60 067
8280	18	46	81	.60 349	54	19	.60 384
8340	19	45	81	.60 662	54	19	.60 698
8400	20	4.685 45	81	8.60 973	5.314 54	18	8.61 009
8460	21	45	82	.61 282	54	18	.61 319
8520	22	45	82	.61 589	55	18	.61 626
8580	23	45	82	.61 893	55	17	.61 931
8640	24	45	83	.62 196	55	17	.62 234
8700	25	4.685 44	83	8.62 496	5.314 55	16	8.62 535
8760	26	44	83	.62 795	55	16	.62 834
8820	27	44	84	.63 091	55	16	.63 131
8880	28	44	84	.63 385	56	15	.63 425
8940	29	44	84	.63 677	56	15	.63 718
9000	30	4.685 43	85	8.63 968	5.314 56	15	8.64 009
9060	31	43	85	.64 256	56	14	.64 298
9120	32	43	86	.64 543	56	14	.64 585
9180	33	43	86	.64 827	57	14	.64 870
9240	34	43	86	.65 110	57	13	.65 153
9300	35	4.685 43	87	8.65 391	5.314 57	13	8.65 435
9360	36	42	87	.65 670	57	12	.65 715
9420	37	42	87	.65 947	57	12	.65 993
9480	38	42	88	.66 223	58	12	.66 269
9540	39	42	88	.66 497	58	11	.66 543
9600	40	4.685 42	89	8.66 769	5.314 58	11	8.66 816
9660	41	41	89	.67 039	58	10	.67 087
9720	42	41	89	.67 308	58	10	.67 356
9780	43	41	90	.67 575	59	10	.67 624
9840	44	41	90	.67 840	59	09	.67 890
9900	45	4.685 41	91	8.68 104	5.314 59	09	8.68 154
9960	46	40	91	.68 366	59	08	.68 417
10020	47	40	91	.68 627	59	08	.68 678
10080	48	40	92	.68 886	60	08	.68 938
10140	49	40	92	.69 144	60	07	.69 196
10200	50	4.685 40	93	8.69 400	5.314 60	07	8.69 453
10260	51	39	93	.69 654	60	06	.69 708
10320	52	39	93	.69 907	60	06	.69 961
10380	53	39	94	.70 159	61	06	.70 214
10440	54	39	94	.70 409	61	05	.70 464
10500	55	4.685 38	95	8.70 657	5.314 61	05	8.70 714
10560	56	38	95	.70 905	61	04	.70 962
10620	57	38	96	.71 150	61	04	.71 208
10680	58	38	96	.71 395	62	03	.71 453
10740	59	38	97	.71 638	62	03	.71 697

′	Log. Sin.	D	Log. Tan.	Com. D.	Log. Cot.	Log. Cos.	
0	−∞		−∞		+∞	0.00 000	60
1	6.46 372	30103	6.46 372	30103	3.53 627	0.00 000	59
2	6.76 475	17609	6.76 475	17609	3.23 524	0.00 000	58
3	6.94 084	12494	6.94 084	12494	3.05 915	0.00 000	57
4	7.06 578	9691	7.06 578	9691	2.93 421	0.00 000	56
5	7.16 269	7918	7.16 269	7918	2.83 730	0.00 000	55
6	7.24 187	6695	7.24 188	6694	2.75 812	0.00 000	54
7	7.30 882	5799	7.30 882	5799	2.69 117	0.00 000	53
8	7.36 681	5115	7.36 681	5115	2.63 318	0.00 000	52
9	7.41 797	4575	7.41 797	4575	2.58 203	0.00 000	51
10	7.46 372	4139	7.46 372	4139	2.53 627	0.00 000	50
11	7.50 512	3778	7.50 512	3779	2.49 488	0.00 000	49
12	7.54 290	3476	7.54 291	3476	2.45 709	9.99 999	48
13	7.57 767	3218	7.57 767	3218	2.42 233	9.99 999	47
14	7.60 985	2996	7.60 985	2996	2.39 014	9.99 999	46
15	7.63 981	2803	7.63 982	2803	2.36 018	9.99 999	45
16	7.66 784	2633	7.66 785	2633	2.33 215	9.99 999	44
17	7.69 417	2482	7.69 418	2482	2.30 582	9.99 999	43
18	7.71 899	2348	7.71 900	2348	2.28 099	9.99 999	42
19	7.74 248	2227	7.74 248	2227	2.25 751	9.99 999	41
20	7.76 475	2119	7.76 476	2119	2.23 524	9.99 999	40
21	7.78 594	2020	7.78 595	2020	2.21 405	9.99 999	39
22	7.80 614	1930	7.80 615	1930	2.19 384	9.99 999	38
23	7.82 545	1848	7.82 546	1848	2.17 454	9.99 999	37
24	7.84 393	1772	7.84 394	1773	2.15 605	9.99 999	36
25	7.86 166	1703	7.86 167	1703	2.13 832	9.99 999	35
26	7.87 869	1639	7.87 871	1639	2.12 129	9.99 999	34
27	7.89 508	1579	7.89 510	1579	2.10 490	9.99 998	33
28	7.91 088	1524	7.91 089	1524	2.08 910	9.99 998	32
29	7.92 612	1472	7.92 613	1472	2.07 386	9.99 998	31
30	7.94 084	1424	7.94 086	1424	2.05 914	9.99 998	30
31	7.95 508	1379	7.95 510	1379	2.04 490	9.99 998	29
32	7.96 887	1336	7.96 889	1336	2.03 111	9.99 998	28
33	7.98 223	1296	7.98 225	1296	2.01 774	9.99 998	27
34	7.99 520	1258	7.99 522	1259	2.00 478	9.99 998	26
35	8.00 778	1223	8.00 781	1223	1.99 219	9.99 997	25
36	8.02 002	1190	8.02 004	1190	1.97 995	9.99 997	24
37	8.03 192	1158	8.03 194	1158	1.96 805	9.99 997	23
38	8.04 350	1128	8.04 352	1128	1.95 647	9.99 997	22
39	8.05 478	1099	8.05 481	1099	1.94 519	9.99 997	21
40	8.06 577	1072	8.06 580	1072	1.93 419	9.99 997	20
41	8.07 650	1046	8.07 653	1046	1.92 347	9.99 997	19
42	8.08 696	1022	8.08 699	1022	1.91 300	9.99 997	18
43	8.09 718	998	8.09 721	999	1.90 278	9.99 996	17
44	8.10 716	976	8.10 720	976	1.89 279	9.99 996	16
45	8.11 692	954	8.11 696	954	1.88 303	9.99 996	15
46	8.12 647	934	8.12 651	934	1.87 349	9.99 996	14
47	8.13 581	914	8.13 585	914	1.86 415	9.99 996	13
48	8.14 495	895	8.14 499	895	1.85 500	9.99 996	12
49	8.15 390	877	8.15 395	877	1.84 605	9.99 995	11
50	8.16 268	860	8.16 272	860	1.83 727	9.99 995	10
51	8.17 128	843	8.17 133	843	1.82 867	9.99 995	9
52	8.17 971	827	8.17 976	827	1.82 023	9.99 995	8
53	8.18 798	811	8.18 803	812	1.81 196	9.99 995	7
54	8.19 610	797	8.19 615	797	1.80 384	9.99 994	6
55	8.20 407	782	8.20 412	783	1.79 587	9.99 994	5
56	8.21 189	768	8.21 195	768	1.78 804	9.99 994	4
57	8.21 958	755	8.21 964	755	1.78 036	9.99 994	3
58	8.22 713	742	8.22 719	742	1.77 280	9.99 994	2
59	8.23 455	730	8.23 462	730	1.76 538	9.99 993	1
60	8.24 185		8.24 192		1.75 808	9.99 993	0
	Log. Cos.	D	Log. Cot.	Com. D.	Log. Tan.	Log. Sin.	′

′	Log. Sin.	D	Log. Tan.	Com. D.	Log. Cot.	Log. Cos.	
0	8.24 185	718	8.24 192	718	1.75 808	9.99 993	60
1	8.24 903	706	8.24 910	706	1.75 090	9.99 993	59
2	8.25 609	694	8.25 616	695	1.74 383	9.99 993	58
3	8.26 304	684	8.26 311	684	1.73 688	9.99 992	57
4	8.26 988	673	8.26 995	673	1.73 004	9.99 992	56
5	8.27 661	663	8.27 669	663	1.72 331	9.99 992	55
6	8.28 324	653	8.28 332	653	1.71 667	9.99 992	54
7	8.28 977	643	8.28 985	643	1.71 014	9.99 992	53
8	8.29 620	634	8.29 629	634	1.70 371	9.99 991	52
9	8.30 254	625	8.30 263	625	1.69 736	9.99 991	51
10	8.30 879	616	8.30 888	616	1.69 111	9.99 991	50
11	8.31 495	607	8.31 504	607	1.68 495	9.99 990	49
12	8.32 102	599	8.32 112	599	1.67 888	9.99 990	48
13	8.32 701	591	8.32 711	591	1.67 288	9.99 990	47
14	8.33 292	583	8.33 302	583	1.66 697	9.99 990	46
15	8.33 875	575	8.33 885	575	1.66 114	9.99 989	45
16	8.34 450	567	8.34 461	568	1.65 539	9.99 989	44
17	8.35 018	560	8.35 029	560	1.64 971	9.99 989	43
18	8.35 578	553	8.35 589	553	1.64 410	9.99 989	42
19	8.36 131	546	8.36 143	546	1.63 857	9.99 988	41
20	8.36 677	539	8.36 689	539	1.63 310	9.99 988	40
21	8.37 217	533	8.37 229	533	1.62 771	9.99 988	39
22	8.37 750	526	8.37 762	527	1.62 238	9.99 987	38
23	8.38 276	520	8.38 289	520	1.61 711	9.99 987	37
24	8.38 796	514	8.38 809	514	1.61 191	9.99 987	36
25	8.39 310	508	8.39 323	508	1.60 676	9.99 986	35
26	8.39 818	502	8.39 831	502	1.60 168	9.99 986	34
27	8.40 320	496	8.40 334	496	1.59 666	9.99 986	33
28	8.40 816	491	8.40 830	491	1.59 169	9.99 986	32
29	8.41 307	485	8.41 321	485	1.58 678	9.99 985	31
30	8.41 792	479	8.41 807	480	1.58 193	9.99 985	30
31	8.42 271	474	8.42 287	475	1.57 713	9.99 985	29
32	8.42 746	469	8.42 762	469	1.57 238	9.99 984	28
33	8.43 215	464	8.43 231	464	1.56 768	9.99 984	27
34	8.43 680	459	8.43 696	460	1.56 304	9.99 984	26
35	8.44 139	454	8.44 156	455	1.55 844	9.99 983	25
36	8.44 594	450	8.44 611	450	1.55 389	9.99 983	24
37	8.45 044	445	8.45 061	445	1.54 938	9.99 982	23
38	8.45 489	440	8.45 507	441	1.54 493	9.99 982	22
39	8.45 930	436	8.45 948	437	1.54 052	9.99 982	21
40	8.46 366	432	8.46 385	432	1.53 615	9.99 981	20
41	8.46 798	428	8.46 817	428	1.53 183	9.99 981	19
42	8.47 226	423	8.47 245	424	1.52 754	9.99 981	18
43	8.47 650	419	8.47 669	419	1.52 330	9.99 980	17
44	8.48 069	415	8.48 089	416	1.51 911	9.99 980	16
45	8.48 485	411	8.48 505	412	1.51 495	9.99 979	15
46	8.48 896	407	8.48 917	408	1.51 083	9.99 979	14
47	8.49 304	404	8.49 325	404	1.50 675	9.99 979	13
48	8.49 708	400	8.49 729	400	1.50 270	9.99 978	12
49	8.50 108	396	8.50 130	396	1.49 870	9.99 978	11
50	8.50 504	393	8.50 526	393	1.49 473	9.99 978	10
51	8.50 897	389	8.50 920	390	1.49 080	9.99 977	9
52	8.51 286	386	8.51 310	386	1.48 690	9.99 977	8
53	8.51 672	382	8.51 696	383	1.48 304	9.99 976	7
54	8.52 055	379	8.52 079	379	1.47 921	9.99 976	6
55	8.52 434	375	8.52 458	376	1.47 541	9.99 975	5
56	8.52 810	373	8.52 835	373	1.47 165	9.99 975	4
57	8.53 183	369	8.53 208	370	1.46 792	9.99 975	3
58	8.53 552	366	8.53 578	366	1.46 422	9.99 974	2
59	8.53 918	363	8.53 944	364	1.46 055	9.99 974	1
60	8.54 282		8.54 308		1.45 691	9.99 973	0
	Log. Cos.	D	Log. Cot.	Com. D.	Log. Tan.	Log. Sin.	′

′	Log. Sin.	D	Log. Tan.	Com. D.	Log. Cot.	Log. Cos.	
0	8.54 282	360	8.54 308	360	1.45 691	9.99 973	60
1	8.54 642	357	8.54 669	358	1.45 331	9.99 973	59
2	8.54 999	354	8.55 027	354	1.44 973	9.99 972	58
3	8.55 354	351	8.55 381	352	1.44 618	9.99 972	57
4	8.55 705	348	8.55 733	349	1.44 266	9.99 971	56
5	8.56 054	346	8.56 083	346	1.43 917	9.99 971	55
6	8.56 400	343	8.56 429	343	1.43 571	9.99 971	54
7	8.56 743	340	8.56 772	341	1.43 227	9.99 970	53
8	8.57 083	338	8.57 113	338	1.42 886	9.99 970	52
9	8.57 421	335	8.57 452	335	1.42 548	9.99 969	51
10	8.57 756	332	8.57 787	333	1.42 212	9.99 969	50
11	8.58 039	330	8.58 121	330	1.41 879	9.99 968	49
12	8.58 419	327	8.58 451	328	1.41 548	9.99 968	48
13	8.58 747	325	8.58 779	325	1.41 220	9.99 967	47
14	8.59 072	323	8.59 105	323	1.40 895	9.99 967	46
15	8.59 395	320	8.59 428	320	1.40 571	9.99 966	45
16	8.59 715	318	8.59 749	318	1.40 251	9.99 966	44
17	8.60 033	316	8.60 067	316	1.39 932	9.99 965	43
18	8.60 349	313	8.60 384	314	1.39 616	9.99 965	42
19	8.60 662	311	8.60 698	311	1.39 302	9.99 964	41
20	8.60 973	309	8.61 009	309	1.38 990	9.99 964	40
21	8.61 282	306	8.61 319	307	1.38 681	9.99 963	39
22	8.61 589	304	8.61 626	305	1.38 374	9.99 963	38
23	8.61 893	302	8.61 931	303	1.38 068	9.99 962	37
24	8.62 196	300	8.62 234	300	1.37 765	9.99 962	36
25	8.62 496	298	8.62 535	299	1.37 465	9.99 961	35
26	8.62 795	296	8.62 834	297	1.37 166	9.99 961	34
27	8.63 091	294	8.63 131	294	1.36 869	9.99 960	33
28	8.63 385	292	8.63 425	293	1.36 574	9.99 959	32
29	8.63 677	290	8.63 718	291	1.36 281	9.99 959	31
30	8.63 968	288	8.64 009	288	1.35 990	9.99 958	30
31	8.64 256	286	8.64 298	287	1.35 702	9.99 958	29
32	8.64 543	284	8.64 585	285	1.35 414	9.99 957	28
33	8.64 827	282	8.64 870	283	1.35 129	9.99 957	27
34	8.65 110	281	8.65 153	281	1.34 846	9.99 956	26
35	8.65 391	279	8.65 435	280	1.34 565	9.99 956	25
36	8.65 670	277	8.65 715	278	1.34 285	9.99 955	24
37	8.65 947	275	8.65 993	276	1.34 007	9.99 954	23
38	8.66 223	274	8.66 269	274	1.33 731	9.99 954	22
39	8.66 497	272	8.66 543	272	1.33 456	9.99 953	21
40	8.66 769	270	8.66 816	271	1.33 184	9.99 953	20
41	8.67 039	268	8.67 087	269	1.32 913	9.99 952	19
42	8.67 308	267	8.67 356	267	1.32 643	9.99 952	18
43	8.67 575	265	8.67 624	266	1.32 376	9.99 951	17
44	8.67 840	264	8.67 890	264	1.32 110	9.99 950	16
45	8.68 104	262	8.68 154	262	1.31 845	9.99 950	15
46	8.68 366	260	8.68 417	261	1.31 583	9.99 949	14
47	8.68 627	259	8.68 678	259	1.31 321	9.99 948	13
48	8.68 886	257	8.68 938	258	1.31 062	9.99 948	12
49	8.69 144	256	8.69 196	256	1.30 803	9.99 947	11
50	8.69 400	254	8.69 453	255	1.30 547	9.99 947	10
51	8.69 654	253	8.69 708	253	1.30 292	9.99 946	9
52	8.69 907	251	8.69 961	252	1.30 038	9.99 945	8
53	8.70 159	250	8.70 214	250	1.29 786	9.99 945	7
54	8.70 409	248	8.70 464	249	1.29 535	9.99 944	6
55	8.70 657	247	8.70 714	248	1.29 286	9.99 943	5
56	8.70 905	245	8.70 962	246	1.29 038	9.99 943	4
57	8.71 150	244	8.71 208	245	1.28 791	9.99 942	3
58	8.71 395	243	8.71 453	243	1.28 546	9.99 942	2
59	8.71 638	241	8.71 697	242	1.28 303	9.99 941	1
60	8.71 880		8.71 939		1.28 060	9.99 940	0
	Log. Cos.	D	Log. Cot.	Com. D.	Log. Tan.	Log. Sin.	′

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	
0	8.71 880	240	8.71 939	241	1.28 060	9.99 940	60
1	8.72 120	239	8.72 180	240	1.27 819	9.99 940	59
2	8.72 359	237	8.72 420	238	1.27 579	9.99 939	58
3	8.72 597	236	8.72 659	237	1.27 341	9.99 938	57
4	8.72 833	235	8.72 896	235	1.27 104	9.99 938	56
5	8.73 069	233	8.73 131	235	1.26 868	9.99 937	55
6	8.73 302	233	8.73 366	233	1.26 633	9.99 936	54
7	8.73 535	231	8.73 599	232	1.26 400	9.99 935	53
8	8.73 766	230	8.73 831	231	1.26 168	9.99 935	52
9	8.73 997	229	8.74 062	229	1.25 937	9.99 934	51
10	8.74 226	227	8.74 292	228	1.25 708	9.99 933	50
11	8.74 453	226	8.74 520	227	1.25 479	9.99 933	49
12	8.74 680	225	8.74 748	226	1.25 252	9.99 932	48
13	8.74 905	224	8.74 974	225	1.25 026	9.99 931	47
14	8.75 129	223	8.75 199	223	1.24 801	9.99 931	46
15	8.75 353	221	8.75 422	223	1.24 577	9.99 930	45
16	8.75 574	221	8.75 645	221	1.24 354	9.99 929	44
17	8.75 795	219	8.75 867	220	1.24 133	9.99 928	43
18	8.76 015	218	8.76 087	219	1.23 913	9.99 928	42
19	8.76 233	217	8.76 306	218	1.23 693	9.99 927	41
20	8.76 451	216	8.76 524	217	1.23 475	9.99 926	40
21	8.76 667	215	8.76 741	216	1.23 258	9.99 925	39
22	8.76 883	214	8.76 958	214	1.23 042	9.99 925	38
23	8.77 097	213	8.77 172	214	1.22 827	9.99 924	37
24	8.77 310	212	8.77 386	213	1.22 613	9.99 923	36
25	8.77 522	211	8.77 599	212	1.22 400	9.99 922	35
26	8.77 733	210	8.77 811	210	1.22 188	9.99 922	34
27	8.77 943	209	8.78 022	210	1.21 978	9.99 921	33
28	8.78 152	208	8.78 232	209	1.21 768	9.99 920	32
29	8.78 360	207	8.78 441	207	1.21 559	9.99 919	31
30	8.78 567	206	8.78 648	207	1.21 351	9.99 919	30
31	8.78 773	205	8.78 855	206	1.21 144	9.99 918	29
32	8.78 978	204	8.79 061	204	1.20 938	9.99 917	28
33	8.79 183	203	8.79 266	204	1.20 734	9.99 916	27
34	8.79 386	202	8.79 470	203	1.20 530	9.99 916	26
35	8.79 588	201	8.79 673	202	1.20 327	9.99 915	25
36	8.79 789	200	8.79 875	201	1.20 125	9.99 914	24
37	8.79 989	199	8.80 076	200	1.19 923	9.99 913	23
38	8.80 189	198	8.80 276	199	1.19 723	9.99 912	22
39	8.80 387	197	8.80 476	198	1.19 524	9.99 912	21
40	8.80 585	197	8.80 674	197	1.19 326	9.99 911	20
41	8.80 782	195	8.80 871	197	1.19 128	9.99 910	19
42	8.80 977	195	8.81 068	195	1.18 931	9.99 909	18
43	8.81 172	194	8.81 264	195	1.18 736	9.99 908	17
44	8.81 366	193	8.81 459	194	1.18 541	9.99 907	16
45	8.81 560	192	8.81 653	193	1.18 347	9.99 907	15
46	8.81 752	191	8.81 846	192	1.18 154	9.99 906	14
47	8.81 943	191	8.82 038	191	1.17 961	9.99 905	13
48	8.82 134	189	8.82 230	190	1.17 770	9.99 904	12
49	8.82 324	189	8.82 420	190	1.17 579	9.99 903	11
50	8.82 513	188	8.82 610	188	1.17 389	9.99 902	10
51	8.82 701	187	8.82 799	188	1.17 201	9.99 902	9
52	8.82 888	186	8.82 987	187	1.17 012	9.99 901	8
53	8.83 075	185	8.83 175	186	1.16 825	9.99 900	7
54	8.83 260	185	8.83 361	185	1.16 638	9.99 899	6
55	8.83 445	184	8.83 547	185	1.16 453	9.99 898	5
56	8.83 629	183	8.83 732	184	1.16 268	9.99 897	4
57	8.83 813	182	8.83 916	183	1.16 083	9.99 896	3
58	8.83 995	182	8.84 100	182	1.15 900	9.99 896	2
59	8.84 177	181	8.84 282	182	1.15 717	9.99 895	1
60	8.84 358		8.84 464		1.15 535	9.99 894	0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	′

P. P.

	330	320	310	300
6	33.0	32.0	31.0	30.0
7	38.5	37.3	36.1	35.0
8	44.0	42.6	41.3	40.0
9	49.5	48.0	46.5	45.0
10	55.0	53.3	51.6	50.0
20	110.0	106.6	103.3	100.0
30	165.0	160.0	155.0	150.0
40	220.0	213.3	206.6	200.0
50	275.0	266.6	258.3	250.0

	290	280	270	260
6	29.0	28.0	27.0	26.0
7	33.8	32.6	31.5	30.3
8	38.6	37.3	36.0	34.6
9	43.5	42.0	40.5	39.0
10	48.3	46.6	45.0	43.3
20	96.6	93.3	90.0	86.6
30	145.0	140.0	135.0	130.0
40	193.3	186.6	180.0	173.3
50	241.6	233.3	225.0	216.6

	250	240	230	220
6	25.0	24.0	23.0	22.0
7	29.1	28.0	26.8	25.6
8	33.3	32.0	30.6	29.3
9	37.5	36.0	34.5	33.0
10	41.6	40.0	38.3	36.6
20	83.3	80.0	76.6	73.3
30	125.0	120.0	115.0	110.0
40	166.6	160.0	153.3	146.6
50	208.3	200.0	191.6	183.3

	210	200	190	180
6	21.0	20.0	19.0	18.0
7	24.5	23.3	22.1	21.0
8	28.0	26.6	25.3	24.0
9	31.5	30.0	28.5	27.0
10	35.0	33.3	31.6	30.0
20	70.0	66.6	63.3	60.0
30	105.0	100.0	95.0	90.0
40	140.0	133.3	126.6	120.0
50	175.0	166.6	158.3	150.0

	9	9	8	7	6	5
6	0.9	0.9	0.8	0.7	0.6	0.5
7	1.1	1.0	0.9	0.8	0.7	0.6
8	1.2	1.2	1.0	0.9	0.8	0.6
9	1.4	1.3	1.2	1.0	0.9	0.7
10	1.6	1.5	1.3	1.1	1.0	0.8
20	3.1	3.0	2.6	2.3	2.0	1.6
30	4.7	4.5	4.0	3.5	3.0	2.5
40	6.3	6.0	5.3	4.6	4.0	3.3
50	7.9	7.5	6.6	5.8	5.0	4.1

	4	4	3	2	1	0
6	0.4	0.4	0.3	0.2	0.1	0.0
7	0.5	0.4	0.3	0.2	0.1	0.0
8	0.6	0.5	0.4	0.2	0.1	0.0
9	0.7	0.6	0.4	0.3	0.1	0.1
10	0.7	0.6	0.5	0.3	0.1	0.1
20	1.5	1.3	1.0	0.6	0.3	0.1
30	2.2	2.0	1.5	1.0	0.5	0.2
40	3.0	2.6	2.0	1.3	0.6	0.3
50	3.7	3.3	2.5	1.6	0.8	0.4

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	
0	8.84 358	180	8.84 464	181	1.15 535	9.99 894	60
1	8.84 538	180	8.84 645	180	1.15 354	9.99 893	59
2	8.84 718	178	8.84 826	179	1.15 174	9.99 892	58
3	8.84 897	178	8.85 005	179	1.14 994	9.99 891	57
4	8.85 075	177	8.85 184	178	1.14 815	9.99 890	56
5	8.85 252	176	8.85 363	177	1.14 637	9.99 889	55
6	8.85 429	176	8.85 540	176	1.14 459	9.99 888	54
7	8.85 605	175	8.85 717	176	1.14 283	9.99 888	53
8	8.85 780	174	8.85 893	175	1.14 107	9.99 887	52
9	8.85 954	174	8.86 068	175	1.13 931	9.99 886	51
10	8.86 128	173	8.86 243	174	1.13 756	9.99 885	50
11	8.86 301	172	8.86 417	173	1.13 582	9.99 884	49
12	8.86 474	171	8.86 590	172	1.13 409	9.99 883	48
13	8.86 645	171	8.86 763	172	1.13 237	9.99 882	47
14	8.86 816	170	8.86 935	171	1.13 065	9.99 881	46
15	8.86 987	169	8.87 106	170	1.12 893	9.99 880	45
16	8.87 156	169	8.87 277	170	1.12 723	9.99 879	44
17	8.87 325	168	8.87 447	169	1.12 553	9.99 878	43
18	8.87 494	167	8.87 616	169	1.12 384	9.99 877	42
19	8.87 661	167	8.87 785	168	1.12 215	9.99 876	41
20	8.87 828	166	8.87 953	167	1.12 047	9.99 875	40
21	8.87 995	165	8.88 120	167	1.11 880	9.99 874	39
22	8.88 160	165	8.88 287	166	1.11 713	9.99 874	38
23	8.88 326	164	8.88 453	165	1.11 547	9.99 873	37
24	8.88 490	163	8.88 618	165	1.11 381	9.99 872	36
25	8.88 654	163	8.88 783	164	1.11 216	9.99 871	35
26	8.88 817	162	8.88 947	163	1.11 052	9.99 870	34
27	8.88 980	162	8.89 111	163	1.10 889	9.99 869	33
28	8.89 142	161	8.89 274	162	1.10 726	9.99 868	32
29	8.89 303	161	8.89 436	162	1.10 563	9.99 867	31
30	8.89 464	160	8.89 598	161	1.10 401	9.99 866	30
31	8.89 624	159	8.89 759	161	1.10 240	9.99 865	29
32	8.89 784	159	8.89 920	160	1.10 079	9.99 864	28
33	8.89 943	158	8.90 080	159	1.09 919	9.99 863	27
34	8.90 101	158	8.90 240	158	1.09 760	9.99 862	26
35	8.90 259	157	8.90 398	158	1.09 601	9.99 861	25
36	8.90 417	156	8.90 557	157	1.09 443	9.99 860	24
37	8.90 573	156	8.90 714	157	1.09 285	9.99 859	23
38	8.90 729	156	8.90 872	156	1.09 128	9.99 858	22
39	8.90 885	155	8.91 028	156	1.08 971	9.99 857	21
40	8.91 040	154	8.91 184	155	1.08 815	9.99 856	20
41	8.91 195	154	8.91 340	155	1.08 660	9.99 855	19
42	8.91 349	153	8.91 495	154	1.08 505	9.99 853	18
43	8.91 502	153	8.91 649	154	1.08 350	9.99 852	17
44	8.91 655	152	8.91 803	153	1.08 196	9.99 851	16
45	8.91 807	151	8.91 957	152	1.08 043	9.99 850	15
46	8.91 959	151	8.92 109	152	1.07 890	9.99 849	14
47	8.92 110	150	8.92 262	151	1.07 738	9.99 848	13
48	8.92 261	150	8.92 413	151	1.07 586	9.99 847	12
49	8.92 411	150	8.92 565	150	1.07 435	9.99 846	11
50	8.92 561	149	8.92 715	150	1.07 284	9.99 845	10
51	8.92 710	148	8.92 866	149	1.07 134	9.99 844	9
52	8.92 858	148	8.93 015	149	1.06 984	9.99 843	8
53	8.93 007	147	8.93 164	149	1.06 835	9.99 842	7
54	8.93 154	147	8.93 313	148	1.06 686	9.99 841	6
55	8.93 301	146	8.93 461	148	1.06 538	9.99 840	5
56	8.93 448	146	8.93 609	147	1.06 390	9.99 839	4
57	8.93 594	146	8.93 756	146	1.06 243	9.99 837	3
58	8.93 740	145	8.93 903	146	1.06 097	9.99 836	2
59	8.93 885	144	8.94 049	145	1.05 950	9.99 835	1
60	8.94 029		8.94 195		1.05 805	9.99 834	0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	′

P. P.

	181	180	178	176
6	18.1	18.0	17.8	17.6
7	21.1	21.0	20.7	20.5
8	24.1	24.0	23.7	23.4
9	27.1	27.0	26.7	26.4
10	30.1	30.0	29.6	29.3
20	60.3	60.0	59.3	58.6
30	90.5	90.0	89.0	88.0
40	120.6	120.0	118.6	117.3
50	150.8	150.0	148.3	146.6

	174	172	170	168
6	17.4	17.2	17.0	16.8
7	20.3	20.0	19.8	19.6
8	23.2	22.9	22.6	22.4
9	26.1	25.8	25.5	25.2
10	29.0	28.6	28.3	28.0
20	58.0	57.3	56.6	56.0
30	87.0	86.0	85.0	84.0
40	116.0	114.6	113.3	112.0
50	145.0	143.3	141.6	140.0

	166	164	162	160
6	16.6	16.4	16.2	16.0
7	19.3	19.1	18.9	18.6
8	22.1	21.8	21.6	21.3
9	24.9	24.6	24.3	24.0
10	27.6	27.3	27.0	26.6
20	55.3	54.6	54.0	53.3
30	83.0	82.0	81.0	80.0
40	110.6	109.3	108.0	106.6
50	138.3	136.6	135.0	133.3

	158	156	154	152
6	15.8	15.6	15.4	15.2
7	18.4	18.2	17.9	17.7
8	21.0	20.8	20.5	20.2
9	23.7	23.4	23.1	22.8
10	26.3	26.0	25.6	25.3
20	52.6	52.0	51.3	50.6
30	79.0	78.0	77.0	76.0
40	105.3	104.0	102.6	101.3
50	131.6	130.0	128.3	126.6

	150	149	148	147
6	15.0	14.9	14.8	14.7
7	17.5	17.4	17.2	17.1
8	20.0	19.8	19.7	19.6
9	22.5	22.3	22.2	22.0
10	25.0	24.8	24.6	24.5
20	50.0	49.6	49.3	49.0
30	75.0	74.5	74.0	73.5
40	100.0	99.3	98.6	98.0
50	125.0	124.1	123.3	122.5

	146	145	$\bar{1}$	1	$\bar{0}$
6	14.6	14.5	0.1	0.1	0.0
7	17.0	16.9	0.2	0.1	0.0
8	19.4	19.3	0.2	0.1	0.0
9	21.9	21.7	0.2	0.1	0.1
10	24.3	24.1	0.2	0.1	0.1
20	48.6	48.3	0.5	0.3	0.1
30	73.0	72.5	0.7	0.5	0.2
40	97.3	96.6	1.0	0.6	0.3
50	121.6	120.8	1.2	0.8	0.4

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	
0	8.94 029	144	8.94 195	145	1.05 805	9.99 834	60
1	8.94 174	143	8.94 340	144	1.05 659	9.99 833	59
2	8.94 317	143	8.94 485	144	1.05 515	9.99 832	58
3	8.94 460	143	8.94 629	144	1.05 370	9.99 831	57
4	8.94 603	142	8.94 773	143	1.05 226	9.99 830	56
5	8.94 745	142	8.94 917	142	1.05 083	9.99 829	55
6	8.94 887	141	8.95 059	142	1.04 940	9.99 827	54
7	8.95 028	141	8.95 202	142	1.04 798	9.99 826	53
8	8.95 169	140	8.95 344	141	1.04 656	9.99 825	52
9	8.95 310	140	8.95 485	141	1.04 514	9.99 824	51
10	8.95 450	139	8.95 626	141	1.04 373	9.99 823	50
11	8.95 589	139	8.95 767	140	1.04 232	9.99 822	49
12	8.95 728	138	8.95 907	140	1.04 092	9.99 821	48
13	8.95 867	138	8.96 047	139	1.03 952	9.99 819	47
14	8.96 005	138	8.96 186	139	1.03 813	9.99 818	46
15	8.96 143	137	8.96 325	138	1.03 674	9.99 817	45
16	8.96 280	137	8.96 464	138	1.03 536	9.99 816	44
17	8.96 417	136	8.96 602	137	1.03 398	9.99 815	43
18	8.96 553	136	8.96 739	137	1.03 260	9.99 814	42
19	8.96 689	135	8.96 876	137	1.03 123	9.99 813	41
20	8.96 825	135	8.97 013	136	1.02 986	9.99 811	40
21	8.96 960	134	8.97 149	136	1.02 850	9.99 810	39
22	8.97 094	134	8.97 285	135	1.02 714	9.99 809	38
23	8.97 229	134	8.97 421	135	1.02 579	9.99 808	37
24	8.97 363	133	8.97 556	134	1.02 444	9.99 807	36
25	8.97 496	133	8.97 690	134	1.02 309	9.99 805	35
26	8.97 629	132	8.97 825	133	1.02 175	9.99 804	34
27	8.97 762	132	8.97 958	133	1.02 041	9.99 803	33
28	8.97 894	132	8.98 092	133	1.01 908	9.99 802	32
29	8.98 026	131	8.98 225	132	1.01 775	9.99 801	31
30	8.98 157	131	8.98 357	132	1.01 642	9.99 799	30
31	8.98 288	130	8.98 490	131	1.01 510	9.99 798	29
32	8.98 419	130	8.98 621	131	1.01 378	9.99 797	28
33	8.98 549	130	8.98 753	131	1.01 247	9.99 796	27
34	8.98 679	129	8.98 884	131	1.01 116	9.99 794	26
35	8.98 808	129	8.99 015	130	1.00 985	9.99 793	25
36	8.98 937	128	8.99 145	130	1.00 855	9.99 792	24
37	8.99 066	128	8.99 275	129	1.00 725	9.99 791	23
38	8.99 194	127	8.99 404	129	1.00 595	9.99 789	22
39	8.99 322	127	8.99 533	129	1.00 466	9.99 788	21
40	8.99 449	127	8.99 662	128	1.00 337	9.99 787	20
41	8.99 577	126	8.99 791	128	1.00 209	9.99 786	19
42	8.99 703	126	8.99 919	127	1.00 081	9.99 784	18
43	8.99 830	126	9.00 046	127	0.99 953	9.99 783	17
44	8.99 956	125	9.00 174	126	0.99 826	9.99 782	16
45	9.00 081	125	9.00 300	126	0.99 699	9.99 781	15
46	9.00 207	125	9.00 427	126	0.99 573	9.99 779	14
47	9.00 332	124	9.00 553	125	0.99 446	9.99 778	13
48	9.00 456	124	9.00 679	125	0.99 321	9.99 777	12
49	9.00 580	124	9.00 804	125	0.99 195	9.99 776	11
50	9.00 704	123	9.00 930	124	0.99 070	9.99 774	10
51	9.00 828	123	9.01 054	124	0.98 945	9.99 773	9
52	9.00 951	122	9.01 179	124	0.98 821	9.99 772	8
53	9.01 073	122	9.01 303	124	0.98 697	9.99 770	7
54	9.01 196	122	9.01 427	123	0.98 573	9.99 769	6
55	9.01 318	122	9.01 550	123	0.98 450	9.99 768	5
56	9.01 440	121	9.01 673	123	0.98 327	9.99 766	4
57	9.01 561	121	9.01 796	122	0.98 204	9.99 765	3
58	9.01 682	120	9.01 918	122	0.98 081	9.99 764	2
59	9.01 803	120	9.02 040	121	0.97 959	9.99 763	1
60	9.01 923		9.02 162		0.97 838	9.99 761	0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	′

P. P.

	145	144	143	142	141
6	14.5	14.4	14.3	14.2	14.1
7	16.9	16.8	16.7	16.5	16.4
8	19.3	19.2	19.0	18.9	18.8
9	21.7	21.6	21.4	21.3	21.1
10	24.1	24.0	23.8	23.6	23.5
20	48.3	48.0	47.6	47.3	47.0
30	72.5	72.0	71.5	71.0	70.5
40	96.6	96.0	95.3	94.6	94.0
50	120.8	120.0	119.1	118.3	117.5

	140	139	138	137	136
6	14.0	13.9	13.8	13.7	13.6
7	16.3	16.2	16.1	16.0	15.8
8	18.6	18.5	18.4	18.2	18.1
9	21.0	20.8	20.7	20.5	20.4
10	23.3	23.1	23.0	22.8	22.6
20	46.6	46.3	46.0	45.6	45.3
30	70.0	69.5	69.0	68.5	68.0
40	93.3	92.6	92.0	91.3	90.6
50	116.6	115.8	115.0	114.1	113.3

	135	134	133	132
6	13.5	13.4	13.3	13.2
7	15.7	15.6	15.5	15.4
8	18.0	17.8	17.7	17.6
9	20.2	20.1	19.9	19.8
10	22.5	22.3	22.1	22.0
20	45.0	44.6	44.3	44.0
30	67.5	67.0	66.5	66.0
40	90.0	89.3	88.6	88.0
50	112.5	111.6	110.8	110.0

	131	130	129	128
6	13.1	13.0	12.9	12.8
7	15.3	15.1	15.0	14.9
8	17.4	17.3	17.2	17.0
9	19.6	19.5	19.3	19.2
10	21.8	21.6	21.5	21.3
20	43.6	43.3	43.0	42.6
30	65.5	65.0	64.5	64.0
40	87.3	86.6	86.0	85.3
50	109.1	108.3	107.5	106.6

	127	126	125	124	123
6	12.7	12.6	12.5	12.4	12.3
7	14.8	14.7	14.6	14.4	14.3
8	16.9	16.8	16.6	16.5	16.4
9	19.0	18.9	18.7	18.6	18.4
10	21.1	21.0	20.8	20.6	20.5
20	42.3	42.0	41.6	41.3	41.0
30	63.5	63.0	62.5	62.0	61.5
40	84.6	84.0	83.3	82.6	82.0
50	105.8	105.0	104.1	103.3	102.5

	122	121	120	$\bar{1}$	1	$\bar{0}$
6	12.2	12.1	12.0	0.1	0.1	0.0
7	14.2	14.1	14.0	0.2	0.1	0.0
8	16.2	16.1	16.0	0.2	0.1	0.0
9	18.3	18.1	18.0	0.2	0.1	0.1
10	20.3	20.1	20.0	0.2	0.1	0.1
20	40.6	40.3	40.0	0.5	0.3	0.1
30	61.0	60.5	60.0	0.7	0.5	0.2
40	81.3	80.6	80.0	1.0	0.6	0.3
50	101.6	100.8	100.0	1.2	0.8	0.4

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	
0	9.01 923	120	9.02 162	121	0.97 838	9.99 761	60
1	9.02 043	119	9.02 283	121	0.97 716	9.99 760	59
2	9.02 163	119	9.02 404	120	0.97 595	9.99 759	58
3	9.02 282	119	9.02 525	120	0.97 475	9.99 757	57
4	9.02 401	119	9.02 645	120	0.97 354	9.99 756	56
5	9.02 520	118	9.02 765	119	0.97 234	9.99 754	55
6	9.02 638	118	9.02 885	119	0.97 115	9.99 753	54
7	9.02 756	118	9.03 004	119	0.96 995	9.99 752	53
8	9.02 874	117	9.03 123	119	0.96 876	9.99 750	52
9	9.02 992	117	9.03 242	118	0.96 757	9.99 749	51
10	9.03 109	116	9.03 361	118	0.96 639	9.99 748	50
11	9.03 225	116	9.03 479	118	0.96 521	9.99 746	49
12	9.03 342	116	9.03 597	117	0.96 403	9.99 745	48
13	9.03 458	116	9.03 714	117	0.96 285	9.99 744	47
14	9.03 574	115	9.03 831	117	0.96 168	9.99 742	46
15	9.03 689	115	9.03 948	116	0.96 051	9.99 741	45
16	9.03 805	114	9.04 065	116	0.95 935	9.99 739	44
17	9.03 919	114	9.04 181	116	0.95 818	9.99 738	43
18	9.04 034	114	9.04 297	115	0.95 702	9.99 737	42
19	9.04 148	114	9.04 413	115	0.95 587	9.99 735	41
20	9.04 262	113	9.04 528	115	0.95 471	9.99 734	40
21	9.04 376	113	9.04 643	114	0.95 356	9.99 732	39
22	9.04 489	113	9.04 758	114	0.95 242	9.99 731	38
23	9.04 602	113	9.04 872	114	0.95 127	9.99 730	37
24	9.04 715	112	9.04 987	114	0.95 013	9.99 728	36
25	9.04 828	112	9.05 101	113	0.94 899	9.99 727	35
26	9.04 940	112	9.05 214	113	0.94 785	9.99 725	34
27	9.05 052	111	9.05 327	113	0.94 672	9.99 724	33
28	9.05 163	111	9.05 440	113	0.94 559	9.99 723	32
29	9.05 275	111	9.05 553	112	0.94 446	9.99 721	31
30	9.05 386	110	9.05 666	112	0.94 334	9.99 720	30
31	9.05 496	110	9.05 778	112	0.94 222	9.99 718	29
32	9.05 607	110	9.05 890	111	0.94 110	9.99 717	28
33	9.05 717	110	9.06 001	111	0.93 998	9.99 715	27
34	9.05 827	109	9.06 113	111	0.93 887	9.99 714	26
35	9.05 936	109	9.06 224	111	0.93 776	9.99 712	25
36	9.06 046	109	9.06 335	110	0.93 665	9.99 711	24
37	9.06 155	109	9.06 445	110	0.93 554	9.99 710	23
38	9.06 264	108	9.06 555	110	0.93 444	9.99 708	22
39	9.06 372	108	9.06 665	109	0.93 334	9.99 707	21
40	9.06 480	108	9.06 775	109	0.93 225	9.99 705	20
41	9.06 588	107	9.06 884	109	0.93 115	9.99 704	19
42	9.06 696	107	9.06 994	108	0.93 006	9.99 702	18
43	9.06 803	107	9.07 102	109	0.92 897	9.99 701	17
44	9.06 910	107	9.07 211	108	0.92 788	9.99 699	16
45	9.07 017	106	9.07 319	108	0.92 680	9.99 698	15
46	9.07 124	106	9.07 428	107	0.92 572	9.99 696	14
47	9.07 230	106	9.07 535	107	0.92 464	9.99 695	13
48	9.07 336	106	9.07 643	107	0.92 357	9.99 693	12
49	9.07 442	105	9.07 750	107	0.92 249	9.99 692	11
50	9.07 548	105	9.07 857	107	0.92 142	9.99 690	10
51	9.07 653	105	9.07 964	106	0.92 035	9.99 689	9
52	9.07 758	104	9.08 071	106	0.91 929	9.99 687	8
53	9.07 863	104	9.08 177	106	0.91 822	9.99 686	7
54	9.07 967	104	9.08 283	105	0.91 716	9.99 684	6
55	9.08 072	104	9.08 389	105	0.91 611	9.99 683	5
56	9.08 176	103	9.08 494	105	0.91 505	9.99 681	4
57	9.08 279	103	9.08 600	105	0.91 400	9.99 679	3
58	9.08 383	103	9.08 705	105	0.91 295	9.99 678	2
59	9.08 486	103	9.08 810	104	0.91 190	9.99 676	1
60	9.08 589		9.08 914		0.91 085	9.99 675	0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	′

P. P.

	121	121	120	119	118
6	12.1	12.1	12.0	11.9	11.8
7	14.2	14.1	14.0	13.9	13.7
8	16.2	16.1	16.0	15.8	15.7
9	18.2	18.1	18.0	17.8	17.7
10	20.2	20.1	20.0	19.8	19.6
20	40.5	40.3	40.0	39.6	39.3
30	60.7	60.5	60.0	59.5	59.0
40	81.0	80.6	80.0	79.3	78.6
50	101.2	100.8	100.0	99.1	98.3

	117	117	116	115
6	11.7	11.7	11.6	11.5
7	13.7	13.6	13.5	13.4
8	15.6	15.6	15.4	15.3
9	17.6	17.5	17.4	17.2
10	19.6	19.5	19.3	19.1
20	39.1	39.0	38.6	38.3
30	58.7	58.5	58.0	57.5
40	78.3	78.0	77.3	76.6
50	97.9	97.5	96.6	95.8

	114	114	113	112	111
6	11.4	11.4	11.3	11.2	11.1
7	13.3	13.3	13.2	13.0	12.9
8	15.2	15.2	15.0	14.9	14.8
9	17.2	17.1	16.9	16.8	16.6
10	19.1	19.0	18.8	18.6	18.5
20	38.1	38.0	37.6	37.3	37.0
30	57.2	57.0	56.5	56.0	55.5
40	76.3	76.0	75.3	74.6	74.0
50	95.4	95.0	94.1	93.3	92.5

	110	110	109	108
6	11.0	11.0	10.9	10.8
7	12.9	12.8	12.7	12.6
8	14.7	14.6	14.5	14.4
9	16.6	16.5	16.3	16.2
10	18.4	18.3	18.1	18.0
20	36.8	36.6	36.3	36.0
30	55.2	55.0	54.5	54.0
40	73.6	73.3	72.6	72.0
50	92.1	91.6	90.8	90.0

	107	107	106	105	104
6	10.7	10.7	10.6	10.5	10.4
7	12.5	12.5	12.3	12.2	12.1
8	14.3	14.2	14.1	14.0	13.8
9	16.1	16.0	15.9	15.7	15.6
10	17.9	17.8	17.6	17.5	17.3
20	35.8	35.6	35.3	35.0	34.6
30	53.7	53.5	53.0	52.5	52.0
40	71.6	71.3	70.6	70.0	69.3
50	89.6	89.1	88.3	87.5	86.6

	103	103	2	1	1
6	10.3	10.3	0.2	0.1	0.1
7	12.1	12.0	0.2	0.2	0.1
8	13.8	13.7	0.2	0.2	0.1
9	15.5	15.4	0.3	0.2	0.1
10	17.2	17.1	0.3	0.2	0.1
20	34.5	34.3	0.6	0.5	0.3
30	51.7	51.5	1.0	0.7	0.5
40	69.0	68.6	1.3	1.0	0.6
50	86.2	85.8	1.6	1.2	0.8

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	′
0	9.08 589	102	9.08 914	104	0.91 085	9.99 675	60
1	9.08 692	102	9.09 018	104	0.90 981	9.99 673	59
2	9.08 794	102	9.09 123	103	0.90 877	9.99 672	58
3	9.08 897	102	9.09 226	103	0.90 773	9.99 670	57
4	9.08 999	102	9.09 330	103	0.90 670	9.99 669	56
5	9.09 101	101	9.09 433	103	0.90 566	9.99 667	55
6	9.09 202	101	9.09 536	103	0.90 463	9.99 665	54
7	9.09 303	101	9.09 639	102	0.90 360	9.99 664	53
8	9.09 404	101	9.09 742	102	0.90 258	9.99 662	52
9	9.09 505	100	9.09 844	102	0.90 155	9.99 661	51
10	9.09 603	100	9.09 947	101	0.90 053	9.99 659	50
11	9.09 706	100	9.10 048	102	0.89 951	9.99 658	49
12	9.09 806	100	9.10 150	101	0.89 849	9.99 656	48
13	9.09 906	99	9.10 252	101	0.89 748	9.99 654	47
14	9.10 006	99	9.10 353	101	0.89 647	9.99 653	46
15	9.10 105	99	9.10 454	101	0.89 546	9.99 651	45
16	9.10 205	98	9.10 555	100	0.89 445	9.99 650	44
17	9.10 303	99	9.10 655	100	0.89 344	9.99 648	43
18	9.10 402	98	9.10 756	100	0.89 244	9.99 646	42
19	9.10 501	98	9.10 856	100	0.89 144	9.99 645	41
20	9.10 599	98	9.10 956	99	0.89 044	9.99 643	40
21	9.10 697	97	9.11 055	99	0.88 944	9.99 641	39
22	9.10 795	97	9.11 155	99	0.88 845	9.99 640	38
23	9.10 892	97	9.11 254	99	0.88 745	9.99 638	37
24	9.10 990	97	9.11 353	98	0.88 64	9.99 637	36
25	9.11 087	96	9.11 452	98	0.88 548	9.99 635	35
26	9.11 184	97	9.11 550	98	0.88 449	9.99 63	34
27	9.11 281	96	9.11 649	98	0.88 351	9.99 632	33
28	9.11 377	96	9.11 747	98	0.88 253	9.99 630	32
29	9.11 473	96	9.11 845	98	0.88 155	9.99 628	31
30	9.11 570	95	9.11 943	97	0.88 057	9.99 627	30
31	9.11 665	96	9.12 040	97	0.87 959	9.99 625	29
32	9.11 761	95	9.12 137	97	0.87 862	9.99 623	28
33	9.11 856	95	9.12 235	96	0.87 765	9.99 622	27
34	9.11 952	95	9.12 331	97	0.87 668	9.99 620	26
35	9.12 047	94	9.12 428	96	0.87 571	9.99 618	25
36	9.12 141	94	9.12 525	96	0.87 475	9.99 617	24
37	9.12 236	94	9.12 621	96	0.87 379	9.99 615	23
38	9.12 330	94	9.12 717	96	0.87 283	9.99 613	22
39	9.12 425	93	9.12 813	95	0.87 187	9.99 611	21
40	9.12 518	94	9.12 908	95	0.87 091	9.99 610	20
41	9.12 612	93	9.13 004	95	0.86 996	9.99 608	19
42	9.12 706	93	9.13 099	95	0.86 900	9.99 606	18
43	9.12 799	93	9.13 194	95	0.86 805	9.99 605	17
44	9.12 892	93	9.13 289	94	0.86 710	9.99 603	16
45	9.12 985	92	9.13 384	94	0.86 616	9.99 601	15
46	9.13 078	92	9.13 478	94	0.86 521	9.99 600	14
47	9.13 170	92	9.13 572	94	0.86 427	9.99 598	13
48	9.13 263	92	9.13 666	94	0.86 333	9.99 596	12
49	9.13 355	92	9.13 760	93	0.86 239	9.99 594	11
50	9.13 447	91	9.13 854	93	0.86 146	9.99 593	10
51	9.13 538	92	9.13 947	93	0.86 052	9.99 591	9
52	9.13 630	91	9.14 041	93	0.85 959	9.99 589	8
53	9.13 721	91	9.14 134	93	0.85 866	9.99 587	7
54	9.13 813	90	9.14 227	92	0.85 773	9.99 586	6
55	9.13 903	91	9.14 319	92	0.85 680	9.99 584	5
56	9.13 994	90	9.14 412	92	0.85 588	9.99 582	4
57	9.14 085	90	9.14 504	92	0.85 495	9.99 580	3
58	9.14 175	90	9.14 596	92	0.85 403	9.99 579	2
59	9.14 265	90	9.14 688	92	0.85 311	9.99 577	1
60	9.14 355		9.14 780		0.85 219	9.99 575	0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	′

P. P.

	104	103	102	101
6	10.4	10.3	10.2	10.1
7	12.1	12.0	11.9	11.8
8	13.8	13.7	13.6	13.4
9	15.6	15.4	15.3	15.1
10	17.3	17.1	17.0	16.8
20	34.6	34.3	34.0	33.6
30	52.0	51.5	51.0	50.5
40	69.3	68.6	68.0	67.3
50	86.6	85.8	85.0	84.1

	100	100	99	98
6	10.0	10.0	9.9	9.8
7	11.7	11.6	11.5	11.4
8	13.4	13.3	13.2	13.0
9	15.1	15.0	14.8	14.7
10	16.7	16.6	16.5	16.3
20	33.5	33.3	33.0	32.6
30	50.2	50.0	49.5	49.0
40	67.0	66.6	66.0	65.3
50	83.7	83.3	82.5	81.6

	97	97	96	95
6	9.7	9.7	9.6	9.5
7	11.4	11.3	11.2	11.1
8	13.0	12.9	12.8	12.6
9	14.6	14.5	14.4	14.2
10	16.2	16.1	16.0	15.8
20	32.5	32.3	32.0	31.6
30	48.7	48.5	48.0	47.5
40	65.0	64.6	64.0	63.3
50	81.2	80.8	80.0	79.1

	94	94	93	92
6	9.4	9.4	9.3	9.2
7	11.0	10.9	10.8	10.7
8	12.6	12.5	12.4	12.2
9	14.2	14.1	13.9	13.8
10	15.7	15.6	15.5	15.3
20	31.5	31.3	31.0	30.6
30	47.2	47.0	46.5	46.0
40	63.0	62.6	62.0	61.3
50	78.7	78.3	77.5	76.6

	91	91	90	2	1
6	9.1	9.1	9.0	0.2	0.1
7	10.7	10.6	10.5	0.2	0.2
8	12.2	12.1	12.0	0.2	0.2
9	13.7	13.6	13.5	0.3	0.2
10	15.2	15.1	15.0	0.3	0.2
20	30.5	30.3	30.0	0.6	0.5
30	45.7	45.5	45.0	1.0	0.7
40	81.0	60.6	60.0	1.3	1.0
50	76.2	75.8	75.0	1.6	1.2

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	
0	9.14 355	90	9.14 780	91	0.85 219	9.99 575	60
1	9.14 445	89	9.14 872	91	0.85 128	9.99 573	59
2	9.14 535	89	9.14 963	91	0.85 037	9.99 571	58
3	9.14 624	89	9.15 054	91	0.84 945	9.99 570	57
4	9.14 713	89	9.15 145	91	0.84 854	9.99 568	56
5	9.14 802	89	9.15 236	90	0.84 763	9.99 566	55
6	9.14 891	88	9.15 327	90	0.84 673	9.99 564	54
7	9.14 980	88	9.15 417	90	0.84 582	9.99 563	53
8	9.15 068	88	9.15 507	90	0.84 492	9.99 561	52
9	9.15 157	88	9.15 598	89	0.84 402	9.99 559	51
10	9.15 245	88	9.15 687	90	0.84 312	9.99 557	50
11	9.15 333	88	9.15 777	89	0.84 222	9.99 555	49
12	9.15 421	87	9.15 867	89	0.84 133	9.99 553	48
13	9.15 508	87	9.15 956	89	0.84 043	9.99 552	47
14	9.15 595	87	9.16 045	89	0.83 954	9.99 550	46
15	9.15 683	87	9.16 134	89	0.83 865	9.99 548	45
16	9.15 770	87	9.16 223	89	0.83 776	9.99 546	44
17	9.15 857	86	9.16 312	88	0.83 687	9.99 544	43
18	9.15 943	86	9.16 401	88	0.83 599	9.99 542	42
19	9.16 030	86	9.16 489	88	0.83 511	9.99 541	41
20	9.16 116	86	9.16 577	88	0.83 422	9.99 539	40
21	9.16 202	86	9.16 665	87	0.83 334	9.99 537	39
22	9.16 288	86	9.16 753	88	0.83 247	9.99 535	38
23	9.16 374	85	9.16 841	87	0.83 159	9.99 533	37
24	9.16 460	85	9.16 928	87	0.83 071	9.99 531	36
25	9.16 545	85	9.17 015	87	0.82 984	9.99 529	35
26	9.16 630	85	9.17 103	87	0.82 897	9.90 528	34
27	9.16 716	85	9.17 190	86	0.82 810	9.99 526	33
28	9.16 801	84	9.17 276	87	0.82 723	9.99 524	32
29	9.16 885	84	9.17 363	86	0.82 636	9.99 522	31
30	9.16 970	84	9.17 450	86	0.82 550	9.99 520	30
31	9.17 054	84	9.17 536	86	0.82 464	9.99 518	29
32	9.17 139	84	9.17 622	86	0.82 377	9.99 516	28
33	9.17 223	84	9.17 708	85	0.82 291	9.99 514	27
34	9.17 307	84	9.17 794	86	0.82 206	9.99 512	26
35	9.17 391	83	9.17 8[illegible]0	85	0.82 120	9.99 511	25
36	9.17 474	83	9.17 965	85	0.82 034	9.99 509	24
37	9.17 558	83	9.18 051	85	0.81 949	9.99 507	23
38	9.17 641	83	9.18 136	85	0.81 864	9.99 505	22
39	9.17 724	83	9.18 221	85	0.81 779	9.99 503	21
40	9.17 807	83	9.18 306	84	0.81 694	9.99 501	20
41	9.17 890	82	9.18 390	84	0.81 609	9.99 499	19
42	9.17 972	82	9.18 475	84	0.81 525	9.99 497	18
43	9.18 055	82	9.18 559	84	0.81 440	9.99 495	17
44	9.18 137	82	9.18 644	84	0.81 356	9.99 493	16
45	9.18 219	82	9.18 728	84	0.81 272	9.99 491	15
46	9.18 301	82	9.18 812	84	0.81 188	9.99 489	14
47	9.18 383	81	9.18 896	83	0.81 104	9.99 487	13
48	9.18 465	81	9.18 979	83	0.81 020	9.99 485	12
49	9.18 546	81	9.19 063	83	0.80 937	9.99 484	11
50	9.18 628	81	9.19 146	83	0.80 854	9.99 482	10
51	9.18 709	81	9.19 229	83	0.80 770	9.99 480	9
52	9.18 790	80	9.19 312	83	0.80 687	9.99 478	8
53	9.18 871	81	9.19 395	82	0.80 604	9.99 476	7
54	9.18 952	80	9.19 478	82	0.80 522	9.99 474	6
55	9.19 032	80	9.19 560	82	0.80 439	9.99 472	5
56	9.19 113	80	9.19 643	82	0.80 357	9.99 470	4
57	9.19 193	80	9.19 725	82	0.80 274	9.99 468	3
58	9.19 273	80	9.19 807	82	0.80 192	9.99 466	2
59	9.19 353	79	9.19 889	82	0.80 110	9.99 464	1
60	9.19 433		9.19 971		0.80 028	9.99 462	0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	′

P. P.

	91	91	90	89
6	9.1	9.1	9.0	8.9
7	10.7	10.6	10.5	10.4
8	12.2	12.1	12.0	11.8
9	13.7	13.6	13.5	13.3
10	15.2	15.1	15.0	14.8
20	30.5	30.3	30.0	29.6
30	45.7	45.5	45.0	44.5
40	61.0	60.6	60.0	59.3
50	76.2	75.8	75.0	74.1

	88	88	87	86
6	8.8	8.8	8.7	8.6
7	10.3	10.2	10.1	10.0
8	11.8	11.7	11.6	11.4
9	13.3	13.2	13.0	12.9
10	14.7	14.6	14.5	14.3
20	29.5	29.3	29.0	28.6
30	44.2	44.0	43.5	43.0
40	59.0	58.6	58.0	57.3
50	73.7	73.3	72.5	71.6

	85	85	84	83
6	8.5	8.5	8.4	8.3
7	10.0	9.9	9.8	9.7
8	11.4	11.3	11.2	11.0
9	12.8	12.7	12.6	12.4
10	14.2	14.1	14.0	13.8
20	28.5	28.3	28.0	27.6
30	42.7	42.5	42.0	41.5
40	57.0	56.6	56.0	55.3
50	71.2	70.8	70.0	69.1

	82	82	81	80
6	8.2	8.2	8.1	8.0
7	9.6	9.5	9.4	9.3
8	11.0	10.9	10.8	10.6
9	12.4	12.3	12.1	12.0
10	13.7	13.6	13.5	13.3
20	27.5	27.3	27.0	26.6
30	41.2	41.0	40.5	40.0
40	55.0	54.6	54.0	53.3
50	68.7	68.3	67.5	66.6

	79	2	1
6	7.9	0.2	0.1
7	9.3	0.2	0.2
8	10.6	0.2	0.2
9	11.9	0.3	0.2
10	13.2	0.3	0.2
20	26.5	0.6	0.5
30	39.7	1.0	0.7
40	53.0	1.3	1.0
50	66.2	1.6	1.2

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	
0	9.19 433	80	9.19 971	81	0.80 028	9.99 462	60
1	9.19 513	79	9.20 053	81	0.79 947	9.99 460	59
2	9.19 592	79	9.20 134	81	0.79 865	9.99 458	58
3	9.19 672	79	9.20 216	81	0.79 784	9.99 456	57
4	9.19 751	79	9.20 297	81	0.79 703	9.99 454	56
5	9.19 830	79	9.20 378	81	0.79 622	9.99 452	55
6	9.19 909	79	9.20 459	81	0.79 541	9.99 450	54
7	9.19 988	78	9.20 540	80	0.79 460	9.99 448	53
8	9.20 066	78	9.20 620	81	0.79 379	9.99 446	52
9	9.20 145	78	9.20 701	80	0.79 298	9.99 444	51
10	9.20 223	78	9.20 781	80	0.79 218	9.99 442	50
11	9.20 301	78	9.20 862	80	0.79 138	9.99 440	49
12	9.20 379	78	9.20 942	80	0.79 058	9.99 437	48
13	9.20 457	78	9.21 022	80	0.78 978	9.99 435	47
14	9.20 535	77	9.21 102	79	0.78 898	9.99 433	46
15	9.20 613	77	9.21 181	79	0.78 818	9.99 431	45
16	9.20 690	77	9.21 261	79	0.78 739	9.99 429	44
17	9.20 768	77	9.21 340	79	0.78 659	9.99 427	43
18	9.20 845	77	9.21 420	79	0.78 580	9.99 425	42
19	9.20 922	77	9.21 499	79	0.78 501	9.99 423	41
20	9.20 999	77	9.21 578	79	0.78 422	9.99 421	40
21	9.21 076	76	9.21 657	78	0.78 343	9.99 419	39
22	9.21 152	76	9.21 735	78	0.78 264	9.99 417	38
23	9.21 229	76	9.21 814	78	0.78 186	9.99 415	37
24	9.21 305	76	9.21 892	78	0.78 107	9.99 413	36
25	9.21 382	76	9.21 971	78	0.78 029	9.99 411	35
26	9.21 458	76	9.22 049	78	0.77 951	9.99 408	34
27	9.21 534	75	9.22 127	78	0.77 873	9.99 406	33
28	9.21 609	76	9.22 205	78	0.77 795	9.99 404	32
29	9.21 685	75	9.22 283	77	0.77 717	9.99 402	31
30	9.21 761	75	9.22 360	77	0.77 639	9.99 400	30
31	9.21 836	75	9.22 438	77	0.77 562	9.99 398	29
32	9.21 911	75	9.22 515	77	0.77 484	9.99 396	28
33	9.21 987	75	9.22 593	77	0.77 407	9.99 394	27
34	9.22 062	74	9.22 670	77	0.77 330	9.99 392	26
35	9.22 136	75	9.22 747	77	0.77 253	9.99 389	25
36	9.22 211	74	9.22 824	76	0.77 176	9.99 387	24
37	9.22 286	74	9.22 900	77	0.77 099	9.99 385	23
38	9.22 360	74	9.22 977	76	0.77 022	9.99 383	22
39	9.22 435	74	9.23 054	76	0.76 946	9.99 381	21
40	9.22 509	74	9.23 130	76	0.76 870	9.99 379	20
41	9.22 583	74	9.23 206	76	0.76 793	9.99 377	19
42	9.22 657	73	9.23 282	76	0.76 717	9.99 374	18
43	9.22 731	74	9.23 358	76	0.76 641	9.99 372	17
44	9.22 805	73	9.23 434	76	0.76 565	9.99 370	16
45	9.22 878	73	9.23 510	75	0.76 489	9.99 368	15
46	9.22 952	73	9.23 586	75	0.76 414	9.99 366	14
47	9.23 025	73	9.23 661	75	0.76 338	9.99 364	13
48	9.23 098	73	9.23 737	75	0.76 263	9.99 361	12
49	9.23 171	73	9.23 812	75	0.76 188	9.99 359	11
50	9.23 244	72	9.23 887	75	0.76 113	9.99 357	10
51	9.23 317	73	9.23 962	75	0.76 038	9.99 355	9
52	9.23 390	72	9.24 037	75	0.75 963	9.99 353	8
53	9.23 462	72	9.24 112	75	0.75 888	9.99 350	7
54	9.23 535	72	9.24 186	74	0.75 813	9.99 348	6
55	9.23 607	72	9.24 261	74	0.75 739	9.99 346	5
56	9.23 679	72	9.24 335	74	0.75 664	9.99 344	4
57	9.23 751	72	9.24 409	74	0.75 590	9.99 342	3
58	9.23 823	72	9.24 484	74	0.75 516	9.99 339	2
59	9.23 895	71	9.24 558	74	0.75 442	9.99 337	1
60	9.23 967		9.24 632		0.75 368	9.99 335	0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	′

P. P.

	81	81	80	79
6	8.1	8.1	8.0	7.9
7	9.5	9.4	9.3	9.2
8	10.8	10.8	10.6	10.5
9	12.2	12.1	12.0	11.8
10	13.6	13.5	13.3	13.1
20	27.1	27.0	26.6	26.3
30	40.7	40.5	40.0	39.5
40	54.3	54.0	53.3	52.6
50	67.9	67.5	66.6	65.8

	78	78	77
6	7.8	7.8	7.7
7	9.1	9.1	9.0
8	10.4	10.4	10.2
9	11.8	11.7	11.5
10	13.1	13.0	12.8
20	26.1	26.0	25.6
30	39.2	39.0	38.5
40	52.3	52.0	51.3
50	65.4	65.0	64.1

	76	76	75	74
6	7.6	7.6	7.5	7.4
7	8.9	8.8	8.7	8.6
8	10.2	10.1	10.0	9.8
9	11.5	11.4	11.2	11.1
10	12.7	12.6	12.5	12.3
20	25.5	25.3	25.0	24.6
30	38.2	38.0	37.5	37.0
40	51.0	50.6	50.0	49.3
50	63.7	63.3	62.5	61.6

	73	73	72
6	7.3	7.3	7.2
7	8.6	3.5	8.4
8	9.8	9.7	9.6
9	11.0	10.9	10.8
10	12.2	12.1	12.0
20	24.5	24.3	24.0
30	36.7	36.5	36.0
40	40.0	48.6	48.0
50	61.2	60.8	60.0

	71	71	2	2
6	7.1	7.1	0.2	0.2
7	8.3	8.3	0.3	0.2
8	9.5	9.4	0.3	0.2
9	10.7	10.6	0.4	0.3
10	11.9	11.8	0.4	0.3
20	23.8	23.6	0.8	0.6
30	35.7	35.5	1.2	1.0
40	47.6	47.3	1.6	1.3
50	59.6	59.1	2.1	1.6

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	
0	9.23 967	71	9.24 632	73	0.75 368	9.99 335	60
1	9.24 038	71	9.24 705	74	0.75 294	9.99 333	59
2	9.24 110	71	9.24 779	73	0.75 220	9.99 330	58
3	9.24 181	71	9.24 853	73	0.75 147	9.99 328	57
4	9.24 252	71	9.24 926	73	0.75 073	9.99 326	56
5	9.24 323	71	9.25 000	73	0.75 000	9.99 324	55
6	9.24 394	71	9.25 073	73	0.74 927	9.99 321	54
7	9.24 465	71	9.25 146	73	0.74 854	9.99 319	53
8	9.24 536	70	9.25 219	73	0.74 781	9.99 317	52
9	9.24 607	70	9.25 292	73	0.74 708	9.99 315	51
10	9.24 677	70	9.25 365	72	0.74 635	9.99 312	50
11	9.24 748	70	9.25 437	72	0.74 562	9.99 310	49
12	9.24 818	70	9.25 510	72	0.74 490	9.99 308	48
13	9.24 888	70	9.25 582	72	0.74 417	9.99 306	47
14	9.24 958	69	9.25 654	72	0.74 345	9.99 303	46
15	9.25 028	70	9.25 727	72	0.74 273	9.99 301	45
16	9.25 098	69	9.25 799	72	0.74 201	9.99 299	44
17	9.25 167	70	9.25 871	72	0.74 129	9.99 296	43
18	9.25 237	69	9.25 943	71	0.74 057	9.99 294	42
19	9.25 306	69	9.26 014	72	0.73 985	9.99 292	41
20	9.25 376	69	9.26 086	71	0.73 913	9.99 290	40
21	9.25 445	69	9.26 158	71	0.73 842	9.99 287	39
22	9.25 514	69	9.26 229	71	0.73 771	9.99 285	38
23	9.25 583	69	9.26 300	71	0.73 699	9.99 283	37
24	9.25 652	68	9.26 371	71	0.73 628	9.99 280	36
25	9.25 721	69	9.26 443	71	0.73 557	9.99 278	35
26	9.25 790	68	9.26 514	70	0.73 486	9.99 276	34
27	9.25 858	68	9.26 584	71	0.73 415	9.99 273	33
28	9.25 927	68	9.26 655	70	0.73 344	9.99 271	32
29	9.25 995	68	9.26 726	70	0.73 274	9.99 269	31
30	9.26 063	68	9.26 796	70	0.73 203	9.99 266	30
31	9.26 131	68	9.26 867	70	0.73 133	9.99 264	29
32	9.26 199	68	9.26 937	70	0.73 062	9.99 262	28
33	9.26 267	67	9.27 007	70	0.72 992	9.99 259	27
34	9.26 335	67	9.27 078	70	0.72 922	9.99 257	26
35	9.26 402	68	9.27 148	70	0.72 852	9.99 255	25
36	9.26 470	67	9.27 218	69	0.72 782	9.99 252	24
37	9.26 537	67	9.27 287	70	0.72 712	9.99 250	23
38	9.26 605	67	9.27 357	69	0.72 642	9.99 248	22
39	9.26 672	67	9.27 427	69	0.72 573	9.99 245	21
40	9.26 739	67	9.27 496	69	0.72 503	9.99 243	20
41	9.26 806	67	9.27 566	69	0.72 434	9.99 240	19
42	9.26 873	66	9.27 635	69	0.72 365	9.99 238	18
43	9.26 940	67	9.27 704	69	0.72 295	9.99 236	17
44	9.27 007	66	9.27 773	69	0.72 226	9.99 233	16
45	9.27 073	66	9.27 842	69	0.72 157	9.99 231	15
46	9.27 140	66	9.27 911	68	0.72 088	9.99 228	14
47	9.27 206	66	9.27 980	69	0.72 020	9.99 226	13
48	9.27 272	66	9.28 049	68	0.71 951	9.99 224	12
49	9.27 339	66	9.28 117	68	0.71 882	9.99 221	11
50	9.27 405	66	9.28 186	68	0.71 814	9.99 219	10
51	9.27 471	65	9.28 254	68	0.71 746	9.99 216	9
52	9.27 536	66	9.28 322	68	0.71 677	9.99 214	8
53	9.27 602	65	9.28 390	68	0.71 609	9.99 212	7
54	9.27 668	65	9.28 459	68	0.71 541	9.99 209	6
55	9.27 733	65	9.28 527	67	0.71 473	9.99 207	5
56	9.27 799	65	9.28 594	68	0.71 405	9.99 204	4
57	9.27 864	65	9.28 662	67	0.71 337	9.99 202	3
58	9.27 929	65	9.28 730	67	0.71 270	9.99 199	2
59	9.27 995	65	9.28 797	67	0.71 202	9.99 197	1
60	9.28 060		9.28 865		0.71 135	9.99 194	0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	′

P. P.

	74	73	73
6	7.4	7.3	7.3
7	8.6	8.6	8.5
8	9.8	9.8	9.7
9	11.1	11.0	10.9
10	12.3	12.2	12.1
20	24.6	24.5	24.3
30	37.0	36.7	36.5
40	49.3	49.0	48.6
50	61.6	61.2	60.8

	72	72	71	71
6	7.2	7.2	7.1	7.1
7	8.4	8.4	8.3	8.3
8	9.6	9.6	9.5	9.4
9	10.9	10.8	10.7	10.6
10	12.1	12.0	11.9	11.8
20	24.1	24.0	23.8	23.6
30	36.2	36.0	35.7	35.5
40	48.3	48.0	47.6	47.3
50	60.4	60.0	59.6	59.1

	70	70	69	69
6	7.0	7.0	6.9	6.9
7	8.2	8.1	8.1	8.0
8	9.4	9.3	9.2	9.2
9	10.6	10.5	10.4	10.3
10	11.7	11.6	11.6	11.5
20	23.5	23.3	23.1	23.0
30	35.2	35.0	34.7	34.5
40	47.0	46.6	46.3	46.0
50	58.7	58.3	57.9	57.5

	68	68	67	67
6	6.8	6.8	6.7	6.7
7	8.0	7.9	7.9	7.8
8	9.1	9.0	9.0	8.9
9	10.3	10.2	10.1	10.0
10	11.4	11.3	11.2	11.1
20	22.8	22.6	22.5	22.3
30	34.2	34.0	33.7	33.5
40	45.6	45.3	45.0	44.6
50	57.1	56.6	56.2	55.8

	66	66	65	65
6	6.6	6.6	6.5	6.5
7	7.7	7.7	7.6	7.6
8	8.8	8.8	8.7	8.6
9	10.0	9.9	9.8	9.7
10	11.1	11.0	10.9	10.8
20	22.1	22.0	21.8	21.6
30	33.2	33.0	32.7	32.5
40	44.3	44.0	43.6	43.3
50	55.4	55.0	54.6	54.1

	2	2
6	0.2	0.2
7	0.3	0.2
8	0.3	0.2
9	0.4	0.3
10	0.4	0.3
20	0.8	0.6
30	1.2	1.0
40	1.6	1.3
50	2.1	1.6

P. P.

'	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	
0	9.28 060	65	9.28 865	67	0.71 135	9.99 194	60
1	9.28 125	64	9.28 932	67	0.71 067	9.99 192	59
2	9.28 189	65	9.29 000	67	0.71 000	9.99 189	58
3	9.28 254	64	9.29 067	67	0.70 933	9.99 187	57
4	9.28 319	64	9.29 134	67	0.70 866	9.99 185	56
5	9.28 383	64	9.29 201	66	0.70 798	9.99 182	55
6	9.28 448	64	9.29 268	67	0.70 732	9.99 180	54
7	9.28 512	64	9.29 335	66	0.70 665	9.99 177	53
8	9.28 576	64	9.29 401	67	0.70 598	9.99 175	52
9	9.28 641	64	9.29 468	66	0.70 531	9.99 172	51
10	9.28 705	64	9.29 535	66	0.70 465	9.99 170	50
11	9.28 769	63	9.29 601	66	0.70 398	9.99 167	49
12	9.28 832	64	9.29 667	66	0.70 332	9.99 165	48
13	9.28 896	63	9.29 734	66	0.70 266	9.99 162	47
14	9.28 960	63	9.29 800	66	0.70 200	9.99 160	46
15	9.29 023	63	9.29 866	66	0.70 134	9.99 157	45
16	9.29 087	63	9.29 932	66	0.70 068	9.99 155	44
17	9.29 150	63	9.29 998	66	0.70 002	9.99 152	43
18	9.29 213	63	9.30 064	65	0.69 936	9.99 150	42
19	9.29 277	63	9.30 129	65	0.69 870	9.99 147	41
20	9.29 340	63	9.30 195	65	0.69 805	9.99 145	40
21	9.29 403	63	9.30 260	65	0.69 739	9.99 142	39
22	9.29 466	62	9.30 326	65	0.69 674	9.99 139	38
23	9.29 528	63	9.30 391	65	0.69 608	9.99 137	37
24	9.29 591	62	9.30 456	65	0.69 543	9.99 134	36
25	9.29 654	62	9.30 522	65	0.69 478	9.99 132	35
26	9.29 716	62	9.30 587	65	0.69 413	9.99 129	34
27	9.29 779	62	9.30 652	65	0.69 348	9.99 127	33
28	9.29 841	62	9.30 717	64	0.69 283	9.99 124	32
29	9.29 903	62	9.30 781	65	0.69 218	9.99 122	31
30	9.29 965	62	9.30 846	64	0.69 153	9.99 119	30
31	9.30 027	62	9.30 911	64	0.69 089	9.99 116	29
32	9.30 089	62	9.30 975	64	0.69 024	9.99 114	28
33	9.30 151	61	9.31 040	64	0.68 960	9.99 111	27
34	9.30 213	62	9.31 104	64	0.68 896	9.99 109	26
35	9.30 275	61	9.31 168	64	0.68 831	9.99 106	25
36	9.30 336	61	9.31 232	64	0.68 767	9.99 104	24
37	9.30 398	61	9.31 297	64	0.68 703	9.99 101	23
38	9.30 459	61	9.31 361	63	0.68 639	9.99 098	22
39	9.30 520	61	9.31 424	64	0.68 575	9.99 096	21
40	9.30 582	61	9.31 488	64	0.68 511	9.99 093	20
41	9.30 643	61	9.31 552	63	0.68 447	9.99 091	19
42	9.30 704	61	9.31 616	63	0.68 384	9.99 088	18
43	9.30 765	61	9.31 679	63	0.68 320	9.99 085	17
44	9.30 826	60	9.31 743	63	0.68 257	9.99 083	16
45	9.30 886	61	9.31 806	63	0.68 193	9.99 080	15
46	9.30 947	60	9.31 869	63	0.68 130	9.99 077	14
47	9.31 008	60	9.31 933	63	0.68 067	9.99 075	13
48	9.31 068	60	9.31 996	63	0.68 004	9.99 072	12
49	9.31 129	60	9.32 059	63	0.67 941	9.99 069	11
50	9.31 189	60	9.32 122	63	0.67 878	9.99 067	10
51	9.31 249	60	9.32 185	63	0.67 815	9.99 064	9
52	9.31 309	60	9.32 248	62	0.67 752	9.99 062	8
53	9.31 370	59	9.32 310	63	0.67 689	9.99 059	7
54	9.31 429	60	9.32 373	62	0.67 626	9.99 056	6
55	9.31 489	60	9.32 436	62	0.67 564	9.99 054	5
56	9.31 549	59	9.32 498	62	0.67 501	9.99 051	4
57	9.31 609	60	9.32 560	62	0.67 439	9.99 048	3
58	9.31 669	59	9.32 623	62	0.67 377	9.99 046	2
59	9.31 728	59	9.32 685	62	0.67 314	9.99 043	1
60	9.31 788		9.32 747		0.67 252	9.99 040	0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	'

P. P.

	67	67
6	6.7	6.7
7	7.9	7.8
8	9.0	8.9
9	10.1	10.0
10	11.2	11.1
20	22.5	22.3
30	33.7	33.5
40	45.0	44.6
50	56.2	55.8

	66	66	65	65
6	6.6	6.6	6.5	6.5
7	7.7	7.7	7.6	7.6
8	8.8	8.8	8.7	8.6
8	10.0	9.9	9.8	9.7
10	11.1	11.0	10.9	10.8
20	22.1	22.0	21.8	21.6
30	33.2	33.0	32.7	32.5
40	44.3	44.0	43.6	43.3
50	55.4	55.0	54.6	54.1

	64	64	63	63
6	6.4	6.4	6.3	6.3
7	7.5	7.4	7.4	7.3
8	8.6	8.5	8.4	8.4
9	9.7	9.6	9.5	9.4
10	10.7	10.6	10.6	10.5
20	21.5	21.3	21.1	21.0
30	32.2	32.0	31.7	31.5
40	43.0	42.6	42.3	42.0
50	53.7	53.3	52.9	52.5

	62	62	61	61
6	6.2	6.2	6.1	6.1
7	7.3	7.2	7.2	7.1
8	8.3	8.2	8.2	8.1
9	9.4	9.3	9.2	9.1
10	10.4	10.3	10.2	10.1
20	20.8	20.6	20.5	20.3
30	31.2	31.0	30.7	30.5
40	41.6	41.3	41.0	40.6
50	52.1	51.6	51.2	50.8

	60	60	59
6	6.0	6.0	5.9
7	7.0	7.0	6.9
8	8.0	8.0	7.9
9	9.1	9.0	8.9
10	10.1	10.0	9.9
20	20.1	20.0	19.8
30	30.2	30.0	29.7
40	40.3	40.0	39.6
50	50.4	50.0	49.6

	3	2	2
6	0.3	0.2	0.2
7	0.3	0.3	0.2
8	0.4	0.3	0.2
9	0.4	0.4	0.3
10	0.5	0.4	0.3
20	1.0	0.8	0.6
30	1.5	1.2	1.0
40	2.0	1.6	1.3
50	2.5	2.1	1.6

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	
0	9.31 788	59	9.32 747	62	0.67 252	9.99 040	60
1	9.31 847	59	9.32 809	62	0.67 190	9.99 038	59
2	9.31 906	59	9.32 871	62	0.67 128	9.99 035	58
3	9.31 966	59	9.32 933	62	0.67 066	9.99 032	57
4	9.32 025	59	9.32 995	61	0.67 004	9.99 029	56
5	9.32 084	59	9.33 057	61	0.66 943	9.99 027	55
6	9.32 143	59	9.33 118	62	0.66 881	9.99 024	54
7	9.32 202	58	9.33 180	61	0.66 819	9.99 021	53
8	9.32 260	59	9.33 242	61	0.66 758	9.99 019	52
9	9.32 319	58	9.33 303	61	0.66 696	9.99 016	51
10	9.32 378	58	9.33 364	61	0.66 635	9.99 013	50
11	9.32 436	58	9.33 426	61	0.66 574	9.99 010	49
12	9.32 495	58	9.33 487	61	0.66 513	9.99 008	48
13	9.32 553	58	9.33 548	61	0.66 452	9.99 005	47
14	9.32 611	58	9.33 609	60	0.66 390	9.99 002	46
15	9.32 670	58	9.33 670	61	0.66 330	9.98 999	45
16	9.32 728	58	9.33 731	61	0.66 269	9.98 997	44
17	9.32 786	58	9.33 792	60	0.66 208	9.98 994	43
18	9.32 844	58	9.33 852	61	0.66 147	9.98 991	42
19	9.32 902	58	9.33 913	60	0.66 086	9.98 988	41
20	9.32 960	57	9.33 974	60	0.66 026	9.98 986	40
21	9.33 017	58	9.34 034	60	0.65 965	9.98 983	39
22	9.33 075	57	9.34 095	60	0.65 905	9.98 980	38
23	9.33 133	57	9.34 155	60	0.65 845	9.98 977	37
24	9.33 190	57	9.34 215	60	0.65 784	9.98 975	36
25	9.33 248	57	9.34 275	60	0.65 724	9.98 972	35
26	9.33 305	57	9.34 336	60	0.65 664	9.98 969	34
27	9.33 362	57	9.34 396	60	0.65 604	9.98 966	33
28	9.33 419	57	9.34 456	59	0.65 544	9.98 963	32
29	9.33 476	57	9.34 515	60	0.65 484	9.98 961	31
30	9.33 533	57	9.34 575	60	0.65 424	9.98 958	30
31	9.33 590	57	9.34 635	59	0.65 364	9.98 955	29
32	9.33 647	57	9.34 695	59	0.65 305	9.98 952	28
33	9.33 704	56	9.34 754	59	0.65 245	9.98 949	27
34	9.33 761	56	9.34 814	59	0.65 186	9.98 947	26
35	9.33 817	56	9.34 873	59	0.65 126	9.98 944	25
36	9.33 874	56	9.34 933	59	0.65 067	9.98 941	24
37	9.33 930	56	9.34 992	59	0.65 008	9.98 938	23
38	9.33 987	56	9.35 051	59	0.64 948	9.98 935	22
39	9.34 043	56	9.35 110	59	0.64 889	9.98 933	21
40	9.34 099	56	9.35 169	59	0.64 830	9.98 930	20
41	9.34 156	56	9.35 228	59	0.64 771	9.98 927	19
42	9.34 212	56	9.35 287	59	0.64 712	9.98 924	18
43	9.34 268	56	9.35 346	59	0.64 653	9.98 921	17
44	9.34 324	55	9.35 405	58	0.64 594	9.98 918	16
45	9.34 379	56	9.35 464	58	0.64 536	9.98 915	15
46	9.34 435	55	9.35 522	59	0.64 477	9.98 913	14
47	9.34 491	56	9.35 581	58	0.64 418	9.98 910	13
48	9.34 547	55	9.35 640	58	0.64 360	9.98 907	12
49	9.34 602	55	9.35 698	58	0.64 302	9.98 904	11
50	9.34 658	55	9.35 756	58	0.64 243	9.98 901	10
51	9.34 713	55	9.35 815	58	0.64 185	9.98 898	9
52	9.34 768	55	9.35 873	58	0.64 127	9.98 895	8
53	9.34 824	55	9.35 931	58	0.64 068	9.98 892	7
54	9.34 879	55	9.35 989	58	0.64 010	9.98 890	6
55	9.34 934	55	9.36 047	58	0.63 952	9.98 887	5
56	9.34 989	55	9.36 105	57	0.63 894	9.98 884	4
57	9.35 044	54	9.36 163	58	0.63 837	9.98 881	3
58	9.35 099	55	9.36 221	57	0.63 779	9.98 878	2
59	9.35 154	55	9.36 278	58	0.63 721	9.98 875	1
60	9.35 209		9.36 336		0.63 663	9.98 872	0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	′

P. P.

	62	61̄	61
6	6.2	6.1	6.1
7	7.2	7.2	7.1
8	8.2	8.2	8.1
9	9.3	9.2	9.1
10	10.3	10.2	10.1
20	20.6	20.5	20.3
30	31.0	30.7	30.5
40	41.3	41.0	40.6
50	51.6	51.2	50.8

	60̄	60	59̄	59
6	6.0	6.0	5.9	5.9
7	7.0	7.0	6.9	6.9
8	8.0	8.0	7.9	7.8
9	9.1	9.0	8.9	8.8
10	10.1	10.0	9.9	9.8
20	20.1	20.0	19.8	19.6
30	30.2	30.0	29.7	29.5
40	40.3	40.0	39.6	39.3
50	50.4	50.0	49.6	49.1

	58̄	58	57̄	57
6	5.8	5.8	5.7	5.7
7	6.8	6.7	6.7	6.6
8	7.8	7.7	7.6	7.6
9	8.8	8.7	8.6	8.5
10	9.7	9.6	9.6	9.5
20	19.5	19.3	19.1	19.0
30	29.2	29.0	28.7	28.5
40	39.0	38.6	38.3	38.0
50	48.7	48.3	47.9	47.5

	56̄	56	55̄	55
6	5.6	5.6	5.5	5.5
7	6.6	6.5	6.5	6.4
8	7.5	7.4	7.4	7.3
9	8.5	8.4	8.3	8.2
10	9.4	9.3	9.2	9.1
20	18.8	18.6	18.5	18.3
30	28.2	28.0	27.7	27.5
40	37.6	37.3	37.0	36.6
50	47.1	46.6	46.2	45.8

	54̄	3	2̄
6	5.4	0.3	0.2
7	6.3	0.3	0.3
8	7.2	0.4	0.3
9	8.2	0.4	0.4
10	9.1	0.5	0.4
20	18.1	1.0	0.8
30	27.2	1.5	1.2
40	36.3	2.0	1.6
50	45.4	2.5	2.1

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	
0	9.35 209	54	9.36 336	57	0.63 663	9.98 872	60
1	9.35 263	54	9.36 394	57	0.63 606	9.98 869	59
2	9.35 318	54	9.36 451	57	0.63 548	9.98 866	58
3	9.35 372	54	9.36 509	57	0.63 491	9.98 863	57
4	9.35 427	54	9.36 566	57	0.63 433	9.98 860	56
5	9.35 481	54	9.36 623	57	0.63 376	9.98 858	55
6	9.35 536	54	9.36 681	57	0.63 319	9.98 855	54
7	9.35 590	54	9.36 738	57	0.63 262	9.98 852	53
8	9.35 644	54	9.36 795	57	0.63 204	9.98 849	52
9	9.35 698	54	9.36 852	57	0.63 147	9.98 846	51
10	9.35 752	54	9.36 909	57	0.63 090	9.98 843	50
11	9.35 806	54	9.36 966	56	0.63 033	9.98 840	49
12	9.35 860	53	9.37 023	57	0.62 977	9.98 837	48
13	9.35 914	54	9.37 080	56	0.62 920	9.98 834	47
14	9.35 968	53	9.37 136	57	0.62 863	9.98 831	46
15	9.36 021	53	9.37 193	56	0.62 806	9.98 828	45
16	9.36 075	53	9.37 250	56	0.62 750	9.98 825	44
17	9.36 128	53	9.37 306	56	0.62 693	9.98 822	43
18	9.36 182	53	9.37 363	56	0.62 637	9.98 819	42
19	9.36 235	53	9.37 419	56	0.62 580	9.98 816	41
20	9.36 289	53	9.37 475	56	0.62 524	9.98 813	40
21	9.36 342	53	9.37 532	56	0.62 468	9.98 810	39
22	9.36 395	53	9.37 588	56	0.62 412	9.98 807	38
23	9.36 448	53	9.37 644	56	0.62 356	9.98 804	37
24	9.36 501	53	9.37 700	56	0.62 299	9.98 801	36
25	9.36 554	53	9.37 756	55	0.62 243	9.98 798	35
26	9.36 607	53	9.37 812	56	0.62 188	9.98 795	34
27	9.36 660	52	9.37 868	56	0.62 132	9.98 792	33
28	9.36 713	53	9.37 924	55	0.62 076	9.98 789	32
29	9.36 766	52	9.37 979	56	0.62 020	9.98 786	31
30	9.36 818	52	9.38 035	55	0.61 964	9.98 783	30
31	9.36 871	52	9.38 091	55	0.61 909	9.98 780	29
32	9.36 923	52	9.38 146	55	0.61 853	9.98 777	28
33	9.36 976	52	9.38 202	55	0.61 798	9.98 774	27
34	9.37 028	52	9.38 257	55	0.61 742	9.98 771	26
35	9.37 081	52	9.38 313	55	0.61 687	9.98 768	25
36	9.37 133	52	9.38 368	55	0.61 632	9.98 765	24
37	9.37 185	52	9.38 423	55	0.61 576	9.98 762	23
38	9.37 237	52	9.38 478	55	0.61 521	9.98 759	22
39	9.37 289	52	9.38 533	55	0.61 466	9.98 755	21
40	9.37 341	52	9.38 589	55	0.61 411	9.98 752	20
41	9.37 393	51	9.38 644	54	0.61 356	9.98 749	19
42	9.37 445	52	9.38 698	55	0.61 301	9.98 746	18
43	9.37 497	51	9.38 753	55	0.61 246	9.98 743	17
44	9.37 548	52	9.38 808	54	0.61 191	9.98 740	16
45	9.37 600	51	9.38 863	55	0.61 137	9.98 737	15
46	9.37 652	51	9.38 918	54	0.61 082	9.98 734	14
47	9.37 703	51	9.38 972	54	0.61 027	9.98 731	13
48	9.37 755	51	9.39 027	54	0.60 973	9.98 728	12
49	9.37 806	51	9.39 081	54	0.60 918	9.98 725	11
50	9.37 857	51	9.39 136	54	0.60 864	9.98 721	10
51	9.37 909	51	9.39 190	54	0.60 809	9.98 718	9
52	9.37 960	51	9.39 244	54	0.60 755	9.98 715	8
53	9.38 011	51	9.39 299	54	0.60 701	9.98 712	7
54	9.38 062	51	9.39 353	54	0.60 647	9.98 709	6
55	9.38 113	51	9.39 407	54	0.60 592	9.98 706	5
56	9.38 164	50	9.39 461	54	0.60 538	9.98 703	4
57	9.38 215	51	9.39 515	54	0.60 484	9.98 700	3
58	9.38 266	51	9.39 569	54	0.60 430	9.98 696	2
59	9.38 317	50	9.39 623	53	0.60 376	9.98 693	1
60	9.38 367		9.39 677		0.60 323	9.98 690	0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	′

P. P.

	$\overline{57}$	57	$\overline{56}$	56
6	5.7	5.7	5.6	5.6
7	6.7	6.6	6.6	6.5
8	7.6	7.6	7.5	7.4
9	8.6	8.5	8.5	8.4
10	9.6	9.5	9.4	9.3
20	19.1	19.0	18.8	18.6
30	28.7	28.5	28.2	28.0
40	38.3	38.0	37.6	37.3
50	47.9	47.5	47.1	46.6

	$\overline{55}$	55	$\overline{54}$	54
6	5.5	5.5	5.4	5.4
7	6.5	6.4	6.3	6.3
8	7.4	7.3	7.2	7.2
9	8.3	8.2	8.2	8.1
10	9.2	9.1	9.1	9.0
20	18.5	18.3	18.1	18.0
30	27.7	27.5	27.2	27.0
40	37.0	36.6	36.3	36.0
50	46.2	45.8	45.4	45.0

	$\overline{53}$	53	$\overline{52}$	52
6	5.3	5.3	5.2	5.2
7	6.2	6.2	6.1	6.0
8	7.1	7.0	7.0	6.9
9	8.0	7.9	7.9	7.8
10	8.9	8.8	8.7	8.6
20	17.8	17.6	17.5	17.3
30	26.7	26.5	26.2	26.0
40	35.6	35.3	35.0	34.6
50	44.6	44.1	43.7	43.3

	$\overline{51}$	51	$\overline{50}$
6	5.1	5.1	5.0
7	6.0	5.9	5.9
8	6.8	6.8	6.7
9	7.7	7.6	7.6
10	8.6	8.5	8.4
20	17.1	17.0	16.8
30	25.7	25.5	25.2
40	34.3	34.0	33.6
50	42.9	42.5	42.1

	$\overline{3}$	3	$\overline{2}$
6	0.3	0.3	0.2
7	0.4	0.3	0.3
8	0.4	0.4	0.3
9	0.5	0.4	0.4
10	0.6	0.5	0.4
20	1.1	1.0	0.8
30	1.7	1.5	1.2
40	2.3	2.0	1.6
50	2.9	2.5	2.1

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.38 367	50	9.39 677	54	0.60 323	9.98 690	3	60
1	9.38 418	50	9.39 731	53	0.60 269	9.98 687	3	59
2	9.38 468	50	9.39 784	54	0.60 215	9.98 684	3	58
3	9.38 519	50	9.39 838	53	0.60 161	9.98 681	3	57
4	9.38 569	50	9.39 892	53	0.60 108	9.98 678	3	56
5	9.38 620	50	9.39 945	53	0.60 054	9.98 674	3	55
6	9.38 670	50	9.39 999	53	0.60 001	9.98 671	3	54
7	9.38 720	50	9.40 052	53	0.59 947	9.98 668	3	53
8	9.38 771	50	9.40 106	53	0.59 894	9.98 665	3	52
9	9.38 821	50	9.40 159	53	0.59 841	9.98 662	3	51
10	9.38 871	50	9.40 212	53	0.59 787	9.98 658	3	50
11	9.38 921	50	9.40 265	53	0.59 734	9.98 655	3	49
12	9.38 971	50	9.40 318	53	0.59 681	9.98 652	3	48
13	9.39 021	50	9.40 372	53	0.59 628	9.98 649	3	47
14	9.39 071	49	9.40 425	53	0.59 575	9.98 646	3	46
15	9.39 120	50	9.40 478	53	0.59 522	9.98 642	3	45
16	9.39 170	49	9.40 531	52	0.59 469	9.98 639	3	44
17	9.39 220	49	9.40 583	53	0.59 416	9.98 636	3	43
18	9.39 269	49	9.40 636	52	0.59 363	9.98 633	3	42
19	9.39 319	49	9.40 689	53	0.59 311	9.98 630	3	41
20	9.39 368	49	9.40 742	52	0.59 258	9.98 626	3	40
21	9.39 418	49	9.40 794	52	0.59 205	9.98 623	3	39
22	9.39 467	49	9.40 847	52	0.59 153	9.98 620	3	38
23	9.39 516	49	9.40 899	52	0.59 101	9.98 617	3	37
24	9.39 566	49	9.40 952	52	0.59 048	9.98 613	3	36
25	9.39 615	49	9.41 004	52	0.58 996	9.98 610	3	35
26	9.39 664	49	9.41 057	52	0.58 943	9.98 607	3	34
27	9.39 713	49	9.41 109	52	0.58 891	9.98 604	3	33
28	9.39 762	49	9.41 161	52	0.58 838	9.98 600	3	32
29	9.39 811	49	9.41 213	52	0.58 786	9.98 597	3	31
30	9.39 860	49	9.41 266	52	0.58 734	9.98 594	3	30
31	9.39 909	48	9.41 318	52	0.58 682	9.98 591	3	29
32	9.39 957	48	9.41 370	52	0.58 630	9.98 587	3	28
33	9.40 006	49	9.41 422	52	0.58 578	9.98 584	3	27
34	9.40 055	48	9.41 474	51	0.58 526	9.98 581	3	26
35	9.40 103	48	9.41 525	52	0.58 474	9.98 578	3	25
36	9.40 152	48	9.41 577	52	0.58 422	9.98 574	3	24
37	9.40 200	48	9.41 629	51	0.58 370	9.98 571	3	23
38	9.40 249	48	9.41 681	51	0.58 319	9.98 568	3	22
39	9.40 297	48	9.41 732	51	0.58 267	9.98 564	3	21
40	9.40 345	48	9.41 784	52	0.58 216	9.98 561	3	20
41	9.40 394	48	9.41 836	51	0.58 164	9.98 558	3	19
42	9.40 442	48	9.41 887	51	0.58 112	9.98 554	3	18
43	9.40 490	48	9.41 938	51	0.58 061	9.98 551	3	17
44	9.40 538	48	9.41 990	51	0.58 010	9.98 548	3	16
45	9.40 586	48	9.42 041	51	0.57 958	9.98 544	3	15
46	9.40 634	48	9.42 092	51	0.57 907	9.98 541	3	14
47	9.40 682	48	9.42 144	51	0.57 856	9.98 538	3	13
48	9.40 730	47	9.42 195	51	0.57 805	9.98 534	3	12
49	9.40 777	48	9.42 246	51	0.57 753	9.98 531	3	11
50	9.40 825	47	9.42 297	51	0.57 702	9.98 528	3	10
51	9.40 873	47	9.42 348	51	0.57 651	9.98 524	3	9
52	9.40 920	47	9.42 399	51	0.57 600	9.98 521	3	8
53	9.40 968	47	9.42 450	50	0.57 549	9.98 518	3	7
54	9.41 015	47	9.42 501	51	0.57 499	9.98 514	3	6
55	9.41 063	47	9.42 552	50	0.57 448	9.98 511	3	5
56	9.41 110	47	9.42 602	51	0.57 397	9.98 508	3	4
57	9.41 158	47	9.42 653	50	0.57 346	9.98 504	3	3
58	9.41 205	47	9.42 704	50	0.57 296	9.98 501	3	2
59	9.41 252	47	9.42 754	50	0.57 245	9.98 498	3	1
60	9.41 299		9.42 805		0.57 195	9.98 494		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	54	53	53
6	5.4	5.3	5.3
7	6.3	6.2	6.2
8	7.2	7.1	7.0
9	8.1	8.0	7.9
10	9.0	8.9	8.8
20	18.0	17.8	17.6
30	27.0	26.7	26.5
40	36.0	35.6	35.3
50	45.0	44.6	44.1

	52	52	51	51
6	5.2	5.2	5.1	5.1
7	6.1	6.0	6.0	5.9
8	7.0	6.9	6.8	6.8
9	7.9	7.8	7.7	7.6
10	8.7	8.6	8.6	8.5
20	17.5	17.3	17.1	17.0
30	26.2	26.0	25.7	25.5
40	35.0	34.6	34.3	34.0
50	43.7	43.3	42.9	42.5

	50	50	49	49
6	5.0	5.0	4.9	4.9
7	5.9	5.8	5.8	5.7
8	6.7	6.6	6.6	6.5
9	7.6	7.5	7.4	7.3
10	8.4	8.3	8.2	8.1
20	16.8	16.6	16.5	16.3
30	25.2	25.0	24.7	24.5
40	33.6	33.3	33.0	32.6
50	42.1	41.6	41.2	40.8

	48	48	47	47
6	4.8	4.8	4.7	4.7
7	5.6	5.6	5.5	5.5
8	6.4	6.4	6.3	6.2
9	7.3	7.2	7.1	7.0
10	8.1	8.0	7.9	7.8
20	16.1	16.0	15.8	15.6
30	24.2	24.0	23.7	23.5
40	32.3	32.0	31.6	31.3
50	40.4	40.0	39.6	39.1

	3	3
6	0.3	0.3
7	0.4	0.3
8	0.4	0.4
9	0.5	0.4
10	0.6	0.5
20	1.1	1.0
30	1.7	1.5
40	2.3	2.0
50	2.9	2.5

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.41 299	47	9.42 805	51	0.57 195	9.98 494	3	60
1	9.41 346	47	9.42 856	50	0.57 144	9.98 491	3	59
2	9.41 394	47	9.42 906	50	0.57 094	9.98 487	3	58
3	9.41 441	47	9.42 956	50	0.57 043	9.98 484	3	57
4	9.41 488	46	9.43 007	50	0.56 993	9.98 481	3	56
5	9.41 534	47	9.43 057	50	0.56 942	9.98 477	3	55
6	9.41 581	47	9.43 107	50	0.56 892	9.98 474	3	54
7	9.41 628	46	9.43 157	50	0.56 842	9.98 470	3	53
8	9.41 675	46	9.43 208	50	0.56 792	9.98 467	3	52
9	9.41 721	47	9.43 258	50	0.56 742	9.98 464	3	51
10	9.41 768	46	9.43 308	50	0.56 692	9.98 460	3	50
11	9.41 815	46	9.43 358	50	0.56 642	9.98 457	3	49
12	9.41 861	46	9.43 408	50	0.56 592	9.98 453	3	48
13	9.41 908	46	9.43 458	50	0.56 542	9.98 450	3	47
14	9.41 954	46	9.43 508	49	0.56 492	9.98 446	3	46
15	9.42 000	46	9.43 557	50	0.56 442	9.98 443	3	45
16	9.42 047	46	9.43 607	49	0.56 392	9.98 439	3	44
17	9.42 093	46	9.43 657	49	0.56 343	9.98 436	3	43
18	9.42 139	46	9.43 706	50	0.56 293	9.98 433	3	42
19	9.42 185	46	9.43 756	49	0.56 243	9.98 429	3	41
20	9.42 232	46	9.43 806	49	0.56 194	9.98 426	3	40
21	9.42 278	46	9.43 855	49	0.56 144	9.98 422	3	39
22	9.42 324	45	9.43 905	49	0.56 095	9.98 419	3	38
23	9.42 369	46	9.43 954	49	0.56 045	9.98 415	3	37
24	9.42 415	46	9.44 003	49	0.55 996	9.98 412	3	36
25	9.42 461	46	9.44 053	49	0.55 947	9.98 408	3	35
26	9.42 507	45	9.44 102	49	0.55 898	9.98 405	3	34
27	9.42 553	45	9.44 151	49	0.55 848	9.98 401	3	33
28	9.42 598	46	9.44 200	49	0.55 799	9.98 398	3	32
29	9.42 644	45	9.44 249	49	0.55 750	9.98 394	3	31
30	9.42 690	45	9.44 299	49	0.55 701	9.98 391	3	30
31	9.42 735	45	9.44 348	49	0.55 652	9.98 387	3	29
32	9.42 781	45	9.44 397	49	0.55 603	9.98 384	3	28
33	9.42 826	45	9.44 446	48	0.55 554	9.98 380	3	27
34	9.42 871	45	9.44 494	49	0.55 505	9.98 377	3	26
35	9.42 917	45	9.44 543	49	0.55 456	9.98 373	3	25
36	9.42 962	45	9.44 592	48	0.55 407	9.98 370	3	24
37	9.43 007	45	9.44 641	49	0.55 359	9.98 366	3	23
38	9.43 052	45	9.44 690	48	0.55 310	9.98 363	3	22
39	9.43 098	45	9.44 738	48	0.55 261	9.98 359	3	21
40	9.43 143	45	9.44 787	48	0.55 213	9.98 356	3	20
41	9.43 188	45	9.44 835	48	0.55 164	9.98 352	4	19
42	9.43 233	45	9.44 884	48	0.55 116	9.98 348	3	18
43	9.43 278	44	9.44 932	48	0.55 067	9.98 345	3	17
44	9.43 322	45	9.44 981	48	0.55 019	9.98 341	3	16
45	9.43 367	44	9.45 029	48	0.54 970	9.98 338	3	15
46	9.43 412	45	9.45 077	48	0.54 922	9.98 334	3	14
47	9.43 457	44	9.45 126	48	0.54 874	9.98 331	3	13
48	9.43 501	44	9.45 174	48	0.54 825	9.98 327	3	12
49	9.43 546	45	9.45 222	48	0.54 777	9.98 324	4	11
50	9.43 591	44	9.45 270	48	0.54 729	9.98 320	3	10
51	9.43 635	44	9.45 318	48	0.54 681	9.98 316	3	9
52	9.43 680	44	9.45 367	48	0.54 633	9.98 313	3	8
53	9.43 724	44	9.45 415	48	0.54 585	9.98 309	3	7
54	9.43 768	44	9.45 463	47	0.54 537	9.98 306	4	6
55	9.43 813	44	9.45 510	48	0.54 489	9.98 302	3	5
56	9.43 857	44	9.45 558	48	0.54 441	9.98 298	3	4
57	9.43 901	44	9.45 606	47	0.54 393	9.98 295	3	3
58	9.43 945	44	9.45 654	48	0.54 346	9.98 291	3	2
59	9.43 989	44	9.45 702	47	0.54 298	9.98 288	4	1
60	9.44 034		9.45 749		0.54 250	9.98 284		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	50	50
6	5.0	5.0
7	5.9	5.8
8	6.7	6.6
9	7.6	7.5
10	8.4	8.3
20	16.8	16.6
30	25.2	25.0
40	33.6	33.3
50	42.1	41.6

	49	49	48	48
6	4.9	4.9	4.8	4.8
7	5.8	5.7	5.6	5.6
8	6.6	6.5	6.4	6.4
9	7.4	7.3	7.3	7.2
10	8.2	8.1	8.1	8.0
20	16.5	16.3	16.1	16.0
30	24.7	24.5	24.2	24.0
40	33.0	32.6	32.3	32.0
50	41.2	40.8	40.4	40.0

	47	47	46	46
6	4.7	4.7	4.6	4.6
7	5.5	5.5	5.4	5.3
8	6.3	6.2	6.2	6.1
9	7.1	7.0	7.0	6.9
10	7.9	7.8	7.7	7.6
20	15.8	15.6	15.5	15.3
30	23.7	23.5	23.2	23.0
40	31.6	31.3	31.0	30.6
50	39.6	39.1	38.7	38.3

	45	45	44	44
6	4.5	4.5	4.4	4.4
7	5.3	5.2	5.2	5.1
8	6.0	6.0	5.9	5.8
9	6.8	6.7	6.7	6.6
10	7.6	7.5	7.4	7.3
20	15.1	15.0	14.8	14.6
30	22.7	22.5	22.2	22.0
40	30.3	30.0	29.6	29.3
50	37.9	37.5	37.1	36.6

	4	3	3
6	0.4	0.3	0.3
7	0.4	0.4	0.3
8	0.5	0.4	0.4
9	0.6	0.5	0.4
10	0.6	0.6	0.5
20	1.3	1.1	1.0
30	2.0	1.7	1.5
40	2.6	2.3	2.0
50	3.3	2.9	2.5

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.44 034	44	9.45 749	48	0.54 250	9.98 284	3	60
1	9.44 078	44	9.45 797	47	0.54 202	9.98 280	3	59
2	9.44 122	44	9.45 845	47	0.54 155	9.98 277	3	58
3	9.44 166	43	9.45 892	47	0.54 107	9.98 273	4	57
4	9.44 209	44	9.45 940	47	0.54 060	9.98 269	3	56
5	9.44 253	44	9.45 987	47	0.54 012	9.98 266	3	55
6	9.44 297	43	9.46 035	47	0.53 965	9.98 262	4	54
7	9.44 341	43	9.46 082	47	0.53 917	9.98 258	3	53
8	9.44 384	44	9.46 129	47	0.53 870	9.98 255	3	52
9	9.44 428	43	9.46 177	47	0.53 823	9.98 251	4	51
10	9.44 472	43	9.46 224	47	0.53 776	9.98 247	3	50
11	9.44 515	43	9.46 271	47	0.53 728	9.98 244	3	49
12	9.44 559	43	9.46 318	47	0.53 681	9.98 240	4	48
13	9.44 602	43	9.46 366	47	0.53 634	9.98 236	3	47
14	9.44 646	43	9.46 413	47	0.53 587	9.98 233	3	46
15	9.44 689	43	9.46 460	47	0.53 540	9.98 229	4	45
16	9.44 732	43	9.46 507	47	0.53 493	9.98 225	3	44
17	9.44 776	43	9.46 554	47	0.53 446	9.98 222	3	43
18	9.44 819	43	9.46 601	46	0.53 399	9.98 218	4	42
19	9.44 862	43	9.46 647	47	0.53 352	9.98 214	3	41
20	9.44 905	43	9.46 694	47	0.53 305	9.98 211	4	40
21	9.44 948	43	9.46 741	46	0.53 258	9.98 207	3	39
22	9.44 991	43	9.46 788	46	0.53 212	9.98 203	3	38
23	9.45 034	43	9.46 834	47	0.53 165	9.98 200	4	37
24	9.45 077	43	9.46 881	46	0.53 118	9.98 196	3	36
25	9.45 120	42	9.46 928	46	0.53 072	9.98 192	4	35
26	9.45 163	43	9.46 974	46	0.53 025	9.98 188	3	34
27	9.45 206	43	9.47 021	46	0.52 979	9.98 185	4	33
28	9.45 249	42	9.47 067	46	0.52 932	9.98 181	3	32
29	9.45 291	42	9.47 114	46	0.52 886	9.98 177	4	31
30	9.45 334	43	9.47 160	46	0.52 839	9.98 173	3	30
31	9.45 377	42	9.47 207	46	0.52 793	9.98 170	4	29
32	9.45 419	42	9.47 253	46	0.52 747	9.98 166	3	28
33	9.45 462	42	9.47 299	46	0.52 700	9.98 162	4	27
34	9.45 504	42	9.47 345	46	0.52 654	9.98 158	3	26
35	9.45 547	42	9.47 392	46	0.52 608	9.98 155	4	25
36	9.45 589	42	9.47 438	46	0.52 562	9.98 151	3	24
37	9.45 631	42	9.47 484	46	0.52 516	9.98 147	4	23
38	9.45 674	42	9.47 530	46	0.52 469	9.98 143	3	22
39	9.45 716	42	9.47 576	46	0.52 423	9.98 140	4	21
40	9.45 758	42	9.47 622	46	0.52 377	9.98 136	3	20
41	9.45 800	42	9.47 668	45	0.52 331	9.98 132	4	19
42	9.45 842	42	9.47 714	46	0.52 286	9.98 128	4	18
43	9.45 885	42	9.47 760	46	0.52 240	9.98 124	3	17
44	9.45 927	42	9.47 806	45	0.52 194	9.98 121	4	16
45	9.45 969	42	9.47 851	46	0.52 148	9.98 117	3	15
46	9.46 011	41	9.47 897	45	0.52 102	9.98 113	4	14
47	9.46 052	42	9.47 943	46	0.52 057	9.98 109	4	13
48	9.46 094	42	9.47 989	45	0.52 011	9.98 105	3	12
49	9.46 136	41	9.48 034	45	0.51 965	9.98 102	4	11
50	9.46 178	42	9.48 080	45	0.51 920	9.98 098	4	10
51	9.46 220	41	9.48 125	45	0.51 874	9.98 094	3	9
52	9.46 261	41	9.48 171	45	0.51 829	9.98 090	4	8
53	9.46 303	42	9.48 216	45	0.51 783	9.98 086	4	7
54	9.46 345	41	9.48 262	45	0.51 738	9.98 082	3	6
55	9.46 386	41	9.48 307	45	0.51 692	9.98 079	4	5
56	9.46 428	41	9.48 353	45	0.51 647	9.98 075	4	4
57	9.46 469	41	9.48 398	45	0.51 602	9.98 071	3	3
58	9.46 511	41	9.48 443	45	0.51 556	9.98 067	4	2
59	9.46 552	41	9.48 488	45	0.51 511	9.98 063	4	1
60	9.46 593		9.48 534		0.51 466	9.98 059		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	48	47	47
6	4.8	4.7	4.7
7	5.6	5.5	5.5
8	6.4	6.3	6.2
9	7.2	7.1	7.0
10	8.0	7.9	7.8
20	16.0	15.8	15.6
30	24.0	23.7	23.5
40	32.0	31.6	31.3
50	40.0	39.6	39.1

	46	46	45	45
6	4.6	4.6	4.5	4.5
7	5.4	5.3	5.3	5.2
8	6.2	6.1	6.0	6.0
9	7.0	6.9	6.8	6.7
10	7.7	7.6	7.6	7.5
20	15.5	15.3	15.1	15.0
30	23.2	23.0	22.7	22.5
40	31.0	30.6	30.3	30.0
50	38.7	38.3	37.9	37.5

	44	43	43
6	4.4	4.3	4.3
7	5.1	5.1	5.0
8	5.8	5.8	5.7
9	6.6	6.5	6.4
10	7.3	7.2	7.1
20	14.6	14.5	14.3
30	22.0	21.7	21.5
40	29.3	29.0	28.6
50	36.6	36.2	35.8

	42	42	41	41
6	4.2	4.2	4.1	4.1
7	4.9	4.9	4.8	4.8
8	5.6	5.6	5.5	5.4
9	6.4	6.3	6.2	6.1
10	7.1	7.0	6.9	6.8
20	14.1	14.0	13.8	13.6
30	21.2	21.0	20.7	20.5
40	28.3	28.0	27.6	27.3
50	35.4	35.0	34.6	34.1

	4	3
6	0.4	0.3
7	0.4	0.4
8	0.5	0.4
9	0.6	0.5
10	0.6	0.6
20	1.3	1.1
30	2.0	1.7
40	2.6	2.3
50	3.3	2.9

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.46 593	41	9.48 534	45	0.51 466	9.98 059	3	60
1	9.46 635	41	9.48 579	45	0.51 421	9.98 056	4	59
2	9.46 676	41	9.48 624	45	0.51 376	9.98 052	4	58
3	9.46 717	41	9.48 669	45	0.51 330	9.98 048	4	57
4	9.46 758	41	9.48 714	45	0.51 285	9.98 044	3	56
5	9.46 799	41	9.48 759	45	0.51 240	9.98 040	4	55
6	9.46 840	41	9.48 804	44	0.51 195	9.98 036	4	54
7	9.46 881	41	9.48 849	45	0.51 151	9.98 032	4	53
8	9.46 922	41	9.48 894	45	0.51 106	9.98 028	4	52
9	9.46 963	41	9.48 939	45	0.51 061	9.98 024	3	51
10	9.47 004	41	9.48 984	44	0.51 016	9.98 021	4	50
11	9.47 045	41	9.49 028	45	0.50 971	9.98 017	4	49
12	9.47 086	40	9.49 073	44	0.50 926	9.98 013	4	48
13	9.47 127	41	9.49 118	44	0.50 882	9.98 009	4	47
14	9.47 168	40	9.49 162	45	0.50 837	9.98 005	4	46
15	9.47 208	40	9.49 207	44	0.50 792	9.98 001	3	45
16	9.47 249	41	9.49 252	44	0.50 748	9.97 997	4	44
17	9.47 290	40	9.49 296	44	0.50 703	9.97 993	4	43
18	9.47 330	40	9.49 341	44	0.50 659	9.97 989	4	42
19	9.47 371	40	9.49 385	44	0.50 614	9.97 985	4	41
20	9.47 411	40	9.49 430	44	0.50 570	9.97 981	4	40
21	9.47 452	40	9.49 474	44	0.50 525	9.97 977	4	39
22	9.47 492	40	9.49 518	44	0.50 481	9.97 973	4	38
23	9.47 532	40	9.49 563	44	0.50 437	9.97 969	3	37
24	9.47 573	40	9.49 607	44	0.50 392	9.97 966	4	36
25	9.47 613	40	9.49 651	44	0.50 348	9.97 962	4	35
26	9.47 653	40	9.49 695	44	0.50 304	9.97 958	4	34
27	9.47 694	40	9.49 740	44	0.50 260	9.97 954	4	33
28	9.47 734	40	9.49 784	44	0.50 216	9.97 950	4	32
29	9.47 774	40	9.49 828	44	0.50 172	9.97 946	4	31
30	9.47 814	40	9.49 872	44	0.50 128	9.97 942	4	30
31	9.47 854	40	9.49 916	44	0.50 083	9.97 938	4	29
32	9.47 894	40	9.49 960	43	0.50 039	9.97 934	4	28
33	9.47 934	40	9.50 004	44	0.49 996	9.97 930	4	27
34	9.47 974	40	9.50 048	44	0.49 952	9.97 926	4	26
35	9.48 014	40	9.50 092	44	0.49 908	9.97 922	4	25
36	9.48 054	39	9.50 136	43	0.49 864	9.97 918	4	24
37	9.48 093	40	9.50 179	44	0.49 820	9.97 914	4	23
38	9.48 133	39	9.50 223	43	0.49 776	9.97 910	4	22
39	9.48 173	40	9.50 267	44	0.49 733	9.97 906	4	21
40	9.48 213	39	9.50 311	43	0.49 689	9.97 902	4	20
41	9.48 252	39	9.50 354	43	0.49 645	9.97 898	4	19
42	9.48 292	39	9.50 398	44	0.49 602	9.97 894	4	18
43	9.48 331	39	9.50 442	43	0.49 558	9.97 890	4	17
44	9.48 371	39	9.50 485	43	0.49 514	9.97 886	4	16
45	9.48 410	39	9.50 529	43	0.49 471	9.97 881	4	15
46	9.48 450	39	9.50 572	43	0.49 427	9.97 877	4	14
47	9.48 489	39	9.50 616	43	0.49 384	9.97 873	4	13
48	9.48 529	39	9.50 659	43	0.49 340	9.97 869	4	12
49	9.48 568	39	9.50 702	43	0.49 297	9.97 865	4	11
50	9.48 607	39	9.50 746	43	0.49 254	9.97 861	4	10
51	9.48 646	39	9.50 789	43	0.49 210	9.97 857	4	9
52	9.48 686	39	9.50 832	43	0.49 167	9.97 853	4	8
53	9.48 725	39	9.50 876	43	0.49 124	9.97 849	4	7
54	9.48 764	39	9.50 919	43	0.49 081	9.97 845	4	6
55	9.48 803	39	9.50 962	43	0.49 038	9.97 841	4	5
56	9.48 842	39	9.51 005	43	0.48 994	9.97 837	4	4
57	9.48 881	39	9.51 048	43	0.48 951	9.97 833	4	3
58	9.48 920	39	9.51 091	43	0.48 908	9.97 829	4	2
59	9.48 959	38	9.51 134	43	0.48 865	9.97 824	4	1
60	9.48 998		9.51 177		0.48 822	9.97 820		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	45̄	45	44̄	44
6	4.5	4.5	4.4	4.4
7	5.3	5.2	5.2	5.1
8	6.0	6.0	5.9	5.8
9	6.8	6.7	6.7	6.6
10	7.6	7.5	7.4	7.3
20	15.1	15.0	14.8	14.6
30	22.7	22.5	22.2	22.0
40	30.3	30.0	29.6	29.3
50	37.9	37.5	37.1	36.6

	43̄	43
6	4.3	4.3
7	5.1	5.0
8	5.8	5.7
9	6.5	6.4
10	7.2	7.1
20	14.5	14.3
30	21.7	21.5
40	29.0	28.6
50	36.2	35.8

	41̄	41	40̄	40
6	4.1	4.1	4.0	4.0
7	4.8	4.8	4.7	4.6
8	5.5	5.4	5.4	5.3
9	6.2	6.1	6.1	6.0
10	6.9	6.8	6.7	6.6
20	13.8	13.6	13.5	13.3
30	20.7	20.5	20.2	20.0
40	27.6	27.3	27.0	26.6
50	34.6	34.1	33.7	33.3

	39̄	39	38̄
6	3.9	3.9	3.8
7	4.6	4.5	4.5
8	5.2	5.2	5.1
9	5.9	5.8	5.8
10	6.6	6.5	6.4
20	13.1	13.0	12.8
30	19.7	19.5	19.2
40	26.3	26.0	25.6
50	32.9	32.5	32.1

	4̄	4	3̄
6	0.4	0.4	0.3
7	0.5	0.4	0.4
8	0.6	0.5	0.4
9	0.7	0.6	0.5
10	0.7	0.6	0.6
20	1.5	1.3	1.1
30	2.2	2.0	1.7
40	3.0	2.6	2.3
50	3.7	3.3	2.9

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.48 998	39	9.51 177	43	0.48 822	9.97 820	4	60
1	9.49 037	39	9.51 220	43	0.48 779	9.97 816	4	59
2	9.49 076	38	9.51 263	43	0.48 736	9.97 812	4	58
3	9.49 114	39	9.51 306	43	0.48 693	9.97 808	4	57
4	9.49 153	38	9.51 349	42	0.48 650	9.97 804	4	56
5	9.49 192	39	9.51 392	43	0.48 608	9.97 800	4	55
6	9.49 231	38	9.51 435	42	0.48 565	9.97 796	4	54
7	9.49 269	38	9.51 477	43	0.48 522	9.97 792	4	53
8	9.49 308	38	9.51 520	42	0.48 479	9.97 787	4	52
9	9.49 346	38	9.51 563	42	0.48 437	9.97 783	4	51
10	9.49 385	38	9.51 605	43	0.48 394	9.97 779	4	50
11	9.49 423	38	9.51 648	42	0.48 351	9.97 775	4	49
12	9.49 462	38	9.51 691	42	0.48 309	9.97 771	4	48
13	9.49 500	38	9.51 733	42	0.48 266	9.97 767	4	47
14	9.49 539	38	9.51 776	42	0.48 224	9.97 763	4	46
15	9.49 577	38	9.51 818	42	0.48 181	9.97 758	4	45
16	9.49 615	38	9.51 861	42	0.48 139	9.97 754	4	44
17	9.49 653	38	9.51 903	42	0.48 096	9.97 750	4	43
18	9.49 692	38	9.51 946	42	0.48 054	9.97 746	4	42
19	9.49 730	38	9.51 988	42	0.48 012	9.97 742	4	41
20	9.49 768	38	9.52 030	42	0.47 969	9.97 737	4	40
21	9.49 806	38	9.52 073	42	0.47 927	9.97 733	4	39
22	9.49 844	38	9.52 115	42	0.47 885	9.97 729	4	38
23	9.49 882	38	9.52 157	42	0.47 842	9.97 725	4	37
24	9.49 920	38	9.52 199	42	0.47 800	9.97 721	4	36
25	9.49 958	38	9.52 241	42	0.47 758	9.97 716	4	35
26	9.49 996	37	9.52 284	42	0.47 716	9.97 712	4	34
27	9.50 034	38	9.52 326	42	0.47 674	9.97 708	4	33
28	9.50 072	38	9.52 368	42	0.47 632	9.97 704	4	32
29	9.50 110	37	9.52 410	42	0.47 590	9.97 700	4	31
30	9.50 147	38	9.52 452	42	0.47 548	9.97 695	4	30
31	9.50 185	37	9.52 494	42	0.47 506	9.97 691	4	29
32	9.50 223	37	9.52 536	42	0.47 464	9.97 687	4	28
33	9.50 260	38	9.52 578	41	0.47 422	9.97 683	4	27
34	9.50 298	37	9.52 619	42	0.47 380	9.97 678	4	26
35	9.50 336	37	9.52 661	42	0.47 338	9.97 674	4	25
36	9.50 373	37	9.52 703	41	0.47 296	9.97 670	4	24
37	9.50 411	37	9.52 745	42	0.47 255	9.97 666	4	23
38	9.50 448	37	9.52 787	41	0.47 213	9.97 661	4	22
39	9.50 486	37	9.52 828	41	0.47 171	9.97 657	4	21
40	9.50 523	37	9.52 870	42	0.47 130	9.97 653	4	20
41	9.50 561	37	9.52 912	41	0.47 088	9.97 649	4	19
42	9.50 598	37	9.52 953	41	0.47 046	9.97 644	4	18
43	9.50 635	37	9.52 995	41	0.47 005	9.97 640	4	17
44	9.50 672	37	9.53 036	41	0.46 963	9.97 636	4	16
45	9.50 710	37	9.53 078	41	0.46 922	9.97 632	4	15
46	9.50 747	37	9.53 119	41	0.46 880	9.97 627	4	14
47	9.50 784	37	9.53 161	41	0.46 839	9.97 623	4	13
48	9.50 821	37	9.53 202	41	0.46 797	9.97 619	4	12
49	9.50 858	37	9.53 244	41	0.46 756	9.97 614	4	11
50	9.50 895	37	9.53 285	41	0.46 714	9.97 610	4	10
51	9.50 932	37	9.53 326	41	0.46 673	9.97 606	4	9
52	9.50 969	37	9.53 368	41	0.46 632	9.97 601	4	8
53	9.51 006	37	9.53 409	41	0.46 591	9.97 597	4	7
54	9.51 043	37	9.53 450	41	0.46 549	9.97 593	4	6
55	9.51 080	36	9.53 491	41	0.46 508	9.97 588	4	5
56	9.51 117	37	9.53 533	41	0.46 467	9.97 584	4	4
57	9.51 154	36	9.53 574	41	0.46 426	9.97 580	4	3
58	9.51 190	37	9.53 615	41	0.46 385	9.97 575	4	2
59	9.51 227	36	9.53 656	41	0.46 344	9.97 571	4	1
60	9.51 264		9.53 697		0.46 303	9.97 567		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	43	42̄	42
6	4.3	4.2	4.2
7	5.0	4.9	4.9
8	5.7	5.6	5.6
9	6.4	6.4	6.3
10	7.1	7.1	7.0
20	14.3	14.1	14.0
30	21.5	21.2	21.0
40	28.6	28.3	28.0
50	35.8	35.4	35.0

	41̄	41
6	4.1	4.1
7	4.8	4.8
8	5.5	5.4
9	6.2	6.1
10	6.9	6.8
20	13.8	13.6
30	20.7	20.5
40	27.6	27.3
50	34.6	34.1

	39	38̄	38
6	3.9	3.8	3.8
7	4.5	4.5	4.4
8	5.2	5.1	5.0
9	5.8	5.8	5.7
10	6.5	6.4	6.3
20	13.0	12.8	12.6
30	19.5	19.2	19.0
40	26.0	25.6	25.3
50	32.5	32.1	31.6

	37̄	37	36̄
6	3.7	3.7	3.6
7	4.4	4.3	4.2
8	5.0	4.9	4.8
9	5.6	5.5	5.5
10	6.2	6.1	6.1
20	12.5	12.3	12.1
30	18.7	18.5	18.2
40	25.0	24.6	24.3
50	31.2	30.8	30.4

	4̄	4
6	0.4	0.4
7	0.5	0.4
8	0.6	0.5
9	0.7	0.6
10	0.7	0.6
20	1.5	1.3
30	2.2	2.0
40	3.0	2.6
50	3.7	3.3

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.51 264	37	9.53 697	41	0.46 303	9.97 567	4	60
1	9.51 301	36	9.53 738	41	0.46 262	9.97 562	4	59
2	9.51 337	36	9.53 779	41	0.46 221	9.97 558	4	58
3	9.51 374	36	9.53 820	41	0.46 180	9.97 554	4	57
4	9.51 410	36	9.53 861	41	0.46 139	9.97 549	4	56
5	9.51 447	36	9.53 902	41	0.46 098	9.97 545	4	55
6	9.51 483	36	9.53 943	40	0.46 057	9.97 541	4	54
7	9.51 520	36	9.53 983	41	0.46 016	9.97 536	4	53
8	9.51 556	36	9.54 024	41	0.45 975	9.97 532	4	52
9	9.51 593	36	9.54 065	40	0.45 934	9.97 527	4	51
10	9.51 629	36	9.54 106	41	0.45 894	9.97 523	4	50
11	9.51 665	36	9.54 147	40	0.45 853	9.97 519	4	49
12	9.51 702	36	9.54 187	40	0.45 812	9.97 514	4	48
13	9.51 738	36	9.54 228	41	0.45 772	9.97 510	4	47
14	9.51 774	36	9.54 269	40	0.45 731	9.97 505	4	46
15	9.51 810	36	9.54 309	40	0.45 690	9.97 501	4	45
16	9.51 847	36	9.54 350	40	0.45 650	9.97 497	4	44
17	9.51 883	36	9.54 390	40	0.45 609	9.97 492	4	43
18	9.51 919	36	9.54 431	40	0.45 569	9.97 488	4	42
19	9.51 955	36	9.54 471	40	0.45 528	9.97 483	4	41
20	9.51 991	36	9.54 512	40	0.45 488	9.97 479	4	40
21	9.52 027	36	9.54 552	40	0.45 447	9.97 475	4	39
22	9.52 063	36	9.54 593	40	0.45 407	9.97 470	4	38
23	9.52 099	36	9.54 633	40	0.45 367	9.97 466	4	37
24	9.52 135	35	9.54 673	40	0.45 326	9.97 461	4	36
25	9.52 170	36	9.54 714	40	0.45 286	9.97 457	4	35
26	9.52 206	36	9.54 754	40	0.45 246	9.97 452	4	34
27	9.52 242	35	9.54 794	40	0.45 205	9.97 448	4	33
28	9.52 278	36	9.54 834	40	0.45 165	9.97 443	4	32
29	9.52 314	35	9.54 874	40	0.45 125	9.97 439	4	31
30	9.52 349	35	9.54 915	40	0.45 085	9.97 434	4	30
31	9.52 385	36	9.54 955	40	0.45 045	9.97 430	4	29
32	9.52 421	35	9.54 995	40	0.45 005	9.97 425	4	28
33	9.52 456	35	9.55 035	40	0.44 965	9.97 421	4	27
34	9.52 492	35	9.55 075	40	0.44 925	9.97 416	4	26
35	9.52 527	35	9.55 115	39	0.44 884	9.97 412	4	25
36	9.52 563	35	9.55 155	40	0.44 845	9.97 407	4	24
37	9.52 598	35	9.55 195	40	0.44 805	9.97 403	4	23
38	9.52 634	35	9.55 235	40	0.44 765	9.97 398	4	22
39	9.52 669	35	9.55 275	40	0.44 725	9.97 394	4	21
40	9.52 704	35	9.55 315	40	0.44 685	9.97 389	4	20
41	9.52 740	35	9.55 355	39	0.44 645	9.97 385	4	19
42	9.52 775	35	9.55 394	40	0.44 605	9.97 380	4	18
43	9.52 810	35	9.55 434	39	0.44 565	9.97 376	4	17
44	9.52 846	35	9.55 474	40	0.44 526	9.97 371	4	16
45	9.52 881	35	9.55 514	39	0.44 486	9.97 367	4	15
46	9.52 916	35	9.55 553	40	0.44 446	9.97 362	4	14
47	9.52 951	35	9.55 593	39	0.44 406	9.97 358	4	13
48	9.52 986	35	9.55 633	39	0.44 367	9.97 353	4	12
49	9.53 021	35	9.55 672	39	0.44 327	9.97 349	4	11
50	9.53 056	35	9.55 712	39	0.44 288	9.97 344	4	10
51	9.53 091	35	9.55 751	40	0.44 248	9.97 340	5	9
52	9.53 126	35	9.55 791	39	0.44 208	9.97 335	4	8
53	9.53 161	35	9.55 831	39	0.44 169	9.97 330	4	7
54	9.53 196	34	9.55 870	39	0.44 129	9.97 326	4	6
55	9.53 231	35	9.55 909	39	0.44 090	9.97 321	4	5
56	9.53 266	35	9.55 949	39	0.44 051	9.97 317	4	4
57	9.53 301	34	9.55 988	39	0.44 011	9.97 312	4	3
58	9.53 335	35	9.56 028	39	0.43 972	9.97 308	5	2
59	9.53 370	34	9.56 067	39	0.43 932	9.97 303	4	1
60	9.53 405		9.56 106		0.43 893	9.97 298		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	41	$\overline{40}$	40
6	4.1	4.0	4.0
7	4.8	4.7	4.6
8	5.4	5.4	5.3
9	6.1	6.1	6.0
10	6.8	6.7	6.6
20	13.6	13.5	13.3
30	20.5	20.2	20.0
40	27.3	27.0	26.6
50	34.1	33.7	33.3

	$\overline{39}$	39
6	3.9	3.9
7	4.6	4.5
8	5.2	5.2
9	5.9	5.8
10	6.6	6.5
20	13.1	13.0
30	19.7	19.5
40	26.3	26.0
50	32.9	32.5

	37	$\overline{36}$	36
6	3.7	3.6	3.6
7	4.3	4.2	4.2
8	4.9	4.8	4.8
9	5.5	5.5	5.4
10	6.1	6.1	6.0
20	12.3	12.1	12.0
30	18.5	18.2	18.0
40	24.6	24.3	24.0
50	30.8	30.4	30.0

	$\overline{35}$	35	$\overline{34}$
6	3.5	3.5	3.4
7	4.1	4.1	4.0
8	4.7	4.6	4.6
9	5.3	5.2	5.2
10	5.9	5.8	5.7
20	11.8	11.6	11.5
30	17.7	17.5	17.2
40	23.6	23.3	23.0
50	29.6	29.1	28.7

	5	$\overline{4}$	4
6	0.5	0.4	0.4
7	0.6	0.5	0.4
8	0.6	0.6	0.5
9	0.7	0.7	0.6
10	0.8	0.7	0.6
20	1.6	1.5	1.3
30	2.5	2.2	2.0
40	3.3	3.0	2.6
50	4.1	3.7	3.3

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	d.	
0	9.53 405	35	9.56 106	39	0.43 893	9.97 298	4	60
1	9.53 440	34	9.56 146	39	0.43 854	9.97 294	4	59
2	9.53 474	34	9.56 185	39	0.43 815	9.97 289	4	58
3	9.53 509	35	9.56 224	39	0.43 775	9.97 285	5	57
4	9.53 544	34	9.56 263	39	0.43 736	9.97 280	4	56
5	9.53 578	34	9.56 303	39	0.43 697	9.97 275	4	55
6	9.53 613	34	9.56 342	39	0.43 658	9.97 271	4	54
7	9.53 647	34	9.56 381	39	0.43 619	9.97 266	5	53
8	9.53 682	34	9.56 420	39	0.43 580	9.97 261	4	52
9	9.53 716	34	9.56 459	39	0.43 540	9.97 257	4	51
10	9.53 750	34	9.56 498	39	0.43 501	9.97 252	4	50
11	9.53 785	34	9.56 537	39	0.43 462	9.97 248	5	49
12	9.53 819	34	9.56 576	39	0.43 423	9.97 243	4	48
13	9.53 854	34	9.56 615	38	0.43 384	9.97 238	4	47
14	9.53 888	34	9.56 654	39	0.43 346	9.97 234	5	46
15	9.53 922	34	9.56 693	39	0.43 307	9.97 229	4	45
16	9.53 956	34	9.56 732	39	0.43 268	9.97 224	4	44
17	9.53 990	34	9.56 771	39	0.43 229	9.97 220	5	43
18	9.54 025	34	9.56 810	38	0.43 190	9.97 215	4	42
19	9.54 059	34	9.56 848	39	0.43 151	9.97 210	4	41
20	9.54 093	34	9.56 887	38	0.43 112	9.97 206	5	40
21	9.54 127	34	9.56 926	39	0.43 074	9.97 201	4	39
22	9.54 161	34	9.56 965	38	0.43 035	9.97 196	5	38
23	9.54 195	34	9.57 003	38	0.42 996	9.97 191	4	37
24	9.54 229	33	9.57 042	39	0.42 958	9.97 187	4	36
25	9.54 263	34	9.57 081	38	0.42 919	9.97 182	5	35
26	9.54 297	34	9.57 119	38	0.42 880	9.97 177	4	34
27	9.54 331	34	9.57 158	38	0.42 842	9.97 173	5	33
28	9.54 365	33	9.57 196	38	0.42 803	9.97 168	4	32
29	9.54 398	34	9.57 235	39	0.42 765	9.97 163	4	31
30	9.54 432	34	9.57 274	38	0.42 726	9.97 159	5	30
31	9.54 466	33	9.57 312	38	0.42 687	9.97 154	4	29
32	9.54 500	34	9.57 350	38	0.42 649	9.97 149	5	28
33	9.54 534	33	9.57 389	38	0.42 611	9.97 144	4	27
34	9.54 567	33	9.57 427	38	0.42 572	9.97 140	5	26
35	9.54 601	33	9.57 466	38	0.42 534	9.97 135	4	25
36	9.54 634	34	9.57 504	38	0.42 495	9.97 130	5	24
37	9.54 668	33	9.57 542	38	0.42 457	9.97 125	4	23
38	9.54 702	33	9.57 581	38	0.42 419	9.97 121	5	22
39	9.54 735	33	9.57 619	38	0.42 380	9.97 116	4	21
40	9.54 769	33	9.57 657	38	0.42 342	9.97 111	5	20
41	9.54 802	33	9.57 696	38	0.42 304	9.97 106	4	19
42	9.54 836	33	9.57 734	38	0.42 266	9.97 102	5	18
43	9.54 869	33	9.57 772	38	0.42 227	9.97 097	5	17
44	9.54 902	33	9.57 810	38	0.42 189	9.97 092	4	16
45	9.54 936	33	9.57 848	38	0.42 151	9.97 087	5	15
46	9.54 969	33	9.57 886	38	0.42 113	9.97 082	4	14
47	9.55 002	33	9.57 925	38	0.42 075	9.97 078	5	13
48	9.55 036	33	9.57 963	38	0.42 037	9.97 073	4	12
49	9.55 069	33	9.58 001	38	0.41 999	9.97 068	5	11
50	9.55 102	33	9.58 039	38	0.41 961	9.97 063	5	10
51	9.55 135	33	9.58 077	38	0.41 923	9.97 058	4	9
52	9.55 168	33	9.58 115	38	0.41 885	9.97 054	5	8
53	9.55 202	33	9.58 153	37	0.41 847	9.97 049	5	7
54	9.55 235	33	9.58 190	38	0.41 809	9.97 044	4	6
55	9.55 268	33	9.58 228	38	0.41 771	9.97 039	5	5
56	9.55 301	33	9.58 266	38	0.41 733	9.97 034	5	4
57	9.55 334	33	9.58 304	37	0.41 695	9.97 029	4	3
58	9.55 367	33	9.58 342	38	0.41 658	9.97 025	5	2
59	9.55 400	33	9.58 380	37	0.41 620	9.97 020	5	1
60	9.55 433		9.58 417		0.41 582	9.97 015		0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	$\overline{39}$	39
6	3.9	3.9
7	4.6	4.5
8	5.2	5.2
9	5.9	5.8
10	6.6	6.5
20	13.1	13.0
30	19.7	19.5
40	26.3	26.0
50	32.9	32.5

	$\overline{38}$	38	$\overline{37}$
6	3.8	3.8	3.7
7	4.5	4.4	4.4
8	5.1	5.0	5.0
9	5.8	5.7	5.6
10	6.4	6.3	6.2
20	12.8	12.6	12.5
30	19.2	19.0	18.7
40	25.6	25.3	25.0
50	32.1	31.6	31.2

	35	$\overline{34}$	34
6	3.5	3.4	3.4
7	4.1	4.0	3.9
8	4.6	4.6	4.5
9	5.2	5.2	5.1
10	5.8	5.7	5.6
20	11.6	11.5	11.3
30	17.5	17.2	17.0
40	23.3	23.0	22.6
50	29.1	28.7	28.3

	$\overline{33}$	33
6	3.3	3.3
7	3.9	3.8
8	4.4	4.4
9	5.0	4.9
10	5.6	5.5
20	11.1	11.0
30	16.7	16.5
40	22.3	22.0
50	27.9	27.5

	5	$\overline{4}$
6	0.5	0.4
7	0.6	0.5
8	0.6	0.6
9	0.7	0.7
10	0.8	0.7
20	1.6	1.5
30	2.5	2.2
40	3.3	3.0
50	4.1	3.7

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.55 433	33	9.58 417	33	0.41 582	9.97 015	4	60
1	9.55 466	32	9.58 455	37	0.41 544	9.97 010	5	59
2	9.55 498	33	9.58 493	38	0.41 507	9.97 005	5	58
3	9.55 531	33	9.58 531	37	0.41 469	9.97 000	5	57
4	9.55 564	32	9.58 5[illegible]	37	0.41 431	9.96 995	4	56
5	9.55 597	33	9.58 606	38	0.41 394	9.96 991	5	55
6	9.55 630	32	9.58 644	37	0.41 356	9.96 986	5	54
7	9.55 662	33	9.58 681	37	0.41 318	9.96 981	5	53
8	9.55 695	32	9.58 719	37	0.41 281	9.96 976	4	52
9	9.55 728	32	9.58 756	37	0.41 243	9.96 971	5	51
10	9.55 760	32	9.58 794	37	0.41 206	9.96 966	5	50
11	9.55 793	33	9.58 831	37	0.41 168	9.96 961	5	49
12	9.55 826	32	9.58 869	37	0.41 131	9.96 956	4	48
13	9.55 858	32	9.58 906	37	0.41 093	9.96 952	5	47
14	9.55 891	32	9.58 944	37	0.41 056	9.96 947	5	46
15	9.55 923	32	9.58 981	37	0.41 018	9.96 942	5	45
16	9.55 956	32	9.59 019	37	0.40 981	9.96 937	5	44
17	9.55 988	32	9.59 056	37	0.40 944	9.96 932	5	43
18	9.56 020	32	9.59 093	37	0.40 906	9.96 927	4	42
19	9.56 053	32	9.59 131	37	0.40 869	9.96 922	5	41
20	9.56 085	32	9.59 168	37	0.40 832	9.96 917	5	40
21	9.56 118	32	9.59 205	37	0.40 794	9.96 912	5	39
22	9.56 150	32	9.59 242	37	0.40 757	9.96 907	5	38
23	9.56 182	32	9.59 280	37	0.40 720	9.96 902	5	37
24	9.56 214	32	9.59 317	37	0.40 683	9.96 897	5	36
25	9.56 247	32	9.59 354	37	0.40 646	9.96 892	5	35
26	9.56 279	32	9.59 391	37	0.40 608	9.96 887	5	34
27	9.56 311	32	9.59 428	37	0.40 571	9.96 882	5	33
28	9.56 343	32	9.59 465	37	0.40 534	9.96 877	4	32
29	9.56 375	32	9.59 50[illegible]	37	0.40 497	9.96 873	5	31
30	9.56 407	32	9.59 540	37	0.40 460	9.96 868	5	30
31	9.56 439	32	9.59 577	37	0.40 423	9.96 863	5	29
32	9.56 471	32	9.59 614	37	0.40 386	9.96 858	5	28
33	9.56 503	32	9.59 651	37	0.40 349	9.96 853	5	27
34	9.56 535	32	9.59 688	36	0.40 312	9.96 848	5	26
35	9.56 567	32	9.59 724	37	0.40 275	9.96 843	5	25
36	9.56 599	32	9.59 761	37	0.40 238	9.96 838	5	24
37	9.56 631	31	9.59 798	37	0.40 201	9.96 833	5	23
38	9.56 663	32	9.59 835	36	0.40 164	9.96 828	5	22
39	9.56 695	32	9.59 872	37	0.40 128	9.96 823	5	21
40	9.56 727	31	9.59 909	37	0.40 091	9.96 818	5	20
41	9.56 758	32	9.59 946	36	0.40 054	9.96 813	5	19
42	9.56 790	31	9.59 982	37	0.40 017	9.96 808	5	18
43	9.56 822	32	9.60 019	36	0.39 980	9.96 802	5	17
44	9.56 854	31	9.60 056	37	0.39 944	9.96 797	5	16
45	9.56 885	31	9.60 093	36	0.39 907	9.96 792	5	15
46	9.56 917	32	9.60 129	37	0.39 870	9.96 787	5	14
47	9.56 949	31	9.60 166	36	0.39 833	9.96 782	5	13
48	9.56 980	31	9.60 203	36	0.39 797	9.96 777	5	12
49	9.57 012	31	9.60 239	36	0.39 760	9.96 772	5	11
50	9.57 043	31	9.60 276	36	0.39 724	9.96 767	5	10
51	9.57 075	31	9.60 312	37	0.39 687	9.96 762	5	9
52	9.57 106	31	9.60 349	36	0.39 650	9.96 757	5	8
53	9.57 138	31	9.60 386	36	0.39 614	9.96 752	5	7
54	9.57 169	31	9.60 422	36	0.39 577	9.96 747	5	6
55	9.57 201	31	9.60 459	36	0.39 541	9.96 742	5	5
56	9.57 232	31	9.60 495	36	0.39 504	9.96 737	5	4
57	9.57 263	31	9.60 531	36	0.39 468	9.96 732	5	3
58	9.57 295	31	9.60 568	36	0.39 432	9.96 727	5	2
59	9.57 326	31	9.60 604	36	0.39 395	9.96 721	5	1
60	9.57 357		9.60 641		0.39 359	9.96 716		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	38	37̄	37
6	3.8	3.7	3.7
7	4.4	4.4	4.3
8	5.0	5.0	4.9
9	5.7	5.6	5.5
10	6.3	6.2	6.1
20	12.6	12.5	12.3
30	19.0	18.7	18.5
40	25.3	25.0	24.6
50	31.6	31.2	30.8

	36̄	36
6	3.6	3.6
7	4.2	4.2
8	4.8	4.8
9	5.5	5.4
10	6.1	6.0
20	12.1	12.0
30	18.2	18.0
40	24.3	24.0
50	30.4	30.0

	33	32̄	32
6	3.3	3.2	3.2
8	3.8	3.8	3.7
7	4.4	4.3	4.2
9	4.9	4.9	4.8
10	5.5	5.4	5.3
20	11.0	10.8	10.6
30	16.5	16.2	16.0
40	22.0	21.6	21.3
50	27.5	27.1	26.6

	31̄	31
6	3.1	3.1
7	3.7	3.6
8	4.2	4.1
9	4.7	4.6
10	5.2	5.1
20	10.5	10.3
30	15.7	15.5
40	21.0	20.6
50	26.2	25.8

	5̄	5	4̄
6	0.5	0.5	0.4
7	0.6	0.6	0.5
8	0.7	0.6	0.6
9	0.8	0.7	0.7
10	0.9	0.8	0.7
20	1.8	1.6	1.5
30	2.7	2.5	2.2
40	3.6	3.3	3.0
50	4.6	4.1	3.7

P. P.

'	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.57 357	31	9.60 641	36	0.39 359	9.96 716	5	60
1	9.57 389	31	9.60 677	36	0.39 322	9.96 711	5	59
2	9.57 420	31	9.60 713	36	0.39 286	9.96 706	5	58
3	9.57 451	31	9.60 750	36	0.39 250	9.96 701	5	57
4	9.57 482	31	9.60 786	36	0.39 213	9.96 696	5	56
5	9.57 513	31	9.60 822	36	0.39 177	9.96 691	5	55
6	9.57 544	31	9.60 859	36	0.39 141	9.96 686	5	54
7	9.57 576	31	9.60 895	36	0.39 105	9.96 681	5	53
8	9.57 607	31	9.60 931	36	0.39 069	9.96 675	5	52
9	9.57 638	31	9.60 967	36	0.39 032	9.96 670	5	51
10	9.57 669	31	9.61 003	36	0.38 996	9.96 665	5	50
11	9.57 700	31	9.61 039	36	0.38 960	9.96 660	5	49
12	9.57 731	31	9.61 076	36	0.38 924	9.96 655	5	48
13	9.57 762	30	9.61 112	36	0.38 888	9.96 650	5	47
14	9.57 792	31	9.61 148	36	0.38 852	9.96 644	5	46
15	9.57 823	31	9.61 184	36	0.38 816	9.96 639	5	45
16	9.57 854	31	9.61 220	36	0.38 780	9.96 634	5	44
17	9.57 885	30	9.61 256	36	0.38 744	9.96 629	5	43
18	9.57 916	31	9.61 292	36	0.38 708	9.96 624	5	42
19	9.57 947	30	9.61 328	36	0.38 672	9.96 619	5	41
20	9.57 977	31	9.61 364	36	0.38 636	9.96 613	5	40
21	9.58 008	30	9.61 400	36	0.38 600	9.96 608	5	39
22	9.58 039	31	9.61 436	36	0.38 564	9.96 603	5	38
23	9.58 070	30	9.61 472	35	0.38 528	9.96 598	5	37
24	0.58 100	30	9.61 507	36	0.38 492	9.96 593	5	36
25	9.58 131	31	9.61 543	36	0.38 456	9.96 587	5	35
26	9.58 162	30	7.61 579	35	0.38 420	9.96 582	5	34
27	9.58 192	30	9.61 615	36	0.38 385	9.96 577	5	33
28	9.58 223	30	9.61 651	35	0.38 349	9.96 572	5	32
29	9.58 253	30	9.61 686	36	0.38 313	9.96 567	5	31
30	9.58 284	30	9.61 722	35	0.38 277	9.96 561	5	30
31	9.58 314	30	9.61 758	36	0.38 242	9.96 556	5	29
32	9.58 345	30	9.61 794	35	0.38 206	9.96 551	5	28
33	9.58 375	30	9.61 829	35	0.38 170	9.96 546	5	27
34	9.58 406	30	9.61 865	36	0.38 135	9.96 540	5	26
35	9.58 436	30	9.61 901	35	0.38 099	9.96 535	5	25
36	9.58 466	30	9.61 936	35	0.38 063	9.96 530	5	24
37	9.58 497	30	9.61 972	35	0.38 028	9.96 525	5	23
38	9.58 527	30	9.62 007	35	0.37 992	9.96 519	5	22
39	9.58 557	30	9.62 043	35	0.37 957	9.96 514	5	21
40	9.58 587	30	9.62 078	35	0.37 921	9.96 509	5	20
41	9.58 618	30	9.62 114	35	0.37 886	9.96 503	5	19
42	9.58 648	30	9.62 149	35	0.37 850	9.96 498	5	18
43	9.58 678	30	9.62 185	35	0.37 815	9.96 493	5	17
44	9.58 708	30	9.62 220	35	0.37 779	9.96 488	5	16
45	9.58 738	30	9.62 256	35	0.37 744	9.96 482	5	15
46	9.58 769	30	9.62 291	35	0.37 708	9.96 477	5	14
47	9.58 799	30	9.62 327	35	0.37 673	9.96 472	5	13
48	9.58 829	30	9.62 362	35	0.37 637	9.96 466	5	12
49	9.58 859	30	9.62 397	35	0.37 602	9.96 461	5	11
50	9.58 889	30	9.62 433	35	0.37 567	9.96 456	5	10
51	9.58 919	30	9.62 468	35	0.37 531	9.96 450	5	9
52	9.58 949	30	9.62 503	35	0.37 496	9.96 445	5	8
53	9.58 979	30	9.62 539	35	0.37 461	9.96 440	5	7
54	9.59 009	29	9.62 574	35	0.37 426	9.96 434	5	6
55	9.59 038	30	9.62 609	35	0.37 390	9.96 429	5	5
56	9.59 068	30	9.62 644	35	0.37 355	9.96 424	5	4
57	9.59 098	29	9.62 679	35	0.37 320	9.96 418	5	3
58	9.59 128	30	9.62 715	35	0.37 285	9.96 413	5	2
59	9.59 158	30	9.62 750	35	0.37 250	9.96 408	5	1
60	9.59 188		9.62 785		0.37 215	9.96 402		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	'

P. P.

	36	36
6	3.6	3.6
7	4.2	4.2
8	4.8	4.8
9	5.5	5.4
10	6.1	6.0
20	12.1	12.0
30	18.2	18.0
40	24.3	24.0
50	30.4	30.0

	35	35
6	3.5	3.5
7	4.1	4.1
8	4.7	4.6
9	5.3	5.2
10	5.9	5.8
20	11.8	11.6
30	17.7	17.5
40	23.6	23.3
50	29.6	29.1

	31	31
6	3.1	3.1
7	3.7	3.6
8	4.2	4.1
9	4.7	4.6
10	5.2	5.1
20	10.5	10.3
30	15.7	15.5
40	21.0	20.6
50	26.2	25.8

	30	30	29
6	3.0	3.0	2.9
7	3.5	3.5	3.4
8	4.0	4.0	3.9
9	4.6	4.5	4.4
10	5.1	5.0	4.9
20	10.1	10.0	9.8
30	15.2	15.0	14.7
40	20.3	20.0	19.6
50	25.4	25.0	24.6

	5	5
6	0.5	0.5
7	0.6	0.6
8	0.7	0.6
9	0.8	0.7
10	0.9	0.8
20	1.8	1.6
30	2.7	2.5
40	3.6	3.3
50	4.6	4.1

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.59 188	29	9.62 785	35	0.37 215	9.96 402	5	60
1	9.59 217	30	9.62 820	35	0.37 179	9.96 397	5	59
2	9.59 247	29	9.62 855	35	0.37 144	9.96 392	5	58
3	9.59 277	29	9.62 890	35	0.37 109	9.96 386	5	57
4	9.59 306	30	9.62 925	35	0.37 074	9.96 381	5	56
5	9.59 336	29	9.62 960	35	0.37 039	9.96 375	5	55
6	9.59 366	29	9.62 995	35	0.37 004	9.96 370	5	54
7	9.59 395	29	9.63 030	35	0.36 969	9.96 365	5	53
8	9.59 425	29	9.63 065	35	0.36 934	9.96 359	5	52
9	9.59 454	29	9.63 100	35	0.36 899	9.96 354	5	51
10	9.59 484	29	9.63 135	35	0.36 864	9.96 349	5	50
11	9.59 513	29	9.63 170	35	0.36 829	9.96 343	5	49
12	9.59 543	29	9.63 205	35	0.36 794	9.96 338	5	48
13	9.59 572	29	9.63 240	34	0.36 760	9.96 332	5	47
14	9.59 602	29	9.63 275	35	0.36 725	9.96 327	5	46
15	9.59 631	29	9.63 310	35	0.36 690	9.96 321	5	45
16	9.59 661	29	9.63 344	34	0.36 655	9.96 316	5	44
17	9.59 690	29	9.63 379	35	0.36 620	9.96 311	5	43
18	9.59 719	29	9.63 414	35	0.36 585	9.96 305	5	42
19	9.59 749	29	9.63 449	34	0.36 551	9.96 300	5	41
20	9.59 778	29	9.63 484	35	0.36 516	9.96 294	5	40
21	9.59 807	29	9.63 518	34	0.36 481	9.96 289	5	39
22	9.59 837	29	9.63 553	34	0.36 447	9.96 283	5	38
23	9.59 866	29	9.63 588	35	0.36 412	9.96 278	5	37
24	9.59 895	29	9.63 622	34	0.36 377	9.96 272	5	36
25	9.59 924	29	9.63 657	34	0.36 343	9.96 267	5	35
26	9.59 953	29	9.63 692	35	0.36 308	9.96 261	5	34
27	9.59 982	29	9.63 726	34	0.36 273	9.96 256	5	33
28	9.60 012	29	9.63 761	34	0.36 239	9.96 251	5	32
29	9.60 041	29	9.63 795	34	0.36 204	9.96 245	5	31
30	9.60 070	29	9.63 830	34	0.36 170	9.96 240	5	30
31	9.60 099	29	9.63 864	34	0.36 135	9.96 234	5	29
32	9.60 128	29	9.63 899	34	0.36 101	9.96 229	5	28
33	9.60 157	29	9.63 933	34	0.36 066	9.96 223	5	27
34	9.60 186	29	9.63 968	34	0.36 032	9.96 218	5	26
35	9.60 215	29	9.64 002	34	0.35 997	9.96 212	6	25
36	9.60 244	29	9.64 037	34	0.35 963	9.96 206	5	24
37	9.60 273	28	9.64 071	34	0.35 928	9.96 201	5	23
38	9.60 301	29	9.64 106	34	0.35 894	9.96 195	5	22
39	9.60 330	29	9.64 140	34	0.35 859	9.96 190	5	21
40	9.60 359	29	9.64 174	34	0.35 825	9.96 184	5	20
41	9.60 388	28	9.64 209	34	0.35 791	9.96 179	5	19
42	9.60 417	29	9.64 243	34	0.35 756	9.96 173	5	18
43	9.60 445	28	9.64 277	34	0.35 722	9.96 168	5	17
44	9.60 474	29	9.64 312	34	0.35 688	9.96 162	5	16
45	9.60 503	28	9.64 346	34	0.35 653	9.96 157	5	15
46	9.60 532	29	9.64 380	34	0.35 619	9.96 151	5	14
47	9.60 560	28	9.64 415	34	0.35 585	9.96 146	6	13
48	9.60 589	28	9.64 449	34	0.35 551	9.96 140	5	12
49	9.60 618	29	9.64 483	34	0.35 517	9.96 134	5	11
50	9.60 646	28	9.64 517	34	0.35 482	9.96 129	5	10
51	9.60 675	28	9.64 551	34	0.35 448	9.96 123	5	9
52	9.60 703	28	9.64 585	34	0.35 414	9.96 118	5	8
53	9.60 732	28	9.64 620	34	0.35 380	9.96 112	6	7
54	9.60 760	28	9.64 654	34	0.35 346	9.96 106	5	6
55	9.60 789	28	9.64 688	34	0.35 312	9.96 101	5	5
56	9.60 817	28	9.64 722	34	0.35 278	9.96 095	5	4
57	9.60 846	28	9.64 756	34	0.35 244	9.96 090	5	3
58	9.60 874	28	9.64 790	34	0.35 209	9.96 084	6	2
59	9.60 903	28	9.64 824	34	0.35 175	9.96 078	5	1
60	9.60 931		9.64 858		0.35 141	9.96 073		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	35	35
6	3.5	3.5
7	4.1	4.1
8	4.7	4.6
9	5.3	5.2
10	5.9	5.8
20	11.8	11.6
30	17.7	17.5
40	23.6	23.3
50	29.6	29.1

	34	34
6	3.4	3.4
7	4.0	3.9
8	4.6	4.5
9	5.2	5.1
10	5.7	5.6
20	11.5	11.3
30	17.2	17.0
40	23.0	22.6
50	28.7	28.3

	30
6	3.0
7	3.5
8	4.0
9	4.5
10	5.0
20	10.0
30	15.0
40	20.0
50	25.0

	29	29	28
6	2.9	2.9	2.8
7	3.4	3.4	3.3
8	3.9	3.8	3.8
9	4.4	4.3	4.3
10	4.9	4.8	4.7
20	9.8	9.6	9.5
30	14.7	14.5	14.2
40	19.6	19.3	19.0
50	24.6	24.1	23.7

	6	5	5
6	0.6	0.5	0.5
7	0.7	0.6	0.6
8	0.8	0.7	0.6
9	0.9	0.8	0.7
10	1.0	0.9	0.8
20	2.0	1.8	1.6
30	3.0	2.7	2.5
40	4.0	3.6	3.3
50	5.0	4.6	4.1

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.60 931	28	9.64 858	34	0.35 141	9.96 073	5	60
1	9.60 959	28	9.64 892	34	0.35 107	9.96 067	5	59
2	9.60 988	28	9.64 926	33	0.35 073	9.96 062	6	58
3	9.61 016	28	9.64 960	34	0.35 040	9.96 056	5	57
4	9.61 044	28	9.64 994	34	0.35 006	9.96 050	5	56
5	9.61 073	28	9.65 028	34	0.34 972	9.96 045	6	55
6	9.61 101	28	9.65 062	34	0.34 938	9.96 039	5	54
7	9.61 129	28	9.65 096	33	0.34 904	9.96 033	5	53
8	9.61 157	28	9.65 129	34	0.34 870	9.96 028	6	52
9	9.61 186	28	9.65 163	34	0.34 836	9.96 022	5	51
10	9.61 214	28	9.65 197	33	0.34 802	9.96 016	5	50
11	9.61 242	28	9.65 231	34	0.34 769	9.96 011	6	49
12	9.61 270	28	9.65 265	34	0.34 735	9.96 005	5	48
13	9.61 298	28	9.65 299	33	0.34 701	9.95 999	5	47
14	9.61 326	28	9.65 332	34	0.34 667	9.95 994	6	46
15	9.61 354	28	9.65 366	33	0.34 633	9.95 988	5	45
16	9.61 382	28	9.65 400	33	0.34 600	9.95 982	5	44
17	9.61 410	28	9.65 433	34	0.34 566	9.95 977	6	43
18	9.61 438	28	9.65 467	33	0.34 532	9.95 971	5	42
19	9.61 466	28	9.65 501	34	0.34 499	9.95 965	6	41
20	9.61 494	28	9.65 535	33	0.34 465	9.95 959	5	40
21	9.61 522	27	9.65 568	33	0.34 431	9.95 954	6	39
22	9.61 550	28	9.65 602	33	0.34 398	9.95 948	5	38
23	9.61 578	28	9.65 635	33	0.34 364	9.95 942	5	37
24	9.61 606	28	9.65 669	34	0.34 331	9.95 937	6	36
25	9.61 634	27	9.65 703	33	0.34 297	9.95 931	5	35
26	9.61 661	28	9.65 736	33	0.34 263	9.95 925	6	34
27	9.61 689	27	9.65 770	33	0.34 230	9.95 919	5	33
28	9.61 717	28	9.65 803	33	0.34 196	9.95 914	6	32
29	9.61 745	27	9.65 837	33	0.34 163	9.95 908	5	31
30	9.61 772	28	9.65 870	33	0.34 129	9.95 902	6	30
31	9.61 800	27	9.65 904	33	0.34 096	9.95 896	5	29
32	9.61 828	28	9.65 937	33	0.34 062	9.95 891	6	28
33	9.61 856	27	9.65 971	33	0.34 029	9.95 885	6	27
34	9.61 883	27	9.66 004	33	0.33 996	9.95 879	5	26
35	9.61 911	27	9.66 037	33	0.33 962	9.95 873	6	25
36	9.61 938	27	9.66 071	33	0.33 929	9.95 867	5	24
37	9.61 966	28	9.66 104	33	0.33 895	9.95 862	6	23
38	9.61 994	27	9.66 137	33	0.33 862	9.95 856	5	22
39	9.62 021	27	9.66 171	33	0.33 829	9.95 850	6	21
40	9.62 049	27	9.66 204	33	0.33 795	9.95 844	6	20
41	9.62 076	27	9.66 237	33	0.33 762	9.95 838	5	19
42	9.62 104	27	9.66 271	33	0.33 729	9.95 833	6	18
43	9.62 131	27	9.66 304	33	0.33 696	9.95 827	5	17
44	9.62 158	27	9.66 337	33	0.33 662	9.95 821	6	16
45	9.62 186	27	9.66 370	33	0.33 629	9.95 815	6	15
46	9.62 213	27	9.66 404	33	0.33 596	9.95 809	5	14
47	9.62 241	27	9.66 437	33	0.33 563	9.95 804	6	13
48	9.62 268	27	9.66 470	33	0.33 529	9.95 798	6	12
49	9.62 295	27	9.66 503	33	0.33 496	9.95 792	5	11
50	9.62 323	27	9.66 536	33	0.33 463	9.95 786	6	10
51	9.62 350	27	9.66 570	33	0.33 430	9.95 780	6	9
52	9.62 377	27	9.66 603	33	0.33 397	9.95 774	6	8
53	9.62 404	27	9.66 636	33	0.33 364	9.95 768	5	7
54	9.62 432	27	9.66 669	33	0.33 331	9.95 763	6	6
55	9.62 459	27	9.66 702	33	0.33 298	9.95 757	6	5
56	9.62 486	27	9.66 735	33	0.33 265	9.95 751	6	4
57	9.62 513	27	9.66 768	33	0.33 232	9.95 745	5	3
58	9.62 540	27	9.66 801	33	0.33 198	9.95 739	6	2
59	9.62 567	27	9.66 834	33	0.33 165	9.95 733	6	1
60	9.62 595		9.66 867		0.33 132	9.95 727		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	34	33	33
6	3.4	3.3	3.3
7	3.9	3.9	3.8
8	4.5	4.4	4.4
9	5.1	5.0	4.9
10	5.6	5.6	5.5
20	11.3	11.1	11.0
30	17.0	16.7	16.5
40	22.6	22.3	22.0
50	28.3	27.9	27.5

	28	28
6	2.8	2.8
7	3.3	3.2
8	3.8	3.7
9	4.3	4.2
10	4.7	4.6
20	9.5	9.3
30	14.2	14.0
40	19.0	18.6
50	23.7	23.3

	27	27
6	2.7	2.7
7	3.2	3.1
8	3.6	3.6
9	4.1	4.0
10	4.6	4.5
20	9.1	9.0
30	13.7	13.5
40	18.3	18.0
50	22.9	22.5

	6	5
6	0.6	0.5
7	0.7	0.6
8	0.8	0.7
9	0.9	0.8
10	1.0	0.9
20	2.0	1.8
30	3.0	2.7
40	4.0	3.6
50	5.0	4.6

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.62 595	27	9.66 867	32	0.33 132	9.95 727	6	60
1	9.62 622	27	9.66 900	33	0.33 100	9.95 721	5	59
2	9.62 649	27	9.66 933	33	0.33 067	9.95 716	6	58
3	9.62 676	27	9.66 966	33	0.33 034	9.95 710	6	57
4	9.62 703	27	9.66 999	33	0.33 001	9.95 704	6	56
5	9.62 730	27	9.67 032	33	0.32 968	9.95 698	6	55
6	9.62 757	27	9.67 065	32	0.32 935	9.95 692	6	54
7	9.62 784	27	9.67 097	33	0.32 902	9.95 686	5	53
8	9.62 811	27	9.67 130	33	0.32 869	9.95 680	6	52
9	9.62 838	26	9.67 163	33	0.32 836	9.95 674	6	51
10	9.62 864	27	9.67 196	32	0.32 803	9.95 668	6	50
11	9.62 891	27	9.67 229	33	0.32 771	9.95 662	6	49
12	9.62 918	27	9.67 262	32	0.32 738	9.95 656	6	48
13	9.62 945	26	9.67 294	33	0.32 705	9.95 650	6	47
14	9.62 972	27	9.67 327	32	0.32 672	9.95 644	6	46
15	9.62 999	26	9.67 360	33	0.32 640	9.95 638	6	45
16	9.63 025	27	9.67 393	32	0.32 607	9.95 632	5	44
17	9.63 052	26	9.67 425	33	0.32 574	9.95 627	6	43
18	9.63 079	27	9.67 458	32	0.32 541	9.95 621	6	42
19	9.63 106	26	9.67 491	32	0.32 509	9.95 615	6	41
20	9.63 132	27	9.67 523	33	0.32 476	9.95 609	6	40
21	9.63 159	26	9.67 556	32	0.32 443	9.95 603	6	39
22	9.63 186	26	9.67 589	32	0.32 411	9.95 597	6	38
23	9.63 212	26	9.67 621	33	0.32 378	9.95 591	6	37
24	9.63 239	27	9.67 654	32	0.32 345	9.95 585	6	36
25	9.63 266	26	9.67 687	32	0.32 313	9.95 579	6	35
26	9.63 292	26	9.67 719	32	0.32 280	9.95 573	6	34
27	9.63 319	26	9.67 752	32	0.32 248	9.95 567	6	33
28	9.63 345	26	9.67 784	32	0.32 215	9.95 561	6	32
29	9.63 372	26	9.67 817	32	0.32 183	9.95 555	6	31
30	9.63 398	26	9.67 849	32	0.32 150	9.95 549	6	30
31	9.63 425	26	9.67 882	32	0.32 118	9.95 543	6	29
32	9.63 451	26	9.67 914	32	0.32 085	9.95 537	6	28
33	9.63 478	26	9.67 947	32	0.32 053	9.95 530	6	27
34	9.63 504	26	9.67 979	32	0.32 020	9.95 524	6	26
35	9.63 530	26	9.68 012	32	0.31 988	9.95 518	6	25
36	9.63 557	26	9.68 044	32	0.31 955	9.95 512	6	24
37	9.63 583	26	9.68 077	32	0.31 923	9.95 506	6	23
38	9.63 609	26	9.68 109	32	0.31 891	9.95 500	6	22
39	9.63 636	26	9.68 141	32	0.31 858	9.95 494	6	21
40	9.63 662	26	9.68 174	32	0.31 826	9.95 488	6	20
41	9.63 688	26	9.68 206	32	0.31 793	9.95 482	6	19
42	9.63 715	26	9.68 238	32	0.31 761	9.95 476	6	18
43	9.63 741	26	9.68 271	32	0.31 729	9.95 470	6	17
44	9.63 767	26	9.68 303	32	0.31 696	9.95 464	6	16
45	9.63 793	26	9.68 335	32	0.31 664	9.95 458	6	15
46	9.63 819	26	9.68 368	32	0.31 632	9.95 452	6	14
47	9.63 846	26	9.68 400	32	0.31 600	9.95 445	6	13
48	9.63 872	26	9.68 432	32	0.31 567	9.95 439	6	12
49	9.63 898	26	9.68 464	32	0.31 535	9.95 433	6	11
50	9.63 924	26	9.68 497	32	0.31 503	9.95 427	6	10
51	9.63 950	26	9.68 529	32	0.31 471	9.95 421	6	9
52	9.63 976	26	9.68 561	32	0.31 439	9.95 415	6	8
53	9.64 002	26	9.68 593	32	0.31 406	9.95 409	6	7
54	9.64 028	26	9.68 625	32	0.31 374	9.95 403	6	6
55	9.64 054	26	9.68 657	32	0.31 342	9.95 397	6	5
56	9.64 080	26	9.68 690	32	0.31 310	9.95 390	6	4
57	9.64 106	26	9.68 722	32	0.31 278	9.95 384	6	3
58	9.64 132	26	9.68 754	32	0.31 246	9.95 378	6	2
59	9.64 158	25	9.68 786	32	0.31 214	9.95 372	6	1
60	9.64 184		9.68 818		0.31 182	9.95 366		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	33	32	32
6	3.3	3.2	3.2
7	3.8	3.8	3.7
8	4.4	4.3	4.2
9	4.9	4.9	4.8
10	5.5	5.4	5.3
20	11.0	10.8	10.6
30	16.5	16.2	16.0
40	22.0	21.6	21.3
50	27.5	27.1	26.6

	27
6	2.7
7	3.1
8	3.6
9	4.0
10	4.5
20	9.0
30	13.5
40	18.0
50	22.5

	26	26	25
6	2.6	2.6	2.5
7	3.1	3.0	3.0
8	3.5	3.4	3.4
9	4.0	3.9	3.8
10	4.4	4.3	4.2
20	8.8	8.6	8.5
30	13.2	13.0	12.7
40	17.6	17.3	17.0
50	22.1	21.6	21.2

	6	6	5
6	0.6	0.6	0.5
7	0.7	0.7	0.6
8	0.8	0.8	0.7
9	1.0	0.9	0.8
10	1.1	1.0	0.9
20	2.1	2.0	1.8
30	3.2	3.0	2.7
40	4.3	4.0	3.6
50	5.4	5.0	4.6

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.64 184	26	9.68 818	32	0.31 182	9.95 366	6	60
1	9.64 210	26	9.68 850	32	0.31 150	9.95 360	6	59
2	9.64 236	26	9.68 882	32	0.31 117	9.95 353	6	58
3	9.64 262	25	9.68 914	32	0.31 085	9.95 347	6	57
4	9.64 287	26	9.68 946	32	0.31 053	9.95 341	6	56
5	9.64 313	26	9.68 978	32	0.31 021	9.95 335	6	55
6	9.64 339	25	9.69 010	32	0.30 989	9.95 329	6	54
7	9.64 365	26	9.69 042	31	0.30 957	9.95 323	6	53
8	9.64 391	25	9.69 074	32	0.30 926	9.95 316	6	52
9	9.64 416	26	9.69 106	32	0.30 894	9.95 310	6	51
10	9.64 442	25	9.69 138	32	0.30 862	9.95 304	6	50
11	9.64 468	25	9.69 170	32	0.30 830	9.95 298	6	49
12	9.64 493	26	9.69 202	32	0.30 798	9.95 292	6	48
13	9.64 519	25	9.69 234	31	0.30 766	9.95 285	6	47
14	9.64 545	25	9.69 265	32	0.30 734	9.95 279	6	46
15	9.64 570	25	9.69 297	32	0.30 702	9.95 273	6	45
16	9.64 596	26	9.69 329	31	0.30 670	9.95 267	6	44
17	9.64 622	25	9.69 361	32	0.30 639	9.95 260	6	43
18	9.64 647	25	9.69 393	32	0.30 607	9.95 254	6	42
19	9.64 673	25	9.69 425	31	0.30 575	9.95 248	6	41
20	9.64 698	25	9.69 456	32	0.30 543	9.95 242	6	40
21	9.64 724	25	9.69 488	31	0.30 511	9.95 235	6	39
22	9.64 749	25	9.69 520	32	0.30 480	9.95 229	6	38
23	9.64 775	25	9.69 552	31	0.30 448	9.95 223	6	37
24	9.64 800	25	9.69 583	32	0.30 416	9.95 217	6	36
25	9.64 826	25	9.69 615	31	0.30 384	9.95 210	6	35
26	9.64 851	25	9.69 647	31	0.30 353	9.95 204	6	34
27	9.64 876	25	9.69 678	32	0.30 321	9.95 198	6	33
28	9.64 902	25	9.69 710	31	0.30 289	9.95 191	6	32
29	9.64 927	25	9.69 742	31	0.30 258	9.95 185	6	31
30	9.64 952	25	9.69 773	32	0.30 226	9.95 179	6	30
31	9.64 978	25	9.69 805	31	0.30 194	9.95 173	6	29
32	9.65 003	25	9.69 837	31	0.30 163	9.95 166	6	28
33	9.65 028	25	9.69 868	31	0.30 131	9.95 160	6	27
34	9.65 054	25	9.69 900	31	0.30 100	9.95 154	6	26
35	9.65 079	25	9.69 931	31	0.30 068	9.95 147	6	25
36	9.65 104	25	9.69 963	31	0.30 037	9.95 141	6	24
37	9.65 129	25	9.69 994	32	0.30 005	9.95 135	6	23
38	9.65 155	25	9.70 026	31	0.29 973	9.95 128	6	22
39	9.65 180	25	9.70 058	31	0.29 942	9.95 122	6	21
40	9.65 205	25	9.70 089	31	0.29 910	9.95 116	6	20
41	9.65 230	25	9.70 121	31	0.29 879	9.95 109	6	19
42	9.65 255	25	9.70 152	31	0.29 847	9.95 103	6	18
43	9.65 280	25	9.70 183	31	0.29 816	9.95 097	6	17
44	9.65 305	25	9.70 215	31	0.29 785	9.95 090	6	16
45	9.65 331	25	9.70 246	31	0.29 753	9.95 084	6	15
46	9.65 356	25	9.70 278	31	0.29 722	9.95 078	6	14
47	9.65 381	25	9.70 309	31	0.29 690	9.95 071	6	13
48	9.65 406	25	9.70 341	31	0.29 659	9.95 065	6	12
49	9.65 431	25	9.70 372	31	0.29 628	9.95 058	6	11
50	9.65 456	25	9.70 403	31	0.29 596	9.95 052	6	10
51	9.65 481	25	9.70 435	31	0.29 565	9.95 046	6	9
52	9.65 506	24	9.70 466	31	0.29 533	9.95 039	6	8
53	9.65 530	25	9.70 497	31	0.29 502	9.95 033	6	7
54	9.65 555	25	9.70 529	31	0.29 471	9.95 026	6	6
55	9.65 580	25	9.70 560	31	0.29 439	9.95 020	6	5
56	9.65 605	24	9.70 591	31	0.29 408	9.95 014	6	4
57	9.65 630	25	9.70 623	31	0.29 377	9.95 007	6	3
58	9.65 655	25	9.70 654	31	0.29 346	9.95 001	6	2
59	9.65 680	24	9.70 685	31	0.29 314	9.94 994	6	1
60	9.65 704		9.70 716		0.29 283	9.94 988		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	32	32
6	3.2	3.2
7	3.8	3.7
8	4.3	4.2
9	4.9	4.8
10	5.4	5.3
20	10.8	10.6
30	16.2	16.0
40	21.6	21.3
50	27.1	26.6

	31	31
6	3.1	3.1
7	3.7	3.6
8	4.2	4.1
9	4.7	4.6
10	5.2	5.1
20	10.5	10.3
30	15.7	15.5
40	21.0	20.6
50	26.2	25.8

	26	25	25
6	2.6	2.5	2.5
7	3.0	3.0	2.9
8	3.4	3.4	3.3
9	3.9	3.8	3.7
10	4.3	4.2	4.1
20	8.6	8.5	8.3
30	13.0	12.7	12.5
40	17.3	17.0	16.6
50	21.6	21.2	20.8

	24	6	6
6	2.4	0.6	0.6
7	2.8	0.7	0.7
8	3.2	0.8	0.8
9	3.7	1.0	0.9
10	4.1	1.1	1.0
20	8.1	2.1	2.0
30	12.2	3.2	3.0
40	16.3	4.3	4.0
50	20.4	5.4	5.0

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot	Log. Cos.	d.	
0	9.65 704	25	9.70 716	31	0.29 283	9.94 988	6	60
1	9.65 729	24	9.70 748	31	0.29 252	9.94 981	6	59
2	9.65 754	25	9.70 779	31	0.29 221	9.94 975	6	58
3	9.65 779	24	9.70 810	31	0.29 190	9.94 969	6	57
4	9.65 803	25	9.70 841	31	0.29 158	9.94 962	6	56
5	9.65 828	24	9.70 872	31	0.29 127	9.94 956	6	55
6	9.65 853	25	9.70 903	31	0.29 096	9.94 949	6	54
7	9.65 878	24	9.70 935	31	0.29 065	9.94 943	6	53
8	9.65 902	24	9.70 966	31	0.29 034	9.94 936	6	52
9	9.65 927	24	9.70 997	31	0.29 003	9.94 930	6	51
10	9.65 951	25	9.71 028	31	0.28 972	9.94 923	6	50
11	9.65 976	24	9.71 059	31	0.28 940	9.94 917	6	49
12	9.66 001	24	9.71 090	31	0.28 909	9.94 910	6	48
13	9.66 025	24	9.71 121	31	0.28 878	9.94 904	6	47
14	9.66 050	24	9.71 152	31	0.28 847	9.94 897	6	46
15	9.66 074	24	9.71 183	31	0.28 816	9.94 891	6	45
16	9.66 099	24	9.71 214	31	0.28 785	9.94 884	6	44
17	9.66 123	24	9.71 245	31	0.28 754	9.94 878	6	43
18	9.66 148	24	9.71 276	31	0.28 723	9.94 871	6	42
19	9.66 172	24	9.71 307	31	0.28 692	9.94 865	6	41
20	9.66 197	24	9.71 338	31	0.28 661	9.94 858	6	40
21	9.66 221	24	9.71 369	31	0.28 630	9.94 852	6	39
22	9.66 246	24	9.71 400	31	0.28 599	9.94 845	6	38
23	9.66 270	24	9.71 431	31	0.28 568	9.94 839	6	37
24	9.66 294	24	9.71 462	31	0.28 537	9.94 832	7	36
25	9.66 319	24	9.71 493	30	0.28 506	9.94 825	6	35
26	9.66 343	24	9.71 524	31	0.28 476	9.94 819	6	34
27	9.66 367	24	9.71 555	31	0.28 445	9.94 812	6	33
28	9.66 392	24	9.71 586	31	0.28 414	9.94 806	6	32
29	9.66 416	24	9.71 617	30	0.28 383	9.94 799	6	31
30	9.66 440	24	9.71 647	31	0.28 352	9.94 793	6	30
31	9.66 465	24	9.71 678	31	0.28 321	9.94 786	7	29
32	9.66 489	24	9.71 709	30	0.28 290	9.94 779	6	28
33	9.66 513	24	9.71 740	31	0.28 260	9.94 773	6	27
34	9.66 537	24	9.71 771	30	0.28 229	9.94 766	6	26
35	9.66 561	24	9.71 801	31	0.28 198	9.94 760	6	25
36	9.66 586	24	9.71 832	31	0.28 167	9.94 753	7	24
37	9.66 610	24	9.71 863	30	0.28 136	9.94 746	6	23
38	9.66 634	24	9.71 894	31	0.28 106	9.94 740	6	22
39	9.66 658	24	9.71 925	30	0.28 075	9.94 733	6	21
40	9.66 682	24	9.71 955	30	0.28 044	9.94 727	6	20
41	9.66 706	24	9.71 986	31	0.28 014	9.94 720	7	19
42	9.66 730	24	9.72 017	30	0.27 983	9.94 713	6	18
43	9.66 754	24	9.72 047	31	0.27 952	9.94 707	6	17
44	9.66 778	24	9.72 078	30	0.27 921	9.94 700	7	16
45	9.66 802	24	9.72 109	30	0.27 891	9.94 693	6	15
46	9.66 826	24	9.72 139	30	0.27 860	9.94 687	6	14
47	9.66 850	24	9.72 170	31	0.27 830	9.94 680	6	13
48	9.66 874	24	9.72 201	30	0.27 799	9.94 674	7	12
49	9.66 898	24	9.72 231	30	0.27 768	9.94 667	6	11
50	9.66 922	24	9.72 262	30	0.27 738	9.94 660	6	10
51	9.66 946	24	9.72 292	30	0.27 707	9.94 654	7	9
52	9.66 970	23	9.72 323	31	0.27 677	9.94 647	6	8
53	9.66 994	24	9.72 354	30	0.27 646	9.94 640	7	7
54	9.67 018	24	9.72 384	30	0.27 615	9.94 633	6	6
55	9.67 042	24	9.72 415	30	0.27 585	9.94 627	6	5
56	9.67 066	23	9.72 445	30	0.27 554	9.94 620	7	4
57	9.67 089	24	9.72 476	30	0.27 524	9.94 613	6	3
58	9.67 113	23	9.72 506	30	0.27 493	9.94 607	7	2
59	9.67 137	24	9.72 537	30	0.27 463	9.94 600	6	1
60	9.67 161		9.72 567		0.27 432	9.94 593		0
	Log. Cos.	d.	Log. Cot	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	31̄	31	30̄
6	3.1	3.1	3.0
7	3.7	3.6	3.5
8	4.2	4.1	4.0
9	4.7	4.6	4.6
10	5.2	5.1	5.1
20	10.5	10.3	10.1
30	15.7	15.5	15.2
40	21.0	20.6	20.3
50	26.2	25.8	25.4

	25
6	2.5
7	2.9
8	3.3
9	3.7
10	4.1
20	8.3
30	12.5
40	16.6
50	20.8

	24̄	24	23̄
6	2.4	2.4	2.3
7	2.8	2.8	2.7
8	3.2	3.2	3.1
9	3.7	3.6	3.5
10	4.1	4.0	3.9
20	8.1	8.0	7.8
30	12.2	12.0	11.7
40	16.3	16.0	15.6
50	20.4	20.0	19.6

	7	6̄	6
6	0.7	0.6	0.6
7	0.8	0.7	0.7
8	0.9	0.8	0.8
9	1.0	1.0	0.9
10	1.1	1.1	1.0
20	2.3	2.1	2.0
30	3.5	3.2	3.0
40	4.6	4.3	4.0
50	5.8	5.4	5.0

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.67 161		9.72 567		0.27 432	9.94 593		60
1	9.67 184	23	9.72 598	30	0.27 402	9.94 587	6	59
2	9.67 208	24	9.72 628	30	0.27 371	9.94 580	7	58
3	9.67 232	23	9.72 659	30	0.27 341	9.94 573	6	57
4	9.67 256	24	9.72 689	30	0.27 311	9.94 566	7	56
5	9.67 279	23	9.72 719	30	0.27 280	9.94 560	6	55
6	9.67 303	23	9.72 750	30	0.27 250	9.94 553	7	54
7	9.67 327	24	9.72 780	30	0.27 219	9.94 546	6	53
8	9.67 350	23	9.72 811	30	0.27 189	9.94 539	7	52
9	9.67 374	23	9.72 841	30	0.27 159	9.94 533	6	51
10	9.67 397	23	9.72 871	30	0.27 128	9.94 526	7	50
11	9.67 421	24	9.72 902	30	0.27 098	9.94 519	6	49
12	9.67 445	23	9.72 932	30	0.27 067	9.94 512	7	48
13	9.67 468	23	9.72 962	30	0.27 037	9.94 506	6	47
14	9.67 492	23	9.72 993	30	0.27 007	9.94 499	7	46
15	9.67 515	23	9.73 023	30	0.26 976	9.94 492	7	45
16	9.67 539	23	9.73 053	30	0.26 946	9.94 485	6	44
17	9.67 562	23	9.73 084	30	0.26 916	9.94 478	7	43
18	9.67 586	23	9.73 114	30	0.26 886	9.94 472	6	42
19	9.67 609	23	9.73 144	30	0.26 855	9.94 465	7	41
20	9.67 633	23	9.73 174	30	0.26 825	9.94 458	7	40
21	9.67 656	23	9.73 205	30	0.26 795	9.94 451	6	39
22	9.67 679	23	9.73 235	30	0.26 765	9.94 444	7	38
23	9.67 703	23	9.73 265	30	0.26 734	9.94 437	7	37
24	9.67 726	23	9.73 295	30	0.26 704	9.94 431	6	30
25	9.67 750	23	9.73 325	30	0.26 674	9.94 424	7	35
26	9.67 773	23	9.73 356	30	0.26 644	9.94 417	7	34
27	9.67 796	23	9.73 386	30	0.26 614	9.94 410	6	33
28	9.67 819	23	9.73 416	30	0.26 584	9.94 403	7	32
29	9.67 843	23	9.73 446	30	0.26 553	9.94 396	7	31
30	9.67 866	23	9.73 476	30	0.26 523	9.94 390	6	30
31	9.67 889	23	9.73 506	30	0.26 493	9.94 383	7	29
32	9.67 913	23	9.73 536	30	0.26 463	9.94 376	7	28
33	9.67 936	23	9.73 567	30	0.26 433	9.94 369	6	27
34	9.67 959	23	9.73 597	30	0.26 403	9.94 362	7	26
35	9.67 982	23	9.73 627	30	0.26 373	9.94 355	7	25
36	9.68 005	23	9.73 657	30	0.26 343	9.94 348	7	24
37	9.68 029	23	9.73 687	30	0.26 313	9.94 341	7	23
38	9.68 052	23	9.73 717	30	0.26 283	9.94 335	6	22
39	9.68 075	23	9.73 747	30	0.26 253	9.94 328	7	21
40	9.68 098	23	9.73 777	30	0.26 223	9.94 321	7	20
41	9.68 121	23	9.73 807	30	0.26 193	9.94 314	7	19
42	9.68 144	23	9.73 837	30	0.26 163	9.94 307	7	18
43	9.68 167	23	9.73 867	30	0.26 133	9.94 300	6	17
44	9.68 190	23	9.73 897	30	0.26 103	9.94 293	7	16
45	9.68 213	23	9.73 927	30	0.26 073	9.94 286	7	15
46	9.68 236	23	9.73 957	30	0.26 043	9.94 279	7	14
47	9.68 259	23	9.73 987	30	0.26 013	9.94 272	7	13
48	9.68 282	23	9.74 017	30	0.25 983	9.94 265	7	12
49	9.68 305	23	9.74 047	30	0.25 953	9.94 258	7	11
50	9.68 328	23	9.74 076	29	0.25 923	9.94 251	7	10
51	9.68 351	23	9.74 106	30	0.25 893	9.94 245	6	9
52	9.68 374	23	9.74 136	30	0.25 863	9.94 238	7	8
53	9.68 397	22	9.74 166	30	0.25 833	9.94 231	7	7
54	9.68 420	23	9.74 196	29	0.25 804	9.94 224	7	6
55	9.68 443	23	9.74 226	30	0.25 774	9.94 217	7	5
56	9.68 466	23	9.74 256	30	0.25 744	9.94 210	7	4
57	9.68 488	22	9.74 286	30	0.25 714	9.94 203	7	3
58	9.68 511	23	9.74 315	29	0.25 684	9.94 196	7	2
59	9.68 534	23	9.74 345	30	0.25 654	9.94 189	7	1
60	9.68 557	22	9.74 375	29	0.25 625	9.94 182	7	0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	$\overline{30}$	30	$\overline{29}$
6	3.0	3.0	2.9
7	3.5	3.5	3.4
8	4.0	4.0	3.9
9	4.6	4.5	4.4
10	5.1	5.0	4.9
20	10.1	10.0	9.8
30	15.2	15.0	14.7
40	20.3	20.0	19.6
50	25.4	25.0	24.6

	24
6	2.4
7	2.8
8	3.2
9	3.6
10	4.0
20	8.0
30	12.0
40	16.0
50	20.0

	$\overline{23}$	23	$\overline{22}$
6	2.3	2.3	2.2
7	2.7	2.7	2.6
8	3.1	3.0	3.0
9	3.5	3.4	3.4
10	3.9	3.8	3.7
20	7.8	7.6	7.5
30	11.7	11.5	11.2
40	15.6	15.3	15.0
50	19.6	19.1	18.7

	7	$\overline{6}$
6	0.7	0.6
7	0.8	0.7
8	0.9	0.8
9	1.0	1.0
10	1.1	1.1
20	2.3	2.1
30	3.5	3.2
40	4.6	4.3
50	5.8	5.4

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.68 557	23	9.74 375	30	0.25 625	9.94 182	7	60
1	9.68 580	22	9.74 405	30	0.25 595	9.94 175	7	59
2	9.68 602	23	9.74 435	29	0.25 565	9.94 168	7	58
3	9.68 625	22	9.74 464	30	0.25 535	9.94 161	7	57
4	9.68 648	23	9.74 494	29	0.25 505	9.94 154	7	56
5	9.68 671	22	9.74 524	30	0.25 476	9.94 147	7	55
6	9.68 693	23	9.74 554	29	0.25 446	9.94 140	7	54
7	9.68 716	22	9.74 583	29	0.25 416	9.94 133	7	53
8	9.68 739	22	9.74 613	30	0.25 387	9.94 126	7	52
9	9.68 761	23	9.74 643	29	0.25 357	9.94 118	7	51
10	9.68 784	22	9.74 672	30	0.25 327	9.94 111	7	50
11	9.68 807	22	9.74 702	29	0.25 297	9.94 104	7	49
12	9.68 829	22	9.74 732	29	0.25 268	9.94 097	7	48
13	9.68 852	22	9.74 761	30	0.25 238	9.94 090	7	47
14	9.68 874	22	9.74 791	29	0.25 208	9.94 083	7	46
15	9.68 897	23	9.74 821	29	0.25 179	9.94 076	7	45
16	9.68 920	22	9.74 850	29	0.25 149	9.94 069	7	44
17	9.68 942	22	9.74 880	29	0.25 120	9.94 062	7	43
18	9.68 965	22	9.74 909	30	0.25 090	9.94 055	7	42
19	9.68 987	22	9.74 939	29	0.25 060	9.94 048	7	41
20	9.69 010	22	9.74 969	29	0.25 031	9.94 041	7	40
21	9.69 032	22	9.74 998	29	0.25 001	9.94 034	7	39
22	9.69 055	22	9.75 028	29	0.24 972	9.94 026	7	38
23	9.69 077	22	9.75 057	29	0.24 942	9.94 019	7	37
24	9.69 099	22	9.75 087	29	0.24 913	9.94 012	7	36
25	9.69 122	22	9.75 116	29	0.24 883	9.94 005	7	35
26	9.69 144	22	9.75 146	29	0.24 854	9.93 998	7	34
27	9.69 167	22	9.75 175	29	0.24 824	9.93 991	7	33
28	9.69 189	22	9.75 205	29	0.24 795	9.93 984	7	32
29	9.69 211	22	9.75 234	29	0.24 765	9.93 977	7	31
30	9.69 234	22	9.75 264	29	0.24 736	9.93 969	7	30
31	9.69 256	22	9.75 293	29	0.24 706	9.93 962	7	29
32	9.69 278	22	9.75 323	29	0.24 677	9.93 955	7	28
33	9.69 301	22	9.75 352	29	0.24 647	9.93 948	7	27
34	9.69 323	22	9.75 382	29	0.24 618	9.93 941	7	26
35	9.69 345	22	9.75 411	29	0.24 588	9.93 934	7	25
36	9.69 367	22	9.75 441	29	0.24 559	9.93 926	7	24
37	9.69 390	22	9.75 470	29	0.24 529	9.93 919	7	23
38	9.69 412	22	9.75 499	29	0.24 500	9.93 912	7	22
39	9.69 434	22	9.75 529	29	0.24 471	9.93 905	7	21
40	9.69 456	22	9.75 558	29	0.24 441	9.93 898	7	20
41	9.69 478	22	9.75 588	29	0.24 412	9.93 891	7	19
42	9.69 500	22	9.75 617	29	0.24 383	9.93 883	7	18
43	9.69 523	22	9.75 646	29	0.24 353	9.93 876	7	17
44	9.69 545	22	9.75 676	29	0.24 324	9.93 869	7	16
45	9.69 567	22	9.75 705	29	0.24 295	9.93 862	7	15
46	9.69 589	22	9.75 734	29	0.24 265	9.93 854	7	14
47	9.69 611	22	9.75 764	29	0.24 236	9.93 847	7	13
48	9.69 633	22	9.75 793	29	0.24 207	9.93 840	7	12
49	9.69 655	22	9.75 822	29	0.24 177	9.93 833	7	11
50	9.69 677	22	9.75 851	29	0.24 148	9.93 826	7	10
51	9.69 699	22	9.75 881	29	0.24 119	9.93 818	7	9
52	9.69 721	22	9.75 910	29	0.24 090	9.93 811	7	8
53	9.69 743	22	9.75 939	29	0.24 060	9.93 804	7	7
54	9.69 765	22	9.75 968	29	0.24 031	9.93 796	7	6
55	9.69 787	22	9.75 998	29	0.24 002	9.93 789	7	5
56	9.69 809	22	9.76 027	29	0.23 973	9.93 782	7	4
57	9.69 831	22	9.76 056	29	0.23 943	9.93 775	7	3
58	9.69 853	21	9.76 085	29	0.23 914	9.93 767	7	2
59	9.69 875	22	9.76 115	29	0.23 885	9.93 760	7	1
60	9.69 897	22	9.76 144	29	0.23 856	9.93 753	7	0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	30	29	29
6	3.0	2.9	2.9
7	3.5	3.4	3.4
8	4.0	3.9	3.8
9	4.5	4.4	4.3
10	5.0	4.9	4.8
20	10.0	9.8	9.6
30	15.0	14.7	14.5
40	20.0	19.6	19.3
50	25.0	24.6	24.1

	23
6	2.3
7	2.7
8	3.0
9	3.4
10	3.8
20	7.6
30	11.5
40	15.3
50	19.1

	22	22	21
6	2.2	2.2	2.1
7	2.6	2.5	2.5
8	3.0	2.9	2.8
9	3.4	3.3	3.2
10	3.7	3.6	3.6
20	7.5	7.3	7.1
30	11.2	11.0	10.7
40	15.0	14.6	14.3
50	18.7	18.3	17.9

	7	7
6	0.7	0.7
7	0.9	0.8
8	1.0	0.9
9	1.1	1.0
10	1.2	1.1
20	2.5	2.3
30	3.7	3.5
40	5.0	4.6
50	6.2	5.8

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.69 897	22	9.76 144	29	0.23 856	9.93 753	7	60
1	9.69 919	21	9.76 173	29	0.23 827	9.93 746	7	59
2	9.69 940	22	9.76 202	29	0.23 797	9.93 738	7	58
3	9.69 962	22	9.76 231	29	0.23 768	9.93 731	7	57
4	9.69 984	21	9.76 260	29	0.23 739	9.93 724	7	56
5	9.70 006	22	9.76 289	29	0.23 710	9.93 716	7	55
6	9.70 028	22	9.76 319	29	0.23 681	9.93 709	7	54
7	9.70 050	21	9.76 348	29	0.23 652	9.93 702	7	53
8	9.70 071	22	9.76 377	29	0.23 623	9.93 694	7	52
9	9.70 093	21	9.76 406	29	0.23 594	9.93 687	7	51
10	9.70 115	22	9.76 435	29	0.23 565	9.93 680	7	50
11	9.70 137	21	9.76 464	29	0.23 535	9.93 672	7	49
12	9.70 158	21	9.76 493	29	0.23 506	9.93 665	7	48
13	9.70 180	22	9.76 522	29	0.23 477	9.93 658	7	47
14	9.70 202	21	9.76 551	29	0.23 448	9.93 650	7	46
15	9.70 223	21	9.76 580	29	0.23 419	9.93 643	7	45
16	9.70 245	22	9.76 609	29	0.23 390	9.93 635	7	44
17	9.70 267	21	9.76 638	29	0.23 361	9.93 628	7	43
18	9.70 288	21	9.76 667	29	0.23 332	9.93 621	7	42
19	9.70 310	21	9.76 696	29	0.23 303	9.93 613	7	41
20	9.70 331	22	9.76 725	29	0.23 274	9.93 606	7	40
21	9.70 353	21	9.76 754	29	0.23 245	9.93 599	7	39
22	9.70 375	21	9.76 783	29	0.23 216	9.93 591	7	38
23	9.70 396	21	9.76 812	29	0.23 187	9.93 584	7	37
24	9.70 418	21	9.76 841	29	0.23 158	9.93 576	7	36
25	9.70 439	21	9.76 870	28	0.23 129	9.93 569	7	35
26	9.70 461	21	9.76 899	29	0.23 101	9.93 562	7	34
27	9.70 482	21	9.76 928	29	0.23 072	9.93 554	7	33
28	9.70 504	21	9.76 957	29	0.23 043	9.93 547	7	32
29	9.70 525	21	9.76 986	29	0.23 014	9.93 539	7	31
30	9.70 547	21	9.77 015	28	0.22 985	9.93 532	7	30
31	9.70 568	21	9.77 043	29	0.22 956	9.93 524	7	29
32	9.70 590	21	9.77 072	29	0.22 927	9.93 517	7	28
33	9.70 611	21	9.77 101	29	0.22 898	9.93 509	7	27
34	9.70 632	21	9.77 130	28	0.22 869	9.93 502	7	26
35	9.70 654	21	9.77 159	29	0.22 841	9.93 495	7	25
36	9.70 675	21	9.77 188	29	0.22 812	9.93 487	7	24
37	9.70 696	21	9.77 217	28	0.22 783	9.93 480	7	23
38	9.70 718	21	9.77 245	29	0.22 754	9.93 472	7	22
39	9.70 739	21	9.77 274	29	0.22 725	9.93 465	7	21
40	9.70 760	21	9.77 303	28	0.22 696	9.93 457	7	20
41	9.70 782	21	9.77 332	29	0.22 668	9.93 450	7	19
42	9.70 803	21	9.77 361	28	0.22 639	9.93 442	7	18
43	9.70 824	21	9.77 389	29	0.22 610	9.93 435	7	17
44	9.70 846	21	9.77 418	28	0.22 581	9.93 427	7	16
45	9.70 867	21	9.77 447	29	0.22 553	9.93 420	7	15
46	9.70 888	21	9.77 476	28	0.22 524	9.93 412	7	14
47	9.70 909	21	9.77 504	29	0.22 495	9.93 405	7	13
48	9.70 930	21	9.77 533	28	0.22 466	9.93 397	7	12
49	9.70 952	21	9.77 562	29	0.22 438	9.93 390	8	11
50	9.70 973	21	9.77 591	28	0.22 409	9.93 382	7	10
51	9.70 994	21	9.77 619	28	0.22 380	9.93 374	7	9
52	9.71 015	21	9.77 648	29	0.22 352	9.93 367	7	8
53	9.71 036	21	9.77 677	28	0.22 323	9.93 359	7	7
54	9.71 057	21	9.77 705	28	0.22 294	9.93 352	7	6
55	9.71 078	21	9.77 734	29	0.22 266	9.93 344	7	5
56	9.71 099	21	9.77 763	28	0.22 237	9.93 337	7	4
57	9.71 121	21	9.77 791	28	0.22 208	9.93 329	8	3
58	9.71 142	21	9.77 820	29	0.22 180	9.93 321	7	2
59	9.71 163	21	9.77 849	28	0.22 151	9.93 314	7	1
60	9.71 184		9.77 877		0.22 122	9.93 306		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	29	29	28
6	2.9	2.9	2.8
7	3.4	3.4	3.3
8	3.9	3.8	3.8
9	4.4	4.3	4.3
10	4.9	4.8	4.7
20	9.8	9.6	9.5
30	14.7	14.5	14.2
40	19.6	19.3	19.0
50	24.6	24.1	23.7

	22	21	21
6	2.2	2.1	2.1
7	2.5	2.5	2.4
8	2.9	2.8	2.8
9	3.3	3.2	3.1
10	3.6	3.6	3.5
20	7.3	7.1	7.0
30	11.0	10.7	10.5
40	14.6	14.3	14.0
50	18.3	17.9	17.5

	8	7	7
6	0.8	0.7	0.7
7	0.9	0.9	0.8
8	1.0	1.0	0.9
9	1.2	1.1	1.0
10	1.3	1.2	1.1
20	2.6	2.5	2.3
30	4.0	3.7	3.5
40	5.3	5.0	4.6
50	6.6	6.2	5.8

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	d.	
0	9.71 184	21	9.77 877	28	0.22 122	9.93 306	7	60
1	9.71 205	21	9.77 906	28	0.22 094	9.93 299	7	59
2	9.71 226	21	9.77 934	28	0.22 065	9.93 291	7	58
3	9.71 247	21	9.77 963	29	0.22 037	9.93 284	8	57
4	9.71 268	21	9.77 992	28	0.22 008	9.93 276	7	56
5	9.71 289	21	9.78 020	28	0.21 979	9.93 268	7	55
6	9.71 310	21	9.78 049	28	0.21 951	9.93 261	7	54
7	9.71 331	20	9.78 077	28	0.21 922	9.93 253	8	53
8	9.71 351	21	9.78 106	28	0.21 894	9.93 245	7	52
9	9.71 372	21	9.78 134	28	0.21 865	9.93 238	7	51
10	9.71 393	21	9.78 163	28	0.21 837	9.93 230	7	50
11	9.71 414	20	9.78 191	28	0.21 808	9.93 223	8	49
12	9.71 435	21	9.78 220	28	0.21 780	9.93 215	7	48
13	9.71 456	21	9.78 248	28	0.21 751	9.93 207	7	47
14	9.71 477	21	9.78 277	28	0.21 723	9.93 200	8	46
15	9.71 498	20	9.78 305	28	0.21 694	9.93 192	7	45
16	9.71 518	21	9.78 334	28	0.21 666	9.93 184	7	44
17	9.71 539	20	9.78 362	28	0.21 637	9.93 177	8	43
18	9.71 560	21	9.78 391	28	0.21 609	9.93 169	7	42
19	9.71 581	20	9.78 419	28	0.21 580	9.93 161	8	41
20	9.71 601	21	9.78 448	28	0.21 552	9.93 153	7	40
21	9.71 622	20	9.78 476	28	0.21 523	9.93 146	7	39
22	9.71 643	21	9.78 505	28	0.21 495	9.93 138	8	38
23	9.71 664	20	9.78 533	28	0.21 467	9.93 130	7	37
24	9.71 684	21	9.78 561	28	0.21 438	9.93 123	8	36
25	9.71 705	20	9.78 590	28	0.21 410	9.93 115	7	35
26	9.71 726	20	9.78 618	28	0.21 381	9.93 107	7	34
27	9.71 746	21	9.78 647	28	0.21 353	9.93 100	8	33
28	9.71 767	20	9.78 675	28	0.21 325	9.93 092	7	32
29	9.71 788	20	9.78 703	28	0.21 296	9.93 084	8	31
30	9.71 808	20	9.78 732	28	0.21 268	9.93 076	7	30
31	9.71 829	20	9.78 760	28	0.21 239	9.93 069	8	29
32	9.71 849	21	9.78 788	28	0.21 211	9.93 061	7	28
33	9.71 870	20	9.78 817	28	0.21 183	9.93 053	8	27
34	9.71 891	20	9.78 845	28	0.21 154	9.93 045	7	26
35	9.71 911	20	9.78 873	28	0.21 126	9.93 038	8	25
36	9.71 932	20	9.78 902	28	0.21 098	9.93 030	7	24
37	9.71 952	20	9.78 930	28	0.21 070	9.93 022	8	23
38	9.71 973	20	9.78 958	28	0.21 041	9.93 014	8	22
39	9.71 993	20	9.78 987	28	0.21 013	9.93 006	7	21
40	9.72 014	20	9.79 015	28	0.20 985	9.92 999	8	20
41	9.72 034	20	9.79 043	28	0.20 956	9.92 991	7	19
42	9.72 055	20	9.79 071	28	0.20 928	9.92 983	8	18
43	9.72 075	20	9.79 100	28	0.20 900	9.92 975	8	17
44	9.72 096	20	9.79 128	28	0.20 872	9.92 967	7	16
45	9.72 116	20	9.79 156	28	0.20 843	9.92 960	8	15
46	9.72 136	20	9.79 184	28	0.20 815	9.92 952	8	14
47	9.72 157	20	9.79 213	28	0.20 787	9.92 944	7	13
48	9.72 177	20	9.79 241	28	0.20 759	9.92 936	8	12
49	9.72 198	20	9.79 269	28	0.20 731	9.92 928	8	11
50	9.72 218	20	9.79 297	28	0.20 702	9.92 920	7	10
51	9.72 238	20	9.79 325	28	0.20 674	9.92 913	8	9
52	9.72 259	20	9.79 354	28	0.20 646	9.92 905	8	8
53	9.72 279	20	9.79 382	28	0.20 618	9.92 897	7	7
54	9.72 299	20	9.79 410	28	0.20 590	9.92 889	8	6
55	9.72 319	20	9.79 438	28	0.20 561	9.92 881	8	5
56	9.72 340	20	9.79 466	28	0.20 533	9.92 873	8	4
57	9.72 360	20	9.79 494	28	0.20 505	9.92 865	7	3
58	9.72 380	20	9.79 522	28	0.20 477	9.92 858	8	2
59	9.72 400	20	9.79 551	28	0.20 449	9.92 850	8	1
60	9.72 421		9.79 579		0.20 421	9.92 842		0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	29	28	28
6	2.9	2.8	2.8
7	3.4	3.3	3.2
8	3.8	3.8	3.7
9	4.3	4.3	4.2
10	4.8	4.7	4.6
20	9.6	9.5	9.3
30	14.5	14.2	14.0
40	19.3	19.0	18.6
50	24.1	23.7	23.3

	21	20	20
6	2.1	2.0	2.0
7	2.4	2.4	2.3
8	2.8	2.7	2.6
9	3.1	3.1	3.0
10	3.5	3.4	3.3
20	7.0	6.8	6.6
30	10.5	10.2	10.0
40	14.0	13.6	13.3
50	17.5	17.1	16.6

	8	7
6	0.8	0.7
7	0.9	0.9
8	1.0	1.0
9	1.2	1.1
10	1.3	1.2
20	2.6	2.5
30	4.0	3.7
40	5.3	5.0
50	6.6	6.2

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.72 421	20	9.79 579	28	0.20 421	9.92 842	8	60
1	9.72 441	20	9.79 607	28	0.20 393	9.92 834	7	59
2	9.72 461	20	9.79 635	28	0.20 365	9.92 826	8	58
3	9.72 481	20	9.79 663	28	0.20 337	9.92 818	8	57
4	9.72 501	20	9.79 691	28	0.20 308	9.92 810	8	56
5	9.72 522	20	9.79 719	28	0.20 280	9.92 802	8	55
6	9.72 542	20	9.79 747	28	0.20 252	9.92 794	8	54
7	9.72 562	20	9.79 775	28	0.20 224	9.92 786	8	53
8	9.72 582	20	9.79 803	28	0.20 196	9.92 778	7	52
9	9.72 602	20	9.79 831	28	0.20 168	9.92 771	8	51
10	9.72 622	20	9.79 859	28	0.20 140	9.92 763	8	50
11	9.72 642	20	9.79 887	28	0.20 112	9.92 755	8	49
12	9.72 662	20	9.79 915	28	0.20 084	9.92 747	8	48
13	9.72 682	20	9.79 943	28	0.20 056	9.92 739	8	47
14	9.72 702	20	9.79 971	28	0.20 028	9.92 731	8	46
15	9.72 723	20	9.79 999	28	0.20 000	9.92 723	8	45
16	9.72 743	20	9.80 027	28	0.19 972	9.92 715	8	44
17	9.72 763	20	9.80 055	28	0.19 944	9.92 707	8	43
18	9.72 783	19	9.80 083	28	0.19 916	9.92 699	8	42
19	9.72 802	20	9.80 111	28	0.19 888	9.92 691	8	41
20	9.72 822	20	9.80 139	28	0.19 860	9.92 683	8	40
21	9.72 842	20	9.80 167	28	0.19 832	9.92 675	8	39
22	9.72 862	20	9.80 195	28	0.19 804	9.92 667	8	38
23	9.72 882	20	9.80 223	28	0.19 776	9.92 659	8	37
24	9.72 902	20	9.80 251	27	0.19 748	9.92 651	8	36
25	9.72 922	19	9.80 279	28	0.19 721	9.92 643	8	35
26	9.72 942	20	9.80 307	28	0.19 693	9.92 635	8	34
27	9.72 962	20	9.80 335	28	0.19 665	9.92 627	8	33
28	9.72 982	20	9.80 363	28	0.19 637	9.92 619	8	32
29	9.73 002	19	9.80 391	27	0.19 609	9.92 611	8	31
30	9.73 021	20	9.80 418	28	0.19 581	9.92 603	8	30
31	9.73 041	20	9.80 446	28	0.19 553	9.92 595	8	29
32	9.73 061	19	9.80 474	28	0.19 525	9.92 587	8	28
33	9.73 081	20	9.80 502	27	0.19 497	9.92 579	8	27
34	9.73 101	19	9.80 530	28	0.19 470	9.92 570	8	26
35	9.73 120	20	9.80 558	28	0.19 442	9.92 562	8	25
36	9.73 140	19	9.80 586	27	0.19 414	9.92 554	8	24
37	9.73 160	20	9.80 613	28	0.19 386	9.92 546	8	23
38	9.73 180	19	9.80 641	28	0.19 358	9.92 538	8	22
39	9.73 199	20	9.80 669	27	0.19 330	9.92 530	8	21
40	9.73 219	19	9.80 697	28	0.19 303	9.92 522	8	20
41	9.73 239	19	9.80 725	27	0.19 275	9.92 514	8	19
42	9.73 258	20	9.80 752	28	0.19 247	9.92 506	8	18
43	9.73 278	19	9.80 780	28	0.19 219	9.92 498	8	17
44	9.73 298	19	9.80 808	27	0.19 191	9.92 489	8	16
45	9.73 317	20	9.80 836	28	0.19 164	9.92 481	8	15
46	9.73 337	19	9.80 864	27	0.19 136	9.92 473	8	14
47	9.73 357	19	9.80 891	28	0.19 108	9.92 465	8	13
48	9.73 376	19	9.80 919	27	0.19 080	9.92 457	8	12
49	9.73 396	19	9.80 947	28	0.19 053	9.92 449	8	11
50	9.73 415	20	9.80 975	27	0.19 025	9.92 441	8	10
51	9.73 435	19	9.81 002	27	0.18 997	9.92 433	8	9
52	9.73 455	19	9.81 030	28	0.18 970	9.92 424	8	8
53	9.73 474	19	9.81 058	27	0.18 942	9.92 416	8	7
54	9.73 494	19	9.81 085	28	0.18 914	9.92 408	8	6
55	9.73 513	19	9.81 113	27	0.18 886	9.92 400	8	5
56	9.73 533	19	9.81 141	27	0.18 859	9.92 392	8	4
57	9.73 552	19	9.81 168	28	0.18 831	9.92 383	8	3
58	9.73 572	19	9.81 196	27	0.18 803	9.92 375	8	2
59	9.73 591	19	9.81 224	27	0.18 776	9.92 367	8	1
60	9.73 611		9.81 251		0.18 748	9.92 359		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	28	28	27
6	2.8	2.8	2.7
7	3.3	3.2	3.2
8	3.8	3.7	3.6
9	4.3	4.2	4.1
10	4.7	4.6	4.6
20	9.5	9.3	9.1
30	14.2	14.0	13.7
40	19.0	18.6	18.3
50	23.7	23.3	22.9

	20	20	19
6	2.0	2.0	1.9
7	2.4	2.3	2.3
8	2.7	2.6	2.6
9	3.1	3.0	2.9
10	3.4	3.3	3.2
20	6.8	6.6	6.5
30	10.2	10.0	9.7
40	13.6	13.3	13.0
50	17.1	16.6	16.2

	8	8	7
6	0.8	0.8	0.7
7	1.0	0.9	0.9
8	1.1	1.0	1.0
9	1.3	1.2	1.1
10	1.4	1.3	1.2
20	2.8	2.6	2.5
30	4.2	4.0	3.7
40	5.6	5.3	5.0
50	7.1	6.6	6.2

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d	
0	9.73 611	19	9.81 251	28	0.18 748	9.92 359	8	60
1	9.73 630	19	9.81 279	27	0.18 720	9.92 351	8	59
2	9.73 650	19	9.81 307	27	0.18 693	9.92 342	8	58
3	9.73 669	19	9.81 334	28	0.18 665	9.92 334	8	57
4	9.73 688	19	9.81 362	27	0.18 637	9.92 326	8	56
5	9.73 708	19	9.81 390	27	0.18 610	9.92 318	8	55
6	9.73 727	19	9.81 417	27	0.18 582	9.92 310	8	54
7	9.73 746	19	9.81 445	28	0.18 555	9.92 301	8	53
8	9.73 766	19	9.81 473	27	0.18 527	9.92 293	8	52
9	9.73 785	19	9.81 500	27	0.18 499	9.92 285	8	51
10	9.73 805	19	9.81 528	27	0.18 472	9.92 277	8	50
11	9.73 824	19	9.81 555	27	0.18 444	9.92 268	8	49
12	9.73 843	19	9.81 583	27	0.18 417	9.92 260	8	48
13	9.73 862	19	9.81 610	27	0.18 389	9.92 252	8	47
14	9.73 882	19	9.81 638	28	0.18 362	9.92 244	8	46
15	9.73 901	19	9.81 666	27	0.18 334	9.92 235	8	45
16	9.73 920	19	9.81 693	27	0.18 306	9.92 227	8	44
17	9.73 940	19	9.81 721	27	0.18 279	9.92 219	8	43
18	9.73 959	19	9.81 748	27	0.18 251	9.92 210	8	42
19	9.73 978	19	9.81 776	27	0.18 224	9.92 202	8	41
20	9.73 997	19	9.81 803	27	0.18 196	9.92 194	8	40
21	9.74 016	19	9.81 831	27	0.18 169	9.92 185	8	39
22	9.74 036	19	9.81 858	27	0.18 141	9.92 177	8	38
23	9.74 055	19	9.81 886	27	0.18 114	9.92 169	8	37
24	9.74 074	19	9.81 913	27	0.18 086	9.92 160	8	36
25	9.74 093	19	9.81 941	27	0.18 059	9.92 152	8	35
26	9.74 112	19	9.81 968	27	0.18 031	9.92 144	8	34
27	9.74 131	19	9.81 996	27	0.18 004	9.92 135	8	33
28	9.74 151	19	9.82 023	27	0.17 976	9.92 127	8	32
29	9.74 170	19	9.82 051	27	0.17 949	9.92 119	8	31
30	9.74 189	19	9.82 078	27	0.17 921	9.92 110	8	30
31	9.74 208	19	9.82 105	27	0.17 894	9.92 102	8	29
32	9.74 227	19	9.82 133	27	0.17 867	9.92 094	8	28
33	9.74 246	19	9.82 160	27	0.17 839	9.92 085	8	27
34	9.74 265	19	9.82 188	27	0.17 812	9.92 077	8	26
35	9.74 284	19	9.82 215	27	0.17 784	9.92 069	8	25
36	9.74 303	19	9.82 243	27	0.17 757	9.92 060	8	24
37	9.74 322	19	9.82 270	27	0.17 729	9.92 052	8	23
38	9.74 341	18	9.82 297	27	0.17 702	9.92 043	8	22
39	9.74 360	19	9.82 325	27	0.17 675	9.92 035	8	21
40	9.74 379	19	9.82 352	27	0.17 647	9.92 027	8	20
41	9.74 398	19	9.82 380	27	0.17 620	9.92 018	8	19
42	9.74 417	19	9.82 407	27	0.17 593	9.92 010	8	18
43	9.74 436	19	9.82 434	27	0.17 565	9.92 001	8	17
44	9.74 455	19	9.82 462	27	0.17 538	9.91 993	8	16
45	9.74 474	19	9.82 489	27	0.17 510	9.91 984	8	15
46	9.74 493	18	9.82 516	27	0.17 483	9.91 976	8	14
47	9.74 511	19	9.82 544	27	0.17 456	9.91 967	8	13
48	9.74 530	19	9.82 571	27	0.17 428	9.91 959	8	12
49	9.74 549	19	9.82 598	27	0.17 401	9.91 951	8	11
50	9.74 568	18	9.82 626	27	0.17 374	9.91 942	8	10
51	9.74 587	19	9.82 653	27	0.17 347	9.91 934	8	9
52	9.74 606	19	9.82 680	27	0.17 319	9.91 925	8	8
53	9.74 625	18	9.82 708	27	0.17 292	9.91 917	8	7
54	9.74 643	19	9.82 735	27	0.17 265	9.91 908	8	6
55	9.74 662	18	9.82 762	27	0.17 237	9.91 900	8	5
56	9.74 681	19	9.82 789	27	0.17 210	9.91 891	8	4
57	9.74 700	18	9.82 817	27	0.17 183	9.91 883	8	3
58	9.74 718	19	9.82 844	27	0.17 156	9.91 874	8	2
59	9.74 737	18	9.82 871	27	0.17 128	9.91 866	8	1
60	9.74 756		9.82 898		0.17 101	9.91 857		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	28	27	27
6	2.8	2.7	2.7
7	3.2	3.2	3.1
8	3.7	3.6	3.6
9	4.2	4.1	4.0
10	4.6	4.6	4.5
20	9.3	9.1	9.0
30	14.0	13.7	13.5
40	18.6	18.3	18.0
50	23.3	22.9	22.5

	19	19	18
6	1.9	1.9	1.8
7	2.3	2.2	2.1
8	2.6	2.5	2.4
9	2.9	2.8	2.8
10	3.2	3.1	3.1
20	6.5	6.3	6.1
30	9.7	9.5	9.2
40	13.0	12.6	12.3
50	16.2	15.8	15.4

	8	8
6	0.8	0.8
7	1.0	0.9
8	1.1	1.0
9	1.3	1.2
10	1.4	1.3
20	2.8	2.6
30	4.2	4.0
40	5.6	5.3
50	7.1	6.6

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.74 756	19	9.82 898	27	0.17 101	9.91 857	8	60
1	9.74 775	18	9.82 926	27	0.17 074	9.91 849	8	59
2	9.74 793	19	9.82 953	27	0.17 047	9.91 840	8	58
3	9.74 812	18	9.82 980	27	0.17 019	9.91 832	8	57
4	9.74 831	18	9.83 007	27	0.16 992	9.91 823	9	56
5	9.74 849	19	9.83 035	27	0.16 965	9.91 814	8	55
6	9.74 868	18	9.83 062	27	0.16 938	9.91 806	8	54
7	9.74 887	18	9.83 089	27	0.16 910	9.91 797	8	53
8	9.74 905	19	9.83 116	27	0.16 883	9.91 789	8	52
9	9.74 924	18	9.83 143	27	0.16 856	9.91 780	8	51
10	9.74 943	18	9.83 171	27	0.16 829	9.91 772	8	50
11	9.74 961	18	9.83 198	27	0.16 802	9.91 763	8	49
12	9.74 980	18	9.83 225	27	0.16 774	9.91 755	9	48
13	9.74 998	18	9.83 252	27	0.16 747	9.91 746	8	47
14	9.75 017	19	9.83 279	27	0.16 720	9.91 737	8	46
15	9.75 036	18	9.83 307	27	0.16 693	9.91 729	8	45
16	9.75 054	18	9.83 334	27	0.16 666	9.91 720	8	44
17	9.75 073	18	9.83 361	27	0.16 639	9.91 712	9	43
18	9.75 091	18	9.83 388	27	0.16 612	9.91 703	8	42
19	9.75 110	18	9.83 415	27	0.16 584	9.91 694	8	41
20	9.75 128	18	9.83 442	27	0.16 557	9.91 686	8	40
21	9.75 147	18	9.83 469	27	0.16 530	9.91 677	9	39
22	9.75 165	18	9.83 496	27	0.16 503	9.91 668	8	38
23	9.75 184	18	9.83 524	27	0.16 476	9.91 660	8	37
24	9.75 202	18	9.83 551	27	0.16 449	9.91 651	9	36
25	9.75 221	18	9.83 578	27	0.16 422	9.91 642	8	35
26	9.75 239	18	9.83 605	27	0.16 395	9.91 634	8	34
27	9.75 257	18	9.83 632	27	0.16 368	9.91 625	9	33
28	9.75 276	18	9.83 659	27	0.16 340	9.91 616	8	32
29	9.75 294	18	9.83 686	27	0.16 313	9.91 608	8	31
30	9.75 313	18	9.83 713	27	0.16 286	9.91 599	9	30
31	9.75 331	18	9.83 740	27	0.16 259	9.91 590	8	29
32	9.75 349	18	9.83 767	27	0.16 232	9.91 582	8	28
33	9.75 368	18	9.83 794	27	0.16 205	9.91 573	9	27
34	9.75 386	18	9.83 821	27	0.16 178	9.91 564	8	26
35	9.75 404	18	9.83 848	27	0.16 151	9.91 556	9	25
36	9.75 423	18	9.83 875	27	0.16 124	9.91 547	8	24
37	9.75 441	18	9.83 902	27	0.16 097	9.91 538	9	23
38	9.75 459	18	9.83 929	27	0.16 070	9.91 529	8	22
39	9.75 478	18	9.83 957	27	0.16 043	9.91 521	8	21
40	9.75 496	18	9.83 984	27	0.16 016	9.91 512	9	20
41	9.75 514	18	9.84 011	27	0.15 989	9.91 503	8	19
42	9.75 532	18	9.84 038	27	0.15 962	9.91 495	9	18
43	9.75 551	18	9.84 065	26	0.15 935	9.91 486	8	17
44	9.75 569	18	9.84 091	27	0.15 908	9.91 477	9	16
45	9.75 587	18	9.84 118	27	0.15 881	9.91 468	8	15
46	9.75 605	18	9.84 145	27	0.15 854	9.91 460	9	14
47	9.75 623	18	9.84 172	27	0.15 827	9.91 451	9	13
48	9.75 642	18	9.84 199	27	0.15 800	9.91 442	8	12
49	9.75 660	18	9.84 226	27	0.15 773	9.91 433	9	11
50	9.75 678	18	9.84 253	27	0.15 746	9.91 424	8	10
51	9.75 696	18	9.84 280	27	0.15 719	9.91 416	9	9
52	9.75 714	18	9.84 307	27	0.15 692	9.91 407	9	8
53	9.75 732	18	9.84 334	26	0.15 665	9.91 398	8	7
54	9.75 750	18	9.84 361	27	0.15 639	9.91 389	9	6
55	9.75 769	18	9.84 388	27	0.15 612	9.91 380	8	5
56	9.75 787	18	9.84 415	27	0.15 585	9.91 372	9	4
57	9.75 805	18	9.84 442	27	0.15 558	9.91 363	9	3
58	9.75 823	18	9.84 469	27	0.15 531	9.91 354	8	2
59	9.75 841	18	9.84 496	26	0.15 504	9.91 345	9	1
60	9.75 859		9.84 522		0.15 477	9.91 336		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	27	27	26
6	2.7	2.7	2.6
7	3.2	3.1	3.1
8	3.6	3.6	3.5
9	4.1	4.0	4.0
10	4.6	4.5	4.4
20	9.1	9.0	8.8
30	13.7	13.5	13.2
40	18.3	18.0	17.6
50	22.9	22.5	22.1

	19	18	18
6	1.9	1.8	1.8
7	2.2	2.1	2.1
8	2.5	2.4	2.4
9	2.8	2.8	2.7
10	3.1	3.1	3.0
20	6.3	6.1	6.0
30	9.5	9.2	9.0
40	12.6	12.3	12.0
50	15.8	15.4	15.0

	9	8
6	0.9	0.8
7	1.0	1.0
8	1.2	1.1
9	1.3	1.3
10	1.5	1.4
20	3.0	2.8
30	4.5	4.2
40	6.0	5.6
50	7.5	7.1

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.75 859	18	9.84 522	27	0.15 477	9.91 336	9	60
1	9.75 877	18	9.84 549	27	0.15 450	9.91 327	9	59
2	9.75 895	18	9.84 576	27	0.15 423	9.91 318	8	58
3	9.75 913	18	9.84 603	26	0.15 396	9.91 310	9	57
4	9.75 931	18	9.84 630	27	0.15 370	9.91 301	9	56
5	9.75 949	18	9.84 657	27	0.15 343	9.91 292	8	55
6	9.75 967	18	9.84 684	27	0.15 316	9.91 283	9	54
7	9.75 985	18	9.84 711	26	0.15 289	9.91 274	9	53
8	9.76 003	18	9.84 737	27	0.15 262	9.91 265	9	52
9	9.76 021	18	9.84 764	27	0.15 235	9.91 256	9	51
10	9.76 039	18	9.84 791	26	0.15 208	9.91 247	8	50
11	9.76 057	18	9.84 818	27	0.15 182	9.91 239	9	49
12	9.76 075	17	9.84 845	26	0.15 155	9.91 230	9	48
13	9.76 092	18	9.84 871	27	0.15 128	9.91 221	9	47
14	9.76 110	18	9.84 898	27	0.15 101	9.91 212	9	46
15	9.76 128	18	9.84 925	26	0.15 074	9.91 203	9	45
16	9.76 146	17	9.84 952	27	0.15 048	9.91 194	8	44
17	9.76 164	18	9.84 979	26	0.15 021	9.91 185	9	43
18	9.76 182	18	9.85 005	27	0.14 994	9.91 176	9	42
19	9.76 200	17	9.85 032	27	0.14 967	9.91 167	9	41
20	9.76 217	18	9.85 059	26	0.14 940	9.91 158	9	40
21	9.76 235	18	9.85 086	27	0.14 914	9.91 149	9	39
22	9.76 253	17	9.85 113	26	0.14 887	9.91 140	9	38
23	9.76 271	18	9.85 139	27	0.14 860	9.91 131	9	37
24	9.76 289	17	9.85 166	26	0.14 833	9.91 122	9	36
25	9.76 306	18	9.85 193	27	0.14 807	9.91 113	9	35
26	9.76 324	17	9.85 220	26	0.14 780	9.91 104	9	34
27	9.76 342	18	9.85 246	27	0.14 753	9.91 095	9	33
28	9.76 360	17	9.85 273	26	0.14 726	9.91 086	9	32
29	9.76 377	18	9.85 300	27	0.14 700	9.91 077	9	31
30	9.76 395	17	9.85 327	26	0.14 673	9.91 068	9	30
31	9.76 413	18	9.85 353	26	0.14 646	9.91 059	9	29
32	9.76 431	17	9.85 380	27	0.14 620	9.91 050	9	28
33	9.76 448	17	9.85 407	26	0.14 593	9.91 041	9	27
34	9.76 466	18	9.85 433	27	0.14 566	9.91 032	9	26
35	9.76 484	17	9.85 460	26	0.14 539	9.91 023	9	25
36	9.76 501	17	9.85 487	26	0.14 513	9.91 014	9	24
37	9.76 519	17	9.85 513	27	0.14 486	9.91 005	9	23
38	9.76 536	18	9.85 540	26	0.14 459	9.90 996	9	22
39	9.76 554	17	9.85 567	27	0.14 433	9.90 987	9	21
40	9.76 572	17	9.85 594	26	0.14 406	9.90 978	9	20
41	9.76 589	17	9.85 620	26	0.14 379	9.90 969	9	19
42	9.76 607	17	9.85 647	26	0.14 353	9.90 960	9	18
43	9.76 624	18	9.85 673	27	0.14 326	9.90 951	9	17
44	9.76 642	17	9.85 700	26	0.14 299	9.90 942	9	16
45	9.76 660	17	9.85 727	26	0.14 273	9.90 933	9	15
46	9.76 677	17	9.85 753	27	0.14 246	9.90 923	9	14
47	9.76 695	17	9.85 780	26	0.14 219	9.90 914	9	13
48	9.76 712	17	9.85 807	26	0.14 193	9.90 905	9	12
49	9.76 730	17	9.85 833	26	0.14 166	9.90 896	9	11
50	9.76 747	17	9.85 860	27	0.14 140	9.90 887	9	10
51	9.76 765	17	9.85 887	26	0.14 113	9.90 878	9	9
52	9.76 782	17	9.85 913	26	0.14 086	9.90 869	9	8
53	9.76 800	17	9.85 940	26	0.14 060	9.90 860	9	7
54	9.76 817	17	9.85 966	26	0.14 033	9.90 850	9	6
55	9.76 835	17	9.85 993	27	0.14 007	9.90 841	9	5
56	9.76 852	17	9.86 020	26	0.13 980	9.90 832	9	4
57	9.76 869	17	9.86 046	26	0.13 953	9.90 823	9	3
58	9.76 887	17	9.86 073	26	0.13 927	9.90 814	9	2
59	9.76 904	17	9.86 099	26	0.13 900	9.90 805	9	1
60	9.76 922		9.86 126		0.13 874	9.90 796		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	27	26
6	2.7	2.6
7	3.1	3.1
8	3.6	3.5
9	4.0	4.0
10	4.5	4.4
20	9.0	8.8
30	13.5	13.2
40	18.0	17.6
50	22.5	22.1

	18	17	17
6	1.8	1.7	1.7
7	2.1	2.0	2.0
8	2.4	2.3	2.2
9	2.7	2.6	2.5
10	3.0	2.9	2.8
20	6.0	5.8	5.6
30	9.0	8.7	8.5
40	12.0	11.6	11.3
50	15.0	14.6	14.1

	9	9	8
6	0.9	0.9	0.8
7	1.1	1.0	1.0
8	1.2	1.2	1.1
9	1.4	1.3	1.3
10	1.6	1.5	1.4
20	3.1	3.0	2.8
30	4.7	4.5	4.2
40	6.3	6.0	5.6
50	7.9	7.5	7.1

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.76 922	17	9.86 126	26	0.13 874	9.90 796	9	60
1	9.76 939	17	9.86 152	26	0.13 847	9.90 786	9	59
2	9.76 956	17	9.86 179	27	0.13 821	9.90 777	9	58
3	9.76 974	17	9.86 206	26	0.13 794	9.90 768	9	57
4	9.76 991	17	9.86 232	26	0.13 767	9.90 759	9	56
5	9.77 008	17	9.86 259	26	0.13 741	9.90 750	9	55
6	9.77 026	17	9.86 285	26	0.13 714	9.90 740	9	54
7	9.77 043	17	9.86 312	26	0.13 688	9.90 731	9	53
8	9.77 060	17	9.86 338	26	0.13 661	9.90 722	9	52
9	9.77 078	17	9.86 365	26	0.13 635	9.90 713	9	51
10	9.77 095	17	9.86 391	26	0.13 608	9.90 703	9	50
11	9.77 112	17	9.86 418	26	0.13 582	9.90 694	9	49
12	9.77 130	17	9.86 444	26	0.13 555	9.90 685	9	48
13	9.77 147	17	9.86 471	26	0.13 529	9.90 676	9	47
14	9.77 164	17	9.86 497	26	0.13 502	9.90 666	9	46
15	9.77 181	17	9.86 524	26	0.13 476	9.90 657	9	45
16	9.77 198	17	9.86 550	26	0.13 449	9.90 648	9	44
17	9.77 216	17	9.86 577	26	0.13 423	9.90 639	9	43
18	9.77 233	17	9.86 603	26	0.13 396	9.90 629	9	42
19	9.77 250	17	9.86 630	26	0.13 370	9.90 620	9	41
20	9.77 267	17	9.86 656	26	0.13 343	9.90 611	9	40
21	9.77 284	17	9.86 683	26	0.13 317	9.90 602	9	39
22	9.77 302	17	9.86 709	26	0.13 290	9.90 592	9	38
23	9.77 319	17	9.86 736	26	0.13 264	9.90 583	9	37
24	9.77 336	17	9.86 762	26	0.13 237	9.90 574	9	36
25	9.77 353	17	9.86 788	26	0.13 211	9.90 564	9	35
26	9.77 370	17	9.86 815	26	0.13 185	9.90 555	9	34
27	9.77 387	17	9.86 841	26	0.13 158	9.90 546	9	33
28	9.77 404	17	9.86 868	26	0.13 132	9.90 536	9	32
29	9.77 421	17	9.86 894	26	0.13 105	9.90 527	9	31
30	9.77 439	17	9.86 921	26	0.13 079	9.90 518	9	30
31	9.77 456	17	9.86 947	26	0.13 052	9.90 508	9	29
32	9.77 473	17	9.86 973	26	0.13 026	9.90 499	9	28
33	9.77 490	17	9.87 000	26	0.13 000	9.90 490	9	27
34	9.77 507	17	9.87 026	26	0.12 973	9.90 480	9	26
35	9.77 524	17	9.87 053	26	0.12 947	9.90 471	9	25
36	9.77 541	17	9.87 079	26	0.12 920	9.90 461	9	24
37	9.77 558	17	9.87 105	26	0.12 894	9.90 452	9	23
38	9.77 575	17	9.87 132	26	0.12 868	9.90 443	9	22
39	9.77 592	17	9.87 158	26	0.12 841	9.90 433	9	21
40	9.77 609	17	9.87 185	26	0.12 815	9.90 424	9	20
41	9.77 626	17	9.87 211	26	0.12 789	9.90 414	9	19
42	9.77 643	17	9.87 237	26	0.12 762	9.90 405	9	18
43	9.77 660	17	9.87 264	26	0.12 736	9.90 396	9	17
44	9.77 677	16	9.87 290	26	0.12 709	9.90 386	9	16
45	9.77 693	17	9.87 316	26	0.12 683	9.90 377	9	15
46	9.77 710	17	9.87 343	26	0.12 657	9.90 367	9	14
47	9.77 727	17	9.87 369	26	0.12 630	9.90 358	9	13
48	9.77 744	17	9.87 395	26	0.12 604	9.90 348	9	12
49	9.77 761	16	9.87 422	26	0.12 578	9.90 339	9	11
50	9.77 778	17	9.87 448	26	0.12 551	9.90 330	9	10
51	9.77 795	17	9.87 474	26	0.12 525	9.90 320	9	9
52	9.77 812	16	9.87 501	26	0.12 499	9.90 311	9	8
53	9.77 828	17	9.87 527	26	0.12 472	9.90 301	9	7
54	9.77 845	17	9.87 553	26	0.12 446	9.90 292	9	6
55	9.77 862	16	9.87 580	26	0.12 420	9.90 282	9	5
56	9.77 879	17	9.87 606	26	0.12 393	9.90 273	9	4
57	9.77 896	17	9.87 632	26	0.12 367	9.90 263	9	3
58	9.77 913	16	9.87 659	26	0.12 341	9.90 254	9	2
59	9.77 929	17	9.87 685	26	0.12 315	9.90 244	9	1
60	9.77 946		9.87 711		0.12 288	9.90 235		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	27	26	26
6	2.7	2.6	2.6
7	3.1	3.1	3.0
8	3.6	3.5	3.4
9	4.0	4.0	3.9
10	4.5	4.4	4.3
20	9.0	8.8	8.6
30	13.5	13.2	13.0
40	18.0	17.6	17.3
50	22.5	22.1	21.6

	17	17	16
6	1.7	1.7	1.6
7	2.0	2.0	1.9
8	2.3	2.2	2.2
9	2.6	2.5	2.5
10	2.9	2.8	2.7
20	5.8	5.6	5.5
30	8.7	8.5	8.2
40	11.6	11.3	11.0
50	14.6	14.1	13.7

	9	9
6	0.9	0.9
7	1.1	1.0
8	1.2	1.2
9	1.4	1.3
10	1.6	1.5
20	3.1	3.0
30	4.7	4.5
40	6.3	6.0
50	7.9	7.5

P. P.

'	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.77 946	16	9.87 711	26	0.12 288	9.90 235	9	60
1	9.77 963	17	9.87 737	26	0.12 262	9.90 225	9	59
2	9.77 980	16	9.87 764	26	0.12 236	9.90 216	9	58
3	9.77 996	17	9.87 790	26	0.12 209	9.90 206	10	57
4	9.78 013	16	9.87 816	26	0.12 183	9.90 196	9	56
5	9.78 030	16	9.87 843	26	0.12 157	9.90 187	9	55
6	9.78 046	17	9.87 869	26	0.12 131	9.90 177	9	54
7	9.78 063	16	9.87 895	26	0.12 104	9.90 168	9	53
8	9.78 080	17	9.87 921	26	0.12 078	9.90 158	9	52
9	9.78 097	16	9.87 948	26	0.12 052	9.90 149	9	51
10	9.78 113	16	9.87 974	26	0.12 026	9.90 139	9	50
11	9.78 130	17	9.88 000	26	0.11 999	9.90 130	10	49
12	9.78 147	16	9.88 026	26	0.11 973	9.90 120	9	48
13	9.78 163	16	9.88 053	26	0.11 947	9.90 110	9	47
14	9.78 180	16	9.88 079	26	0.11 921	9.90 101	9	46
15	9.78 196	16	9.88 105	26	0.11 895	9.90 091	9	45
16	9.78 213	17	9.88 131	26	0.11 868	9.90 082	10	44
17	9.78 230	16	9.88 157	26	0.11 842	9.90 072	9	43
18	9.78 246	16	9.88 184	26	0.11 816	9.90 062	9	42
19	9.78 263	16	9.88 210	26	0.11 790	9.90 053	9	41
20	9.78 279	16	9.88 236	26	0.11 763	9.90 043	10	40
21	9.78 296	16	9.88 262	26	0.11 737	9.90 033	9	39
22	9.78 312	16	9.88 288	26	0.11 711	9.90 024	9	38
23	9.78 329	17	9.88 315	26	0.11 685	9.90 014	10	37
24	9.78 346	16	9.88 341	26	0.11 659	9.90 004	9	36
25	9.78 362	16	9.88 367	26	0.11 633	9.89 995	9	35
26	9.78 379	16	9.88 393	26	0.11 606	9.89 985	10	34
27	9.78 395	16	9.88 419	26	0.11 580	9.89 975	9	33
28	9.78 412	16	9.88 445	26	0.11 554	9.89 966	9	32
29	9.78 428	16	9.88 472	26	0.11 528	9.89 956	10	31
30	9.78 444	16	9.88 498	26	0.11 502	9.89 946	9	30
31	9.78 461	16	9.88 524	26	0.11 476	9.89 937	9	29
32	9.78 477	16	9.88 550	26	0.11 449	9.89 927	10	28
33	9.78 494	16	9.88 576	26	0.11 423	9.89 917	9	27
34	9.78 510	16	9.88 602	26	0.11 397	9.89 908	10	26
35	9.78 527	16	9.88 629	26	0.11 371	9.89 898	9	25
36	9.78 543	16	9.88 655	26	0.11 345	9.89 888	10	24
37	9.78 559	16	9.88 681	26	0.11 319	9.89 878	9	23
38	9.78 576	16	9.88 707	26	0.11 293	9.89 869	10	22
39	9.78 592	16	9.88 733	26	0.11 266	9.89 859	9	21
40	9.78 609	16	9.88 759	26	0.11 240	9.89 849	10	20
41	9.78 625	16	9.88 785	26	0.11 214	9.89 839	9	19
42	9.78 641	16	9.88 811	26	0.11 188	9.89 830	10	18
43	9.78 658	16	9.88 838	26	0.11 162	9.89 820	9	17
44	9.78 674	16	9.88 864	26	0.11 136	9.89 810	10	16
45	9.78 690	16	9.88 890	26	0.11 110	9.89 800	9	15
46	9.78 707	16	9.88 916	26	0.11 084	9.89 791	10	14
47	9.78 723	16	9.88 942	26	0.11 058	9.89 781	10	13
48	9.78 739	16	9.88 968	26	0.11 032	9.89 771	9	12
49	9.78 755	16	9.88 994	26	0.11 005	9.89 761	10	11
50	9.78 772	16	9.89 020	26	0.10 979	9.89 751	9	10
51	9.78 788	16	9.89 046	26	0.10 953	9.89 742	10	9
52	9.78 804	16	9.89 072	26	0.10 927	9.89 732	10	8
53	9.78 821	16	9.89 098	26	0.10 901	9.89 722	9	7
54	9.78 837	16	9.89 124	26	0.10 875	9.89 712	10	6
55	9.78 853	16	9.89 150	26	0.10 849	9.89 702	10	5
56	9.78 869	16	9.89 177	26	0.10 823	9.89 692	9	4
57	9.78 885	16	9.89 203	26	0.10 797	9.89 683	10	3
58	9.78 902	16	9.89 229	26	0.10 771	9.89 673	10	2
59	9.78 918	16	9.89 255	26	0.10 745	9.89 663	10	1
60	9.78 934		9.89 281		0.10 719	9.89 653		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	'

P. P.

	26	26
6	2.6	2.6
7	3.1	3.0
8	3.5	3.4
9	4.0	3.9
10	4.4	4.3
20	8.8	8.6
30	13.2	13.0
40	17.6	17.3
50	22.1	21.6

	17	16	16
6	1.7	1.6	1.6
7	2.0	1.9	1.8
8	2.2	2.2	2.1
9	2.5	2.5	2.4
10	2.8	2.7	2.6
20	5.6	5.5	5.3
30	8.5	8.2	8.0
40	11.3	11.0	10.6
50	14.1	13.7	13.3

	10	9
6	1.0	0.9
7	1.1	1.1
8	1.3	1.2
9	1.5	1.4
10	1.6	1.6
20	3.3	3.1
30	5.0	4.7
40	6.6	6.3
50	8.3	7.9

P. P.

′	Log. Sin.	d.	Log. Tan.	c.d.	Log. Cot.	Log. Cos.	d.	′
0	9.78 934	16	9.89 281	26	0.10 719	9.89 653	9	60
1	9.78 950	16	9.89 307	26	0.10 693	9.89 643	10	59
2	9.78 966	16	9.89 333	26	0.10 667	9.89 633	10	58
3	9.78 982	16	9.89 359	26	0.10 641	9.89 623	10	57
4	9.78 999	16	9.89 385	26	0.10 615	9.89 613	9	56
5	9.79 015	16	9.89 411	26	0.10 589	9.89 604	10	55
6	9.79 031	16	9.89 437	26	0.10 563	9.89 594	10	54
7	9.79 047	16	9.89 463	26	0.10 537	9.89 584	10	53
8	9.79 063	16	9.89 489	26	0.10 511	9.89 574	10	52
9	9.79 079	16	9.89 515	26	0.10 485	9.89 564	10	51
10	9.79 095	16	9.89 541	26	0.10 459	9.89 554	9	50
11	9.79 111	16	9.89 567	26	0.10 433	9.89 544	10	49
12	9.79 127	16	9.89 593	26	0.10 407	9.89 534	10	48
13	9.79 143	16	9.89 619	26	0.10 381	9.89 524	10	47
14	9.79 159	16	9.89 645	26	0.10 355	9.89 514	10	46
15	9.79 175	16	9.89 671	26	0.10 329	9.89 504	10	45
16	9.79 191	16	9.89 697	26	0.10 303	9.89 494	10	44
17	9.79 207	16	9.89 723	26	0.10 277	9.89 484	10	43
18	9.79 223	16	9.89 749	26	0.10 251	9.89 474	10	42
19	9.79 239	16	9.89 775	26	0.10 225	9.89 464	10	41
20	9.79 255	16	9.89 801	26	0.10 199	9.89 454	10	40
21	9.79 271	16	9.89 827	26	0.10 173	9.89 444	10	39
22	9.79 287	16	9.89 853	26	0.10 147	9.89 434	10	38
23	9.79 303	16	9.89 879	26	0.10 121	9.89 424	10	37
24	9.79 319	16	9.89 905	26	0.10 095	9.89 414	10	36
25	9.79 335	16	9.89 931	26	0.10 069	9.89 404	10	35
26	9.79 351	16	9.89 957	25	0.10 043	9.89 394	10	34
27	9.79 367	16	9.89 982	26	0.10 017	9.89 384	10	33
28	9.79 383	15	9.90 008	26	0.09 991	9.89 374	10	32
29	9.79 399	16	9.90 034	26	0.09 965	9.89 364	10	31
30	9.79 415	16	9.90 060	26	0.09 939	9.89 354	10	30
31	9.79 431	15	9.90 086	26	0.09 913	9.89 344	10	29
32	9.79 446	16	9.90 112	26	0.09 887	9.89 334	10	28
33	9.79 462	16	9.90 138	25	0.09 861	9.89 324	10	27
34	9.79 478	15	9.90 164	26	0.09 836	9.89 314	10	26
35	9.79 494	16	9.90 190	26	0.09 810	9.89 304	10	25
36	9.79 510	16	9.90 216	26	0.09 784	9.89 294	10	24
37	9.79 526	15	9.90 242	26	0.09 758	9.89 284	10	23
38	9.79 541	16	9.90 268	26	0.09 732	9.89 274	10	22
39	9.79 557	16	9.90 294	25	0.09 706	9.89 264	10	21
40	9.79 573	15	9.90 319	26	0.09 680	9.89 253	10	20
41	9.79 589	16	9.90 345	26	0.09 654	9.89 243	10	19
42	9.79 605	15	9.90 371	26	0.09 628	9.89 233	10	18
43	9.79 620	16	9.90 397	25	0.09 602	9.89 223	10	17
44	9.79 636	15	9.90 423	26	0.09 577	9.89 213	10	16
45	9.79 652	16	9.90 449	26	0.09 551	9.89 203	10	15
46	9.79 668	15	9.90 475	26	0.09 525	9.89 193	10	14
47	9.79 683	16	9.90 501	25	0.09 499	9.89 182	10	13
48	9.79 699	15	9.90 526	26	0.09 473	9.89 172	10	12
49	9.79 715	15	9.90 552	26	0.09 447	9.89 162	10	11
50	9.79 730	16	9.90 578	26	0.09 421	9.89 152	10	10
51	9.79 746	15	9.90 604	25	0.09 395	9.89 142	10	9
52	9.79 762	15	9.90 630	26	0.09 370	9.89 132	10	8
53	9.79 777	16	9.90 656	26	0.09 344	9.89 121	10	7
54	9.79 793	15	9.90 682	25	0.09 318	9.89 111	10	6
55	9.79 809	15	9.90 707	26	0.09 292	9.89 101	10	5
56	9.79 824	16	9.90 733	26	0.09 266	9.89 091	10	4
57	9.79 840	15	9.90 759	26	0.09 240	9.89 081	10	3
58	9.79 856	15	9.90 785	25	0.09 214	9.89 070	10	2
59	9.79 871	15	9.90 811	26	0.09 189	9.89 060	10	1
60	9.79 887		9.90 837		0.09 163	9.89 050		0
	Log. Cos.	d.	Log. Cot.	c.d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	26	25
6	2.6	2.5
7	3.0	3.0
8	3.4	3.4
9	3.9	3.8
10	4.3	4.2
20	8.6	8.5
30	13.0	12.7
40	17.3	17.0
50	21.6	21.2

	16	16	15
6	1.6	1.6	1.5
7	1.9	1.8	1.8
8	2.2	2.1	2.0
9	2.5	2.4	2.3
10	2.7	2.6	2.6
20	5.5	5.3	5.1
30	8.2	8.0	7.7
40	11.0	10.6	10.3
50	13.7	13.3	12.9

	10	10	9
6	1.0	1.0	0.9
7	1.2	1.1	1.1
8	1.4	1.3	1.2
9	1.6	1.5	1.4
10	1.7	1.6	1.6
20	3.5	3.3	3.1
30	5.2	5.0	4.7
40	7.0	6.6	6.3
50	8.7	8.3	7.9

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.79 887	16	9.90 837	26	0.09 163	9.89 050	10	60
1	9.79 903	15	9.90 863	25	0.09 137	9.89 040	10	59
2	9.79 918	15	9.90 888	26	0.09 111	9.89 030	10	58
3	9.79 934	15	9.90 914	25	0.09 085	9.89 019	10	57
4	9.79 949	15	9.90 940	26	0.09 060	9.89 009	10	56
5	9.79 965	15	9.90 966	26	0.09 034	9.88 999	10	55
6	9.79 980	15	9.90 992	25	0.09 008	9.88 989	10	54
7	9.79 996	15	9.91 017	26	0.08 982	9.88 978	10	53
8	9.80 011	15	9.91 043	26	0.08 956	9.88 968	10	52
9	9.80 027	15	9.91 069	25	0.08 930	9.88 958	10	51
10	9.80 042	15	9.91 095	26	0.08 905	9.88 947	10	50
11	9.80 058	15	9.91 121	25	0.08 879	9.88 937	10	49
12	9.80 073	15	9.91 146	26	0.08 853	9.88 927	10	48
13	9.80 089	15	9.91 172	25	0.08 827	9.88 917	10	47
14	9.80 104	15	9.91 198	26	0.08 802	9.88 906	10	46
15	9.80 120	15	9.91 224	26	0.08 776	9.88 896	10	45
16	9.80 135	15	9.91 250	25	0.08 750	9.88 886	10	44
17	9.80 151	15	9.91 275	26	0.08 724	9.88 875	10	43
18	9.80 166	15	9.91 301	25	0.08 698	9.88 865	10	42
19	9.80 182	15	9.91 327	26	0.08 673	9.88 855	10	41
20	9.80 197	15	9.91 353	25	0.08 647	9.88 844	10	40
21	9.80 213	15	9.91 378	26	0.08 621	9.88 834	10	39
22	9.80 228	15	9.91 404	25	0.08 595	9.88 823	10	38
23	9.80 243	15	9.91 430	26	0.08 570	9.88 813	10	37
24	9.80 259	15	9.91 456	25	0.08 544	9.88 803	10	36
25	9.80 274	15	9.91 481	26	0.08 518	9.88 792	10	35
26	9.80 289	15	9.91 507	25	0.08 492	9.88 782	10	34
27	9.80 305	15	9.91 533	26	0.08 467	9.88 772	10	33
28	9.80 320	15	9.91 559	25	0.08 441	9.88 761	10	32
29	9.80 335	15	9.91 584	26	0.08 415	9.88 751	10	31
30	9.80 351	15	9.91 610	25	0.08 389	9.88 740	10	30
31	9.80 366	15	9.91 636	26	0.08 364	9.88 730	10	29
32	9.80 381	15	9.91 662	25	0.08 338	9.88 720	10	28
33	9.80 397	15	9.91 687	26	0.08 312	9.88 709	10	27
34	9.80 412	15	9.91 713	25	0.08 286	9.88 699	10	26
35	9.80 427	15	9.91 739	26	0.08 261	9.88 688	10	25
36	9.80 443	15	9.91 765	25	0.08 235	9.88 678	10	24
37	9.80 458	15	9.91 790	26	0.08 209	9.88 667	10	23
38	9.80 473	15	9.91 816	25	0.08 183	9.88 657	10	22
39	9.80 488	15	9.91 842	25	0.08 158	9.88 646	10	21
40	9.80 504	15	9.91 867	26	0.08 132	9.88 636	10	20
41	9.80 519	15	9.91 893	25	0.08 106	9.88 625	10	19
42	9.80 534	15	9.91 919	26	0.08 081	9.88 615	10	18
43	9.80 549	15	9.91 945	25	0.08 055	9.88 604	10	17
44	9.80 564	15	9.91 970	25	0.08 029	9.88 594	10	16
45	9.80 580	15	9.91 996	26	0.08 004	9.88 583	10	15
46	9.80 595	15	9.92 022	25	0.07 978	9.88 573	10	14
47	9.80 610	15	9.92 047	26	0.07 952	9.88 562	10	13
48	9.80 625	15	9.92 073	25	0.07 926	9.88 552	10	12
49	9.80 640	15	9.92 099	25	0.07 901	9.88 541	10	11
50	9.80 655	15	9.92 124	26	0.07 875	9.88 531	10	10
51	9.80 671	15	9.92 150	25	0.07 849	9.88 520	10	9
52	9.80 686	15	9.92 176	25	0.07 824	9.88 510	10	8
53	9.80 701	15	9.92 201	26	0.07 798	9.88 499	10	7
54	9.80 716	15	9.92 227	25	0.07 772	9.88 489	10	6
55	9.80 731	15	9.92 253	25	0.07 747	9.88 478	11	5
56	9.80 746	15	9.92 278	26	0.07 721	9.88 467	10	4
57	9.80 761	15	9.92 304	25	0.07 695	9.88 457	10	3
58	9.80 776	15	9.92 330	25	0.07 670	9.88 446	10	2
59	9.80 791	15	9.92 355	26	0.07 644	9.88 436	10	1
60	9.80 806		9.92 381		0.07 618	9.88 425		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	26	25
6	2.6	2.5
7	3.0	3.0
8	3.4	3.4
9	3.9	3.8
10	4.3	4.2
20	8.6	8.5
30	13.0	12.7
40	17.3	17.0
50	21.6	21.2

	16	15	15
6	1.6	1.5	1.5
7	1.8	1.8	1.7
8	2.1	2.0	2.0
9	2.4	2.3	2.2
10	2.6	2.6	2.5
20	5.3	5.1	5.0
30	8.0	7.7	7.5
40	10.6	10.3	10.0
50	13.3	12.9	12.5

	11	10	10
6	1.1	1.0	1.0
7	1.3	1.2	1.1
8	1.4	1.4	1.3
9	1.6	1.6	1.5
10	1.8	1.7	1.6
20	3.6	3.5	3.3
30	5.5	5.2	5.0
40	7.3	7.0	6.6
50	9.1	8.7	8.3

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.80 806	15	9.92 381	25	0.07 618	9.88 425	10	60
1	9.80 822	15	9.92 407	25	0.07 593	9.88 415	11	59
2	9.80 837	15	9.92 432	26	0.07 567	9.88 404	10	58
3	9.80 852	15	9.92 458	25	0.07 541	9.88 393	10	57
4	9.80 867	15	9.92 484	25	0.07 516	9.88 383	10	56
5	9.80 882	15	9.92 509	25	0.07 490	9.88 372	11	55
6	9.80 897	15	9.92 535	26	0.07 465	9.88 361	10	54
7	9.80 912	15	9.92 561	25	0.07 439	9.88 351	10	53
8	9.80 927	15	9.92 586	25	0.07 413	9.88 340	11	52
9	9.80 942	15	9.92 612	26	0.07 388	9.88 329	10	51
10	9.80 957	15	9.92 638	25	0.07 362	9.88 319	10	50
11	9.80 972	15	9.92 663	25	0.07 336	9.88 308	11	49
12	9.80 987	14	9.92 689	25	0.07 311	9.88 297	10	48
13	9.81 001	15	9.92 714	26	0.07 285	9.88 287	10	47
14	9.81 016	15	9.92 740	25	0.07 259	9.88 276	11	46
15	9.81 031	15	9.92 766	25	0.07 234	9.88 265	10	45
16	9.81 046	15	9.92 791	25	0.07 208	9.88 255	10	44
17	9.81 061	15	9.92 817	25	0.07 183	9.88 244	11	43
18	9.81 076	14	9.92 842	26	0.07 157	9.88 233	10	42
19	9.81 091	15	9.92 868	25	0.07 131	9.88 223	11	41
20	9.81 106	15	9.92 894	25	0.07 106	9.88 212	10	40
21	9.81 121	15	9.92 919	25	0.07 080	9.88 201	11	39
22	9.81 136	14	9.92 945	26	0.07 055	9.88 190	10	38
23	9.81 150	15	9.92 971	25	0.07 029	9.88 180	11	37
24	9.81 165	15	9.92 996	25	0.07 003	9.88 169	10	36
25	9.81 180	14	9.93 022	25	0.06 978	9.88 158	11	35
26	9.81 195	15	9.93 047	25	0.06 952	9.88 147	10	34
27	9.81 210	15	9.93 073	25	0.06 927	9.88 137	11	33
28	9.81 225	14	9.93 098	26	0.06 901	9.88 126	10	32
29	9.81 239	15	9.93 124	25	0.06 875	9.88 115	11	31
30	9.81 254	14	9.93 150	25	0.06 850	9.88 104	10	30
31	9.81 269	15	9.93 175	25	0.06 824	9.88 094	11	29
32	9.81 284	15	9.93 201	25	0.06 799	9.88 083	11	28
33	9.81 299	14	9.93 226	25	0.06 773	9.88 072	10	27
34	9.81 313	15	9.93 252	26	0.06 748	9.88 061	11	26
35	9.81 328	14	9.93 278	25	0.06 722	9.88 050	11	25
36	9.81 343	15	9.93 303	25	0.06 696	9.88 039	10	24
37	9.81 358	14	9.93 329	25	0.06 671	9.88 029	11	23
38	9.81 372	14	9.93 354	25	0.06 645	9.88 018	11	22
39	9.81 387	15	9.93 380	25	0.06 620	9.88 007	10	21
40	9.81 402	14	9.93 405	25	0.06 594	9.87 996	11	20
41	9.81 416	15	9.93 431	25	0.06 569	9.87 985	11	19
42	9.81 431	14	9.93 456	25	0.06 543	9.87 974	11	18
43	9.81 446	14	9.93 482	26	0.06 518	9.87 963	10	17
44	9.81 460	15	9.93 508	25	0.06 492	9.87 953	11	16
45	9.81 475	14	9.93 533	25	0.06 466	9.87 942	11	15
46	9.81 490	14	9.93 559	25	0.06 441	9.87 931	11	14
47	9.81 504	15	9.93 584	25	0.06 415	9.87 920	10	13
48	9.81 519	14	9.93 610	25	0.06 390	9.87 909	11	12
49	9.81 534	14	9.93 635	25	0.06 364	9.87 898	11	11
50	9.81 548	14	9.93 661	25	0.06 339	9.87 887	11	10
51	9.81 563	15	9.93 686	25	0.06 313	9.87 876	11	9
52	9.81 578	14	9.93 712	25	0.06 288	9.87 865	11	8
53	9.81 592	14	9.93 737	25	0.06 262	9.87 854	10	7
54	9.81 607	14	9.93 763	25	0.06 237	9.87 844	11	6
55	9.81 621	14	9.93 788	25	0.06 211	9.87 833	11	5
56	9.81 636	14	9.93 814	26	0.06 186	9.87 822	11	4
57	9.81 650	14	9.93 840	25	0.06 160	9.87 811	11	3
58	9.81 665	15	9.93 865	25	0.06 134	9.87 800	11	2
59	9.81 680	14	9.93 891	25	0.06 109	9.87 789	11	1
60	9.81 694		9.93 916		0.06 083	9.87 778		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	26	25
6	2.6	2.5
7	3.0	3.0
8	3.4	3.4
9	3.9	3.8
10	4.3	4.2
20	8.6	8.5
30	13.0	12.7
40	17.3	17.0
50	21.6	21.2

	15	15	14
6	1.5	1.5	1.4
7	1.8	1.7	1.7
8	2.0	2.0	1.9
9	2.3	2.2	2.2
10	2.6	2.5	2.4
20	5.1	5.0	4.8
30	7.7	7.5	7.2
40	10.3	10.0	9.6
50	12.9	12.5	12.1

	11	10
6	1.1	1.0
7	1.3	1.2
8	1.4	1.4
9	1.6	1.6
10	1.8	1.7
20	3.6	3.5
30	5.5	5.2
40	7.3	7.0
50	9.1	8.7

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.81 694	14	9.93 916	25	0.06 083	9.87 778	11	60
1	9.81 709	14	9.93 942	25	0.06 058	9.87 767	11	59
2	9.81 723	14	9.93 967	25	0.06 032	9.87 756	11	58
3	9.81 738	14	9.93 993	25	0.06 007	9.87 745	11	57
4	9.81 752	14	9.94 018	25	0.05 981	9.87 734	11	56
5	9.81 767	14	9.94 044	25	0.05 956	9.87 723	11	55
6	9.81 781	14	9.94 069	25	0.05 930	9.87 712	11	54
7	9.81 796	14	9.94 095	25	0.05 905	9.87 701	11	53
8	9.81 810	14	9.94 120	25	0.05 879	9.87 690	11	52
9	9.81 824	14	9.94 146	25	0.05 854	9.87 679	11	51
10	9.81 839	14	9.94 171	25	0.05 828	9.87 668	11	50
11	9.81 853	14	9.94 197	25	0.05 803	9.87 657	11	49
12	9.81 868	14	9.94 222	25	0.05 777	9.87 645	11	48
13	9.81 882	14	9.94 248	25	0.05 752	9.87 634	11	47
14	9.81 897	14	9.94 273	25	0.05 726	9.87 623	11	46
15	9.81 911	14	9.94 299	25	0.05 701	9.87 612	11	45
16	9.81 925	14	9.94 324	25	0.05 675	9.87 601	11	44
17	9.81 940	14	9.94 350	25	0.05 650	9.87 590	11	43
18	9.81 954	14	9.94 375	25	0.05 625	9.87 579	11	42
19	9.81 969	14	9.94 400	25	0.05 599	9.87 568	11	41
20	9.81 983	14	9.94 426	25	0.05 574	9.87 557	11	40
21	9.81 997	14	9.94 451	25	0.05 548	9.87 546	11	39
22	9.82 012	14	9.94 477	25	0.05 523	9.87 535	11	38
23	9.82 026	14	9.94 502	25	0.05 497	9.87 523	11	37
24	9.82 040	14	9.94 528	25	0.05 472	9.87 512	11	36
25	9.82 055	14	9.94 553	25	0.05 446	9.87 501	11	35
26	9.82 069	14	9.94 579	25	0.05 421	9.87 490	11	34
27	9.82 083	14	9.94 604	25	0.05 395	9.87 479	11	33
28	9.82 098	14	9.94 630	25	0.05 370	9.87 468	11	32
29	9.82 112	14	9.94 655	25	0.05 344	9.87 457	11	31
30	9.82 126	14	9.94 681	25	0.05 319	9.87 445	11	30
31	9.82 140	14	9.94 706	25	0.05 293	9.87 434	11	29
32	9.82 155	14	9.94 732	25	0.05 268	9.87 423	11	28
33	9.82 169	14	9.94 757	25	0.05 243	9.87 412	11	27
34	9.82 183	14	9.94 782	25	0.05 217	9.87 401	11	26
35	9.82 197	14	9.94 808	25	0.05 192	9.87 389	11	25
36	9.82 212	14	9.94 833	25	0.05 166	9.87 378	11	24
37	9.82 226	14	9.94 859	25	0.05 141	9.87 367	11	23
38	9.82 240	14	9.94 884	25	0.05 115	9.87 356	11	22
39	9.82 254	14	9.94 910	25	0.05 090	9.87 345	11	21
40	9.82 269	14	9.94 935	25	0.05 064	9.87 333	11	20
41	9.82 283	14	9.94 961	25	0.05 039	9.87 322	11	19
42	9.82 297	14	9.94 986	25	0.05 014	9.87 311	11	18
43	9.82 311	14	9.95 011	25	0.04 988	9.87 300	11	17
44	9.82 325	14	9.95 037	25	0.04 963	9.87 288	11	16
45	9.82 339	14	9.95 062	25	0.04 937	9.87 277	11	15
46	9.82 354	14	9.95 088	25	0.04 912	9.87 266	11	14
47	9.82 368	14	9.95 113	25	0.04 886	9.87 254	11	13
48	9.82 382	14	9.95 139	25	0.04 861	9.87 243	11	12
49	9.82 396	14	9.95 164	25	0.04 836	9.87 232	11	11
50	9.82 410	14	9.95 189	25	0.04 810	9.87 221	11	10
51	9.82 424	14	9.95 215	25	0.04 785	9.87 209	11	9
52	9.82 438	14	9.95 240	25	0.04 759	9.87 198	11	8
53	9.82 452	14	9.95 266	25	0.04 734	9.87 187	11	7
54	9.82 467	14	9.95 291	25	0.04 708	9.87 175	11	6
55	9.82 481	14	9.95 316	25	0.04 683	9.87 164	11	5
56	9.82 495	14	9.95 342	25	0.04 658	9.87 153	11	4
57	9.82 509	14	9.95 367	25	0.04 632	9.87 141	11	3
58	9.82 523	14	9.95 393	25	0.04 607	9.87 130	11	2
59	9.82 537	14	9.95 418	25	0.04 581	9.87 118	11	1
60	9.82 551	14	9.95 443	25	0.04 556	9.87 107	11	0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	25̄	25
6	2.5	2.5
7	3.0	2.9
8	3.4	3.3
9	3.8	3.7
10	4.2	4.1
20	8.5	8.3
30	12.7	12.5
40	17.0	16.6
50	21.2	20.8

	14̄	14
6	1.4	1.4
7	1.7	1.6
8	1.9	1.8
9	2.2	2.1
10	2.4	2.3
20	4.8	4.6
30	7.2	7.0
40	9.6	9.3
50	12.1	11.6

	11̄	11
6	1.1	1.1
7	1.3	1.3
8	1.5	1.4
9	1.7	1.6
10	1.9	1.8
20	3.8	3.6
30	5.7	5.5
40	7.6	7.3
50	9.6	9.1

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.82 551	14	9.95 443	25	0.04 556	9.87 107	11	60
1	9.82 565	14	9.95 469	25	0.04 531	9.87 096	11	59
2	9.82 579	14	9.95 494	25	0.04 505	9.87 084	11	58
3	9.82 593	14	9.95 520	25	0.04 480	9.87 073	11	57
4	9.82 607	14	9.95 545	25	0.04 454	9.87 062	11	56
5	9.82 621	14	9.95 571	25	0.04 429	9.87 050	11	55
6	9.82 635	14	9.95 596	25	0.04 404	9.87 039	11	54
7	9.82 649	14	9.95 621	25	0.04 378	9.87 027	11	53
8	9.82 663	14	9.95 647	25	0.04 353	9.87 016	11	52
9	9.82 677	14	9.95 672	25	0.04 327	9.87 004	11	51
10	9.82 691	14	9.95 697	25	0.04 302	9.86 993	11	50
11	9.82 705	14	9.95 723	25	0.04 277	9.86 982	11	49
12	9.82 719	14	9.95 748	25	0.04 251	9.86 970	11	48
13	9.82 733	13	9.95 774	25	0.04 226	9.86 959	11	47
14	9.82 746	14	9.95 799	25	0.04 200	9.86 947	11	46
15	9.82 760	14	9.95 824	25	0.04 175	9.86 936	11	45
16	9.82 774	14	9.95 850	25	0.04 150	9.86 924	11	44
17	9.82 788	14	9.95 875	25	0.04 124	9.86 913	11	43
18	9.82 802	13	9.95 901	25	0.04 099	9.86 901	11	42
19	9.82 816	14	9.95 926	25	0.04 074	9.86 890	11	41
20	9.82 830	14	9.95 951	25	0.04 048	9.86 878	11	40
21	9.82 844	14	9.95 977	25	0.04 023	9.86 867	11	39
22	9.82 858	13	9.96 002	25	0.03 997	9.86 855	11	38
23	9.82 871	14	9.96 027	25	0.03 972	9.86 844	11	37
24	9.82 885	14	9.96 053	25	0.03 947	9.86 832	11	36
25	9.82 899	13	9.96 078	25	0.03 921	9.86 821	11	35
26	9.82 913	14	9.96 104	25	0.03 896	9.86 809	11	34
27	9.82 927	13	9.96 129	25	0.03 871	9.86 798	12	33
28	9.82 940	14	9.96 154	25	0.03 845	9.86 786	11	32
29	9.82 954	14	9.96 180	25	0.03 820	9.86 774	11	31
30	9.82 968	13	9.96 205	25	0.03 795	9.86 763	11	30
31	9.82 982	14	9.96 230	25	0.03 769	9.86 751	11	29
32	9.82 996	13	9.96 256	25	0.03 744	9.86 740	11	28
33	9.83 009	14	9.96 281	25	0.03 718	9.86 728	12	27
34	9.83 023	13	9.96 306	25	0.03 693	9.86 716	11	26
35	9.83 037	14	9.96 332	25	0.03 668	9.86 705	11	25
36	9.83 051	13	9.96 357	25	0.03 642	9.86 693	11	24
37	9.83 064	14	9.96 383	25	0.03 617	9.86 682	11	23
38	9.83 078	13	9.96 408	25	0.03 592	9.86 670	12	22
39	9.83 092	14	9.96 433	25	0.03 566	9.86 658	11	21
40	9.83 106	13	9.96 459	25	0.03 541	9.86 647	11	20
41	9.83 119	13	9.96 484	25	0.03 516	9.86 635	12	19
42	9.83 133	14	9.96 509	25	0.03 490	9.86 623	11	18
43	9.83 147	13	9.96 535	25	0.03 465	9.86 612	11	17
44	9.83 160	13	9.96 560	25	0.03 440	9.86 600	12	16
45	9.83 174	14	9.96 585	25	0.03 414	9.86 588	11	15
46	9.83 188	13	9.96 611	25	0.03 389	9.86 577	11	14
47	9.83 201	13	9.96 636	25	0.03 364	9.86 565	12	13
48	9.83 215	14	9.96 661	25	0.03 338	9.86 553	11	12
49	9.83 229	13	9.96 687	25	0.03 313	9.86 542	12	11
50	9.83 242	13	9.96 712	25	0.03 287	9.86 530	11	10
51	9.83 256	13	9.96 737	25	0.03 262	9.86 518	11	9
52	9.83 269	14	9.96 763	25	0.03 237	9.86 507	12	8
53	9.83 283	13	9.96 788	25	0.03 211	9.86 495	11	7
54	9.83 297	13	9.96 813	25	0.03 186	9.86 483	12	6
55	9.83 310	13	9.96 839	25	0.03 161	9.86 471	11	5
56	9.83 324	13	9.96 864	25	0.03 135	9.86 460	12	4
57	9.83 337	13	9.96 889	25	0.03 110	9.86 448	11	3
58	9.83 351	14	9.96 915	25	0.03 085	9.86 436	12	2
59	9.83 365	13	9.96 940	25	0.03 059	9.86 424	12	1
60	9.83 378		9.96 965		0.03 034	9.86 412		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	$\overline{25}$	25
6	2.5	2.5
7	3.0	2.9
8	3.4	3.3
9	3.8	3.7
10	4.2	4.1
20	8.5	8.3
30	12.7	12.5
40	17.0	16.6
50	21.2	20.8

	14	$\overline{13}$
6	1.4	1.3
7	1.6	1.6
8	1.8	1.8
9	2.1	2.0
10	2.3	2.2
20	4.6	4.5
30	7.0	6.7
40	9.3	9.0
50	11.6	11.2

	12	$\overline{11}$	11
6	1.2	1.1	1.1
7	1.4	1.3	1.3
8	1.6	1.5	1.4
9	1.8	1.7	1.6
10	2.0	1.9	1.8
20	4.0	3.8	3.6
30	6.0	5.7	5.5
40	8.0	7.6	7.3
50	10.0	9.6	9.1

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.83 378	13	9.96 965	25	0.03 034	9.86 412	11	60
1	9.83 392	13	9.96 991	25	0.03 009	9.86 401	12	59
2	9.83 405	13	9.97 016	25	0.02 984	9.86 389	11	58
3	9.83 419	13	9.97 041	25	0.02 958	9.86 377	12	57
4	9.83 432	13	9.97 067	25	0.02 933	9.86 365	11	56
5	9.83 446	13	9.97 092	25	0.02 908	9.86 354	12	55
6	9.83 459	13	9.97 117	25	0.02 882	9.86 342	12	54
7	9.83 473	13	9.97 143	25	0.02 857	9.86 330	11	53
8	9.83 486	13	9.97 168	25	0.02 832	9.86 318	12	52
9	9.83 500	13	9.97 193	25	0.02 806	9.86 306	12	51
10	9.83 513	13	9.97 219	25	0.02 781	9.86 294	12	50
11	9.83 527	13	9.97 244	25	0.02 756	9.86 282	11	49
12	9.83 540	13	9.97 269	25	0.02 730	9.86 271	12	48
13	9.83 554	13	9.97 295	25	0.02 705	9.86 259	12	47
14	9.83 567	13	9.97 320	25	0.02 680	9.86 247	11	46
15	9.83 580	13	9.97 345	25	0.02 654	9.86 235	12	45
16	9.83 594	13	9.97 370	25	0.02 629	9.86 223	12	44
17	9.83 607	13	9.97 396	25	0.02 604	9.86 211	12	43
18	9.83 621	13	9.97 421	25	0.02 578	9.86 199	12	42
19	9.83 634	13	9.97 446	25	0.02 553	9.86 187	11	41
20	9.83 647	13	9.97 472	25	0.02 528	9.86 176	12	40
21	9.83 661	13	9.97 497	25	0.02 502	9.86 164	12	39
22	9.83 674	13	9.97 522	25	0.02 477	9.86 152	12	38
23	9.83 688	13	9.97 548	25	0.02 452	9.86 140	12	37
24	9.83 701	13	9.97 573	25	0.02 427	9.86 128	12	36
25	9.83 714	13	9.97 598	25	0.02 401	9.86 116	12	35
26	9.83 728	13	9.97 624	25	0.02 376	9.86 104	12	34
27	9.83 741	13	9.97 649	25	0.02 351	9.86 092	12	33
28	9.83 754	13	9.97 674	25	0.02 325	9.86 080	12	32
29	9.83 768	13	9.97 699	25	0.02 300	9.86 068	12	31
30	9.83 781	13	9.97 725	25	0.02 275	9.86 056	12	30
31	9.83 794	13	9.97 750	25	0.02 249	9.86 044	12	29
32	9.83 808	13	9.97 775	25	0.02 224	9.86 032	12	28
33	9.83 821	13	9.97 801	25	0.02 199	9.86 020	12	27
34	9.83 834	13	9.97 826	25	0.02 174	9.86 008	12	26
35	9.83 847	13	9.97 851	25	0.02 148	9.85 996	12	25
36	9.83 861	13	9.97 877	25	0.02 123	9.85 984	12	24
37	9.83 874	13	9.97 902	25	0.02 098	9.85 972	12	23
38	9.83 887	13	9.97 927	25	0.02 072	9.85 960	12	22
39	9.83 900	13	9.97 952	25	0.02 047	9.85 948	12	21
40	9.83 914	13	9.97 978	25	0.02 022	9.85 936	12	20
41	9.83 927	13	9.98 003	25	0.01 996	9.85 924	12	19
42	9.83 940	13	9.98 028	25	0.01 971	9.85 912	12	18
43	9.83 953	13	9.98 054	25	0.01 946	9.85 900	12	17
44	9.83 967	13	9.98 079	25	0.01 921	9.85 887	12	16
45	9.83 980	13	9.98 104	25	0.01 895	9.85 875	12	15
46	9.83 993	13	9.98 129	25	0.01 870	9.85 863	12	14
47	9.84 006	13	9.98 155	25	0.01 845	9.85 851	12	13
48	9.84 019	13	9.98 180	25	0.01 819	9.85 839	12	12
49	9.84 033	13	9.98 205	25	0.01 794	9.85 827	12	11
50	9.84 046	13	9.98 231	25	0.01 769	9.85 815	12	10
51	9.84 059	13	9.98 256	25	0.01 744	9.85 803	12	9
52	9.84 072	13	9.98 281	25	0.01 718	9.85 791	12	8
53	9.84 085	13	9.98 306	25	0.01 693	9.85 778	12	7
54	9.84 098	13	9.98 332	25	0.01 668	9.85 766	12	6
55	9.84 111	13	9.98 357	25	0.01 642	9.85 754	12	5
56	9.84 124	13	9.98 382	25	0.01 617	9.85 742	12	4
57	9.84 138	13	9.98 408	25	0.01 592	9.85 730	12	3
58	9.84 151	13	9.98 433	25	0.01 567	9.85 718	12	2
59	9.84 164	13	9.98 458	25	0.01 541	9.85 705	12	1
60	9.84 177		9.98 483		0.01 516	9.85 693		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	25	25
6	2.5	2.5
7	3.0	2.9
8	3.4	3.3
9	3.8	3.7
10	4.2	4.1
20	8.5	8.3
30	12.7	12.5
40	17.0	16.6
50	21.2	20.8

	13	13
6	1.3	1.3
7	1.6	1.5
8	1.8	1.7
9	2.0	1.9
10	2.2	2.1
20	4.5	4.3
30	6.7	6.5
40	9.0	8.6
50	11.2	10.8

	12	12	11
6	1.2	1.2	1.1
7	1.4	1.4	1.3
8	1.6	1.6	1.5
9	1.9	1.8	1.7
10	2.1	2.0	1.9
20	4.1	4.0	3.8
30	6.2	6.0	5.7
40	8.3	8.0	7.6
50	10.4	10.0	9.6

P. P.

′	Log. Sin.	d.	Log. Tan.	c. d.	Log. Cot.	Log. Cos.	d.	
0	9.84 177	13	9.98 483	25	0.01 516	9.85 693	12	60
1	9.84 190	13	9.98 509	25	0.01 491	9.85 681	12	59
2	9.84 203	13	9.98 534	25	0.01 465	9.85 669	12	58
3	9.84 216	13	9.98 559	25	0.01 440	9.85 657	12	57
4	9.84 229	13	9.98 585	25	0.01 415	9.85 644	12	56
5	9.84 242	13	9.98 610	25	0.01 390	9.85 632	12	55
6	9.84 255	13	9.98 635	25	0.01 364	9.85 620	12	54
7	9.84 268	13	9.98 660	25	0.01 339	9.85 608	12	53
8	9.84 281	13	9.98 686	25	0.01 314	9.85 595	12	52
9	9.84 294	13	9.98 711	25	0.01 289	9.85 583	12	51
10	9.84 307	13	9.98 736	25	0.01 263	9.85 571	12	50
11	9.84 320	13	9.98 762	25	0.01 238	9.85 559	12	49
12	9.84 333	13	9.98 787	25	0.01 213	9.85 546	12	48
13	9.84 346	13	9.98 812	25	0.01 187	9.85 534	12	47
14	9.84 359	13	9.98 837	25	0.01 162	9.85 522	12	46
15	9.84 372	13	9.98 863	25	0.01 137	9.85 509	12	45
16	9.84 385	13	9.98 888	25	0.01 112	9.85 497	12	44
17	9.84 398	13	9.98 913	25	0.01 086	9.85 485	12	43
18	9.84 411	13	9.98 938	25	0.01 061	9.85 472	12	42
19	9.84 424	12	9.98 964	25	0.01 036	9.85 460	12	41
20	9.84 437	13	9.98 989	25	0.01 010	9.85 448	12	40
21	9.84 450	13	9.99 014	25	0.00 985	9.85 435	12	39
22	9.84 463	13	9.99 040	25	0.00 960	9.85 423	12	38
23	9.84 476	13	9.99 065	25	0.00 935	9.85 411	12	37
24	9.84 489	13	9.99 090	25	0.00 909	9.85 398	12	36
25	9.84 502	12	9.99 115	25	0.00 884	9.85 386	12	35
26	9.84 514	13	9.99 141	25	0.00 859	9.85 374	12	34
27	9.84 527	13	9.99 166	25	0.00 834	9.85 361	12	33
28	9.84 540	13	9.99 191	25	0.00 808	9.85 349	12	32
29	9.84 553	12	9.99 216	25	0.00 783	9.85 336	12	31
30	9.84 566	13	9.99 242	25	0.00 758	9.85 324	12	30
31	9.84 579	13	9.99 267	25	0.00 733	9.85 312	12	29
32	9.84 592	12	9.99 292	25	0.00 707	9.85 299	12	28
33	9.84 604	13	9.99 318	25	0.00 682	9.85 287	12	27
34	9.84 617	13	9.99 343	25	0.00 657	9.85 274	12	26
35	9.84 630	12	9.99 368	25	0.00 631	9.85 262	12	25
36	9.84 643	13	9.99 393	25	0.00 606	9.85 249	12	24
37	9.84 656	13	9.99 419	25	0.00 581	9.85 237	12	23
38	9.84 669	12	9.99 444	25	0.00 556	9.85 224	12	22
39	9.84 681	13	9.99 469	25	0.00 530	9.85 212	12	21
40	9.84 694	12	9.99 494	25	0.00 505	9.85 199	12	20
41	9.84 707	13	9.99 520	25	0.00 480	9.85 187	12	19
42	9.84 720	12	9.99 545	25	0.00 455	9.85 174	12	18
43	9.84 732	13	9.99 570	25	0.00 429	9.85 162	12	17
44	9.84 745	12	9.99 595	25	0.00 404	9.85 149	12	16
45	9.84 758	13	9.99 621	25	0.00 379	9.85 137	12	15
46	9.84 771	12	9.99 646	25	0.00 353	9.85 124	12	14
47	9.84 783	13	9.99 671	25	0.00 328	9.85 112	12	13
48	9.84 796	12	9.99 697	25	0.00 303	9.85 099	12	12
49	9.84 809	13	9.99 722	25	0.00 278	9.85 087	12	11
50	9.84 822	12	9.99 747	25	0.00 252	9.85 074	12	10
51	9.84 834	12	9.99 772	25	0.00 227	9.85 062	12	9
52	9.84 847	13	9.99 798	25	0.00 202	9.85 049	12	8
53	9.84 860	12	9.99 823	25	0.00 177	9.85 037	13	7
54	9.84 872	12	9.99 848	25	0.00 151	9.85 024	12	6
55	9.84 885	13	9.99 873	25	0.00 126	9.85 011	12	5
56	9.84 898	12	9.99 899	25	0.00 101	9.84 999	12	4
57	9.84 910	12	9.99 924	25	0.00 076	9.84 986	12	3
58	9.84 923	13	9.99 949	25	0.00 050	9.84 974	13	2
59	9.84 936	12	9.99 974	25	0.00 025	9.84 961	12	1
60	9.84 948		0.00 000		0.00 000	9.84 948		0
	Log. Cos.	d.	Log. Cot.	c. d.	Log. Tan.	Log. Sin.	d.	′

P. P.

	25	25
6	2.5	2.5
7	3.0	2.9
8	3.4	3.3
9	3.8	3.7
10	4.2	4.1
20	8.5	8.3
30	12.7	12.5
40	17.0	16.6
50	21.2	20.8

	13	13
6	1.3	1.3
7	1.6	1.5
8	1.8	1.7
9	2.0	1.9
10	2.2	2.1
20	4.5	4.3
30	6.7	6.5
40	9.0	8.6
50	11.2	10.8

	12	12
6	1.2	1.2
7	1.4	1.4
8	1.6	1.6
9	1.9	1.8
10	2.1	2.0
20	4.1	4.0
30	6.2	6.0
40	8.3	8.0
50	10.4	10.0

P. P.

TABLE VIII.—LOGARITHMIC VERSED SINES AND EXTERNAL SECANTS.

′	0° Log. Vers.	D	0° Log. Exsec.	D	1° Log. Vers.	D	1° Log. Exsec.	D	′
0	− ∞		− ∞		6.18271	1435	6.18278	1436	0
1	2.62642	60206	2.62642	60206	.19707	1412	.19714	1412	1
2	3.22848	35218	3.22848	35218	.21119	1389	.21126	1390	2
3	3.58066	24987	3.58066	24987	.22509	1368	.22516	1368	3
4	3.83054	19382	3.83054	19382	.23877	1346	.23884	1347	4
5	4.02436	15836	4.02436	15836	6.25223	1326	6.25231	1326	5
6	.18272	13389	.18272	13389	.26549	1306	.26557	1306	6
7	.31662	11598	.31662	11598	.27856	1286	.27864	1287	7
8	.43260	10230	.43260	10230	.29142	1268	.29151	1268	8
9	.53490	9151	.53491	9151	.30410	1250	.30419	1250	9
10	4.62642	8278	4.62642	8279	6.31660	1232	6.31669	1232	10
11	.70920	7558	.70921	7557	.32892	1214	.32901	1215	11
12	.78478	6953	.78478	6952	.34107	1198	.34116	1198	12
13	.85431	6437	.85431	6437	.35305	1182	.35315	1182	13
14	.91868	5992	.91868	5993	.36487	1166	.36497	1166	14
15	4.97860	5605	4.97861	5605	6.37653	1150	6.37663	1151	15
16	5.03466	5266	5.03466	5266	.38803	1135	.38814	1135	16
17	.08732	4964	.08732	4964	.39938	1121	.39949	1121	17
18	.13696	4696	.13697	4696	.41059	1106	.41070	1106	18
19	.18393	4455	.18393	4456	.42165	1093	.42177	1093	19
20	5.22848	4238	5.22849	4238	6.43258	1078	6.43270	1079	20
21	.27086	4040	.27087	4040	.44337	1066	.44349	1066	21
22	.31126	3861	.31127	3861	.45403	1052	.45415	1053	22
23	.34987	3697	.34988	3697	.46455	1040	.46468	1040	23
24	.38684	3545	.38685	3545	.47496	1028	.47509	1028	24
25	5.42230	3406	5.42231	3407	6.48524	1016	6.48537	1015	25
26	.45636	3278	.45638	3278	.49539	1004	.49553	1004	26
27	.48915	3158	.48916	3159	.50544	992	.50557	993	27
28	.52073	3048	.52075	3048	.51536	981	.51550	982	28
29	.55121	2944	.55123	2945	.52518	970	.52532	970	29
30	5.58066	2848	5.58068	2848	6.53488	960	6.53503	960	30
31	.60914	2757	.60916	2758	.54448	949	.54463	950	31
32	.63672	2672	.63674	2672	.55397	939	.55413	939	32
33	.66344	2593	.66346	2593	.56336	929	.56352	929	33
34	.68937	2518	.68940	2517	.57265	919	.57281	919	34
35	5.71455	2447	5.71457	2447	6.58184	909	6.58201	909	35
36	.73902	2379	.73904	2380	.59093	900	.59110	900	36
37	.76282	2316	.76284	2316	.59993	891	.60011	891	37
38	.78598	2256	.78601	2256	.60884	882	.60902	882	38
39	.80854	2199	.80857	2199	.61766	872	.61784	873	39
40	5.83053	2145	5.83056	2145	6.62639	864	6.62657	864	40
41	.85198	2093	.85201	2093	.63503	855	.63522	856	41
42	.87291	2044	.87295	2043	.64359	847	.64378	848	42
43	.89335	1996	.89338	1997	.65206	839	.65226	839	43
44	.91332	1952	.91335	1952	.66045	831	.66065	831	44
45	5.93284	1909	5.93288	1909	6.66876	823	6.66897	823	45
46	.95193	1868	.95197	1868	.67700	815	.67720	816	46
47	.97061	1829	.97065	1829	.68515	808	.68536	808	47
48	5.98890	1790	5.98894	1791	.69323	800	.69345	800	48
49	6.00680	1755	6.00685	1755	.70124	793	.70145	794	49
50	6.02435	1720	6.02440	1720	6.70917	786	6.70939	786	50
51	.04155	1686	.04160	1687	.71703	779	.71725	779	51
52	.05842	1654	.05847	1654	.72482	772	.72505	772	52
53	.07496	1623	.07501	1623	.73254	765	.73277	765	53
54	.09120	1594	.09125	1594	.74019	758	.74043	759	54
55	6.10714	1565	6.10719	1565	6.74777	752	6.74802	752	55
56	.12279	1537	.12284	1537	.75529	745	.75554	746	56
57	.13816	1511	.13822	1511	.76275	739	.76300	739	57
58	.15327	1484	.15333	1485	.77014	733	.77040	733	58
59	.16811	1460	.16818	1460	.77747	726	.77773	727	59
60	6.18271		6.18278		6.78474		6.78500		60
′	Log. Vers.	D	Log. Exsec.	D	Log. Vers.	D	Log. Exsec.	D	′

	2°				3°				
′	Log. Vers.	D	Log. Exsec.	D	Log. Vers.	D	Log. Exsec.	D	′
0	6.78474	721	6.78500	721	7.13687	481	7.13746	481	0
1	.79195	714	.79221	715	.14168	478	.14228	479	1
2	.79909	709	.79937	709	.14646	475	.14707	476	2
3	.80618	703	.80646	703	.15122	473	.15183	474	3
4	.81322	697	.81350	698	.15595	470	.15657	471	4
5	6.82019	692	6.82048	692	7.16066	468	7.16129	469	5
6	.82711	686	.82740	687	.16534	466	.16598	466	6
7	.83398	681	.83427	682	.17000	463	.17064	464	7
8	.84079	676	.84109	676	.17463	460	.17528	461	8
9	.84755	670	.84785	671	.17923	458	.17989	459	9
10	6.85425	665	6.85457	666	7.18382	455	7.18448	456	10
11	.86091	660	.86123	660	.18837	453	.18905	454	11
12	.86751	655	.86783	656	.19291	451	.19359	452	12
13	.87407	650	.87439	651	.19742	448	.19811	449	13
14	.88057	646	.88090	646	.20191	446	.20260	447	14
15	6.88703	641	6.88737	641	7.20637	444	7.20707	445	15
16	.89344	636	.89378	636	.21081	442	.21152	442	16
17	.89980	631	.90015	632	.21523	440	.21595	440	17
18	.90612	627	.90647	628	.21963	437	.22035	438	18
19	.91239	622	.91275	623	.22400	435	.22473	436	19
20	6.91862	618	6.91898	618	7.22836	433	7.22909	434	20
21	.92480	613	.92516	614	.23269	431	.23343	431	21
22	.93093	609	.93131	610	.23700	429	.23775	429	22
23	.93703	605	.93741	605	.24129	426	.24204	427	23
24	.94308	601	.94346	601	.24555	424	.24632	425	24
25	6.94909	597	6.94948	597	7.24980	422	7.25057	423	25
26	.95506	592	.95545	593	.25402	420	.25480	421	26
27	.96099	589	.96139	589	.25823	418	.25902	419	27
28	.96688	584	.96728	585	.26241	416	.26321	417	28
29	.97272	581	.97313	581	.26658	414	.26738	415	29
30	6.97853	577	6.97895	577	7.27072	412	7.27153	413	30
31	.98430	573	.98472	574	.27485	410	.27567	411	31
32	.99004	569	.99046	570	.27895	409	.27978	409	32
33	6.99573	565	6.99616	566	.28304	406	.28387	407	33
34	7.00139	562	7.00182	563	.28711	405	.28795	405	34
35	7.00701	558	7.00745	559	7.29116	402	7.29200	404	35
36	.01259	555	.01304	555	.29518	401	.29604	402	36
37	.01814	551	.01860	552	.29919	399	.30006	400	37
38	.02366	548	.02412	548	.30319	397	.30406	398	38
39	.02914	544	.02960	545	.30716	395	.30804	396	39
40	7.03458	541	7.03505	541	7.31112	393	7.31201	394	40
41	.03999	537	.04047	538	.31505	392	.31595	393	41
42	.04537	534	.04585	535	.31897	390	.31988	391	42
43	.05071	531	.05120	531	.32288	388	.32379	389	43
44	.05603	527	.05652	528	.32676	386	.32768	388	44
45	7.06130	525	7.06180	525	7.33063	385	7.33156	385	45
46	.06655	521	.06706	522	.33448	383	.33542	384	46
47	.07177	518	.07228	519	.33831	382	.33926	382	47
48	.07695	515	.07747	516	.34213	380	.34309	380	48
49	.08211	512	.08263	513	.34593	378	.34689	379	49
50	7.08723	509	7.08776	509	7.34971	377	7.35069	377	50
51	.09232	506	.09286	507	.35348	375	.35446	376	51
52	.09739	503	.09793	503	.35723	373	.35822	374	52
53	.10242	500	.10297	501	.36097	371	.36196	373	53
54	.10743	497	.10798	498	.36468	370	.36569	371	54
55	7.11240	495	7.11297	495	7.36839	368	7.36940	369	55
56	.11735	492	.11792	493	.37207	367	.37310	368	56
57	.12227	489	.12285	490	.37574	366	.37678	366	57
58	.12716	486	.12775	487	.37940	364	.38044	365	58
59	.13203	484	.13262	484	.38304	362	.38409	363	59
60	7.13687		7.13746		7.38667		7.38773		60
′	Log. Vers.	D	Log. Exsec.	D	Log. Vers.	D	Log. Exsec.	D	′

′	4° Lg. Vers.	D	4° Log. Exs.	D	5° Lg. Vers.	D	5° Log. Exs.	D	′
0	7.38667	361	7.38773	361	7.58039	289	7.58204	290	0
1	.39028	359	.39134	360	.58328	287	.58494	289	1
2	.39387	358	.39495	359	.58615	287	.58783	288	2
3	.39745	356	.39854	357	.58902	286	.59071	287	3
4	.40102	355	.40211	356	.59188	285	.59358	286	4
5	7.40457	353	7.40567	354	7.59473	284	7.59645	285	5
6	.40810	352	.40922	353	.59758	283	.59930	284	6
7	.41163	350	.41275	352	.60041	282	.60214	283	7
8	.41513	349	.41627	350	.60323	281	.60498	282	8
9	.41863	348	.41977	349	.60604	280	.60780	281	9
10	7.42211	346	7.42326	347	7.60885	279	7.61062	280	10
11	.42557	345	.42673	346	.61164	279	.61342	280	11
12	.42903	343	.43019	345	.61443	277	.61622	279	12
13	.43246	342	.43364	343	.61721	277	.61901	278	13
14	.43589	341	.43708	342	.61998	276	.62179	277	14
15	7.43930	339	7.44050	340	7.62274	275	7.62456	276	15
16	.44270	338	.44390	339	.62549	274	.62733	275	16
17	.44608	337	.44730	338	.62823	273	.63008	274	17
18	.44946	335	.45068	337	.63096	272	.63282	274	18
19	.45281	334	.45405	335	.63369	272	.63556	273	19
20	7.45616	333	7.45740	334	7.63641	270	7.63829	272	20
21	.45949	332	.46075	332	.63911	270	.64101	271	21
22	.46281	330	.46407	332	.64181	269	.64372	270	22
23	.46612	329	.46739	330	.64451	268	.64643	269	23
24	.46941	328	.47070	329	.64719	267	.64912	269	24
25	7.47270	327	7.47399	328	7.64986	266	7.65181	268	25
26	.47597	325	.47727	327	.65253	266	.65449	267	26
27	.47922	324	.48054	325	.65519	265	.65716	266	27
28	.48247	323	.48379	324	.65784	264	.65982	265	28
29	.48570	322	.48703	323	.66048	263	.66247	264	29
30	7.48892	321	7.49026	322	7.66311	263	7.66512	264	30
31	.49213	320	.49348	321	.66574	261	.66776	263	31
32	.49533	318	.49669	319	.66836	261	.67039	262	32
33	.49852	317	.49989	318	.67097	260	.67301	261	33
34	.50169	316	.50307	317	.67357	259	.67562	261	34
35	7.50485	315	7.50624	316	7.67617	258	7.67823	260	35
36	.50800	314	.50941	315	.67875	258	.68083	259	36
37	.51114	313	.51256	313	.68133	257	.68342	258	37
38	.51427	311	.51569	313	.68390	256	.68601	257	38
39	.51739	311	.51882	311	.68647	255	.68858	257	39
40	7.52050	309	7.52194	310	7.68902	255	7.69115	256	40
41	.52359	308	.52504	309	.69157	254	.69371	255	41
42	.52667	307	.52814	308	.69411	253	.69627	254	42
43	.52975	306	.53122	307	.69665	252	.69881	254	43
44	.53281	305	.53429	306	.69917	252	.70135	253	44
45	7.53586	304	7.53735	305	7.70169	251	7.70388	252	45
46	.53890	303	.54041	304	.70421	250	.70641	252	46
47	.54193	302	.54345	303	.70671	250	.70893	251	47
48	.54495	300	.54648	302	.70921	249	.71144	250	48
49	.54796	300	.54950	301	.71170	248	.71394	250	49
50	7.55096	299	7.55251	299	7.71418	247	7.71644	248	50
51	.55395	297	.55550	299	.71666	247	.71892	248	51
52	.55692	297	.55849	298	.71913	246	.72141	247	52
53	.55989	295	.56147	296	.72159	245	.72388	246	53
54	.56285	295	.56444	296	.72404	245	.72635	246	54
55	7.56580	293	7.56740	295	7.72649	244	7.72881	245	55
56	.56873	293	.57035	294	.72893	243	.73126	245	56
57	.57166	292	.57329	292	.73137	242	.73371	244	57
58	.57458	290	.57621	292	.73379	242	.73615	243	58
59	.57749	290	.57913	291	.73621	241	.73859	242	59
60	7.58039		7.58204		7.73863		7.74101		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	360	350	340	330	320	310	300	290	280
6	36.0	35.0	34.0	33.0	32.0	31.0	30.0	29.0	28.0
7	42.0	40.8	39.6	38.5	37.3	36.1	35.0	33.8	32.6
8	48.0	46.6	45.3	44.0	42.6	41.3	40.0	38.6	37.3
9	54.0	51.5	51.0	49.5	48.0	46.5	45.0	43.5	42.0
10	60.0	58.3	56.6	55.0	53.3	51.6	50.0	48.3	46.6
20	120.0	116.6	113.3	110.0	106.6	103.3	100.0	96.6	93.3
30	180.0	175.0	170.0	165.0	160.0	155.0	150.0	145.0	140.0
40	240.0	233.3	226.6	220.0	213.3	206.6	200.0	193.3	186.6
50	300.0	291.6	283.3	275.0	266.6	258.3	250.0	241.6	233.3

	270	260	250	240	230	220	210	200	190
6	27.0	26.0	25.0	24.0	23.0	22.0	21.0	20.0	19.0
7	31.5	30.3	29.1	28.0	26.8	25.6	24.5	23.3	22.1
8	36.0	34.6	33.3	32.0	30.6	29.3	28.0	26.6	25.3
9	40.5	39.0	37.5	36.0	34.5	33.0	31.5	30.0	28.5
10	45.0	43.3	41.6	40.0	38.3	36.6	35.0	33.3	31.6
20	90.0	86.6	83.3	80.0	76.6	73.3	70.0	66.6	63.3
30	135.0	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0
40	180.0	173.3	166.6	160.0	153.3	146.6	140.0	133.3	126.6
50	225.0	216.6	208.3	200.0	191.6	183.3	175.0	166.6	158.3

P. P.

′	6° Lg. Vers.	D	6° Log. Exs.	D	7° Lg. Vers.	D	7° Log. Exs.	D	′
0	7.73863	241	7.74101	242	7.87238	206	7.87563	208	0
1	.74104	240	.74343	241	.87444	205	.87771	207	1
2	.74344	239	.74585	241	.87650	205	.87978	207	2
3	.74583	239	.74826	240	.87855	204	.88185	206	3
4	.74822	238	.75066	239	.88060	204	.88391	206	4
5	7.75060	237	7.75305	239	7.88264	204	7.88597	205	5
6	.75297	236	.75544	238	.88468	203	.88803	205	6
7	.75534	236	.75782	237	.88672	203	.89008	204	7
8	.75770	235	.76019	237	.88875	202	.89212	204	8
9	.76006	234	.76256	236	.89077	202	.89416	203	9
10	7.76240	234	7.76492	235	7.89279	201	7.89620	203	10
11	.76475	233	.76728	235	.89481	201	.89823	202	11
12	.76708	233	.76963	234	.89682	200	.90025	202	12
13	.76941	232	.77197	233	.89882	200	.90228	201	13
14	.77173	232	.77431	233	.90082	199	.90429	201	14
15	7.77405	231	7.77664	232	7.90282	199	7.90630	201	15
16	.77636	230	.77897	231	.90481	198	.90831	200	16
17	.77867	230	.78128	231	.90680	198	.91032	199	17
18	.78097	229	.78360	230	.90878	197	.91231	199	18
19	.78326	228	.78590	230	.91076	197	.91431	199	19
20	7.78554	228	7.78820	229	7.91273	197	7.91630	198	20
21	.78783	227	.79050	229	.91470	196	.91828	198	21
22	.79010	227	.79279	228	.91667	196	.92027	197	22
23	.79237	226	.79507	228	.91863	195	.92224	197	23
24	.79463	225	.79735	227	.92058	195	.92421	197	24
25	7.79689	225	7.79962	226	7.92253	195	7.92618	196	25
26	.79914	224	.80188	226	.92448	194	.92815	195	26
27	.80138	224	.80414	225	.92642	194	.93010	195	27
28	.80362	223	.80639	225	.92836	193	.93206	195	28
29	.80586	222	.80864	224	.93029	193	.93401	195	29
30	7.80808	222	7.81088	224	7.93222	192	7.93596	194	30
31	.81031	221	.81312	223	.93415	192	.93790	194	31
32	.81252	221	.81535	222	.93607	191	.93984	193	32
33	.81473	220	.81758	222	.93799	191	.94177	193	33
34	.81694	220	.81980	221	.93990	190	.94370	192	34
35	7.81914	219	7.82201	221	7.94181	190	7.94562	192	35
36	.82133	219	.82422	220	.94371	190	.94754	192	36
37	.82352	218	.82642	219	.94561	189	.94946	191	37
38	.82570	217	.82862	219	.94751	189	.95137	191	38
39	.82788	217	.83081	219	.94940	189	.95328	190	39
40	7.83005	217	7.83300	218	7.95129	188	7.95519	190	40
41	.83222	216	.83518	217	.95317	187	.95709	189	41
42	.83438	215	.83735	217	.95505	188	.95898	189	42
43	.83653	215	.83952	216	.95693	187	.96088	188	43
44	.83868	214	.84169	216	.95880	186	.96276	188	44
45	7.84083	214	7.84385	215	7.96066	186	7.96465	188	45
46	.84297	213	.84600	215	.96253	186	.96653	188	46
47	.84510	213	.84815	214	.96439	185	.96841	187	47
48	.84723	212	.85030	213	.96624	185	.97028	187	48
49	.84935	212	.85243	213	.96809	184	.97215	186	49
50	7.85147	211	7.85457	213	7.96994	184	7.97401	186	50
51	.85359	211	.85670	212	.97178	184	.97587	185	51
52	.85570	210	.85882	211	.97362	183	.97773	185	52
53	.85780	210	.86094	211	.97546	183	.97958	184	53
54	.85990	209	.86305	211	.97729	183	.98143	184	54
55	7.86199	209	7.86516	210	7.97912	182	7.98327	184	55
56	.86408	208	.86726	210	.98094	182	.98512	183	56
57	.86616	208	.86936	209	.98276	182	.98695	183	57
58	.86824	207	.87146	208	.98458	181	.98879	183	58
59	.87031	206	.87354	208	.98639	181	.99062	182	59
60	7.87238		7.87563		7.98820		7.99244		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	180	$\bar{9}$	9
6	18.0	0.9	0.9
7	21.0	1.1	1.0
8	24.0	1.2	1.2
9	27.0	1.4	1.3
10	30.0	1.6	1.5
20	60.0	3.1	3.0
30	90.0	4.7	4.5
40	120.0	6.3	6.0
50	150.0	7.9	7.5

	$\bar{8}$	8	$\bar{7}$
6	0.8	0.8	0.7
7	1.0	0.9	0.9
8	1.1	1.0	1.0
9	1.3	1.2	1.1
10	1.4	1.3	1.2
20	2.8	2.6	2.5
30	4.2	4.0	3.7
40	5.6	5.3	5.0
50	7.1	6.6	6.2

	7	$\bar{6}$	6
6	0.7	0.6	0.6
7	0.8	0.7	0.7
8	0.9	0.8	0.8
9	1.0	1.0	0.9
10	1.1	1.1	1.0
20	2.3	2.1	2.0
30	3.5	3.2	3.0
40	4.6	4.3	4.0
50	5.8	5.4	5.0

	$\bar{5}$	5	$\bar{4}$	4
6	0.5	0.5	0.4	0.4
7	0.6	0.6	0.5	0.4
8	0.7	0.6	0.6	0.5
9	0.8	0.7	0.7	0.6
10	0.9	0.8	0.7	0.6
20	1.8	1.6	1.5	1.3
30	2.7	3.5	2.2	2.0
40	3.6	3.3	3.0	2.6
50	4.6	4.1	3.7	3.3

	$\bar{3}$	3	$\bar{2}$	2
6	0.3	0.3	0.2	0.2
7	0.4	0.3	0.3	0.2
8	0.4	0.4	0.3	0.2
9	0.5	0.4	0.4	0.3
10	0.6	0.5	0.4	0.3
20	1.1	1.0	0.8	0.6
30	1.7	1.5	1.2	1.0
40	2.3	2.0	1.6	1.3
50	2.9	2.5	2.1	1.6

	$\bar{1}$	1	$\bar{0}$
6	0.1	0.1	0.0
7	0.2	0.1	0.0
8	0.2	0.1	0.0
9	0.2	0.1	0.1
10	0.2	0.1	0.1
20	0.5	0.3	0.1
30	0.7	0.5	0.2
40	1.0	0.6	0.3
50	1.2	0.8	0.4

P. P.

′	8° Lg. Vers.	D	8° Log.Exs.	D	9° Lg. Vers.	D	9° Log.Exs.	D	′
0	7.98820	180	7.99244	182	8.09031	160	8.09569	162	0
1	.99000	180	.99427	182	.09192	160	.09732	162	1
2	.99180	179	.99609	181	.09352	160	.09894	162	2
3	.99360	179	.99790	181	.09512	159	.10056	161	3
4	.99539	179	7.99971	180	.09671	159	.10217	161	4
5	7.99718	178	8.00152	180	8.09830	159	8.10378	161	5
6	7.99897	178	.00332	180	.09989	158	.10539	160	6
7	8.00075	177	.00512	180	.10148	158	.10700	160	7
8	.00253	178	.00692	179	.10306	158	.10860	160	8
9	.00431	177	.00871	179	.10464	157	.11020	160	9
10	8.00608	176	8.01050	178	8.10622	157	8.11180	159	10
11	.00784	176	.01229	178	.10779	157	.11340	159	11
12	.00961	176	.01407	178	.10936	157	.11499	159	12
13	.01137	176	.01585	177	.11093	156	.11658	158	13
14	.01313	175	.01763	177	.11250	156	.11816	158	14
15	8.01488	175	8.01940	177	8.11406	156	8.11975	158	15
16	.01663	175	.02117	176	.11562	155	.12133	158	16
17	.01838	174	.02293	176	.11718	155	.12291	157	17
18	.02012	174	.02469	175	.11873	155	.12448	157	18
19	.02186	173	.02645	175	.12029	155	.12605	157	19
20	8.02359	173	8.02820	175	8.12184	154	8.12762	157	20
21	.02533	173	.02995	175	.12338	154	.12919	156	21
22	.02706	172	.03170	174	.12492	154	.13075	156	22
23	.02878	172	.03345	174	.12647	153	.13232	155	23
24	.03050	172	.03519	173	.12800	153	.13387	156	24
25	8.03222	171	8.03692	173	8.12954	153	8.13543	155	25
26	.03394	171	.03866	173	.13107	153	.13698	155	26
27	.03565	171	.04039	173	.13260	152	.13854	154	27
28	.03736	170	.04212	172	.13413	152	.14008	154	28
29	.03906	170	.04384	172	.13565	152	.14163	154	29
30	8.04076	170	8.04556	171	8.13717	152	8.14317	154	30
31	.04246	169	.04728	171	.13869	151	.14471	153	31
32	.04416	169	.04899	171	.14021	151	.14625	153	32
33	.04585	169	.05070	170	.14172	151	.14778	153	33
34	.04754	168	.05241	170	.14323	151	.14932	153	34
35	8.04922	168	8.05411	170	8.14474	150	8.15085	152	35
36	.05090	168	.05581	170	.14625	150	.15237	152	36
37	.05258	167	.05751	169	.14775	150	.15390	152	37
38	.05426	167	.05921	169	.14925	149	.15542	152	38
39	.05593	167	.06090	169	.15075	150	.15694	152	39
40	8.05760	166	8.06259	168	8.15225	149	8.15846	151	40
41	.05926	166	.06427	168	.15374	149	.15997	151	41
42	.06093	166	.06595	168	.15523	149	.16148	151	42
43	.06259	165	.06763	167	.15672	148	.16299	150	43
44	.06424	165	.06931	167	.15820	148	.16450	150	44
45	8.06589	165	8.07098	167	8.15968	148	8.16600	150	45
46	.06754	165	.07265	166	.16116	148	.16750	150	46
47	.06919	164	.07431	166	.16264	147	.16900	149	47
48	.07083	164	.07598	166	.16412	147	.17050	149	48
49	.07247	164	.07764	165	.16559	147	.17199	149	49
50	8.07411	163	8.07929	165	8.16706	146	8.17349	148	50
51	.07575	163	.08095	165	.16852	146	.17497	149	51
52	.07738	162	.08260	164	.16999	146	.17646	148	52
53	.07900	162	.08424	164	.17145	146	.17795	148	53
54	.08063	162	.08589	164	.17291	145	.17943	148	54
55	8.08225	161	8.08753	163	8.17437	145	8.18091	147	55
56	.08387	162	.08917	164	.17582	145	.18238	147	56
57	.08549	161	.09081	163	.17728	145	.18386	147	57
58	.08710	161	.09244	163	.17873	144	.18533	147	58
59	.08871	160	.09407	162	.18017	144	.18680	146	59
60	8.09031		8.09569		8.18162		8.18827		60
′	Lg. Vers.	D	Log.Exs.	D	Lg. Vers.	D	Log.Exs.	D	′

P. P.

	180	170	16
6	18.0	17.0	16.
7	21.0	19.8	18.
8	24.0	22.6	21.
9	27.0	25.5	24.
10	30.0	28.3	26.
20	60.0	56.6	53.
30	90.0	85.0	80.
40	120.0	113.3	106.
50	150.0	141.6	133.

	150	140
6	15.0	14.0
7	17.5	16.3
8	20.0	18.6
9	22.5	21.0
10	25.0	23.3
20	50.0	46.6
30	75.0	70.0
40	100.0	93.3
50	125.0	116.6

	9	9	8
6	0.9	0.9	0.8
7	1.1	1.0	1.0
8	1.2	1.2	1.1
9	1.4	1.3	1.3
10	1.6	1.5	1.4
20	3.1	3.0	2.8
30	4.7	4.5	4.3
40	6.3	6.0	5.6
50	7.9	7.5	7.1

	8	7	7
6	0.8	0.7	0.7
7	0.9	0.9	0.8
8	1.0	1.0	0.9
9	1.2	1.1	1.0
10	1.3	1.2	1.1
20	2.6	2.5	2.3
30	4.0	3.7	3.5
40	5.3	5.0	4.6
50	6.6	6.2	5.8

	6	6
6	0.6	0.6
7	0.7	0.7
8	0.8	0.8
9	1.0	0.9
10	1.1	1.0
20	2.1	2.0
30	3.2	3.0
40	4.3	4.0
50	5.4	5.0

	5	5
6	0.5	0.5
7	0.6	0.6
8	0.7	0.6
9	0.8	0.7
10	0.9	0.8
20	1.8	1.6
30	2.7	2.5
40	3.6	3.3
50	4.6	4.1

P. P.

′	10° Lg. Vers.	D	10° Log. Exs.	D	11° Lg. Vers.	D	11° Log. Exs.	D	′
0	8.18162	144	8.18827	146	8.26417	131	8.27223	133	0
1	.18306	144	.18973	146	.26548	131	.27356	133	1
2	.18450	144	.19120	146	.26679	131	.27490	133	2
3	.18594	143	.19266	145	.26810	130	.27623	133	3
4	.18738	143	.19411	145	.26941	130	.27756	133	4
5	8.18881	143	8.19557	145	8.27071	130	8.27889	132	5
6	.19024	142	.19702	145	.27201	130	.28021	132	6
7	.19167	142	.19847	145	.27331	130	.28153	132	7
8	.19309	142	.19992	144	.27461	129	.28286	132	8
9	.19452	142	.20137	144	.27590	129	.28418	132	9
10	8.19594	142	8.20281	144	8.27719	129	8.28550	131	10
11	.19736	142	.20425	144	.27849	128	.28681	131	11
12	.19878	141	.20569	144	.27977	129	.28813	131	12
13	.20019	141	.20713	143	.28106	128	.28944	131	13
14	.20160	141	.20857	143	.28235	128	.29075	131	14
15	8.20301	140	8.21000	143	8.28363	128	8.29206	130	15
16	.20442	140	.21143	143	.28491	128	.29336	130	16
17	.20582	140	.21286	142	.28619	128	.29467	130	17
18	.20723	140	.21428	142	.28747	127	.29597	130	18
19	.20863	140	.21571	142	.28875	127	.29727	130	19
20	8.21003	139	8.21713	142	8.29002	127	8.29857	130	20
21	.21142	139	.21855	141	.29129	127	.29987	129	21
22	.21282	139	.21996	141	.29256	127	.30117	129	22
23	.21421	139	.22138	141	.29383	126	.30246	129	23
24	.21560	138	.22279	141	.29510	126	.30375	129	24
25	8.21698	138	8.22420	140	8.29636	126	8.30504	129	25
26	.21837	138	.22561	140	.29763	126	.30633	128	26
27	.21975	138	.22701	140	.29889	126	.30762	128	27
28	.22113	137	.22842	140	.30015	125	.30890	128	28
29	.22251	138	.22982	140	.30140	125	.31019	128	29
30	8.22389	137	8.23122	140	8.30266	125	8.31147	128	30
31	.22526	137	.23262	139	.30391	125	.31275	127	31
32	.22663	136	.23401	139	.30516	125	.31402	127	32
33	.22800	137	.23540	139	.30642	124	.31530	127	33
34	.22937	136	.23679	139	.30766	124	.31657	127	34
35	8.23073	136	8.23818	138	8.30891	124	8.31785	127	35
36	.23209	136	.23957	138	.31015	124	.31912	127	36
37	.23346	135	.24095	138	.31140	124	.32039	126	37
38	.23481	136	.24234	138	.31264	124	.32165	126	38
39	.23617	135	.24372	137	.31388	123	.32292	126	39
40	8.23752	135	8.24509	138	8.31511	124	8.32418	126	40
41	.23888	135	.24647	137	.31635	123	.32544	126	41
42	.24023	135	.24784	137	.31758	123	.32670	126	42
43	.24158	134	.24922	137	.31882	123	.32796	126	43
44	.24292	134	.25059	136	.32005	123	.32922	125	44
45	8.24426	134	8.25195	136	8.32128	122	8.33047	125	45
46	.24561	134	.25332	136	.32250	122	.33173	125	46
47	.24695	133	.25468	136	.32373	122	.33298	125	47
48	.24828	133	.25604	136	.32495	122	.33423	124	48
49	.24962	133	.25740	136	.32617	122	.33547	125	49
50	8.25095	133	8.25876	135	8.32739	122	8.33672	124	50
51	.25228	133	.26012	135	.32861	121	.33797	124	51
52	.25361	132	.26147	135	.32983	121	.33921	124	52
53	.25494	133	.26282	135	.33104	121	.34045	123	53
54	.25627	132	.26417	134	.33225	121	.34169	124	54
55	8.25759	132	8.26552	134	8.33347	121	8.34293	124	55
56	.25891	132	.26686	134	.33468	120	.34417	123	56
57	.26023	132	.26821	134	.33588	120	.34540	123	57
58	.26155	131	.26955	134	.33709	120	.34663	123	58
59	.26286	131	.27089	134	.33829	120	.34786	123	59
60	8.26417		8.27223		8.33950		8.34909		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	130	120
6	13.0	12.0
7	15.1	14.0
8	17.3	16.0
9	19.5	18.0
10	21.6	20.0
20	43.3	40.0
30	65.0	60.0
40	86.6	80.0
50	108.3	100.0

	4	4	3
6	0.4	0.4	0.3
7	0.5	0.4	0.4
8	0.6	0.5	0.4
9	0.7	0.6	0.5
10	0.7	0.6	0.6
20	1.5	1.3	1.1
30	2.2	2.0	1.7
40	3.0	2.6	2.3
50	3.7	3.3	2.9

	3	2
6	0.3	0.2
7	0.3	0.3
8	0.4	0.3
9	0.4	0.4
10	0.5	0.4
20	1.0	0.8
30	1.5	1.2
40	2.0	1.6
50	2.5	2.1

	2	1
6	0.2	0.1
7	0.2	0.2
8	0.2	0.2
9	0.3	0.2
10	0.3	0.2
20	0.6	0.5
30	1.0	0.7
40	1.3	1.0
50	1.6	1.2

	1	0
6	0.1	0.0
7	0.1	0.0
8	0.1	0.0
9	0.1	0.1
10	0.1	0.1
20	0.3	0.1
30	0.5	0.2
40	0.6	0.3
50	0.8	0.4

P. P.

′	12° Lg. Vers.	D	12° Log. Exs.	D	13° Lg. Vers.	D	13° Log. Exs.	D	′
0	8.33950	120	8.34909	123	8.40875	110	8.42002	113	0
1	.34070	120	.35032	122	.40985	110	.42116	113	1
2	.34190	119	.35155	122	.41096	110	.42229	113	2
3	.34309	120	.35277	122	.41206	110	.42343	113	3
4	.34429	119	.35399	122	.41317	110	.42456	113	4
5	8.34549	119	8.35522	122	8.41427	110	8.42569	113	5
6	.34668	119	.35644	121	.41537	110	.42682	113	6
7	.34787	119	.35765	122	.41647	109	.42795	113	7
8	.34906	119	.35887	121	.41757	110	.42908	112	8
9	.35025	118	.36009	121	.41867	109	.43021	112	9
10	8.35143	118	8.36130	121	8.41976	109	8.43133	112	10
11	.35262	118	.36251	121	.42086	109	.43246	112	11
12	.35380	118	.36372	120	.42195	109	.43358	112	12
13	.35498	118	.36493	121	.42304	109	.43470	112	13
14	.35616	117	.36614	120	.42413	109	.43582	112	14
15	8.35734	118	8.36734	120	8.42522	108	8.43694	111	15
16	.35852	117	.36855	120	.42630	109	.43805	111	16
17	.35969	117	.36975	120	.42739	108	.43917	111	17
18	.36086	117	.37095	120	.42847	108	.44028	111	18
19	.36204	117	.37215	120	.42956	108	.44139	111	19
20	8.36321	116	8.37335	119	8.43064	108	8.44251	111	20
21	.36437	117	.37454	119	.43172	108	.44362	111	21
22	.36554	116	.37574	119	.43280	108	.44473	110	22
23	.36671	116	.37693	119	.43388	107	.44583	110	23
24	.36787	116	.37812	119	.43495	107	.44694	110	24
25	8.36903	116	8.37931	118	8.43603	107	8.44804	110	25
26	.37019	116	.38050	119	.43710	107	.44915	110	26
27	.37135	115	.38169	118	.43817	107	.45025	110	27
28	.37251	115	.38287	118	.43924	107	.45135	109	28
29	.37366	115	.38406	118	.44031	106	.45245	110	29
30	8.37482	115	8.38524	118	8.44138	107	8.45355	110	30
31	.37597	115	.38642	118	.44245	106	.45465	109	31
32	.37712	115	.38760	118	.44351	106	.45574	109	32
33	.37827	115	.38878	117	.44458	106	.45684	109	33
34	.37942	114	.38995	117	.44564	106	.45793	109	34
35	8.38057	114	8.39113	117	8.44670	106	8.45902	109	35
36	.38171	114	.39230	117	.44776	105	.46011	109	36
37	.38286	114	.39347	117	.44882	106	.46120	108	37
38	.38400	114	.39464	117	.44988	105	.46229	109	38
39	.38514	114	.39581	116	.45093	105	.46338	108	39
40	8.38628	113	8.39698	116	8.45199	105	8.46446	108	40
41	.38741	114	.39814	116	.45304	105	.46555	108	41
42	.38855	113	.39931	116	.45409	105	.46663	108	42
43	.38969	113	.40047	116	.45514	105	.46771	108	43
44	.39082	113	.40163	116	.45619	105	.46879	108	44
45	8.39195	113	8.40279	116	8.45724	104	8.46987	107	45
46	.39308	113	.40395	115	.45829	105	.47095	108	46
47	.39421	113	.40511	115	.45934	104	.47203	107	47
48	.39534	112	.40626	115	.46038	104	.47310	107	48
49	.39646	112	.40742	115	.46142	104	.47417	107	49
50	8.39758	112	8.40857	115	8.46247	104	8.47525	107	50
51	.39871	112	.40972	115	.46351	104	.47632	107	51
52	.39983	112	.41087	115	.46455	103	.47739	107	52
53	.40095	112	.41202	114	.46558	104	.47846	106	53
54	.40207	111	.41317	114	.46662	103	.47953	107	54
55	8.40318	111	8.41431	114	8.46766	103	8.48060	106	55
56	.40430	111	.41546	114	.46869	103	.48166	106	56
57	.40541	111	.41660	114	.46972	103	.48273	106	57
58	.40652	111	.41774	114	.47076	103	.48379	106	58
59	.40764	111	.41888	114	.47179	103	.48485	106	59
60	8.40875		8.42002		8.47282		8.48591		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	120	119	118
6	12.0	11.9	11.8
7	14.0	13.9	13.7
8	16.0	15.8	15.7
9	18.0	17.8	17.7
10	20.0	19.8	19.6
20	40.0	39.6	39.3
30	60.0	59.5	59.0
40	80.0	79.3	78.6
50	100.0	99.1	98.3

	117	116	115
6	11.7	11.6	11.5
7	13.6	13.5	13.4
8	15.6	15.4	15.3
9	17.5	17.4	17.2
10	19.5	19.3	19.1
20	39.0	38.6	38.3
30	58.5	58.0	57.5
40	78.0	77.3	76.6
50	97.5	96.6	95.8

	114	113	112
6	11.4	11.3	11.2
7	13.3	13.2	13.0
8	15.2	15.0	14.9
9	17.1	16.0	16.8
10	19.0	18.8	18.6
20	38.0	37.6	37.3
30	57.0	56.5	56.0
40	76.0	75.3	74.6
50	95.0	94.1	93.3

	111	110	109
6	11.1	11.0	10.9
7	12.9	12.8	12.7
8	14.8	14.6	14.5
9	16.6	16.5	16.3
10	18.5	18.3	18.1
20	37.0	36.6	36.3
30	55.5	55.0	54.5
40	74.0	73.3	72.6
50	92.5	91.6	90.8

	108	107	106
6	10.8	10.7	10.6
7	12.6	12.5	12.3
8	14.4	14.2	14.1
9	16.2	16.0	15.9
10	18.0	17.8	17.6
20	36.0	35.6	35.3
30	54.0	53.5	53.0
40	72.0	71.3	70.6
50	90.0	89.1	88.3

	105	104	0
6	10.5	10.4	0.0
7	12.2	12.1	0.0
8	14.0	13.8	0.0
9	15.7	15.6	0.1
10	17.5	17.3	0.1
20	35.0	34.6	0.1
30	52.5	52.0	0.2
40	70.0	69.3	0.3
50	87.5	86.6	0.4

P. P.

′	14° Lg. Vers.	D	14° Log. Exs.	D	15° Lg. Vers.	D	15° Log. Exs.	D	′
0	8.47282	102	8.48591	106	8.53242	96	8.54748	99	0
1	.47384	103	.48697	106	.53338	95	.54847	99	1
2	.47487	102	.48803	105	.53434	96	.54946	99	2
3	.47590	102	.48909	105	.53530	95	.55045	99	3
4	.47692	102	.49014	105	.53625	95	.55144	99	4
5	8.47795	102	8.49120	105	8.53721	95	8.55243	99	5
6	.47897	102	.49225	105	.53816	95	.55342	98	6
7	.47999	102	.49331	105	.53911	95	.55441	98	7
8	.48101	102	.49436	105	.54007	95	.55539	98	8
9	.48203	101	.49541	105	.54102	95	.55638	98	9
10	8.48304	101	8.49646	104	8.54197	94	8.55736	98	10
11	.48406	101	.49750	105	.54291	95	.55834	98	11
12	.48507	101	.49855	104	.54386	94	.55933	98	12
13	.48609	101	.49960	104	.54481	94	.56031	98	13
14	.48710	101	.50064	104	.54575	94	.56129	97	14
15	8.48811	101	8.50168	104	8.54670	94	8.56226	98	15
16	.48912	101	.50273	104	.54764	94	.56324	97	16
17	.49013	100	.50377	104	.54858	94	.56422	97	17
18	.49114	101	.50481	104	.54952	94	.56519	97	18
19	.49215	100	.50585	103	.55046	94	.56617	97	19
20	8.49315	100	8.50688	104	8.55140	93	8.56714	97	20
21	.49415	100	.50792	103	.55234	94	.56812	97	21
22	.49516	100	.50896	103	.55328	93	.56909	97	22
23	.49616	100	.50999	103	.55421	93	.57006	97	23
24	.49716	100	.51102	103	.55515	93	.57103	97	24
25	8.49816	100	8.51205	103	8.55608	93	8.57200	96	25
26	.49916	99	.51309	103	.55701	93	.57296	97	26
27	.50015	100	.51412	102	.55795	93	.57393	96	27
28	.50115	99	.51514	103	.55888	93	.57490	96	28
29	.50215	99	.51617	102	.55981	93	.57586	96	29
30	8.50314	99	8.51720	102	8.56074	92	8.57682	96	30
31	.50413	99	.51822	102	.56166	92	.57779	96	31
32	.50512	99	.51925	102	.56259	93	.57875	96	32
33	.50611	99	.52027	102	.56352	92	.57971	96	33
34	.50710	98	.52129	102	.56444	92	.58067	95	34
35	8.50809	99	8.52231	102	8.56536	92	8.58163	96	35
36	.50908	98	.52333	102	.56629	92	.58259	95	36
37	.51006	98	.52435	101	.56721	92	58354	96	37
38	.51105	98	.52537	101	.56813	92	.58450	95	38
39	.51203	98	.52638	101	.56905	92	.58546	95	39
40	8.51301	98	8.52740	101	8.56997	92	8.58641	95	40
41	.51399	98	.52841	101	.57089	91	.58736	95	41
42	.51497	98	.52943	101	.57180	91	.58832	95	42
43	.51595	97	.53044	101	.57272	91	.58927	95	43
44	.51693	98	.53145	101	.57363	91	.59022	95	44
45	8.51791	97	8.53246	101	8.57455	91	8.59117	94	45
46	.51888	97	.53347	101	.57546	91	.59211	95	46
47	.51986	97	.53448	100	.57637	91	.59306	94	47
48	.52083	97	.53548	100	.57728	91	.59401	94	48
49	.52180	97	.53649	100	.57819	91	.59495	94	49
50	8.52277	97	8.53749	100	8.57910	90	8.59590	94	50
51	.52374	97	.53850	100	.58001	91	.59684	94	51
52	.52471	96	.53950	100	.58092	90	.59779	94	52
53	.52568	97	.54050	100	.58182	90	.59873	94	53
54	.52665	96	.54150	100	.58273	90	.59967	94	54
55	8.52761	96	8.54250	100	8.58363	90	8.60061	94	55
56	.52858	96	.54350	99	.58453	90	.60155	94	56
57	.52954	96	.54449	100	.58544	90	.60249	93	57
58	.53050	96	.54549	99	.58634	90	.60342	94	58
59	.53146	96	.54649	99	.58724	90	.60436	93	59
60	8.53242		8.54748		8.58814		8.60530		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	103	102	101
6	10.3	10.2	10.1
7	12.0	11.9	11.8
8	13.7	13.6	13.4
9	15.4	15.3	15.1
10	17.1	17.0	16.8
20	34.3	34.0	33.6
30	51.5	51.0	50.5
40	68.6	68.0	67.3
50	85.8	85.0	84.1

	100	99	98
6	10.0	9.9	9.8
7	11.6	11.5	11.4
8	13.3	13.2	13.0
9	15.0	14.8	14.7
10	16.6	16.5	16.3
20	33.3	33.0	32.6
30	50.0	49.5	49.0
40	66.6	66.0	65.3
50	83.3	82.5	82.6

	97	96	95
6	9.7	9.6	9.5
7	11.3	11.2	11.1
8	12.9	12.8	12.6
9	14.5	14.4	14.2
10	16.1	16.0	15.8
20	32.3	32.0	31.6
30	48.5	48.0	47.5
40	64.6	64.0	63.3
50	80.8	80.0	79.1

	94	93	92
6	9.4	9.3	9.2
7	10.9	10.8	10.7
8	12.5	12.4	12.2
9	14.1	13.9	13.8
10	15.6	15.5	15.3
20	31.3	31.0	30.6
30	47.0	46.5	46.0
40	62.6	62.0	61.3
50	78.3	77.5	76.6

	91	90	0
6	9.1	9.0	0.0
7	10.6	10.5	0.0
8	12.1	12.0	0.0
9	13.6	13.5	0.1
10	15.1	15.0	0.1
20	30.3	30.0	0.1
30	45.5	45.0	0.2
40	60.6	60.0	0.3
50	75.8	75.0	0.4

P. P.

′	16° Lg. Vers.	D	16° Log. Exs.	D	17° Lg. Vers.	D	17° Log. Exs.	D	′
0	8.58814	90	8.60530	93	8.64043	84	8.65984	88	0
1	.58904	89	.60623	93	.64128	84	.66072	88	1
2	.58993	90	.60716	93	.64212	84	.66160	88	2
3	.59083	89	.60810	93	.64296	84	.66248	88	3
4	.59173	89	.60903	93	.64381	84	.66336	88	4
5	8.59262	89	8.60996	93	8.64465	84	8.66425	87	5
6	.59351	89	.61089	93	.64549	84	.66512	88	6
7	.59441	89	.61182	92	.64633	84	.66600	88	7
8	.59530	89	.61275	93	.64717	84	.66688	87	8
9	.59619	89	.61368	92	.64801	83	.63776	87	9
10	8.59708	89	8.61460	92	8.64884	83	8.66863	88	10
11	.59797	89	.61553	92	.64968	84	.66951	87	11
12	.59886	88	.61645	92	.65052	83	.67039	87	12
13	.59974	89	.61738	92	.65135	83	.67126	87	13
14	60063	88	.61830	92	.65218	83	.67213	87	14
15	8.60152	88	8.61922	92	8.65302	83	8.67301	87	15
16	.60240	88	.62014	92	.65385	83	.67388	87	16
17	.60328	88	.62106	92	.65468	83	.67475	87	17
18	.60417	88	.62198	92	.65551	83	.67562	87	18
19	.60506	88	.62290	91	.65634	83	.67649	87	19
20	8.60593	88	8.62382	92	8.65717	83	8.67736	86	20
21	.60681	88	.62474	91	.65800	82	.67822	87	21
22	.60769	88	.62565	91	.65883	82	.67909	86	22
23	.60857	87	.62657	91	.65965	83	.67996	86	23
24	.60944	87	.62748	91	.66048	82	.68082	86	24
25	8.61032	87	8.62840	91	8.66131	82	8.68169	86	25
26	.61119	87	.62931	91	.66213	82	.68255	86	26
27	.61207	87	.63022	91	.66295	82	.68341	86	27
28	.61294	87	.63113	91	.66378	82	.68428	86	28
29	.61381	87	.63204	90	.66460	82	.68514	86	29
30	8.61469	87	8.63295	91	8.66542	82	8.68600	86	30
31	.61556	87	.63386	91	.66624	82	.68686	85	31
32	.61643	87	.63477	90	.66706	82	.68772	86	32
33	.61730	86	.63567	90	.66788	82	.68858	86	33
34	.61816	87	.63658	90	.66870	81	.68944	85	34
35	8.61903	86	8.63748	90	8.66951	81	8.69029	86	35
36	.61990	86	.63839	90	.67033	82	.69115	85	36
37	.62076	86	.63929	90	.67115	81	.69201	85	37
38	.62163	86	.64019	90	.67196	81	.69286	85	38
39	.62249	86	.64109	90	.67277	81	.69372	85	39
40	8.62336	86	8.64199	90	8.67359	81	8.69457	85	40
41	.62422	86	.64289	90	.67440	81	.69542	85	41
42	.62508	86	.64379	90	.67521	81	.69627	85	42
43	.62594	86	.64469	89	.67602	81	.69712	85	43
44	.62680	86	.64559	90	.67683	81	.69798	85	44
45	8.62766	86	8.64649	89	8.67764	81	8.69883	84	45
46	.62852	85	.64738	89	.67845	80	.69967	85	46
47	.62937	85	.64828	89	.67926	81	.70052	85	47
48	.63023	85	.64917	89	.68007	80	.70137	84	48
49	.63108	85	.65006	89	.68087	80	.70222	84	49
50	8.63194	85	8.65096	89	8.68168	80	8.70306	84	50
51	.63279	85	.65185	89	.68248	80	.70391	84	51
52	.63364	85	.65274	89	.68329	80	.70475	84	52
53	.63449	85	.65363	89	.68409	80	.70560	84	53
54	.63534	85	.65452	89	.68489	80	.70644	84	54
55	8.63619	85	8.65541	88	8.68569	80	8.70728	84	55
56	.63704	85	.65629	88	.68650	80	.70813	84	56
57	.63789	84	.65718	89	.68730	80	.70897	84	57
58	.63874	85	.65807	88	.68810	79	.70981	84	58
59	.63959	84	.65895	88	.68889	80	.71065	84	59
60	8.64043		8.65984		8.68969		8.71149		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	93	92	91
6	9.3	9.2	9.1
7	10.8	10.7	10.6
8	12.4	12.2	12.1
9	13.9	13.8	13.6
10	15.5	15.3	15.1
20	31.0	30.6	30.5
30	46.5	46.0	45.5
40	62.0	61.3	60.6
50	77.5	76.6	75.8

	90	89	88
6	9.0	8.9	8.8
7	10.5	10.4	10.2
8	12.0	11.8	11.7
9	13.5	13.3	13.2
10	15.0	14.8	14.6
20	30.0	29.6	29.3
30	45.0	44.5	44.0
40	60.0	59.3	58.6
50	75.0	74.1	73.3

	87	86	85
6	8.7	8.6	8.5
7	10.1	10.0	9.9
8	11.6	11.4	11.3
9	13.0	12.9	12.7
10	14.5	14.3	14.1
20	29.0	28.6	28.3
30	43.5	43.0	42.5
40	58.0	57.3	56.6
50	72.5	71.6	70.8

	84	83	82
6	8.4	8.3	8.2
7	9.8	9.7	9.5
8	11.2	11.0	10.9
9	12.6	12.4	12.3
10	14.0	13.8	13.6
20	28.0	27.6	27.3
30	42.0	41.5	41.0
40	56.0	55.3	54.6
50	70.0	69.1	68.3

	81	80	79
6	8.1	8.0	7.9
7	9.4	9.3	9.2
8	10.8	10.6	10.5
9	12.1	12.0	11.8
10	13.5	13.3	13.1
20	27.0	26.6	26.3
30	40.5	40.0	39.5
40	54.0	53.3	52.6
50	67.5	66.6	65.8

	0
6	0.0
7	0.0
8	0.0
9	0.1
10	0.1
20	0.1
30	0.2
40	0.3
50	0.4

P. P.

′	18° Lg. Vers.	D	18° Log. Exs.	D	19° Lg. Vers.	D	19° Log. Exs.	D	′
0	8.68969	79	8.71149	83	8.73625	75	8.76058	79	0
1	.69049	80	.71232	84	.73700	75	.76137	80	1
2	.69129	79	.71316	83	.73775	75	.76217	79	2
3	.69208	79	.71400	84	.73851	75	.76297	79	3
4	.69288	79	.71484	83	.73926	75	.76376	80	4
5	8.69367	79	8.71567	83	8.74001	75	8.76456	79	5
6	.69446	79	.71651	83	.74076	75	.76536	79	6
7	.69526	79	.71734	83	.74151	75	.76615	79	7
8	.69605	79	.71817	83	.74226	75	.76694	79	8
9	.69684	79	.71901	83	.74301	75	.76774	79	9
10	8.69763	79	8.71984	83	8.74376	74	8.76853	79	10
11	.69842	79	.72067	83	.74451	75	.76932	79	11
12	.69921	78	.72150	83	.74526	74	.77011	79	12
13	.70000	79	.72233	83	.74600	74	.77090	79	13
14	.70079	78	.72316	83	.74675	74	.77169	79	14
15	8.70157	78	8.72399	82	8.74749	74	8.77248	79	15
16	.70236	78	.72481	83	.74824	74	.77327	78	16
17	.70314	78	.72564	82	.74898	74	.77406	79	17
18	.70393	78	.72647	82	.74973	74	.77485	78	18
19	.70471	78	.72729	82	.75047	74	.77563	78	19
20	8.70550	78	8.72812	82	8.75121	74	8.77642	78	20
21	.70628	78	.72894	82	.75195	74	.77720	79	21
22	.70706	78	.72977	82	.75269	74	.77799	78	22
23	.70784	78	.73059	82	.75343	74	.77877	78	23
24	.70862	78	.73141	82	.75417	74	.77956	78	24
25	8.70940	78	8.73223	82	8.75491	73	8.78034	78	25
26	.71018	77	.73306	82	.75565	74	.78112	78	26
27	.71096	78	.73388	82	.75639	73	.78191	78	27
28	.71174	77	.73470	81	.75712	73	.78269	78	28
29	.71251	77	.73551	82	.75786	74	.78347	78	29
30	8.71329	77	8.73633	82	8.75860	73	8.78425	78	30
31	.71406	77	.73715	81	.75933	73	.78503	78	31
32	.71484	77	.73797	81	.76006	73	.78581	78	32
33	.71561	77	.73878	81	.76080	73	.78659	77	33
34	.71639	77	.73960	81	.76153	73	.78736	78	34
35	8.71716	77	8.74041	81	8.76226	73	8.78814	77	35
36	.71793	77	.74123	81	.76300	73	.78892	77	36
37	.71870	77	.74204	81	.76373	73	.78969	77	37
38	.71947	77	.74286	81	.76446	73	.79047	77	38
39	.72024	77	.74367	81	.76519	73	.79124	77	39
40	8.72101	76	8.74448	81	8.76592	72	8.79202	77	40
41	.72178	77	.74529	81	.76664	73	.79279	77	41
42	.72255	76	.74610	81	.76737	72	.79357	77	42
43	.72331	77	.74691	80	.76810	73	.79434	77	43
44	.72408	76	.74772	81	.76883	72	.79511	77	44
45	8.72485	76	8.74853	81	8.76955	72	8.79588	77	45
46	.72561	76	.74934	80	.77028	72	.79665	77	46
47	.72637	76	.75014	80	.77100	72	.79742	77	47
48	.72714	76	.75095	80	.77173	72	.79819	77	48
49	.72790	76	.75175	80	.77245	72	.79896	76	49
50	8.72866	76	8.75256	80	8.77317	72	8.79973	77	50
51	.72942	76	.75336	80	.77390	72	.80050	76	51
52	.73018	76	.75417	80	.77462	72	.80126	77	52
53	.73094	76	.75497	80	.77534	72	.80203	76	53
54	.73170	76	.75577	80	.77606	72	.80280	76	54
55	8.73246	76	8.75658	80	8.77678	72	8.80356	76	55
56	.73322	75	.75738	80	.77750	72	.80433	76	56
57	.73398	75	.75818	80	.77822	71	.80509	76	57
58	.73473	76	.75898	80	.77893	72	.80586	76	58
59	.73549	75	.75978	80	.77965	71	.80662	76	59
60	8.73625		8.76058		8.78037		8.80738		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	84	83	82
6	8.4	8.3	8.2
7	9.8	9.7	9.5
8	11.2	11.0	10.9
9	12.6	12.4	12.3
10	14.0	13.8	13.6
20	28.0	27.6	27.3
30	42.0	41.5	41.0
40	56.0	55.3	54.6
50	70.0	69.1	68.3

	81	80	79
6	8.1	8.0	7.9
7	9.4	9.3	9.2
8	10.8	10.6	10.5
9	12.1	12.0	11.8
10	13.5	13.3	13.1
20	27.0	26.6	26.3
30	40.5	40.0	39.5
40	54.0	53.3	52.6
50	67.5	66.6	65.8

	78	77	76
6	7.8	7.7	7.6
7	9.1	9.0	8.8
8	10.4	10.2	10.1
9	11.7	11.5	11.4
10	13.0	12.8	12.6
20	26.0	25.6	25.3
30	39.0	38.5	38.0
40	52.0	51.3	50.6
50	65.0	64.1	63.3

	75	74	73
6	7.5	7.4	7.3
7	8.7	8.6	8.5
8	10.0	9.8	9.7
9	11.2	11.1	10.9
10	12.5	12.3	12.1
20	25.0	24.6	24.3
30	37.5	37.0	36.5
40	50.0	49.3	48.6
50	62.5	61.6	60.8

	72	71	0
6	7.2	7.1	0.0
7	8.4	8.3	0.0
8	9.6	9.4	0.0
9	10.8	10.6	0.1
10	12.0	11.8	0.1
20	24.0	23.6	0.1
30	36.0	35.5	0.2
40	48.0	47.3	0.3
50	60.0	59.1	0.4

P. P.

	20°				21°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	8.78037	71	8.80738	76	8.82229	68	8.85214	73	0
1	.78108	71	.80814	76	.82297	68	.85287	73	1
2	.78180	71	.80891	76	.82366	68	.85360	72	2
3	.78251	71	.80967	76	.82434	68	.85433	73	3
4	.78323		.81043		.82502		.85506		4
5	8.78394	71	8.81119	76	8.82569	67	8.85579	73	5
6	.78466	71	.81195	76	.82637	68	.85651	72	6
7	.78537	71	.81271	76	.82705	68	.85724	73	7
8	.78608	71	.81346	75	.82773	67	.85797	72	8
9	.78679	71	.81422	76	.82841	68	.85869	72	9
10	8.78750	71	8.81498	75	8.82908	67	8.85942	72	10
11	.78821	71	.81573	75	.82976	67	.86014	72	11
12	.78892	71	.81649	76	.83043	67	.86087	72	12
13	.78963	71	.81725	75	.83111	67	.86159	72	13
14	.79034	70	.81800	75	.83178	67	.86231	72	14
15	8.79105	71	8.81876	75	8.83246	67	8.86304	72	15
16	.79175	70	.81951	75	.83313	67	.86376	72	16
17	.79246	71	.82026	75	.83380	67	.86448	72	17
18	.79317	70	.82102	75	.83447	67	.86520	72	18
19	.79387	70	.82177	75	.83515	67	.86592	72	19
20	8.79458	70	8.82252	75	8.83582	67	8.86664	72	20
21	.79528	70	.82327	75	.83649	67	.86736	72	21
22	.79598	70	.82402	75	.83716	67	.86808	72	22
23	.79669	70	.82477	75	.83783	67	.86880	72	23
24	.79739	70	.82552	74	.83850	67	.86952	71	24
25	8.79809	70	8.82627	75	8.83916	66	8.87024	72	25
26	.79879	70	.82702	75	.83983	67	.87095	71	26
27	.79949	70	.82776	74	.84050	66	.87167	72	27
28	.80019	70	.82851	75	.84117	67	.87239	71	28
29	.80089	70	.82926	74	.84183	66	.87310	71	29
30	8.80159	70	8.83000	74	8.84250	66	8.87382	71	30
31	.80229	70	.83075	74	.84316	66	.87453	71	31
32	.80299	69	.83149	74	.84383	66	.87525	71	32
33	.80369	70	.83224	74	.84449	66	.87596	71	33
34	.80438	69	.83298	74	.84515	66	.87668	71	34
35	8.80508	69	8.83373	74	8.84582	66	8.87739	71	35
36	.80577	69	.83447	74	.84648	66	.87810	71	36
37	.80647	69	.83521	74	.84714	66	.87881	71	37
38	.80716	69	.83595	74	.84780	66	.87953	71	38
39	.80786	69	.83670	74	.84846	66	.88024	71	39
40	8.80855	69	8.83744	74	8.84912	66	8.88095	71	40
41	.80924	69	.83818	74	.84978	66	.88166	71	41
42	.80993	69	.83892	74	.85044	66	.88237	71	42
43	.81063	69	.83966	74	.85110	66	.88308	71	43
44	.81132	69	.84039	73	.85176	66	.88378	70	44
45	8.81201	69	8.84113	74	8.85242	65	8.88449	71	45
46	.81270	69	.84187	73	.85308	66	.88520	71	46
47	.81339	69	.84261	74	.85373	65	.88591	70	47
48	.81407	68	.84334	73	.85439	65	.88661	70	48
49	.81476	69	.84408	73	.85505	66	.88732	71	49
50	8.81545	68	8.84481	73	8.85570	65	8.88803	70	50
51	.81614	69	.84555	73	.85626	65	.88873	70	51
52	.81682	68	.84628	73	.85701	65	.88944	70	52
53	.81751	68	.84702	73	.85766	65	.89014	70	53
54	.81819	68	.84775	73	.85832	65	.89085	70	54
55	8.81888	68	8.84848	73	8.85897	65	8.89156	70	55
56	.81956	68	.84922	73	.85962	65	.89225	70	56
57	.82025	68	.84995	73	.86027	65	.89295	70	57
58	.82093	68	.85068	73	.86092	65	.89366	70	58
59	.82161	68	.85141	73	.86158	65	.89436	70	59
60	8.82229	68	8.85214	73	8.86223	65	8.89506	70	60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	76	75	74
6	7.6	7.5	7.4
7	8.8	8.7	8.6
8	10.1	10.0	9.8
9	11.4	11.2	11.1
10	12.6	12.5	12.3
20	25.3	25.0	21.6
30	38.0	37.5	37.0
40	50.6	50.0	49.3
50	63.3	62.5	61.6

	73	72	71
6	7.3	7.2	7.1
7	8.5	8.4	8.3
8	9.7	9.6	9.4
9	10.9	10.8	10.6
10	12.1	12.0	11.8
20	24.3	24.0	23.6
30	36.5	36.0	35.5
40	48.6	48.0	47.3
50	60.8	60.0	59.1

	70	69	68
6	7.0	6.9	6.8
7	8.1	8.0	7.9
8	9.3	9.2	9.0
9	10.5	10.3	10.2
10	11.6	11.5	11.3
20	23.3	23.0	22.6
30	35.0	34.5	34.0
40	46.6	46.0	45.3
50	58.3	57.5	56.6

	67	66	65
6	6.7	6.6	6.5
7	7.8	7.7	7.6
8	8.9	8.8	8.6
9	10.0	9.9	9.7
10	11.1	11.0	10.8
20	22.3	22.0	21.6
30	33.5	33.0	32.5
40	44.6	44.0	43.3
50	55.8	55.0	54.1

	0
6	0.0
7	0.0
8	0.0
9	0.1
10	0.1
20	0.1
30	0.2
40	0.3
50	0.4

P. P.

′	22° Lg. Vers.	D	22° Log. Exs.	D	23° Lg. Vers.	D	23° Log. Exs.	D	′
0	8.86223	64	8.89506	70	8.90034	62	8.93631	67	0
1	.86287	65	.89576	70	.90096	62	.93699	67	1
2	.86352	65	.89646	70	.90158	62	.93766	67	2
3	.86417	65	.89716	69	.90220	62	.93833	67	3
4	.86482	64	.89786	70	.90282	62	.93901	67	4
5	8.86547	65	8.89856	70	8.90344	62	8.93968	67	5
6	.86612	64	.89926	69	.90406	61	.94035	67	6
7	.86676	64	.89995	70	.90467	62	.94102	67	7
8	.86741	64	.90065	69	.90529	61	.94170	67	8
9	.86805	64	.90135	70	.90591	61	.94237	67	9
10	8.86870	64	8.90205	69	8.90652	62	8.94304	67	10
11	.86934	64	.90274	69	.90714	61	.94371	67	11
12	.86999	64	.90344	69	.90776	61	.94438	67	12
13	.87063	64	.90413	69	.90837	61	.94505	67	13
14	.87127	64	.90483	69	.90899	61	.94572	66	14
15	8.87192	64	8.90552	69	8.90960	61	8.94638	67	15
16	.87256	64	.90622	69	.91021	61	.94705	66	16
17	.87320	64	.90691	69	.91083	61	.94772	67	17
18	.87384	64	.90760	69	.91144	61	.94839	66	18
19	.87448	64	.90830	69	.91205	61	.94905	66	19
20	8.87512	64	8.90899	69	8.91267	61	8.94972	67	20
21	.87576	64	.90968	69	.91328	61	.95039	66	21
22	.87640	64	.91037	69	.91389	61	.95105	66	22
23	.87704	63	.91106	69	.91450	61	.95172	66	23
24	.87768	64	.91175	69	.91511	61	.95238	66	24
25	8.87832	63	8.91244	69	8.91572	61	8.95305	66	25
26	.87895	64	.91313	68	.91633	61	.95371	66	26
27	.87959	63	.91382	69	.91694	61	.95437	66	27
28	.88023	63	.91451	69	.91755	60	.95504	66	28
29	.88086	63	.91520	68	.91815	61	.95570	66	29
30	8.88150	63	8.91588	69	8.91876	60	8.95636	66	30
31	.88213	63	.91657	68	.91937	60	.95703	66	31
32	.88277	63	.91726	68	.91997	61	.95769	66	32
33	.88340	63	.91794	68	.92058	60	.95835	66	33
34	.88404	63	.91863	69	.92119	60	.95901	66	34
35	8.88467	63	8.91932	68	8.92179	60	8.95967	66	35
36	.88530	63	.92000	68	.92240	60	.96033	66	36
37	.88593	63	.92068	68	.92300	60	.96099	66	37
38	.88656	63	.92137	68	.92361	60	.96165	66	38
39	.88720	63	.92205	68	.92421	60	.96231	66	39
40	8.88783	63	8.92274	68	8.92487	60	8.96297	65	40
41	.88846	63	.92342	68	.92542	60	.96362	66	41
42	.88909	62	.92410	68	.92602	60	.96428	65	42
43	.88971	63	.92478	68	.92662	60	.96494	66	43
44	.89034	63	.92546	68	.92722	60	.96560	65	44
45	8.89097	62	8.92615	68	8.92782	60	8.96625	65	45
46	.89160	63	.92683	68	.92842	60	.96691	66	46
47	.89223	62	.92751	68	.92902	60	.96757	65	47
48	.89285	62	.92819	68	.92962	60	.96822	65	48
49	.89348	63	.92887	68	.93022	60	.96888	65	49
50	8.89411	62	8.92955	67	8.93082	59	8.96953	65	50
51	.89473	62	.93022	68	.93142	60	.97018	65	51
52	.89536	62	.93090	67	.93202	59	.97084	65	52
53	.89598	62	.93158	68	.93261	60	.97149	65	53
54	.89660	62	.93226	67	.93321	59	.97214	65	54
55	8.89723	62	8.93293	68	8.93[illegible]1	59	8.97280	65	55
56	.89785	62	.93361	67	.93440	60	.97345	65	56
57	.89847	62	.93429	67	.93500	59	.97410	65	57
58	.89910	62	.93496	67	.93560	59	.97475	65	58
59	.89972	62	.93564	67	.93619	59	.97540	65	59
60	8.00034		8.93631		8.93679		8.97606		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log.Exs.	D	′

P. P.

	70	69	68
6	7.0	6.9	6.8
7	8.1	8.0	7.9
8	9.3	9.2	9.0
9	10.5	10.3	10.2
10	11.6	11.5	11.3
20	23.3	23.0	22.6
30	35.0	34.5	34.0
40	46.6	46.0	45.3
50	58.3	57.5	56.6

	67	66	65
6	6.7	6.6	6.5
7	7.8	7.7	7.6
8	8.9	8.8	8.6
9	10.0	9.9	9.7
10	11.1	11.0	10.8
20	22.3	22.0	21.6
30	33.5	33.0	32.5
40	44.6	44.0	43.3
50	55.8	55.0	54.1

	64	63	62
6	6.4	6.3	6.2
7	7.4	7.3	7.2
8	8.5	8.4	8.2
9	9.6	9.4	9.3
10	10.6	10.5	10.3
20	21.3	21.0	20.6
30	32.0	31.5	31.0
40	42.6	42.0	41.3
50	53.3	52.5	51.6

	61	60	59
6	6.1	6.0	5.9
7	7.1	7.0	6.9
8	8.1	8.0	7.8
9	9.1	9.0	8.8
10	10.1	10.0	9.8
20	20.3	20.0	19.6
30	30.5	30.0	29.5
40	40.6	40.0	39.3
50	50.8	50.0	49.1

	0
6	0.0
7	0.0
8	0.0
9	0.1
10	0.1
20	0.1
30	0.2
40	0.3
50	0.4

P. P.

	24°				25°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	8.93679		8.97606		8.97170		9.01443		0
1	.93738	59	.97671	65	.97227	57	.01505	62	1
2	.93797	59	.97736	65	.97284	56	.01568	63	2
3	.93857	59	.97801	65	.97341	57	.01631	62	3
4	.93916	59	.97865	64	.97398	57	.01694	63	4
5	8.93975	59	8.97930	65	8.97455	57	9.01756	62	5
6	.94034	59	.97995	65	.97511	56	.01819	63	6
7	.94094	59	.98060	64	.97568	57	.01882	62	7
8	.94153	59	.98125	65	.97625	56	.01944	62	8
9	.94212	59	.98190	65	.97681	56	.02007	63	9
10	8.94271	59	8.98254	64	8.97738	56	9.02070	62	10
11	.94330	59	.98319	64	.97795	57	.02132	62	11
12	.94389	59	.98383	64	.97851	56	.02195	62	12
13	.94448	59	.98448	65	.97908	56	.02257	62	13
14	.94506	58	.98513	64	.97964	56	.02319	62	14
15	8.94505	59	8.98577	44	8.98020	56	9.02382	62	15
16	.94624	59	.98642	64	.98077	56	.02444	62	16
17	.94683	58	.98706	64	.98133	56	.02506	62	17
18	.94742	59	.98770	64	.98190	56	.02569	62	18
19	.94800	58	.98835	64	.98246	56	.02631	62	19
20	8.94859	58	8.98899	64	8.98302	56	9.02693	62	20
21	.94917	58	.98963	64	.98358	56	.02755	62	21
22	.94976	58	.99028	64	.98414	56	.02817	62	22
23	.95034	58	.99092	64	.98470	56	.02880	62	23
24	.95093	58	.99156	64	.98527	56	.02942	62	24
25	8.95151	58	8.99220	64	8.98583	56	9.03004	62	25
26	.95210	58	.99284	64	.98639	56	.03066	62	26
27	.95268	58	.99348	64	.98695	56	.03128	62	27
28	.95326	58	.99412	64	.98750	55	.03190	62	28
29	.95384	58	.99476	64	.98806	56	.03252	62	29
30	8.95443	58	8.99540	64	8.98802	56	9.03313	61	30
31	.95501	58	.99604	64	.98918	56	.03375	62	31
32	.95559	58	.99668	64	.98974	55	.03437	62	32
33	.95617	58	.99732	64	.99030	56	.03499	61	33
34	.95675	58	.99796	63	.99085	55	.03561	62	34
35	8.95733	58	8.99860	64	8.99141	55	9.03622	61	35
36	.95791	58	.99923	63	.99197	56	.03684	61	36
37	.95849	57	8.99987	64	.99252	55	.03746	62	37
38	.95907	58	9.00051	63	.99308	55	.03807	61	38
39	.95965	58	.00114	63	.99363	55	.03869	61	39
40	8.96023	58	9.00178	64	8.99419	55	9.03930	61	40
41	.96080	57	.00242	63	.99474	55	.03992	61	41
42	.96138	57	.00305	63	.99529	55	.04053	61	42
43	.96196	58	.00369	63	.99585	55	.04115	61	43
44	.96253	57	.00432	63	.99640	55	.04176	61	44
45	8.96311	57	9.00495	63	8.99695	55	9.04238	61	45
46	.96368	57	.00559	63	.99751	55	.04299	61	46
47	.96426	57	.00622	63	.99806	55	.04360	61	47
48	.96483	57	.00686	63	.99861	55	.04421	61	48
49	.96541	57	.00749	63	.99916	55	.04483	61	49
50	8.96598	57	9.00812	63	8.99971	55	9.04544	61	50
51	.96656	57	.00875	63	9.00026	55	.04605	61	51
52	.96713	57	.00938	63	.00081	55	.04666	61	52
53	.96770	57	.01002	63	.00136	55	.04727	61	53
54	.96827	57	.01065	63	.00191	55	.04788	61	54
55	8.96885	57	9.01128	63	9.00246	55	9.04850	61	55
56	.96942	57	.01191	63	.00301	55	.04911	61	56
57	.96999	57	.01254	63	.00356	55	.04972	61	57
58	.97056	57	.01317	63	.00411	54	.05033	61	58
59	.97113	57	.01380	63	.00466	55	.05093	60	59
60	8.97170	57	9.01443	63	9.00520	54	9.05154	61	60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	65	64	63
6	6.5	6.4	6.3
7	7.6	7.4	7.3
8	8.6	8.5	8.4
9	9.7	9.6	9.4
10	10.8	10.6	10.5
20	21.6	21.3	21.0
30	32.5	32.0	31.5
40	43.3	42.6	42.0
50	54.1	53.3	52.5

	62	61	60
6	6.2	6.1	6.0
7	7.2	7.1	7.0
8	8.2	8.1	8.0
9	9.3	9.1	9.0
10	10.3	10.1	10.0
20	20.6	20.3	20.0
30	31.0	30.5	30.0
40	41.3	40.6	40.0
50	51.6	50.8	50.0

	59	58	57
6	5.9	5.8	5.7
7	6.9	6.7	6.6
8	7.8	7.7	7.6
9	8.8	8.7	8.5
10	9.8	9.6	9.5
20	19.6	19.3	19.0
30	29.5	29.0	28.5
40	39.3	38.6	38.0
50	49.1	48.3	47.5

	56	55	54
6	5.6	5.5	5.4
7	6.5	6.4	6.3
8	7.4	7.3	7.2
9	8.4	8.2	8.1
10	9.3	9.1	9.0
20	18.6	18.3	18.0
30	28.0	27.5	27.0
40	37.3	36.6	36.0
50	46.6	45.8	45.0

	0
6	0.0
7	0.0
8	0.0
9	0.1
10	0.1
20	0.1
30	0.2
40	0.3
50	0.4

P. P.

′	26° Lg. Vers.	D	26° Log. Exs.	D	27° Lg. Vers.	D	27° Log. Exs.	D	′
0	9.00520	55	9.05154	61	9.03740	52	9.08752	59	0
1	.00575	54	.05215	61	.03792	52	.08811	59	1
2	.00630	54	.05276	60	.03845	53	.08870	59	2
3	.00684	54	.05337	61	.03898	52	.08929	59	3
4	.00739	55	.05398	60	.03950	52	.08988	59	4
5	9.00794	54	9.05458	61	9.04002	52	9.09047	59	5
6	.00848	54	.05519	60	.04055	52	.09106	58	6
7	.00903	54	.05580	60	.04107	52	.09164	59	7
8	.00957	54	.05640	60	.04160	52	.09223	59	8
9	.01011	54	.05701	61	.04212	52	.09282	58	9
10	9.01066	54	9.05762	60	9.04264	52	9.09341	59	10
11	.01120	54	.05822	60	.04317	52	.09400	58	11
12	.01174	54	.05883	60	.04369	52	.09458	59	12
13	.01229	54	.05943	60	.04421	52	.09517	58	13
14	.01283	54	.06004	60	.04473	52	.09576	58	14
15	9.01337	54	9.06064	60	9.04525	52	9.09634	58	15
16	.01391	54	.06124	60	.04577	52	.09693	59	16
17	.01445	54	.06185	60	.04630	52	.09752	58	17
18	.01499	54	.06245	60	.04682	52	.09810	58	18
19	.01554	54	.06305	60	.04734	52	.09869	58	19
20	9.01608	54	9.06366	60	9.04786	51	9.09927	58	20
21	.01662	53	.06426	60	.04837	52	.09986	58	21
22	.01715	54	.06486	60	.04889	52	.10044	58	22
23	.01769	54	.06546	60	.04941	52	.10102	58	23
24	.01823	54	.06606	60	.04993	51	.10161	58	24
25	9.01877	53	9.06667	60	9.05045	52	9.10219	58	25
26	.01931	54	.06727	60	.05097	51	.10278	58	26
27	.01985	53	.06787	60	.05148	52	.10336	58	27
28	.02038	54	.06847	60	.05200	52	.10394	58	28
29	.02092	53	.06907	60	.05252	51	.10452	58	29
30	9.02146	53	9.06967	60	9.05303	52	9.10511	58	30
31	.02199	54	.07027	60	.05355	51	.10569	58	31
32	.02253	53	.07087	59	.05407	51	.10627	58	32
33	.02307	53	.07146	60	.05458	51	.10685	58	33
34	.02360	53	.07206	60	.05510	51	.10743	58	34
35	9.02414	53	9.07266	59	9.05561	51	9.10801	58	35
36	.02467	53	.07326	60	.05613	51	.10859	58	36
37	.02521	53	.07386	59	.05664	51	.10917	58	37
38	.02574	53	.07445	60	.05715	51	.10975	58	38
39	.02627	53	.07505	59	.05767	51	.11033	58	39
40	9.02681	53	9.07565	59	9.05818	51	9.11091	58	40
41	.02734	53	.07624	59	.05869	51	.11149	57	41
42	.02787	53	.07684	59	.05921	51	.11207	58	42
43	.02840	53	.07743	60	.05972	51	.11265	58	43
44	.02894	53	.07803	59	.06023	51	.11323	57	44
45	9.02947	53	9.07863	59	9.06074	51	9.11380	58	45
46	.03000	53	.07922	59	.06125	51	.11438	58	46
47	.03053	53	.07981	59	.06176	51	.11496	57	47
48	.03106	53	.08041	59	.06227	51	.11554	57	48
49	.03159	53	.08100	59	.06279	51	.11611	58	49
50	9.03212	53	9.08160	59	9.06330	50	9.11669	57	50
51	.03265	53	.08219	59	.06380	51	.11727	57	51
52	.03318	53	.08278	59	.06431	51	.11784	57	52
53	.03371	52	.08338	59	.06482	51	.11842	57	53
54	.03423	53	.08397	59	.06533	51	.11899	58	54
55	9.03476	53	9.08456	59	9.06584	50	9.11957	57	55
56	.03529	52	.08515	59	.06635	51	.12015	57	56
57	.03582	52	.08574	59	.06686	50	.12072	57	57
58	.03634	53	.08634	59	.06736	51	.12129	57	58
59	.03687	52	.08693	59	.06787	50	.12187	57	59
60	9.03740		9.08752		9.06838		9.12244		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	61	60	59
6	6.1	6.0	5.9
7	7.1	7.0	6.9
8	8.1	8.0	7.8
9	9.1	9.0	8.8
10	10.1	10.0	9.8
20	20.3	20.0	19.6
30	30.5	30.0	29.5
40	40.6	40.0	39.3
50	50.8	50.0	49.1

	58	57
6	5.8	5.7
7	6.7	6.6
8	7.7	7.6
9	8.7	8.5
10	9.6	9.5
20	19.3	19.0
30	29.0	28.5
40	38.6	38.0
50	48.3	47.5

	55	54
6	5.5	5.4
7	6.4	6.3
8	7.3	7.2
9	8.2	8.1
10	9.1	9.0
20	18.3	18.0
30	27.5	27.0
40	36.6	36.0
50	45.8	45.0

	53	52
6	5.3	5.2
7	6.2	6.0
8	7.0	6.9
9	7.9	7.8
10	8.8	8.6
20	17.6	17.3
30	26.5	26.0
40	35.3	34.6
50	44.1	43.3

	51	0
6	5.1	0.0
7	5.9	0.0
8	6.8	0.0
9	7.6	0.1
10	8.5	0.1
20	17.0	0.1
30	25.8	0.2
40	34.0	0.3
50	42.5	0.4

P. P.

28° 29°

′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.06838	50	9.12244	57	9.09823	49	9.15641	56	0
1	.06888	51	.12302	57	.09872	48	.15697	55	1
2	.06939	50	.12359	57	.09920	49	.15752	56	2
3	.06990	50	.12416	57	.09969	48	.15808	55	3
4	.07040	50	.12474	57	.10018	49	.15864	56	4
5	9.07091	50	9.12531	57	9.10067	48	9.15920	55	5
6	.07141	50	.12588	57	.10115	48	.15975	56	6
7	.07192	50	.12645	57	.10164	49	.16031	55	7
8	.07242	50	.12703	57	.10213	48	.16087	55	8
9	.07293	50	.12760	57	.10261	48	.16142	56	9
10	9.07343	50	9.12817	57	9.10310	48	9.16198	55	10
11	.07393	50	.12874	57	.10358	48	.16254	55	11
12	.07444	50	.12931	57	.10407	48	.16309	55	12
13	.07494	50	.12988	57	.10455	48	.16365	55	13
14	.07544	50	.13045	57	.10504	48	.16420	55	14
15	9.07594	50	9.13102	57	9.10552	48	9.16476	55	15
16	.07644	50	.13159	57	.10601	48	.16531	55	16
17	.07695	50	.13216	56	.10649	48	.16587	55	17
18	.07745	50	.13273	57	.10697	48	.16642	55	18
19	.07795	50	.13330	57	.10746	48	.16698	55	19
20	9.07845	50	9.13387	57	9.10794	48	9.16753	55	20
21	.07895	50	.13444	56	.10842	48	.16808	55	21
22	.07945	50	.13500	57	.10890	48	.16864	55	22
23	.07995	50	.13557	56	.10939	48	.16919	55	23
24	.08045	50	.13614	57	.10987	48	.16974	55	24
25	9.08095	50	9.13671	56	9.11035	48	9.17029	55	25
26	.08145	50	.13727	57	.11083	48	.17085	55	26
27	.08195	49	.13784	56	.11131	48	.17140	55	27
28	.08244	50	.13841	56	.11179	48	.17195	55	28
29	.08294	49	.13897	57	.11227	48	.17250	55	29
30	9.08344	50	9.13954	56	9.11275	48	9.17305	55	30
31	.08394	49	.14011	56	.11323	48	.17361	55	31
32	.08443	49	.14067	56	.11371	47	.17416	55	32
33	.08493	50	.14124	56	.11419	48	.17471	55	33
34	.08543	49	.14180	56	.11467	48	.17526	55	34
35	9.08592	49	9.14237	56	9.11515	47	9.17581	55	35
36	.08642	49	.14293	56	.11562	48	.17636	55	36
37	.08691	49	.14350	56	.11610	48	.17691	55	37
38	.08741	49	.14406	56	.11658	47	.17746	55	38
39	.08790	49	.14462	56	.11706	48	.17801	55	39
40	9.08840	49	9.14519	56	9.11754	47	9.17856	54	40
41	.08889	49	.14575	56	.11801	47	.17910	55	41
42	.08939	49	.14631	56	.11849	48	.17965	55	42
43	.08988	49	.14688	56	.11897	47	.18020	54	43
44	.09087	49	.14744	56	.11944	47	.18075	55	44
45	9.09087	49	9.14800	56	9.11992	47	9.18130	55	45
46	.09136	49	.14856	56	.12039	47	.18185	54	46
47	.09185	49	.14913	56	.12087	47	.18239	55	47
48	.09234	49	.14969	56	.12134	47	.18294	54	48
49	.09284	49	.15025	56	.12182	47	.18349	54	49
50	9.09333	49	9.15081	56	9.12229	47	9.18403	55	50
51	.09382	49	.15137	56	.12277	47	.18458	54	51
52	.09431	49	.15193	56	.12324	47	.18513	54	52
53	.09480	49	.15249	56	.12371	47	.18567	54	53
54	.09529	49	.15305	56	.12419	47	.18622	54	54
55	9.09578	49	9.15361	56	9.12466	47	9.18676	54	55
56	.09627	49	.15417	56	.12513	47	.18731	55	56
57	.09676	48	.15473	56	.12560	47	.18786	54	57
58	.09725	49	.15529	55	.12608	47	.18840	54	58
59	.09774	49	.15585	56	.12655	47	.18894	54	59
60	9.09823		9.15641		9.12702		9.18949		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	57	57	56
6	5.7	5.7	5.6
7	6.7	6.6	6.6
8	7.6	7.6	7.5
9	8.6	8.5	8.5
10	9.6	9.5	9.4
20	19.1	19.0	18.8
30	28.7	28.5	28.2
40	38.3	38.0	37.6
50	47.9	47.5	47.1

	56	55	55
6	5.6	5.5	5.5
7	6.5	6.5	6.4
8	7.4	7.4	7.3
9	8.4	8.3	8.2
10	9.3	9.2	9.1
20	18.6	18.5	18.3
30	28.0	27.7	27.5
40	37.3	37.0	36.6
50	46.6	46.2	45.8

	54	54
6	5.4	5.4
7	6.3	6.3
8	7.2	7.2
9	8.2	8.1
10	9.1	9.0
20	18.1	18.0
30	27.2	27.0
40	36.3	36.0
50	45.4	45.0

	51	50	50
6	5.1	5.0	5.0
7	5.9	5.9	5.8
8	6.8	6.7	6.6
9	7.6	7.5	7.5
10	8.5	8.4	8.3
20	17.0	16.8	16.6
30	25.5	25.2	25.0
40	34.0	33.6	33.3
50	42.5	42.1	41.6

	49	49	48
6	4.9	4.9	4.8
7	5.8	5.7	5.6
8	6.6	6.5	6.4
9	7.4	7.3	7.3
10	8.2	8.1	8.1
20	16.5	16.3	16.1
30	24.7	24.5	24.2
40	33.0	32.6	32.3
50	41.2	40.8	40.4

	48	47	47
6	4.8	4.7	4.7
7	5.6	5.5	5.5
8	6.4	6.3	6.2
9	7.2	7.1	7.0
10	8.0	7.9	7.8
20	16.0	15.8	15.6
30	24.0	23.7	23.5
40	32.0	31.6	31.3
50	40.0	39.6	39.1

P. P.

′	30° Lg. Vers.	D	30° Log. Exs.	D	31° Lg. Vers.	D	31° Log. Exs.	D	′
0	9.12702	47	9.18949	54	9.15483	45	9.22176	53	0
1	.12749	47	.19003	54	.15528	45	.22229	53	1
2	.12796	47	.19058	54	.15574	45	.22282	53	2
3	.12843	47	.19112	54	.15619	45	.22335	53	3
4	.12890	47	.19167	54	.15665	45	.22388	53	4
5	9.12937	47	9.19221	54	9.15710	45	9.22441	53	5
6	.12984	47	.19275	54	.15755	45	.22494	53	6
7	.13031	47	.19329	54	.15801	45	.22547	53	7
8	.13078	47	.19384	54	.15846	45	.22600	53	8
9	.13125	47	.19438	54	.15891	45	.22653	53	9
10	9.13172	46	9.19492	54	9.15937	45	9.22706	53	10
11	.13219	47	.19546	54	.15982	45	.22759	53	11
12	.13266	47	.19601	54	.16027	45	.22812	53	12
13	.13313	46	.19655	54	.16073	45	.22865	52	13
14	.13359	47	.19709	54	.16118	45	.22918	53	14
15	9.13406	46	9.19763	54	9.16163	45	9.22971	53	15
16	.13453	47	.19817	54	.16208	45	.23024	52	16
17	.13500	46	.19871	54	.16253	45	.23076	53	17
18	.13546	46	.19925	54	.16298	45	.23129	52	18
19	.13593	46	.19979	54	.16343	45	.23182	53	19
20	9.13639	47	9.20033	54	9.16388	45	9.23235	52	20
21	.13686	46	.20087	54	.16434	45	.23287	53	21
22	.13733	46	.20141	54	.16479	44	.23340	52	22
23	.13779	46	.20195	54	.16523	45	.23393	53	23
24	.13826	46	.20249	53	.16568	45	.23446	52	24
25	9.13872	46	9.20303	54	9.16613	45	9.23498	52	25
26	.13919	46	.20357	54	.16658	45	.23551	52	26
27	.13965	46	.20411	54	.16703	45	.23603	52	27
28	.14011	46	.20465	53	.16748	44	.23656	53	28
29	.14058	46	.20518	54	.16793	45	.23709	52	29
30	9.14104	46	9.20572	53	9.16838	44	9.23761	52	30
31	.14151	46	.20626	54	.16882	45	.23814	52	31
32	.14197	46	.20680	53	.16927	44	.23866	52	32
33	.14243	46	.20733	54	.16972	45	.23919	52	33
34	.14289	46	.20787	53	.17017	44	.23971	53	34
35	9.14336	46	9.20841	53	9.17061	44	9.24024	52	35
36	.14382	46	.20894	54	.17106	45	.24076	52	36
37	.14428	46	.20948	53	.17151	44	.24128	52	37
38	.14474	46	.21002	53	.17195	44	.24181	52	38
39	.14520	46	.21055	53	.17240	44	.24233	52	39
40	9.14566	46	9.21109	53	9.17284	44	9.24285	52	40
41	.14612	46	.21162	53	.17329	44	.24138	52	41
42	.14658	46	.21216	53	.17373	44	.24390	52	42
43	.14704	46	.21269	53	.17418	44	.24442	52	43
44	.14750	46	.21323	53	.17462	44	.24495	52	44
45	9.14796	46	9.21376	53	9.17507	44	9.24547	52	45
46	.14842	46	.21430	53	.17551	44	.24599	52	46
47	.14888	46	.21483	53	.17596	44	.24651	52	47
48	.14934	45	.21537	53	.17640	44	.24704	52	48
49	.14980	46	.21590	53	.17684	44	.24756	52	49
50	9.15026	45	9.21643	53	9.17729	44	9.24808	52	50
51	.15071	46	.21697	53	.17773	44	.24860	52	51
52	.15117	46	.21750	53	.17817	44	.24912	52	52
53	.15163	45	.21803	53	.17861	44	.24964	52	53
54	.15209	45	.21857	53	.17906	44	.25016	52	54
55	9.15254	46	9.21910	53	9.17950	44	9.25068	52	55
56	.15300	45	.21963	53	.17994	44	.25120	52	56
57	.15346	45	.22016	53	.18038	44	.25172	52	57
58	.15391	45	.22070	53	.18082	44	.25224	52	58
59	.15437	46	.22123	53	.18126	44	.25276	52	59
60	9.15483		9.22176		9.18170		9.25328		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	54	54	53
6	5.4	5.4	5.3
7	6.3	6.3	6.2
8	7.2	7.2	7.1
9	8.2	8.1	8.0
10	9.1	9.0	8.9
20	18.1	18.0	17.8
30	27.2	27.0	26.7
40	36.3	36.0	35.6
50	45.4	45.0	44.6

	53	52	52
6	5.3	5.2	5.2
7	6.2	6.1	6.0
8	7.0	7.0	6.9
9	7.9	7.9	7.8
10	8.8	8.7	8.6
20	17.6	17.5	17.3
30	26.5	26.2	26.0
40	35.3	35.0	34.6
50	44.1	43.7	43.3

	47	47	46
6	4.7	4.7	4.6
7	5.5	5.5	5.4
8	6.3	6.2	6.2
9	7.1	7.0	7.0
10	7.9	7.8	7.7
20	15.8	15.6	15.5
30	23.7	23.5	23.2
40	31.6	31.3	31.0
50	39.6	39.1	38.7

	46	45	45
6	4.6	4.5	4.5
7	5.3	5.3	5.2
8	6.1	6.0	6.0
9	6.9	6.8	6.7
10	7.6	7.6	7.5
20	15.3	15.1	15.0
30	23.0	22.7	22.5
40	30.6	30.3	30.0
50	38.3	37.9	37.5

	44	44
6	4.4	4.4
7	5.2	5.1
8	5.9	5.8
9	6.7	6.6
10	7.4	7.3
20	14.8	14.6
30	22.2	22.0
40	29.6	29.3
50	37.1	36.6

P. P.

′	32° Lg. Vers.	D	32° Log. Exs.	D	33° Lg. Vers.	D	33° Log. Exs.	D	′
0	9.18170	44	9.25328	52	9.20771	42	9.28412	51	0
1	.18214	44	.25380	52	.20814	42	.28463	51	1
2	.18258	44	.25432	52	.20856	42	.28514	50	2
3	.18302	44	.25484	51	.20899	43	.28564	51	3
4	.18346	44	.25536	52	.20942	42	.28615	51	4
5	9.18390	44	9.25588	52	9.20984	42	9.28666	50	5
6	.18434	44	.25640	52	.21027	42	.28717	51	6
7	.18478	44	.25692	51	.21069	42	.28768	50	7
8	.18522	43	.25743	52	.21112	42	.28818	50	8
9	.18566	44	.25795	51	.21154	42	.28869	51	9
10	9.18610	44	9.25847	52	9.21196	42	9.28920	50	10
11	.18654	43	.25899	51	.21239	42	.28970	50	11
12	.18697	44	.25950	52	.21281	42	.29021	51	12
13	.18741	43	.26002	51	.21324	42	.29072	50	13
14	.18785	44	.26054	51	.21366	42	.29122	51	14
15	9.18829	43	9.26105	52	9.21408	42	9.29173	50	15
16	.18872	43	.26157	51	.21451	42	.29223	50	16
17	.18916	43	.26209	51	.21493	42	.29274	50	17
18	.18959	44	.26260	51	.21535	42	.29324	51	18
19	.19003	43	.26312	52	.21577	42	.29375	50	19
20	9.19047	43	9.26364	51	9.21620	42	9.29426	50	20
21	.19090	43	.26415	51	.21662	42	.29476	50	21
22	.19134	43	.26467	51	.21704	42	.29527	50	22
23	.19177	43	.26518	51	.21746	42	.29577	50	23
24	.19221	43	.26570	51	.21788	42	.29627	50	24
25	9.19264	43	9.26621	51	9.21830	42	9.29678	50	25
26	.19308	43	.26673	51	.21872	42	.29728	50	26
27	.19351	43	.26724	51	.21914	42	.29779	50	27
28	.19395	43	.26776	51	.21956	42	.29829	50	28
29	.19438	43	.26827	51	.21998	42	.29879	50	29
30	9.19481	43	9.26878	51	9.22040	42	9.29930	50	30
31	.19525	43	.26930	51	.22082	42	.29980	50	31
32	.19568	43	.26981	51	.22124	42	.30030	50	32
33	.19611	43	.27032	51	.22166	42	.30081	50	33
34	.19654	43	.27084	51	.22208	42	.30131	50	34
35	9.19698	43	9.27135	51	9.22250	42	9.30181	50	35
36	.19741	43	.27186	51	.22292	41	.30231	50	36
37	.19784	43	.27238	51	.22334	42	.30282	50	37
38	.19827	43	.27289	51	.22376	42	.30332	50	38
39	.19870	43	.27340	51	.22417	41	.30382	50	39
40	9.19914	43	9.27391	51	9.22459	42	9.30432	50	40
41	.19957	43	.27443	51	.22501	41	.30482	50	41
42	.20000	43	.27494	51	.22543	42	.30533	50	42
43	.20043	43	.27545	51	.22584	41	.30583	50	43
44	.20086	43	.27596	51	.22626	41	.30633	50	44
45	9.20129	43	9.27647	51	9.22668	42	9.30683	50	45
46	.20172	43	.27698	51	.22709	41	.30733	50	46
47	.20215	43	.27749	51	.22751	41	.30783	50	47
48	.20258	43	.27800	51	.22792	41	.30833	50	48
49	.20301	43	.27852	51	.22834	41	.30883	50	49
50	9.20343	42	9.27903	51	9.22876	41	9.30933	50	50
51	.20386	43	.27954	51	.22917	41	.30983	50	51
52	.20429	43	.28005	51	.22959	41	.31033	50	52
53	.20472	43	.28056	51	.23000	41	.31083	50	53
54	.20515	42	.28107	51	.23042	41	.31133	50	54
55	9.20558	43	9.28157	50	9.23083	41	9.31183	49	55
56	.20600	42	.28208	51	.23124	41	.31233	50	56
57	.20643	43	.28259	51	.23166	41	.31283	50	57
58	.20686	43	.28310	51	.23207	41	.31333	50	58
59	.20728	42	.28361	51	.23248	41	.31383	50	59
60	9.20771	43	9.28412	50	9.23290	41	9.31432	49	60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	52	51̄	51
6	5.2	5.1	5.1
7	6.0	6.0	5.9
8	6.9	6.8	6.8
9	7.8	7.7	7.6
10	8.6	8.6	8.5
20	17.3	17.1	17.0
30	26.0	25.7	25.5
40	34.6	34.3	34.0
50	43.3	42.9	42.5

	50̄	50	49̄
6	5.0	5.0	4.9
7	5.9	5.8	5.8
8	6.7	6.6	6.6
9	7.6	7.5	7.4
10	8.4	8.3	8.2
20	16.8	16.6	16.5
30	25.2	25.0	24.7
40	33.6	33.3	33.0
50	42.1	41.6	41.2

	44	43̄	43
6	4.4	4.3	4.3
7	5.1	5.1	5.0
8	5.8	5.8	5.7
9	6.6	6.5	6.4
10	7.3	7.2	7.1
20	14.6	14.5	14.3
30	22.0	21.7	21.5
40	29.3	29.0	28.6
50	36.6	36.2	35.8

	42̄	42	41̄
6	4.2	4.2	4.1
7	4.9	4.9	4.8
8	5.6	5.6	5.5
9	6.4	6.3	6.2
10	7.1	7.0	6.9
20	14.1	14.0	13.8
30	21.2	21.0	20.7
40	28.3	28.0	27.6
50	35.4	35.0	34.6

	41
6	4.1
7	4.8
8	5.4
9	6.1
10	6.8
20	13.6
30	20.5
40	27.3
50	34.1

P. P.

	34°				35°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.23290	41	9.31432	50	9.25731	40	9.34395	49	0
1	.23331	41	.31482	50	.25771	40	.34444	48	1
2	.23372	41	.31532	49	.25811	40	.34492	49	2
3	.23414	41	.31582	50	.25851	40	.34541	49	3
4	.23455	41	.31632	49	.25891	40	.34590	49	4
5	9.23496	41	9.31681	50	9.25931	40	9.34639	48	5
6	.23537	41	.31731	49	.25971	40	.34688	49	6
7	.23579	41	.31781	50	.26011	39	.34737	48	7
8	.23620	41	.31831	49	.26051	40	.34785	49	8
9	.23661	41	.31880	50	.26091	40	.34834	49	9
10	9.23702	41	9.31930	49	9.26131	40	9.34883	48	10
11	.23743	41	.31980	49	.26171	39	.34932	48	11
12	.23784	41	.32029	49	.26210	40	.34980	49	12
13	.23825	41	.32079	50	.26250	40	.34029	48	13
14	.23866	41	.32129	49	.26290	39	.35078	49	14
15	9.23907	41	9.32178	49	9.26330	40	9.35127	48	15
16	.23948	41	.32228	49	.26370	39	.35175	49	16
17	.23989	41	.32277	49	.26409	40	.35224	48	17
18	.24030	41	.32327	50	.26449	39	.35273	48	18
19	.24071	40	.32377	49	.26489	39	.35321	48	19
20	9.24112	41	9.32426	49	9.26528	40	9.35370	49	20
21	.24153	41	.32476	49	.26568	39	.35419	48	21
22	.24194	41	.32525	49	.26608	39	.35467	48	22
23	.24235	40	.32575	49	.26647	39	.35516	48	23
24	.24275	41	.32624	49	.26687	39	.35564	48	24
25	9.24316	40	9.32673	49	9.26726	40	9.35613	48	25
26	.24357	41	.32723	49	.26766	39	.35661	48	26
27	.24398	40	.32772	49	.26806	39	.35710	48	27
28	.24438	41	.32822	49	.26845	39	.35758	48	28
29	.24479	40	.32871	49	.26885	39	.35807	48	29
30	9.24520	41	9.32920	49	9.26924	39	9.35855	48	30
31	.24561	40	.32970	49	.26964	39	.35904	48	31
32	.24601	40	.33019	49	.27003	39	.35952	48	32
33	.24642	40	.33069	49	.27042	39	.36001	48	33
34	.24682	41	.33118	49	.27082	39	.36049	48	34
35	9.24723	40	9.33167	49	9.27121	39	9.36098	48	35
36	.24764	40	.33216	49	.27161	39	.36146	48	36
37	.24804	40	.33266	49	.27200	39	.36194	48	37
38	.24845	40	.33315	49	.27239	39	.36243	48	38
39	.24885	40	.33364	49	.27278	39	.36291	48	39
40	9.24926	40	9.33413	49	9.27318	39	9.36340	48	40
41	.24966	40	.33463	49	.27357	39	.36388	48	41
42	.25007	40	.33512	49	.27396	39	.36436	48	42
43	.25047	40	.33561	49	.27435	39	.36484	48	43
44	.25087	40	.33610	49	.27475	39	.36533	48	44
45	9.25128	40	9.33659	49	9.27514	39	9.36581	48	45
46	.25168	40	.33708	49	.27553	39	.36629	48	46
47	.25209	40	.33758	49	.27592	39	.36678	43	47
48	.25249	40	.33807	49	.27631	39	.36726	48	48
49	.25289	40	.33856	49	.27670	39	.36774	48	49
50	9.25329	40	9.33905	49	9.27709	39	9.36822	48	50
51	.25370	40	.33954	49	.27749	39	.36870	48	51
52	.25410	40	.34003	49	.27788	39	.36919	48	52
53	.25450	40	.34052	49	.27827	39	.36967	48	53
54	.25490	40	.34101	49	.27866	39	.37015	48	54
55	9.25531	40	9.34150	49	9 27905	39	9.37063	48	55
56	.25571	40	.34199	49	.27944	38	.37111	48	56
57	.25611	40	.34248	49	.27982	39	.37159	48	57
58	.25651	40	.34297	49	.28021	39	.37207	48	58
59	.25691	40	.34346	49	.28060	39	.37255	48	59
60	9.25731		9.34395		9.28099		9.37303		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	50	$\overline{49}$	49
6	5.0	4.9	4.9
7	5.8	5.8	5.7
8	6.6	6.6	6.5
9	7.5	7.4	7.3
10	8.3	8.2	8.1
20	16.6	16.5	16.3
30	25.0	24.7	24.5
40	33.3	33.0	32.6
50	41.6	41.2	40.8

	$\overline{48}$	48
6	4.8	4.8
7	5.6	5.6
8	6.4	6.4
9	7.3	7.2
10	8.1	8.0
20	16.1	16.0
30	24.2	24.0
40	32.3	32.0
50	40.4	40.0

	$\overline{41}$	41
6	4.1	4.1
7	4.8	4.8
8	5.5	5.4
9	6.2	6.1
10	6.9	6.8
20	13.8	13.6
30	20.7	20.5
40	27.6	27.3
50	34.6	34.1

	$\overline{40}$	40
6	4.0	4.0
7	4.7	4.[illegible]
8	5.4	5.3
9	6.1	6.0
10	6.7	6.6
20	13.5	13.3
30	20.2	20.0
40	27.0	26.6
50	33.7	33.3

	$\overline{39}$	39
6	3.9	3.9
7	4.6	4.5
8	5.2	5.2
9	5.9	5.8
10	6.6	6.5
20	13.1	13.0
30	19.7	19.5
40	26.3	26.0
50	32.9	32.5

	$\overline{38}$
6	3.8
7	4.5
8	5.1
9	5.8
10	6.4
20	12.8
30	19.2
40	25.6
50	32.1

P. P.

′	36° Lg. Vers.	D	36° Log. Exs.	D	37° Lg. Vers.	D	37° Log. Exs.	D	′
0	9.28099	39	9.37303	48	9.30398	37	9.40163	47	0
1	.28138	38	.37352	48	.30436	38	.40210	47	1
2	.28177	39	.37400	48	.30474	37	.40258	47	2
3	.28816	39	.37448	48	.30511	37	.40305	47	3
4	.28255	38	.37496	48	.30549	38	.40352	47	4
5	9.28293	39	9.37544	48	9.30587	37	9.40399	47	5
6	.28332	38	.37592	48	.30624	37	.40447	47	6
7	.28371	39	.37640	47	.30662	38	.40494	47	7
8	.28410	38	.37687	48	.30700	37	.40541	47	8
9	.28448	39	.37735	48	.30737	37	.40588	47	9
10	9.28487	38	9.37783	48	9.30775	37	9.40635	47	10
11	.28526	38	.37831	48	.30812	37	.40682	47	11
12	.28564	39	.37879	48	.30850	37	.40730	47	12
13	.28603	38	.37927	47	.30887	37	.40777	47	13
14	.28642	38	.37975	48	.30925	37	.40824	47	14
15	9.28680	38	9.38023	48	9.30962	37	9.40871	47	15
16	.28719	38	.38071	48	.31000	37	.40918	47	16
17	.28757	38	.38119	47	.31037	37	.40965	47	17
18	.28796	39	.38166	48	.31075	37	.41012	47	18
19	.28835	38	.38214	47	.31112	37	.41059	47	19
20	9.28873	38	9.38262	48	9.31150	37	9.41106	47	20
21	.28912	38	.38310	47	.31187	37	.41153	47	21
22	.28950	38	.38357	48	.31224	37	.41200	47	22
23	.28988	38	.38405	47	.31262	37	.41247	47	23
24	.29027	38	.38453	48	.31299	37	.41294	47	24
25	9.29065	38	9.38501	47	9.31336	37	9.41341	47	25
26	.29104	38	.38548	48	.31374	37	.41388	47	26
27	.29142	38	.38596	47	.31411	37	.41435	47	27
28	.29180	38	.38644	48	.31448	37	.41482	47	28
29	.29219	38	.38692	47	.31485	37	.41529	46	29
30	9.29257	38	9.38739	47	9.31523	37	9.41576	47	30
31	.29295	38	.38787	47	.31560	37	.41623	47	31
32	.29334	38	.38834	48	.31597	37	.41670	47	32
33	.29372	38	.38882	47	.31634	37	.41717	46	33
34	.29410	38	.38930	47	.31671	37	.41763	47	34
35	9.29448	38	9.38977	47	9.31708	37	9.41810	47	35
36	.29487	38	.39025	47	.31746	37	.41857	46	36
37	.29525	38	.39072	48	.31783	37	.41904	47	37
38	.29563	38	.39120	47	.31820	37	.41951	47	38
39	.29601	38	.39168	47	.31857	37	.41998	46	39
40	9.29639	38	9.39215	48	9.31894	37	9.42044	47	40
41	.29677	38	.39263	47	.31931	37	.42091	46	41
42	.29715	38	.39310	47	.31968	37	.42138	47	42
43	.29754	38	.39358	47	.32005	37	.42185	46	43
44	.29792	38	.39405	47	.32042	37	.42231	47	44
45	9.29830	38	9.39453	47	9.32079	37	9.42278	46	45
46	.29868	38	.39500	47	.32116	37	.42325	47	46
47	.29906	38	.39548	47	.32153	37	.42372	46	47
48	.29944	38	.39595	47	.32190	37	.42418	47	48
49	.29982	38	.39642	47	.32227	36	.42465	46	49
50	9.30020	37	9.39690	47	9.32263	37	9.42512	46	50
51	.30057	38	.39737	47	.32300	37	.42558	47	51
52	.30095	38	.39785	47	.32337	36	.42605	46	52
53	.30133	38	.39832	47	.32374	37	.42652	46	53
54	.30171	38	.39879	47	.32411	36	.42698	46	54
55	9.30209	37	9.39927	47	9.32447	37	9.42745	47	55
56	.30247	38	.39974	47	.32484	36	.42792	46	56
57	.30285	37	.40021	47	.32521	37	.42838	46	57
58	.30322	38	.40069	47	.32558	36	.42885	46	58
59	.30360	38	.40116	47	.32594	37	.42931	46	59
60	9.30398		9.40163		9.32631		9.42978		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	48	48
6	4.8	4.8
7	5.6	5.6
8	6.4	6.4
9	7.3	7.2
10	8.1	8.0
20	16.1	16.0
30	24.2	24.0
40	32.3	32.0
50	40.4	40.0

	47	47
6	4.7	4.7
7	5.5	5.5
8	6.3	6.2
9	7.1	7.0
10	7.9	7.8
20	15.8	15.6
30	23.7	23.5
40	31.6	31.3
50	39.6	39.1

	46
6	4.6
7	5.4
8	6.2
9	7.0
10	7.7
20	15.5
30	23.2
40	31.0
50	38.7

	39	38
6	3.9	3.8
7	4.5	4.5
8	5.2	5.1
9	5.8	5.8
10	6.5	6.4
20	13.0	12.8
30	10.5	19.2
40	26.0	25.6
50	32.5	32.1

	38	37
6	3.8	3.7
7	4.4	4.4
8	5.0	5.0
9	5.7	5.6
10	6.3	6.2
20	12.6	12.5
30	19.0	18.7
40	25.3	25.0
50	31.6	31.2

	37	36
6	3.7	3.6
7	4.3	4.2
8	4.9	4.8
9	5.5	5.5
10	6.1	6.1
20	12.3	12.1
30	18.5	18.2
40	24.6	24.3
50	30.8	30.4

P. P.

	38°				39°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.32631	36	9.42978	46	9.34802	35	9.45752	45	0
1	.32668	36	.43024	47	.34837	36	.45797	46	1
2	.32704	37	.43071	46	.34873	35	.45843	46	2
3	.32741	36	.43118	46	.34909	35	.45889	46	3
4	.32778	36	.43164	46	.34944	35	.45935	45	4
5	9.32814	36	9.43211	46	9.34980	36	9.45981	46	5
6	.32851	37	.43257	46	.35016	35	.46027	46	6
7	.32888	36	.43304	46	.35051	35	.46073	45	7
8	.32924	36	.43350	46	.35087	35	.46118	46	8
9	.32961	36	.43396	46	.35122	35	.46164	46	9
10	9.32997	36	9.43443	46	9.35158	35	9.46210	45	10
11	.33034	36	.43489	46	.35193	35	.46256	46	11
12	.33070	36	.43536	46	.35229	35	.46302	45	12
13	.33107	36	.43582	46	.35264	35	.46347	46	13
14	.33143	36	.43629	46	.35300	35	.46393	45	14
15	9.33180	36	9.43675	46	9.35335	35	9.46439	46	15
16	.33216	36	.43721	46	.35370	35	.46485	45	16
17	.33252	36	.43768	46	.35406	35	.46530	46	17
18	.33289	36	.43814	46	.35441	35	.46576	45	18
19	.33325	36	.43861	46	.35477	35	.46622	46	19
20	9.33361	36	9.43907	46	9.35512	35	9.46668	45	20
21	.33398	36	.43953	46	.35547	35	.46713	45	21
22	.33434	36	.43999	46	.35583	35	.46759	46	22
23	.33470	36	.44046	46	.35618	35	.46805	45	23
24	.33507	36	.44092	46	.35653	35	.46850	45	24
25	9.33543	36	9.44138	46	9.35689	35	9.46896	46	25
26	.33579	36	.44185	46	.35724	35	.46942	45	26
27	.33615	36	.44231	46	.35759	35	.46987	45	27
28	.33652	36	.44277	46	.35794	35	.47033	45	28
29	.33688	36	.44323	46	.35829	35	.47078	46	29
30	9.33724	36	9.44370	46	9.35865	35	9.47124	45	30
31	.33760	36	.44416	46	.35900	35	.47170	45	31
32	.33796	36	.44462	46	.35935	35	.47215	45	32
33	.33833	36	.44508	46	.35970	35	.47261	45	33
34	.33869	36	.44554	46	.36005	35	.47306	46	34
35	9.33905	36	9.44601	46	9.36040	35	9.47352	45	35
36	.33941	36	.44647	46	.36076	35	.47398	45	36
37	.33977	36	.44693	46	.36111	35	.47443	45	37
38	.34013	36	.44739	46	.36146	35	.47489	45	38
39	.34049	36	.44785	46	.36181	35	.47534	45	39
40	9.34085	36	9.44831	46	9.36216	35	9.47580	45	40
41	.34121	36	.44877	46	.36251	35	.47625	45	41
42	.34157	36	.44924	46	.36286	35	.47671	45	42
43	.34193	36	.44970	46	.36321	35	.47716	45	43
44	.34229	36	.45016	46	.36356	35	.47762	45	44
45	9.34265	36	9.45062	46	9.36391	35	9.47807	45	45
46	.34301	36	.45108	46	.36426	35	.47852	45	46
47	.34337	36	.45154	46	.36461	34	.47898	45	47
48	.34373	35	.45200	46	.36495	35	.47943	45	48
49	.34408	36	.45246	46	.36530	35	.47989	45	49
50	9.34444	36	9.45292	46	9.36565	35	9.48034	45	50
51	.34480	35	.45338	46	.36600	34	.48080	45	51
52	.34516	36	.45384	46	.36635	35	.48125	45	52
53	.34552	35	.45430	46	.36670	35	.48170	45	53
54	.34587	36	.45476	46	.36705	34	.48216	45	54
55	9.34623	35	9.45522	46	9.36739	35	9.48261	45	55
56	.34659	36	.45568	46	.36774	34	.48306	45	56
57	.34695	35	.45614	46	.36809	35	.48352	45	57
58	.34730	36	.45660	46	.36844	34	.48397	45	58
59	.34766	35	.45706	46	.36878	35	.48442	45	59
60	9.34802		9.45752		9.36913		9.48488		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	47	46
6	4.7	4.6
7	5.5	5.4
8	6.2	6.2
9	7.0	7.0
10	7.8	7.7
20	15.6	15.5
30	23.5	23.2
40	31.3	31.0
50	39.1	38.7

	46	45
6	4.6	4.5
7	5.3	5.3
8	6.1	6.0
9	6.9	6.8
10	7.6	7.6
20	15.3	15.1
30	23.0	22.7
40	30.6	30.3
50	38.3	37.9

	45
6	4.5
7	5.2
8	6.0
9	6.7
10	7.5
20	15.0
30	22.5
40	30.0
50	37.5

	37	36
6	3.7	3.6
7	4.3	4.2
8	4.9	4.8
9	5.5	5.5
10	6.1	6.1
20	12.3	12.1
30	18.5	18.2
40	24.6	24.3
50	30.8	30.4

	36	35
6	3.6	3.5
7	4.2	4.1
8	4.8	4.7
9	5.4	5.3
10	6.0	5.9
20	12.0	11.8
30	18.0	17.7
40	24.0	23.6
50	30.0	29.6

	35	34
6	3.5	3.4
7	4.1	4.0
8	4.6	4.6
9	5.2	5.2
10	5.8	5.7
20	11.6	11.5
30	17.5	17.2
40	23.3	23.0
50	29.1	28.7

P. P.

	40°				41°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.36913	34	9.48488	45	9.38968	34	9.51190	45	0
1	.36948	34	.48533	45	.39002	33	.51235	44	1
2	.36982	35	.48578	45	.39035	34	.51279	45	2
3	.37017	34	.48624	45	.39069	33	.51324	44	3
4	.37052	34	.48669	45	.39103	34	.51369	45	4
5	9.37086	35	9.48714	45	9.39137	33	9.51414	44	5
6	.37121	34	.48759	45	.39170	33	.51458	45	6
7	.37156	34	.48805	45	.39204	34	.51503	44	7
8	.37190	34	.48850	45	.39238	33	.51548	44	8
9	.37225	34	.48895	45	.39271	33	.51592	45	9
10	9.37259	34	9.48940	45	9.39305	34	9.51637	44	10
11	.37294	34	.48986	45	.39339	33	.51682	44	11
12	.37328	34	.49031	45	.39372	33	.51726	45	12
13	.37363	34	.49076	45	.39406	33	.51771	44	13
14	.37397	34	.49121	45	.39439	33	.51816	44	14
15	9.37432	34	9.49166	45	9.39473	34	9.51860	45	15
16	.37466	34	.49211	45	.39507	33	.51905	44	16
17	.37501	34	.49257	45	.39540	33	.51950	44	17
18	.37535	34	.49302	45	.39574	33	.51994	44	18
19	.37570	34	.49347	45	.39607	33	.52039	45	19
20	9.37604	34	9.49392	45	9.39641	33	9.52084	44	20
21	.37639	34	.49437	45	.39674	33	.52128	44	21
22	.37673	34	.49482	45	.39708	33	.52173	44	22
23	.37707	34	.49527	45	.39741	33	.52217	44	23
24	.37742	34	.49572	45	.39774	33	.52262	44	24
25	9.37776	34	9.49618	45	9.39808	33	9.52306	45	25
26	.37810	34	.49663	45	.39841	33	.52351	44	26
27	.37845	34	.49708	45	.39875	33	.52396	44	27
28	.37879	34	.49753	45	.39908	33	.52440	44	28
29	.37913	34	.49798	45	.39941	33	.52485	44	29
30	9.37947	34	9.49843	45	9.39975	33	9.52529	44	30
31	.37982	34	.49888	45	.40008	33	.52574	44	31
32	.38016	34	.49933	45	.40041	33	.52618	44	32
33	.38050	34	.49978	45	.40075	33	.52663	44	33
34	.38084	34	.50023	45	.40108	33	.52707	44	34
35	9.38118	34	9.50068	45	9.40141	33	9.52752	44	35
36	.38153	34	.50113	45	.40175	33	.52796	44	36
37	.38187	34	.50158	45	.40208	33	.52841	44	37
38	.38221	34	.50203	45	.40241	33	.52885	44	38
39	.38255	34	.50248	45	.40274	33	.52930	44	39
40	9.38289	34	9.50293	45	9.40307	33	9.52974	44	40
41	.38323	34	.50338	45	.40341	33	.53018	44	41
42	.38357	34	.50383	44	.40374	33	.53063	44	42
43	.38391	34	.50427	45	.40407	33	.53107	44	43
44	.38425	34	.50472	45	.40440	33	.53152	44	44
45	9.38459	34	9.50517	45	9.40473	33	9.53196	44	45
46	.38493	34	.50562	45	.40506	33	.53240	44	46
47	.38527	34	.50607	44	.40540	33	.53285	44	47
48	.38561	34	.50652	45	.40573	33	.53329	44	48
49	.38595	34	.50697	45	.40606	33	.53374	44	49
50	9.38629	34	9.50742	45	9.40639	33	9.53418	44	50
51	.38663	34	.50787	44	.40672	33	.53462	44	51
52	.38697	33	.50831	45	.40705	33	.53507	44	52
53	.38731	34	.50876	45	.40738	33	.53551	44	53
54	.38765	34	.50921	44	.40771	33	.53595	44	54
55	9.38799	34	9.50966	45	9.40804	33	9.53640	44	55
56	.38833	33	.51011	44	.40837	33	.53684	44	56
57	.38866	34	.51055	45	.40870	33	.53728	44	57
58	.38900	33	.51100	45	.40903	33	.53773	44	58
59	.38934	34	.51145	44	.40936	33	.53817	44	59
60	9.38968		9.51190		9.40969		9.53861		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	45	45
6	4.5	4.5
7	5.3	5.2
8	6.0	6.0
9	6.8	6.7
10	7.6	7.5
20	15.1	15.0
30	22.7	22.5
40	30.3	30.0
50	37.9	37.5

	44	44
6	4.4	4.4
7	5.2	5.1
8	5.9	5.8
9	6.7	6.6
10	7.4	7.3
20	14.8	14.6
30	22.2	22.0
40	29.6	29.3
50	37.1	36.6

	35	34
6	3.5	3.4
7	4.1	4.0
8	4.6	4.6
9	5.2	5.2
10	5.8	5.7
20	11.6	11.5
30	17.5	17.2
40	23.3	23.0
50	29.1	28.7

	34	33
6	3.4	3.3
7	3.9	3.9
8	4.5	4.4
9	5.1	5.0
10	5.6	5.6
20	11.3	11.1
30	17.0	16.7
40	22.6	22.3
50	28.3	27.9

	33
6	3.3
7	3.8
8	4.4
9	4.9
10	5.5
20	11.0
30	16.5
40	22.0
50	27.5

P. P.

	42°				43°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.40969	32	9.53861	44	9.42918	32	9.56505	43	0
1	.41001	33	.53906	44	.42950	32	.56549	44	1
2	.41034	33	.53950	44	.42982	32	.56593	44	2
3	.41067	33	.53994	44	.43014	32	.56637	43	3
4	.41100	32	.54038	44	.43046	32	.56680	44	4
5	9.41133	33	9.54083	44	9.43078	32	9.56724	44	5
6	.41166	33	.54127	44	.43110	31	.56768	43	6
7	.41199	32	.54171	44	.43142	32	.56812	44	7
8	.41231	33	.54215	44	.43174	32	.56856	43	8
9	.41264	32	.54259	44	.43206	32	.56899	44	9
10	9.41297	33	9.54304	44	9.43238	32	9.56943	44	10
11	.41330	32	.54348	44	.43270	32	.56987	43	11
12	.41362	33	.54392	44	.43302	32	.57031	44	12
13	.41395	32	.54436	44	.43334	31	.57075	43	13
14	.41428	33	.54480	44	.43365	32	.57118	44	14
15	9.41461	32	9.54525	44	9.43397	32	9.57162	43	15
16	.41493	33	.54569	44	.43429	32	.57206	44	16
17	.41526	32	.54613	44	.43461	31	.57250	43	17
18	.41559	32	.54657	44	.43493	32	.57293	44	18
19	.41591	32	.54701	44	.43525	32	.57337	43	19
20	9.41624	33	9.54745	44	9.43557	31	9.57381	43	20
21	.41657	32	.54790	44	.43588	32	.57424	44	21
22	.41689	32	.54834	44	.43620	31	.57468	43	22
23	.41722	32	.54878	44	.43652	32	.57512	44	23
24	.41754	32	.54922	44	.43684	31	.57556	43	24
25	9.41787	32	9.54966	44	9.43715	32	9.57599	43	25
26	.41819	32	.55010	44	.43747	31	.57643	44	26
27	.41852	33	.55054	44	.43779	31	.57687	43	27
28	.41885	32	.55098	44	.43810	32	.57730	43	28
29	.41917	32	.55142	44	.43842	31	.57774	44	29
30	9.41950	32	9.55186	44	9.43874	32	9.57818	43	30
31	.41982	32	.55230	44	.43906	31	.57861	43	31
32	.42014	32	.55275	44	.43937	31	.57905	44	32
33	.42047	32	.55319	44	.43969	31	.57949	43	33
34	.42079	32	.55363	44	.44000	32	.57992	43	34
35	9.42112	32	9.55407	44	9.44032	31	9.58036	43	35
36	.42144	32	.55451	44	.44064	31	.58079	44	36
37	.42177	32	.55495	44	.44095	31	.58123	43	37
38	.42209	32	.55539	44	.44127	31	.58167	43	38
39	.42241	32	.55583	44	.44158	31	.58210	43	39
40	9.42274	32	9.55627	44	9.44190	31	9.58254	43	40
41	.42306	32	.55671	44	.44221	31	.58297	44	41
42	.42338	32	.55715	44	.44253	31	.58341	43	42
43	.42371	32	.55759	44	.44284	31	.58385	43	43
44	.42403	32	.55803	44	.44316	31	.58428	43	44
45	9.42435	32	9.55847	43	9.44347	31	9.58472	43	45
46	.42467	32	.55890	44	.44379	31	.58515	43	46
47	.42500	32	.55934	44	.44410	31	.58559	43	47
48	.42532	32	.55978	44	.44442	31	.58602	43	48
49	.42564	32	.56022	44	.44473	31	.58646	43	49
50	9.42596	32	9.56066	44	9.44504	31	9.58689	43	50
51	.42629	32	.56110	44	.44536	31	.58733	43	51
52	.42661	32	.56154	43	.44567	31	.58776	44	52
53	.42693	32	.56198	44	.44599	31	.58820	43	53
54	.42725	32	.56242	44	.44630	31	.58864	43	54
55	9.42757	32	9.56286	44	9.44661	31	9.58907	43	55
56	.42789	32	.56330	44	.44693	31	.58951	43	56
57	.42822	32	.56374	43	.44724	31	.58994	43	57
58	.42854	32	.56417	44	.44755	31	.59037	43	58
59	.42886	32	.56461	43	.44787	31	.59081	43	59
60	9.42918		9.56505		9.44818		9.59124		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	44	44	43	43	33	32	32	31	31
6	4.4	4.4	4.3	4.3	3.3	3.2	3.2	3.1	3.1
7	5.2	5.1	5.1	5.0	3.8	3.8	3.7	3.7	3.6
8	5.9	5.8	5.8	5.7	4.4	4.3	4.2	4.2	4.1
9	6.7	6.6	6.5	6.4	4.9	4.9	4.8	4.7	4.6
10	7.4	7.3	7.2	7.1	5.5	5.4	5.3	5.2	5.1
20	14.8	14.6	14.5	14.3	11.0	10.8	10.6	10.5	10.3
30	22.2	22.0	21.7	21.5	16.5	16.2	16.0	15.7	15.5
40	29.6	29.3	29.0	28.6	22.0	21.6	21.3	21.0	20.6
50	37.1	36.6	36.2	35.8	27.5	27.1	26.6	26.2	25.8

P. P.

′	44° Lg. Vers.	D	44° Log. Exs.	D	45° Lg. Vers.	D	45° Log. Exs.	D	′
0	9.44818	31	9.59124	43	9.46671	30	9.61722	43	0
1	.44849	31	.59168	43	.46701	30	.61765	43	1
2	.44880	31	.59211	43	.46732	30	.61808	43	2
3	.44912	31	.59255	43	.46762	30	.61852	43	3
4	.44943	31	.59298	43	.46793	30	.61895	43	4
5	9.44974	31	9.59342	43	9.46823	30	9.61938	43	5
6	.45005	31	.59385	43	.46853	30	.61981	43	6
7	.45036	31	.59429	43	.46884	30	.62024	43	7
8	.45068	31	.59472	43	.46914	30	.62067	43	8
9	.45099	31	.59515	43	.46945	30	.62110	43	9
10	9.45130	31	9.59559	43	9.46975	30	9.62153	43	10
11	.45161	31	.59602	43	.47005	30	.62196	43	11
12	.45192	31	.59646	43	.47036	30	.62239	43	12
13	.45223	31	.59689	43	.47066	30	.62282	43	13
14	.45254	31	.59732	43	.47096	30	.62326	43	14
15	9.45285	31	9.59776	43	9.47127	30	9.62369	43	15
16	.45316	31	.59819	43	.47157	30	.62412	43	16
17	.45348	31	.59863	43	.47187	30	.62455	43	17
18	.45379	31	.59906	43	.47218	30	.62498	43	18
19	.45410	31	.59949	43	.47248	30	.62541	43	19
20	9.45441	31	9.59993	43	9.47278	30	9.62584	43	20
21	.45472	31	.60036	43	.47308	30	.62627	43	21
22	.45503	31	.60079	43	.47339	30	.62670	43	22
23	.45534	31	.60123	43	.47369	30	.62713	43	23
24	.45565	30	.60166	43	.47399	30	.62756	43	24
25	9.45595	31	9.60209	43	9.47429	30	9.62799	43	25
26	.45626	31	.60253	43	.47459	30	.62842	43	26
27	.45657	31	.60296	43	.47490	30	.62885	43	27
28	.45688	31	.60339	43	.47520	30	.62928	43	28
29	.45719	31	.60383	43	.47550	30	.62971	43	29
30	9.45750	30	9.60426	43	9.47580	30	9.63014	43	30
31	.45781	31	.60469	43	.47610	30	.63057	43	31
32	.45812	31	.60512	43	.47640	30	.63100	43	32
33	.45843	30	.60556	43	.47670	30	.63143	43	33
34	.45873	31	.60599	43	.47700	30	.63186	43	34
35	9.45904	31	9.60642	43	9.47731	30	9.63229	43	35
36	.45935	30	.60685	43	.47761	30	.63272	43	36
37	.45966	31	.60729	43	.47791	30	.63315	43	37
38	.45997	30	.60772	43	.47821	30	.63358	43	38
39	.46027	31	.60815	43	.47851	30	.63401	42	39
40	9.46058	30	9.60858	43	9.47881	30	9.63443	43	40
41	.46089	31	.60902	43	.47911	30	.63486	43	41
42	.46120	30	.60945	43	.47941	30	.63529	43	42
43	.46150	31	.60988	43	.47971	30	.63572	43	43
44	.46181	30	.61031	43	.48001	30	.63615	43	44
45	9.46212	30	9.61075	43	9.48031	30	9.63658	42	45
46	.46242	31	.61118	43	.48061	29	.63701	43	46
47	.46273	30	.61161	43	.48090	30	.63744	43	47
48	.46304	30	.61204	43	.48120	30	.63787	43	48
49	.46334	31	.61247	43	.48150	30	.63830	43	49
50	9.46365	30	9.61291	43	9.48180	30	9.63873	42	50
51	.46396	30	.61334	43	.48210	29	.63915	43	51
52	.46426	30	.61377	43	.48240	30	.63958	43	52
53	.46457	30	.61420	43	.48270	30	.64001	43	53
54	.46487	31	.61463	43	.48300	29	.64044	42	54
55	9.46518	30	9.61506	43	9.48329	30	9.64087	43	55
56	.46549	30	.61550	43	.48359	30	.64130	43	56
57	.46579	30	.61593	43	.48389	29	.64173	43	57
58	.46610	30	.61636	43	.48419	30	.64216	42	58
59	.46640	30	.61679	43	.48449	29	.64258	43	59
60	9.46671		9.61722		9.48478		9.64301		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	43̄	43
6	4.3	4.3
7	5.1	5.0
8	5.8	5.7
9	6.5	6.4
10	7.2	7.1
20	14.5	14.3
30	21.7	21.5
40	29.0	28.6
50	36.2	35.8

	42̄
6	4.2
7	4.9
8	5.6
9	6.4
10	7.1
20	14.1
30	21.2
40	28.3
50	35.4

	31̄	31
6	3.1	3.1
7	3.7	3.6
8	4.2	4.1
9	4.7	4.6
10	5.2	5.1
20	10.5	10.3
30	15.7	15.5
40	21.0	20.6
50	26.2	25.8

	30̄	30
6	3.0	3.0
7	3.5	3.5
8	4.0	4.0
9	4.6	4.5
10	5.1	5.0
20	10.1	10.0
30	15.2	15.0
40	20.3	20.0
50	25.4	25.0

	29̄
6	2.9
7	3.4
8	3.9
9	4.4
10	4.9
20	9.8
30	14.7
40	19.6
50	24.6

P. P.

′	46° Lg. Vers.	D	46° Log. Exs.	D	47° Lg. Vers.	D	47° Log. Exs.	D	′
0	9.48478	30	9.64301	43	9.50243	29	9.66864	42	0
1	.48508	29	.64344	42	.50272	29	.66907	43	1
2	.48538	30	.64387	43	.50301	29	.66950	42	2
3	.48568	29	.64430	43	.50330	29	.66992	42	3
4	.48597	30	.64473	42	.50359	29	.67035	42	4
5	9.48627	29	9.64515	43	9.50388	29	9.67077	42	5
6	.48657	29	.64558	43	.50417	29	.67120	42	6
7	.48686	30	.64601	42	.50446	29	.67162	43	7
8	.48716	29	.64644	43	.50475	29	.67205	42	8
9	.48746	29	.64687	42	.50504	29	.67248	42	9
10	9.48775	30	9.64729	43	9.50533	29	9.67290	42	10
11	.48805	29	.64772	43	.50562	29	.67333	42	11
12	.48835	29	.64815	42	.50591	28	.67375	42	12
13	.48864	29	.64858	43	.50619	29	.67418	42	13
14	.48894	29	.64901	42	.50648	29	.67460	42	14
15	9.48923	30	9.64943	43	9.50677	29	9.67503	43	15
16	.48953	29	.64986	42	.50706	28	.67546	42	16
17	.48983	29	.65029	43	.50735	29	.67588	42	17
18	.49012	29	.65072	42	.50764	29	.67631	42	18
19	.49042	29	.65114	43	.50793	28	.67673	42	19
20	9.49071	29	9.65157	42	9.50821	29	9.67716	42	20
21	.49101	29	.65200	43	.50850	29	.67758	42	21
22	.49130	29	.65243	42	.50879	28	.67801	42	22
23	.49160	29	.65285	43	.50908	29	.67843	42	23
24	.49189	29	.65328	42	.50937	28	.67886	42	24
25	9.49219	29	9.65371	43	9.50965	29	9.67928	42	25
26	.49248	29	.65414	42	.50994	28	.67971	42	26
27	.49278	29	.65456	43	.51023	29	.68013	42	27
28	.49307	29	.65499	42	.51052	28	.68056	42	28
29	.49336	29	.65542	43	.51080	29	.68098	42	29
30	9.49300	29	9.65585	42	9.51109	28	9.68141	42	30
31	.49395	29	.65627	43	.51138	29	.68183	42	31
32	.49425	29	.65670	42	.51167	28	.68226	42	32
33	.49454	29	.65713	42	.51195	28	.68268	42	33
34	.49483	29	.65755	43	.51224	29	.68311	42	34
35	9.49513	29	9.65798	42	9.51253	28	9.68353	42	35
36	.49542	29	.65841	43	.51281	28	.68396	42	36
37	.49571	29	.65884	42	.51310	28	.68438	42	37
38	.49601	29	.65926	42	.51338	29	.68481	42	38
39	.49630	29	.65969	43	.51367	28	.68523	42	39
40	9.49059	29	9.66012	42	9.51396	28	9.68566	42	40
41	.49689	29	.66054	42	.51424	28	.68608	42	41
42	.49718	29	.66097	43	.51453	28	.68651	42	42
43	.49747	29	.66140	42	.51481	28	.68693	42	43
44	.49776	29	.66182	42	.51510	29	.68735	42	44
45	9.49806	29	9.66225	43	9.51539	28	9.68778	42	45
46	.49835	29	.66268	42	.51567	28	.68820	42	46
47	.49864	29	.66310	42	.51596	28	.68863	42	47
48	.49893	29	.66353	43	.51624	28	.68905	42	48
49	.49922	29	.66396	42	.51653	28	.68948	42	49
50	9.49952	29	9.66438	42	9.51681	28	9.68990	42	50
51	.49981	29	.66481	42	.51710	28	.69033	42	51
52	.50010	29	.66523	43	.51738	28	.69075	42	52
53	.50039	29	.66566	42	.51767	28	.69117	42	53
54	.50068	29	.66609	42	.51795	28	.69160	42	54
55	9.50097	29	9.66651	42	9.51823	28	9.69202	42	55
56	.50126	29	.66694	43	.51852	28	.69245	42	56
57	.50155	29	.66737	42	.51880	28	.69287	42	57
58	.50185	29	.66779	42	.51909	28	.69330	42	58
59	.50214	29	.66822	42	.51937	28	.69372	42	59
60	9.50243		9.66864		9.51965		9.69414		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	43	42
6	4.3	4.2
7	5.0	4.9
8	5.7	5.6
9	6.4	6.4
10	7.1	7.1
20	14.3	14.1
30	21.5	21.2
40	28.6	28.3
50	35.8	35.4

	42
6	4.2
7	4.9
8	5.6
9	6.3
10	7.0
20	14.0
30	21.0
40	28.0
50	35.0

	30	29
6	3.0	2.9
7	3.5	3.4
8	4.0	3.9
9	4.5	4.4
10	5.0	4.9
20	10.0	9.8
30	15.0	14.7
40	20.0	19.6
50	25.0	24.6

	29	28
6	2.9	2.8
7	3.4	3.3
8	3.8	3.8
9	4.3	4.3
10	4.8	4.7
20	9.6	9.5
30	14.5	14.2
40	19.3	19.0
50	24.1	23.7

	28
6	2.8
7	3.2
8	3.7
9	4.2
10	4.6
20	9.3
30	14.0
40	18.6
50	23.3

P. P.

	48°				49°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9·5196$\bar{5}$	2$\bar{8}$	9·6941$\bar{4}$	4$\bar{2}$	9·5364$\bar{8}$	2$\bar{7}$	9·71954	4$\bar{2}$	0
1	·51994	2$\bar{8}$	·69457	4$\bar{2}$	·53676	28	·7199$\bar{6}$	4$\bar{2}$	1
2	·5202$\bar{2}$	28	·69499	4$\bar{2}$	·53704	2$\bar{7}$	·7203$\bar{8}$	4$\bar{2}$	2
3	·5205$\bar{0}$	2$\bar{8}$	·69542	42	·5373$\bar{1}$	2$\bar{7}$	·72081	42	3
4	·52079	2$\bar{8}$	·69584	4$\bar{2}$	·53759	28	·72123	4$\bar{2}$	4
5	9·5210$\bar{7}$	28	9·6962$\bar{6}$	4$\bar{2}$	9·53787	2$\bar{7}$	9·7216$\bar{5}$	4$\bar{2}$	5
6	·5213$\bar{5}$	2$\bar{8}$	·69669	4$\bar{2}$	·5381$\bar{4}$	27	·7220$\bar{7}$	4$\bar{2}$	6
7	·52164	2$\bar{8}$	·6971$\bar{1}$	42	·53842	28	·72250	4$\bar{2}$	7
8	·5219$\bar{2}$	28	·6975$\bar{3}$	4$\bar{2}$	·53870	2$\bar{7}$	·72292	4$\bar{2}$	8
9	·5222$\bar{0}$	2$\bar{8}$	·69796	4$\bar{2}$	·5389$\bar{7}$	2$\bar{7}$	·7233$\bar{4}$	4$\bar{2}$	9
10	9·52249	2$\bar{8}$	9·69838	4$\bar{2}$	9·53925	2$\bar{7}$	9·7237$\bar{6}$	4$\bar{2}$	10
11	·5227$\bar{7}$	2$\bar{8}$	·69881	42	·5395$\bar{2}$	28	·72419	42	11
12	·5230$\bar{5}$	28	·69923	4$\bar{2}$	·53980	2$\bar{7}$	·72461	4$\bar{2}$	12
13	·5233$\bar{3}$	2$\bar{8}$	·69965	4$\bar{2}$	·54008	27	·72503	4$\bar{2}$	13
14	·52362	28	·70008	4$\bar{2}$	·54035	2$\bar{7}$	·7254$\bar{5}$	4$\bar{2}$	14
15	9·52390	28	9·7005$\bar{0}$	4$\bar{2}$	9·54063	2$\bar{7}$	9·7258$\bar{7}$	4$\bar{2}$	15
16	·52418	2$\bar{8}$	·7009$\bar{2}$	4$\bar{2}$	·5409$\bar{0}$	2$\bar{7}$	·72630	4$\bar{2}$	16
17	·5244$\bar{6}$	2$\bar{8}$	·70135	4$\bar{2}$	·54118	2$\bar{7}$	·72672	4$\bar{2}$	17
18	·5247$\bar{4}$	2$\bar{8}$	·70177	4$\bar{2}$	·5414$\bar{5}$	27	·7271$\bar{4}$	42	18
19	·52503	28	·70220	4$\bar{2}$	·54173	2$\bar{7}$	·7275$\bar{6}$	4$\bar{2}$	19
20	9·52531	28	9·70262	4$\bar{2}$	9·5420$\bar{0}$	2$\bar{7}$	9·72799	42	20
21	·52559	2$\bar{8}$	·70304	4$\bar{2}$	·54228	2$\bar{7}$	·72841	4$\bar{2}$	21
22	·5258$\bar{7}$	2$\bar{8}$	·70347	4$\bar{2}$	·54255	2$\bar{7}$	·72883	4$\bar{2}$	22
23	·5261$\bar{5}$	28	·70389	4$\bar{2}$	·54283	27	·7292$\bar{5}$	42	23
24	·5264$\bar{3}$	28	·7043$\bar{1}$	4$\bar{2}$	·5431$\bar{0}$	2$\bar{7}$	·7296$\bar{7}$	4$\bar{2}$	24
25	9·5267$\bar{1}$	28	9·70474	4$\bar{2}$	9·54338	2$\bar{7}$	9·73010	42	25
26	·5269$\bar{9}$	2$\bar{8}$	·7051$\bar{6}$	4$\bar{2}$	·5436$\bar{5}$	2$\bar{7}$	·73052	4$\bar{2}$	26
27	·5272$\bar{7}$	2$\bar{8}$	·7055$\bar{8}$	4$\bar{2}$	·54393	2$\bar{7}$	·73094	4$\bar{2}$	27
28	·52756	28	·70601	42	·5442$\bar{0}$	27	·7313$\bar{6}$	42	28
29	·52784	28	·70643	4$\bar{2}$	·54448	2$\bar{7}$	·7317$\bar{8}$	4$\bar{2}$	29
30	9·52812	28	9·7068$\bar{5}$	4$\bar{2}$	9·5447$\bar{5}$	2$\bar{7}$	9·73221	42	30
31	·52840	28	·70728	4$\bar{2}$	·5450$\bar{2}$	2$\bar{7}$	·73263	4$\bar{2}$	31
32	·52868	28	·70770	4$\bar{2}$	·54530	2$\bar{7}$	·73305	4$\bar{2}$	32
33	·52896	28	·7081$\bar{2}$	42	·5455$\bar{7}$	27	·7334$\bar{7}$	42	33
34	·52924	28	·70854	4$\bar{2}$	·54585	2$\bar{7}$	·7338$\bar{9}$	4$\bar{2}$	34
35	9·52952	28	9·70897	4$\bar{2}$	9·5461$\bar{2}$	2$\bar{7}$	9·7343$\bar{1}$	4$\bar{2}$	35
36	·52980	28	·7093$\bar{9}$	4$\bar{2}$	·5463$\bar{9}$	2$\bar{7}$	·73474	4$\bar{2}$	36
37	·53008	28	·7098$\bar{1}$	4$\bar{2}$	·54667	2$\bar{7}$	·7351$\bar{6}$	4$\bar{2}$	37
38	·53036	28	·71024	4$\bar{2}$	·5469$\bar{4}$	27	·7355$\bar{8}$	42	38
39	·53064	28	·71066	4$\bar{2}$	·5472$\bar{1}$	2$\bar{7}$	·7360$\bar{0}$	4$\bar{2}$	39
40	9·53092	28	9·71108	4$\bar{2}$	9·5474$\bar{8}$	2$\bar{7}$	9·7364$\bar{2}$	4$\bar{2}$	40
41	·53120	27	·71151	4$\bar{2}$	·54776	2$\bar{7}$	·73685	42	41
42	·5314$\bar{7}$	28	·71193	4$\bar{2}$	·5480$\bar{3}$	2$\bar{7}$	·73727	4$\bar{2}$	42
43	·5317$\bar{5}$	28	·71235	4$\bar{2}$	·5483$\bar{0}$	27	·73769	4$\bar{2}$	43
44	·5320$\bar{3}$	28	·71278	4$\bar{2}$	·54858	2$\bar{7}$	·7381$\bar{1}$	42	44
45	9·5323$\bar{1}$	27	9·71320	4$\bar{2}$	9·54885	2$\bar{7}$	9·7385$\bar{3}$	4$\bar{2}$	45
46	·53259	28	·7136$\bar{2}$	4$\bar{2}$	·5491$\bar{2}$	2$\bar{7}$	·7389$\bar{5}$	4$\bar{2}$	46
47	·53287	28	·71404	4$\bar{2}$	·5493$\bar{9}$	2$\bar{7}$	·73938	42	47
48	·53315	28	·71447	42	·54967	27	·73980	42	48
49	·53343	27	·71489	4$\bar{2}$	·54994	2$\bar{7}$	·74022	4$\bar{2}$	49
50	9·5337$\bar{0}$	28	9·7153$\bar{1}$	4$\bar{2}$	9·5502$\bar{1}$	2$\bar{7}$	9·7406$\bar{4}$	42	50
51	·5339$\bar{8}$	28	·7157$\bar{3}$	4$\bar{2}$	·5504$\bar{8}$	27	·7410$\bar{6}$	4$\bar{2}$	51
52	·5342$\bar{6}$	27	·71616	4$\bar{2}$	·5507$\bar{5}$	2$\bar{7}$	·7414$\bar{8}$	4$\bar{2}$	52
53	·53454	28	·7165$\bar{8}$	42	·55103	27	·74191	42	53
54	·53482	27	·7170$\bar{0}$	4$\bar{2}$	·55130	2$\bar{7}$	·74233	4$\bar{2}$	54
55	9·5350$\bar{9}$	28	9·71743	4$\bar{2}$	9·55157	2$\bar{7}$	9·7427$\bar{5}$	4$\bar{2}$	55
56	·5353$\bar{7}$	27	·71785	4$\bar{2}$	·55184	27	·7431$\bar{7}$	42	56
57	·53565	28	·7182$\bar{7}$	4$\bar{2}$	·5521$\bar{1}$	27	·7435$\bar{9}$	4$\bar{2}$	57
58	·53593	27	·71869	42	·5523$\bar{8}$	27	·7440$\bar{1}$	4$\bar{2}$	58
59	·5362$\bar{0}$	28	·71912	4$\bar{2}$	·55265	27	·74444	42	59
60	9·5364$\bar{8}$		9·71954		9·5529$\bar{2}$		9·74486		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	4$\bar{2}$	42
6	4·$\bar{2}$	4·2
7	4·$\bar{9}$	4·9
8	5·$\bar{6}$	5·6
9	6·4	6·3
10	7·$\bar{1}$	7·0
20	14·$\bar{1}$	14·0
30	21·$\bar{2}$	21·0
40	28·$\bar{3}$	28·0
50	35·4	35·0

	2$\bar{8}$	28
6	2·$\bar{8}$	2·8
7	3·3	3·$\bar{2}$
8	3·8	3·$\bar{7}$
9	4·$\bar{3}$	4·$\bar{2}$
10	4·$\bar{7}$	4·$\bar{6}$
20	9·5	9·$\bar{3}$
30	14·$\bar{2}$	14·0
40	19·0	18·$\bar{6}$
50	23·$\bar{7}$	23·3

	2$\bar{7}$	27
6	2·$\bar{7}$	2·$\bar{7}$
7	3·$\bar{2}$	3·$\bar{1}$
8	3·$\bar{6}$	3·$\bar{6}$
9	4·1	4·$\bar{0}$
10	4·$\bar{6}$	4·$\bar{5}$
20	9·$\bar{1}$	9·0
30	13·$\bar{7}$	13·5
40	18·$\bar{3}$	18·0
50	22·9	22·5

P. P.

′	50° Lg. Vers.	D	50° Log. Exs.	D	51° Lg. Vers.	D	51° Log. Exs	D	′
0	9.55292	27	9.74486	42	9.56900	26	9.77012	42	0
1	.55319	27	.74528	42	.56926	26	.77055	42	1
2	.55347	27	.74570	42	.56953	26	.77097	42	2
3	.55374	27	.74612	42	.56979	26	.77139	42	3
4	.55401	27	.74654	42	.57005	26	.77181	42	4
5	9.55428	27	9.74696	42	9.57032	26	9.77223	42	5
6	.55455	27	.74739	42	.57058	26	.77265	42	6
7	.55482	27	.74781	42	.57085	26	.77307	42	7
8	.55509	27	.74823	42	.57111	26	.77349	42	8
9	.55536	27	.74865	42	.57138	26	.77391	42	9
10	9.55563	27	9.74907	42	9.57164	26	9.77433	42	10
11	.55590	27	.74949	42	.57190	26	.77475	42	11
12	.55617	27	.74991	42	.57217	26	.77517	42	12
13	.55644	27	.75033	42	.57243	26	.77560	42	13
14	.55671	27	.75076	42	.57269	26	.77602	42	14
15	9.55698	27	9.75118	42	9.57296	26	9.77644	42	15
16	.55725	26	.75160	42	.57322	26	.77686	42	16
17	.55751	27	.75202	42	.57348	26	.77728	42	17
18	.55778	27	.75244	42	.57375	26	.77770	42	18
19	.55805	27	.75286	42	.57401	26	.77812	42	19
20	9.55832	27	9.75328	42	9.57427	26	9.77854	42	20
21	.55859	26	.75370	42	.57454	26	.77896	42	21
22	.55886	27	.75413	42	.57480	26	.77938	42	22
23	.55913	27	.75455	42	.57506	26	.77980	42	23
24	.55940	26	.75497	42	.57532	26	.78022	42	24
25	9.55966	27	9.75539	42	9.57559	26	9.78064	42	25
26	.55993	27	.75581	42	.57585	26	.78107	42	26
27	.56020	26	.75623	42	.57611	26	.78149	42	27
28	.56047	27	.75665	42	.57637	26	.78191	42	28
29	.56074	27	.75707	42	.57664	26	.78233	42	29
30	9.56101	26	9.75750	42	9.57690	26	9.78275	42	30
31	.56127	27	.75792	42	.57716	26	.78317	42	31
32	.56154	26	.75834	42	.57742	26	.78359	42	32
33	.56181	27	.75876	42	.57768	26	.78401	42	33
34	.56208	26	.75918	42	.57794	26	.78443	42	34
35	9.56234	27	9.75960	42	9.57821	26	9.78485	42	35
36	.56261	26	.76002	42	.57847	26	.78527	42	36
37	.56288	27	.76044	42	.57873	26	.78569	42	37
38	.56315	26	.76086	42	.57899	26	.78611	42	38
39	.56341	26	.76128	42	.57925	26	.78653	42	39
40	9.56368	27	9.76171	42	9.57951	26	9.78696	42	40
41	.56395	26	.76213	42	.57977	26	.78738	42	41
42	.56421	26	.76255	42	.58003	26	.78780	42	42
43	.56448	27	.76297	42	.58029	26	.78822	42	43
44	.56475	26	.76339	42	.58055	26	.78864	42	44
45	9.56501	26	9.76381	42	9.58082	26	9.78906	42	45
46	.56528	26	.76423	42	.58108	26	.78948	42	46
47	.56554	27	.76465	42	.58134	26	.78990	42	47
48	.56581	26	.76507	42	.58160	26	.79032	42	48
49	.56608	26	.76549	42	.58186	26	.79074	42	49
50	9.56634	26	9.76592	42	9.58212	26	9.79116	42	50
51	.56661	26	.76634	42	.58238	26	.79158	42	51
52	.56687	26	.76676	42	.58264	26	.79200	42	52
53	.56714	27	.76718	42	.58290	26	.79242	42	53
54	.56741	26	.76760	42	.58316	26	.79285	42	54
55	9.56767	26	9.76802	42	9.58342	25	9.79327	42	55
56	.56794	26	.76844	42	.58367	26	.79369	42	56
57	.56820	26	.76886	42	.58393	26	.79411	42	57
58	.56847	26	.76928	42	.58419	26	.79453	42	58
59	.56873	26	.76970	42	.58445	26	.79495	42	59
60	9.56900		9.77012		9.58471		9.79537		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	$\bar{42}$	42
6	4.2	4.2
7	4.9	4.9
8	5.6	5.6
9	6.4	6.3
10	7.1	7.0
20	14.1	14.0
30	21.2	21.0
40	28.3	28.0
50	35.4	35.0

	$\bar{27}$	27
6	2.7	2.7
7	3.2	3.1
8	3.6	3.6
9	4.1	4.0
10	4.6	4.5
20	9.1	9.0
30	13.7	13.5
40	18.3	18.0
50	22.9	22.5

	$\bar{26}$	26
6	2.6	2.6
7	3.1	3.0
8	3.5	3.4
9	4.0	3.9
10	4.4	4.3
20	8.8	8.6
30	13.2	13.0
40	17.6	17.3
50	22.1	21.6

	$\bar{25}$
6	2.5
7	3.0
8	3.4
9	3.8
10	4.2
20	8.5
30	12.7
40	17.0
50	21.2

P. P.

′	52° Lg. Vers.	D	52° Log.Exs.	D	53° Lg. Vers.	D	53° Log.Exs.	D	′
0	9.58471	26	9.79537	42	9.60008	25	9.82062	42	0
1	.58497	25	.79579	42	.60034	25	.82104	42	1
2	.58523	26	.79621	42	.60059	25	.82146	42	2
3	.58549	26	.79663	42	.60084	25	.82188	42	3
4	.58575	26	.79705	42	.60110	25	.82230	42	4
5	9.58601	25	9.79747	42	9.60135	25	9.82272	42	5
6	.58626	26	.79789	42	.60160	25	.82315	42	6
7	.58652	26	.79831	42	.60185	25	.82357	42	7
8	.58678	25	.79874	42	.60211	25	.82399	42	8
9	.58704	26	.79916	42	.60236	25	.82441	42	9
10	9.58730	25	9.79958	42	9.60261	25	9.82483	42	10
11	.58755	26	.80000	42	.60286	25	.82525	42	11
12	.58781	26	.80042	42	.60312	25	.82567	42	12
13	.58807	25	.80084	42	.60337	25	.82609	42	13
14	.58833	26	.80126	42	.60362	25	.82651	42	14
15	9.58859	25	9.80168	42	9.60387	25	9.82694	42	15
16	.58884	26	.80210	42	.60412	25	.82736	42	16
17	.58910	25	.80252	42	.60438	25	.82778	42	17
18	.58936	26	.80294	42	.60463	25	.82820	42	18
19	.58962	25	.80336	42	.60488	25	.82862	42	19
20	9.58987	25	9.80378	42	9.60513	25	9.82904	42	20
21	.59013	26	.80420	42	.60538	25	.82946	42	21
22	.59039	25	.80463	42	.60563	25	.82988	42	22
23	.59064	26	.80505	42	.60589	25	.83031	42	23
24	.59090	25	.80547	42	.60614	25	.83073	42	24
25	9.59116	25	9.80589	42	9.60639	25	9.83115	42	25
26	.59141	26	.80631	42	.60664	25	.83157	42	26
27	.59167	25	.80673	42	.60689	25	.83199	42	27
28	.59193	25	.80715	42	.60714	25	.83241	42	28
29	.59218	25	.80757	42	.60739	25	.83283	42	29
30	9.59244	26	9.80799	42	9.60764	25	9.83325	42	30
31	.59270	25	.80841	42	.60789	25	.83368	42	31
32	.59295	25	.80883	42	.60814	25	.83410	42	32
33	.59321	25	.80925	42	.60839	25	.83452	42	33
34	.59346	25	.80968	42	.60864	25	.83494	42	34
35	9.59372	25	9.81010	42	9.60889	25	9.83536	42	35
36	.59397	26	.81052	42	.60914	25	.83578	42	36
37	.59423	25	.81094	42	.60939	25	.83620	42	37
38	.59449	25	.81136	42	.60964	25	.83663	42	38
39	.59474	25	.81178	42	.60989	25	.83705	42	39
40	9.59500	25	9.81220	42	9.61014	25	9.83747	42	40
41	.59525	25	.81262	42	.61039	25	.83789	42	41
42	.59551	25	.81304	42	.61064	25	.83831	42	42
43	.59576	25	.81346	42	.61089	25	.83873	42	43
44	.59602	25	.81388	42	.61114	25	.83916	42	44
45	9.59627	25	9.81430	42	9.61139	25	9.83958	42	45
46	.59653	25	.81473	42	.61164	25	.84000	42	46
47	.59678	25	.81515	42	.61189	24	.84042	42	47
48	.59704	25	.81557	42	.61214	25	.84084	42	48
49	.59729	25	.81599	42	.61239	25	.84126	42	49
50	9.59754	25	9.81641	42	9.61264	25	9.84168	42	50
51	.59780	25	.81683	42	.61289	24	.84211	42	51
52	.59805	25	.81725	42	.61313	25	.84253	42	52
53	.59831	25	.81767	42	.61338	25	.84295	42	53
54	.59856	25	.81809	42	.61363	25	.84337	42	54
55	9.59881	25	9.81851	42	9.61388	24	9.84379	42	55
56	.59907	25	.81894	42	.61413	25	.84422	42	56
57	.59932	25	.81936	42	.61438	24	.84464	42	57
58	.59958	25	.81978	42	.61462	25	.84506	42	58
59	.59983	25	.82020	42	.61487	25	.84548	42	59
60	9.60008		9.82062		9.61512		9.84590		60
′	Lg. Vers.	D	Log.Exs.	D	Lg. Vers.	D	Log.Exs.	D	′

P. P.

	42̄	42
6	4.2	4.2
7	4.9	4.9
8	5.6	5.6
9	6.4	6.3
10	7.1	7.0
20	14.1	14.0
30	21.2	21.0
40	28.3	28.0
50	35.4	35.0

	26	25̄
6	2.6	2.5
7	3.0	3.0
8	3.4	3.4
9	3.9	[illegible]
10	4.3	4.2
20	8.6	8.5
30	13.0	12.7
40	17.3	17.0
50	21.6	21.2

	25	24̄
6	2.5	2.4
7	2.9	2.8
8	3.3	3.2
9	3.7	3.7
10	4.1	4.1
20	8.3	8.1
30	12.5	12.2
40	16.6	16.3
50	20.8	20.4

P. P.

	54°				55°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.61512	24	9.84590	42	9.62984	24	9.87125	42	0
1	.61537	25	.84632	42	.63008	24	.87167	42	1
2	.61562	24	.84675	42	.63032	24	.87209	42	2
3	.61586	25	.84717	42	.63057	24	.87252	42	3
4	.61611	24	.84759	42	.63081	24	.87294	42	4
5	9.61636	25	9.84801	42	9.63105	24	9.87336	42	5
6	.61661	24	.84843	42	.63129	24	.87379	42	6
7	.61685	25	.84886	42	.63154	24	.87421	42	7
8	.61710	24	.84928	42	.63178	24	.87463	42	8
9	.61735	25	.84970	42	.63202	24	.87506	42	9
10	9.61760	24	9.85012	42	9.63226	24	9.87548	42	10
11	.61784	24	.85054	42	.63250	24	.87590	42	11
12	.61809	25	.85097	42	.63274	24	.87633	42	12
13	.61834	24	.85139	42	.63209	24	.87675	42	13
14	.61858	25	.85181	42	.63323	24	.87717	42	14
15	9.61883	24	9.85223	42	9.63347	24	9.87760	42	15
16	.61908	24	.85265	42	.63371	24	.87802	42	16
17	.61932	24	.85308	42	.63395	24	.87844	42	17
18	.61957	25	.85350	42	.63419	24	.87887	42	18
19	.61982	24	.85392	42	.63443	24	.87929	42	19
20	9.62006	24	9.85434	42	9.63468	24	9.87971	42	20
21	.62031	24	.85476	42	.63492	24	.88014	42	21
22	.62055	25	.85519	42	.63516	24	.88056	42	22
23	.62080	24	.85561	42	.63540	24	.88099	42	23
24	.62105	24	.85603	42	.63564	24	.88141	42	24
25	9.62129	24	9.85645	42	9.63588	24	9.88183	42	25
26	.62154	24	.85688	42	.63612	24	.88226	42	26
27	.62178	24	.85730	42	.63636	24	.88268	42	27
28	.62203	24	.85772	42	.63660	24	.88310	42	28
29	.62227	24	.85814	42	.63684	24	.88353	42	29
30	9.62252	24	9.85857	42	9.63708	24	9.88395	42	30
31	.62276	24	.85899	42	.63732	24	.88438	42	31
32	.62301	24	.85941	42	.63756	24	.88480	42	32
33	.62325	24	.85983	42	.63780	24	.88522	42	33
34	.62350	24	.86026	42	.63804	24	.88565	42	34
35	9.62374	24	9.86068	42	9.63828	24	9.88607	42	35
36	.62399	24	.86110	42	.63852	24	.88650	42	36
37	.62423	24	.86152	42	.63876	24	.88692	42	37
38	.62448	24	.86195	42	.63900	24	.88734	42	38
39	.62472	24	.86237	42	.63924	24	.88777	42	39
40	9.62497	24	9.86279	42	9.63948	24	9.88819	42	40
41	.62521	24	.86321	42	.63972	24	.88862	42	41
42	.62546	24	.86364	42	.63996	23	.88904	42	42
43	.62570	24	.86406	42	.64019	24	.88947	42	43
44	.62594	24	.86448	42	.64043	24	.88989	42	44
45	9.62619	24	9.86490	42	9.64067	24	9.89031	42	45
46	.62643	24	.86533	42	.64091	24	.89074	42	46
47	.62668	24	.86575	42	.64115	23	.89116	42	47
48	.62692	24	.86617	42	.64139	24	.89159	42	48
49	.62716	24	.86659	42	.64163	24	.89201	42	49
50	9.62741	24	9.86702	42	9.64187	23	9.89244	42	50
51	.62765	24	.86744	42	.64210	24	.89286	42	51
52	.62789	24	.86786	42	.64234	24	.89329	42	52
53	.62814	24	.86829	42	.64258	23	.89371	42	53
54	.62838	24	.86871	42	.64282	24	.89414	42	54
55	9.62862	24	9.86913	42	9.64306	24	9.89456	42	55
56	.62887	24	.86956	42	.64330	23	.89499	42	56
57	.62911	24	.86998	42	.64353	24	.89541	42	57
58	.62935	24	.87040	42	.64377	23	.89583	42	58
59	.62960	24	.87082	42	.64401	24	.89626	42	59
60	9.62984		9.87125		9.64425		9.89668		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	42	42
6	4.2	4.2
7	4.9	4.9
8	5.6	5.6
9	6.4	6.3
10	7.1	7.0
20	14.1	14.0
30	21.2	21.0
40	28.3	28.0
50	35.4	35.0

	25	24
6	2.5	2.4
7	2.9	2.8
8	3.3	3.2
9	3.7	3.7
10	4.1	4.1
20	8.3	8.1
30	12.5	12.2
40	16.6	16.3
50	20.8	20.4

	24	23
6	2.4	2.3
7	2.8	2.7
8	3.2	3.1
9	3.6	3.5
10	4.0	3.9
20	8.0	7.8
30	12.0	11.7
40	16.0	15.6
50	20.0	19.6

P. P.

′	56° Lg. Vers.	D	56° Log. Exs.	D	57° Lg. Vers.	D	57° Log. Exs.	D	′
0	9.64425	23	9.89668	42	9.65835	23	9.92224	43	0
1	.64448	24	.89711	42	.65859	23	.92267	42	1
2	.64472	23	.89753	42	.65882	23	.92310	43	2
3	.64496	24	.89796	42	.65905	23	.92353	42	3
4	.64520	23	.89838	42	.65928	23	.92395	43	4
5	9.64543	24	9.89881	42	9.65952	23	9.92438	42	5
6	.64567	23	.89923	42	.65975	23	.92481	43	6
7	.64591	23	.89966	42	.65998	23	.92524	42	7
8	.64614	24	.90008	42	.66021	23	.92566	43	8
9	.64638	23	.90051	43	.66044	23	.92609	42	9
10	9.64662	23	9.90094	42	9.66068	23	9.92652	43	10
11	.64685	24	.90136	42	.66091	23	.92695	42	11
12	.64709	23	.90179	42	.66114	23	.92737	43	12
13	.64733	23	.90221	42	.66137	23	.92780	42	13
14	.64756	24	.90264	42	.66160	23	.92823	43	14
15	9.64780	23	9.90306	42	9.66183	23	9.92866	43	15
16	.64804	23	.90349	42	.66207	23	.92909	42	16
17	.64827	23	.90391	42	.66230	23	.92951	43	17
18	.64851	24	.90434	42	.66253	23	.92994	42	18
19	.64875	23	.90476	42	.66276	23	.93037	43	19
20	9.64898	23	9.90519	42	9.66299	23	9.93080	43	20
21	.64922	23	.90561	43	.66322	23	.93123	42	21
22	.64945	23	.90604	42	.66345	23	.93165	43	22
23	.64969	23	.90647	42	.66368	23	.93208	43	23
24	.64992	24	.90689	42	.66391	23	.93251	42	24
25	9.65016	23	9.90732	42	9.66415	23	9.93294	43	25
26	.65040	23	.90774	42	.66438	23	.93337	43	26
27	.65063	23	.90817	43	.66461	23	.93380	42	27
28	.65087	23	.90860	42	.66484	23	.93422	43	28
29	.65110	23	.90902	42	.66507	23	.93465	43	29
30	9.65134	23	9.90945	42	9.66530	23	9.93508	42	30
31	.65157	23	.90987	42	.66553	23	.93551	43	31
32	.65181	23	.91030	43	.66576	23	.93594	43	32
33	.65204	23	.91073	42	.66599	23	.93637	43	33
34	.65228	23	.91115	42	.66622	23	.93680	42	34
35	9.65251	23	9.91158	42	9.66645	23	9.93722	43	35
36	.65275	23	.91200	42	.66668	23	.93765	43	36
37	.65298	23	.91243	43	.66691	23	.93808	43	37
38	.65321	23	.91286	42	.66714	23	.93851	42	38
39	.65345	23	.91328	42	.66737	23	.93894	43	39
40	9.65368	23	9.91371	43	9.66760	23	9.93937	43	40
41	.65392	23	.91414	42	.66783	23	.93980	43	41
42	.65415	23	.91456	42	.66805	23	.94023	43	42
43	.65439	23	.91499	42	.66828	23	.94066	43	43
44	.65462	23	.91541	43	.66851	23	.94109	42	44
45	9.65485	23	9.91584	42	9.66874	23	9.94151	43	45
46	.65509	23	.91627	42	.66897	23	.94194	43	46
47	.65532	23	.91669	43	.66920	22	.94237	43	47
48	.65556	23	.91712	42	.66943	23	.94280	43	48
49	.65579	23	.91755	42	.66966	23	.94323	43	49
50	9.65602	23	9.91797	43	9.66989	23	9.94366	43	50
51	.65626	23	.91840	42	.67012	22	.94409	43	51
52	.65649	23	.91883	43	.67034	23	.94452	43	52
53	.65672	23	.91926	42	.67057	23	.94495	43	53
54	.65696	23	.91968	42	.67080	22	.94538	43	54
55	9.65719	23	9.92011	43	9.67103	23	9.94581	43	55
56	.65742	23	.92054	42	.67126	23	.94624	43	56
57	.65765	23	.92096	43	.67149	22	.94667	43	57
58	.65789	23	.92139	42	.67171	23	.94710	43	58
59	.65812	23	.92182	42	.67194	22	.94753	43	59
60	9.65835		9.92224		9.67217		9.94796		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	43	42
6	4.3	4.2
7	5.0	4.9
8	5.7	5.6
9	6.4	6.4
10	7.1	7.1
20	14.3	14.1
30	21.5	21.2
40	28.6	28.3
50	35.8	35.4

	24	23
6	2.4	2.3
7	2.8	2.7
8	3.2	3.1
9	3.6	3.5
10	4.0	3.9
20	8.0	7.8
30	12.0	11.7
40	16.0	15.6
50	20.0	19.6

	23	22
6	2.3	2.2
7	2.7	2.6
8	3.0	3.0
9	3.4	3.4
10	3.8	3.7
20	7.6	7.5
30	11.5	11.2
40	15.3	15.0
50	19.1	18.7

P. P.

′	58° Lg. Vers.	D	58° Log. Exs.	D	59° Lg. Vers.	D	59° Log. Exs.	D	′
0	9.67217	23	9.94796	43	9.68571	22	9.97387	43	0
1	.67240	23	.94839	43	.68593	22	.97430	43	1
2	.67263	22	.94882	43	.68615	22	.97473	43	2
3	.67285	23	.94925	43	.68637	22	.97517	43	3
4	.67308	22	.94968	43	.68660	22	.97560	43	4
5	9.67331	23	9.95011	43	9.68682	22	9.97603	43	5
6	.67354	22	.95054	43	.68704	22	.97647	43	6
7	.67376	23	.95097	43	.68727	22	.97690	43	7
8	.67399	22	.95140	43	.68749	22	.97734	43	8
9	.67422	23	.95183	43	.68771	22	.97777	43	9
10	9.67445	22	9.95226	43	9.68793	22	9.97820	43	10
11	.67467	22	.95269	43	.68816	22	.97864	43	11
12	.67490	23	.95313	43	.68838	22	.97907	43	12
13	.67513	22	.95356	43	.68860	22	.97951	43	13
14	.67535	22	.95399	43	.68882	22	.97994	43	14
15	9.67558	23	9.95442	43	9.68905	22	9.98038	43	15
16	.67581	22	.95485	43	.68927	22	.98081	43	16
17	.67603	22	.95528	43	.68949	22	.98125	43	17
18	.67626	23	.95571	43	.68971	22	.98168	43	18
19	.67649	22	.95614	43	.68993	22	.98211	43	19
20	9.67671	22	9.95657	43	9.69016	22	9.98255	43	20
21	.67694	23	.95700	43	.69038	22	.98298	43	21
22	.67717	22	.95744	43	.69060	22	.98342	43	22
23	.67739	22	.95787	43	.69082	22	.98385	43	23
24	.67762	22	.95830	43	.69104	22	.98429	43	24
25	9.67784	22	9.95873	43	9.69126	22	9.98472	43	25
26	.67807	23	.95916	43	.69149	22	.98516	43	26
27	.67830	22	.95959	43	.69171	22	.98559	44	27
28	.67852	22	.96002	43	.69193	22	.98603	43	28
29	.67875	22	.96046	43	.69215	22	.98647	43	29
30	9.67897	22	9.96089	43	9.69237	22	9.98690	43	30
31	.67920	22	.96132	43	.69259	22	.98734	43	31
32	.67942	22	.96175	43	.69281	22	.98777	43	32
33	.67965	22	.96218	43	.69303	22	.98821	43	33
34	.67987	22	.96261	43	.69325	22	.98864	43	34
35	9.68010	22	9.96305	43	9.69347	22	9.98908	44	35
36	.68032	22	.96348	43	.69369	22	.98952	43	36
37	.68055	22	.96391	43	.69392	22	.98995	43	37
38	.68077	22	.96434	43	.69414	22	.99039	43	38
39	.68100	22	.96478	43	.69436	22	.99082	43	39
40	9.68122	22	9.96521	43	9.69458	22	9.99126	44	40
41	.68145	22	.96564	43	.69480	22	.99170	43	41
42	.68167	22	.96607	43	.69502	22	.99213	43	42
43	.68190	22	.96650	43	.69524	22	.99257	43	43
44	.68212	22	.96694	43	.69546	22	.99300	44	44
45	9.68235	22	9.96737	43	9.69568	22	9.99344	43	45
46	.68257	22	.96780	43	.69590	22	.99388	43	46
47	.68280	22	.96824	43	.69612	22	.99431	44	47
48	.68302	22	.96867	43	.69634	22	.99475	43	48
49	.68324	22	.96910	43	.69656	22	.99519	43	49
50	9.68347	22	9.96953	43	9.69673	22	9.99562	44	50
51	.68369	22	.96997	43	.69700	21	.99606	43	51
52	.68392	22	.97040	43	.69721	22	.99650	44	52
53	.68414	22	.97083	43	.69743	22	.99694	43	53
54	.68436	22	.97127	43	.69765	22	.99737	44	54
55	9.68459	22	9.97170	43	9.69787	22	9.99781	43	55
56	.68481	22	.97213	43	.69809	22	.99825	43	56
57	.68503	22	.97257	43	.69831	21	.99868	44	57
58	.68526	22	.97300	43	.69853	22	.99912	43	58
59	.68548	22	.97343	43	.69875	22	9.99956	44	59
60	9.68571		9.97387		.69897		10.00000		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	44	43
6	4.4	4.3
7	5.1	5.1
8	5.8	5.8
9	6.6	6.5
10	7.3	7.2
20	14.6	14.5
30	22.0	21.7
40	29.3	29.0
50	36.6	36.2

	43
6	4.3
7	5.0
8	5.7
9	6.4
10	7.1
20	14.3
30	21.5
40	28.6
50	35.8

	23	22
6	2.3	2.2
7	2.7	2.6
8	3.0	3.0
9	3.4	3.4
10	3.8	3.7
20	7.6	7.5
30	11.5	11.2
40	15.3	15.0
50	19.1	18.7

	22	21
6	2.2	2.1
7	2.5	2.5
8	2.9	2.8
9	3.3	3.2
10	3.6	3.6
20	7.3	7.1
30	11.0	10.7
40	14.6	14.3
50	18.3	17.9

P. P.

'	60° Lg. Vers.	D	60° Log. Exs.	D	61° Lg. Vers.	D	61° Log. Exs.	D	'
0	9.69897	22	10.00000	44	9.71197	21	10.02639	44	0
1	.69919	21	.00044	43	.71218	21	.02684	44	1
2	.69940	22	.00087	44	.71239	21	.02728	44	2
3	.69962	22	.00131	43	.71261	21	.02772	44	3
4	.69984	22	.00175	44	.71282	21	.02816	44	4
5	9.70006	21	10.00219	43	9.71304	21	10.02861	44	5
6	.70028	22	.00262	44	.71325	21	.02905	44	6
7	.70050	22	.00306	44	.71346	21	.02949	44	7
8	.70072	21	.00350	43	.71368	21	.02994	44	8
9	.70093	22	.00394	44	.71389	21	.03038	44	9
10	9.70115	21	10.00438	44	9.71411	21	10.03082	44	10
11	.70137	22	.00482	43	.71432	21	.03127	44	11
12	.70159	22	.00525	44	.71453	21	.03171	44	12
13	.70181	21	.00569	44	.71475	21	.03215	44	13
14	.70202	22	.00613	44	.71496	21	.03260	44	14
15	9.70224	21	10.00657	43	9.71517	21	10.03304	44	15
16	.70246	22	.00701	44	.71539	21	.03348	44	16
17	.70268	21	.00745	44	.71560	21	.03393	44	17
18	.70289	22	.00789	44	.71581	21	.03437	44	18
19	.70311	21	.00833	43	.71603	21	.03481	44	19
20	9.70333	22	10.00876	44	9.71624	21	10.03526	44	20
21	.70355	21	.00920	44	.71645	21	.03570	44	21
22	.70376	22	.00964	44	.71667	21	.03615	44	22
23	.70398	21	.01008	44	.71688	21	.03659	44	23
24	.70420	21	.01052	44	.71709	21	.03704	44	24
25	9.70441	22	10.01096	44	9.71730	21	10.03748	44	25
26	.70463	21	.01140	44	.71752	21	.03793	44	26
27	.70485	22	.01184	44	.71773	21	.03837	44	27
28	.70507	21	.01228	44	.71794	21	.03881	44	28
29	.70528	21	.01272	44	.71815	21	.03926	44	29
30	9.70550	22	10.01316	44	9.71837	21	10.03970	44	30
31	.70572	21	.01360	44	.71858	21	.04015	44	31
32	.70593	21	.01404	44	.71879	21	.04059	44	32
33	.70615	21	.01448	44	.71900	21	.04104	45	33
34	.70636	22	.01492	44	.71922	21	.04149	44	34
35	9.70658	21	10.01536	44	9.71943	21	10.04193	44	35
36	.70680	21	.01580	44	.71964	21	.04238	44	36
37	.70701	21	.01624	44	.71985	21	.04282	44	37
38	.70723	22	.01668	44	.72006	21	.04327	44	38
39	.70745	21	.01712	44	.72028	21	.04371	44	39
40	9.70766	21	10.01756	44	9.72049	21	10.04416	45	40
41	.70788	21	.01800	44	.72070	21	.04461	44	41
42	.70809	21	.01844	44	.72091	21	.04505	44	42
43	.70831	21	.01889	44	.72112	21	.04550	44	43
44	.70852	22	.01933	44	.72133	21	.04594	45	44
45	9.70874	21	10.01977	44	9.72154	21	10.04639	44	45
46	.70896	21	.02021	44	.72176	21	.04684	44	46
47	.70917	21	.02065	44	.72197	21	.04728	44	47
48	.70939	21	.02109	44	.72218	21	.04773	45	48
49	.70960	21	.02153	44	.72239	21	.04818	44	49
50	9.70982	21	10.02197	44	9.72260	21	10.04862	45	50
51	.71003	21	.02242	44	.72281	21	.04907	44	51
52	.71025	21	.02286	44	.72302	21	.04952	44	52
53	.71046	21	.02330	44	.72323	21	.04996	45	53
54	.71068	21	.02374	44	.72344	21	.05041	44	54
55	9.71089	21	10.02418	44	9.72365	21	10.05086	45	55
56	.71111	21	.02463	44	.72386	21	.05131	44	56
57	.71132	21	.02507	44	.72408	21	.05175	45	57
58	.71154	21	.02551	44	.72429	21	.05220	44	58
59	.71175	21	.02595	44	.72450	21	.05265	45	59
60	9.71197		10.02639		9.72471		10.05310		60
'	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	'

P. P.

	45	44
6	4.5	4.4
7	5.2	5.2
8	6.0	5.9
9	6.7	6.7
10	7.5	7.4
20	15.0	14.8
30	22.5	22.2
40	30.0	29.6
50	37.5	37.1

	44	43
6	4.4	4.3
7	5.1	5.1
8	5.8	5.8
9	6.6	6.5
10	7.3	7.2
20	14.6	14.5
30	22.0	21.7
40	29.3	29.0
50	36.6	36.2

	22	21
6	2.2	2.1
7	2.5	2.5
8	2.9	2.8
9	3.3	3.2
10	3.6	3.6
20	7.3	7.1
30	11.0	10.7
40	14.6	14.3
50	18.3	17.9

	21
6	2.1
7	2.4
8	2.8
9	3.1
10	3.5
20	7.0
30	10.5
40	14.0
50	17.5

P. P.

′	62° Lg. Vers.	D	62° Log. Exs.	D	63° Lg. Vers.	D	63° Log. Exs.	D	′
0	9.72471	21	10.05310	44	9.73720	20	10.08015	45	0
1	.72492	21	.05354	45	.73740	20	.08061	45	1
2	.72513	21	.05399	45	.73761	21	.08106	45	2
3	.72534	21	.05444	44	.73782	20	.08151	45	3
4	.72555	21	.05489	45	.73802	20	.08197	45	4
5	9.72576	21	10.05534	45	9.73823	20	10.08242	45	5
6	.72597	21	.05579	44	.73843	20	.08288	45	6
7	.72618	21	.05623	45	.73864	20	.08333	45	7
8	.72639	21	.05668	45	.73884	21	.08379	45	8
9	.72660	21	.05713	45	.73905	20	.08424	45	9
10	9.72681	20	10.05758	44	9.73926	20	10.08470	45	10
11	.72701	21	.05803	45	.73946	20	.08515	45	11
12	.72722	21	.05848	45	.73967	20	.08561	45	12
13	.72743	21	.05893	45	.73987	20	.08606	45	13
14	.72764	21	.05938	45	.74008	20	.08652	45	14
15	9.72785	21	10.05983	45	9.74028	20	10.08697	46	15
16	.72806	21	.06028	44	.74049	20	.08743	45	16
17	.72827	20	.06072	45	.74069	20	.08789	45	17
18	.72848	21	.06117	45	.74090	20	.08834	45	18
19	.72869	21	.06162	45	.74110	20	.08880	46	19
20	9.72890	21	10.06207	45	9.74131	20	10.08926	45	20
21	.72911	20	.06252	45	.74151	20	.08971	45	21
22	.72931	21	.06297	45	.74172	20	.09017	45	22
23	.72952	21	.06342	45	.74192	20	.09062	46	23
24	.72973	21	.06387	45	.74213	20	.09108	45	24
25	9.72994	20	10.06432	45	9.74233	20	10.09154	46	25
26	.73015	21	.06477	45	.74254	20	.09200	45	26
27	.73036	21	.06522	45	.74274	20	.09245	45	27
28	.73057	20	.06568	45	.74294	20	.09291	46	28
29	.73077	21	.06613	45	.74315	20	.09337	45	29
30	9.73098	21	10.06658	45	9.74335	20	10.09382	46	30
31	.73119	20	.06703	45	.74356	20	.09428	46	31
32	.73140	21	.06748	45	.74376	20	.09474	45	32
33	.73161	20	.06793	45	.74396	20	.09520	46	33
34	.73181	21	.06838	45	.74417	20	.09566	45	34
35	9.73202	21	10.06883	45	9.74437	20	10.09611	46	35
36	.73223	20	.06928	45	.74458	20	.09657	46	36
37	.73244	21	.06974	45	.74478	20	.09703	45	37
38	.73265	20	.07019	45	.74498	20	.09749	46	38
39	.73285	2	.07064	45	.74519	20	.09795	46	39
40	9.73306	20	10.07109	45	9.74539	20	10.09841	45	40
41	.73327	21	.07154	45	.74559	20	.09886	46	41
42	.73348	20	.07200	45	.74580	20	.09932	46	42
43	.73368	21	.07245	45	.74600	20	.09978	46	43
44	.73389	20	.07290	45	.74620	20	.10024	46	44
45	9.73410	20	10.07335	45	9.74641	20	10.10070	46	45
46	.73430	21	.07380	45	.74661	20	.10116	46	46
47	.73451	20	.07426	45	.74681	20	.10162	45	47
48	.73472	21	.07471	45	.74702	20	.10208	46	48
49	.73493	20	.07516	45	.74722	20	.10254	46	49
50	9.73513	20	10.07562	45	9.74742	20	10.10300	46	50
51	.73534	21	.07607	45	.74762	20	.10346	46	51
52	.73555	20	.07652	45	.74783	20	.10392	46	52
53	.73575	20	.07697	45	.74803	20	.10438	46	53
54	.73596	21	.07743	45	.74823	20	.10484	46	54
55	9.73617	20	10.07788	45	9.74844	20	10.10530	46	55
56	.73637	20	.07834	45	.74864	20	.10576	46	56
57	.73658	21	.07879	45	.74884	20	.10622	46	57
58	.73679	20	.07924	45	.74904	20	.10668	46	58
59	.73699	20	.07970	45	.74924	20	.10714	46	59
60	9.73720		10.08015		9.74945		10.10760		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	$\overline{46}$	46
6	4.6	4.6
7	5.4	5.3
8	6.2	6.1
9	7.0	6.9
10	7.7	7.6
20	15.5	15.3
30	23.2	23.0
40	31.0	30.6
50	38.7	38.3

	$\overline{45}$	45
6	4.5	4.5
7	5.3	5.2
8	6.0	6.0
9	6.8	6.7
10	7.6	7.5
20	15.1	15.0
30	22.7	22.5
40	30.3	30.0
50	37.9	37.5

	$\overline{44}$
6	4.4
7	5.2
8	5.9
9	6.7
10	7.4
20	14.8
30	22.2
40	29.6
50	37.1

	21	$\overline{20}$
6	2.1	2.0
7	2.4	2.4
8	2.8	2.7
9	3.1	3.1
10	3.5	3.4
20	7.0	6.8
30	10.5	10.2
40	14.0	13.6
50	17.5	17.1

	20
6	2.0
7	2.3
8	2.6
9	3.0
10	3.3
20	6.6
30	10.0
40	13.3
50	16.6

P. P.

	64°				65°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.74945	20	10.10760	46	9.76146	19	10.13551	47	0
1	.74965	20	.10807	46	.76166	20	.13598	47	1
2	.74985	20	.10853	46	.76186	20	.13645	47	2
3	.75005	20	.10899	46	.76206	19	.13692	47	3
4	75026	20	.10945	46	.76225	20	.13739	47	4
5	9.75046	20	10.10991	46	9.76245	19	10.13786	47	5
6	.75066	20	.11037	46	.76265	20	.13833	47	6
7	.75086	20	.11084	46	.76285	19	.13880	47	7
8	.75106	20	.11130	46	.76304	20	.13927	47	8
9	.75126	20	.11176	46	.76324	20	.13974	47	9
10	9.75147	20	10.11222	46	9.76344	19	10.14021	47	10
11	.75167	20	.11269	46	76364	20	.14068	47	11
12	.75187	20	.11315	46	.76384	19	.14115	47	12
13	.75207	20	.11361	46	.76403	20	.14162	47	13
14	.75227	20	.11407	46	.76423	19	.14210	47	14
15	9.75247	20	10.11454	46	9.76443	20	10.14257	47	15
16	.75267	20	.11500	46	.76463	19	.14304	47	16
17	.75287	20	.11546	46	.76482	19	.14351	47	17
18	.75308	20	.11593	46	.76502	20	.14398	47	18
19	.75328	20	.11639	46	.76522	19	.14445	47	19
20	9.75348	20	10.11685	46	9.76541	20	10.14493	47	20
21	.75368	20	.11732	46	.76561	19	.14540	47	21
22	.75388	20	.11778	46	.76581	19	.14587	47	22
23	.75408	20	.11825	46	.76600	20	.14634	47	23
24	.75428	20	.11871	46	.76620	19	.14682	47	24
25	9.75448	20	10.11917	46	9.76640	19	10.14729	47	25
26	.75468	20	.11964	46	.76659	20	.14776	47	26
27	.75488	20	.12010	46	.76679	19	.14823	47	27
28	.75508	20	.12057	46	.76699	19	.14871	47	28
29	.75528	20	.12103	46	.76718	20	.14918	47	29
30	9.75548	20	10.12150	46	9.76738	19	10.14965	47	30
31	.75568	20	.12196	46	.76758	19	.15013	47	31
32	.75588	20	.12243	46	.76777	19	.15060	47	32
33	.75608	20	.12289	46	.76797	20	.15108	47	33
34	.75628	20	.12336	47	.76817	19	.15155	47	34
35	9.75648	20	10.12383	46	9.76836	19	10.15202	47	35
36	.75668	20	.12429	46	.76856	19	.15250	47	36
37	.75688	20	.12476	46	.76875	20	.15297	47	37
38	.75708	20	.12522	46	.76895	19	.15345	47	38
39	.75728	20	.12569	47	.76915	19	.15392	47	39
40	9.75748	20	10.12616	46	9.76934	19	10.15440	47	40
41	.75768	20	.12662	46	.76954	19	.15487	47	41
42	.75788	20	.12709	47	.76973	19	.15535	47	42
43	.75808	19	.12756	46	.76993	19	.15582	47	43
44	.75828	20	.12802	46	.77012	20	.15630	48	44
45	9.75848	20	10.12849	47	9.77032	19	10.15678	47	45
46	.75868	20	.12896	46	.77052	19	.15725	47	46
47	.75888	20	.12942	47	.77071	19	.15773	47	47
48	.75908	20	.12989	46	.77091	19	.15820	48	48
49	.75928	19	.13036	47	.77110	19	.15868	47	49
50	9.75947	20	10.13083	47	9.77130	19	10.15916	47	50
51	.75967	20	.13130	46	.77149	19	.15963	48	51
52	.75987	20	.13176	47	.77169	19	.16011	47	52
53	.76007	19	.13223	46	.77188	19	.16059	47	53
54	.76027	20	.13270	47	.77208	19	.16106	48	54
55	9.76047	20	10.13317	47	9.77227	19	10.16154	47	55
56	.76067	20	.13364	47	.77247	19	.16202	48	56
57	.76087	19	.13411	46	.77266	19	.16250	48	57
58	.76106	20	.13457	47	.77286	19	.16298	47	58
59	.76126	20	.13504	47	.77305	19	.16345	48	59
60	9.76146		10.13551		9.77325		10.16393		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	48	47
6	4.8	4.7
7	5.6	5.5
8	6.4	6.3
9	7.2	7.1
10	8.0	7.9
20	16.0	15.8
30	24.0	23.7
40	32.0	31.6
50	40.0	39.6

	47	46
6	4.7	4.6
7	5.5	5.4
8	6.2	6.2
9	7.0	7.0
10	7.8	7.7
20	15.6	15.5
30	23.5	23.2
40	31.3	31.0
50	39.1	38.7

	46
6	4.6
7	5.3
8	6.1
9	6.9
10	7.6
20	15.3
30	23.0
40	30.6
50	38.3

	20	20
6	2.0	2.0
7	.4	2.3
8	.7	2.6
9	3.1	3.0
10	3.4	3.3
20	6.8	6.6
30	10.2	10.0
40	13.6	13.3
50	17.1	16.6

	19
6	1.9
7	2.3
8	2.6
9	2.9
10	3.2
20	6.5
30	9.7
40	13.0
50	16.2

P. P.

	66°				67°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.77325	19	10.16393	48	9.78481	19	10.19293	49	0
1	.77344	19	.16441	47	.78500	19	.19342	49	1
2	.77363	19	.16489	48	.78519	19	.19391	48	2
3	.77383	19	.16537	48	.78538	19	.19439	49	3
4	.77402	19	.16585	48	.78557	19	.19488	49	4
5	9.77422	19	10.16633	47	9.78576	19	10.19537	49	5
6	.77441	19	.16680	48	.78595	19	.19586	49	6
7	.77461	19	.16728	48	.78614	19	.19635	49	7
8	.77480	19	.16776	48	.78633	19	.19684	49	8
9	.77499	19	.16824	48	.78652	19	.19733	49	9
10	9.77519	19	10.16872	48	9.78671	19	10.19782	49	10
11	.77538	19	.16920	48	.78690	19	.19831	49	11
12	.77557	19	.16968	48	.78709	19	.19880	49	12
13	.77577	19	.17016	48	.78728	19	.19929	49	13
14	.77596	19	.17064	48	.78747	19	.19979	49	14
15	9.77616	19	10.17112	48	9.78766	19	10.20028	49	15
16	.77635	19	.17160	48	.78785	19	.20077	49	16
17	.77654	19	.17209	48	.78804	19	.20126	49	17
18	.77674	19	.17257	48	.78823	19	.20175	49	18
19	.77693	19	.17305	48	.78842	19	.20224	49	19
20	9.77712	19	10.17353	48	9.78861	19	10.20273	49	20
21	.77732	19	.17401	48	.78880	19	.20323	49	21
22	.77751	19	.17449	48	.78899	19	.20372	49	22
23	.77770	19	.17498	48	.78918	18	.20421	49	23
24	.77790	19	.17546	48	.78937	19	.20470	49	24
25	9.77809	19	10.17594	48	9.78956	19	10.20520	49	25
26	.77828	19	.17642	48	.78975	19	.20569	49	26
27	.77847	19	.17690	48	.78994	19	.20618	49	27
28	.77867	19	.17739	48	.79013	19	.20668	49	28
29	.77886	19	.17787	48	.79032	19	.20717	49	29
30	9.77905	19	10.17835	48	9.79051	18	10.20767	49	30
31	.77925	19	.17884	48	.79069	19	.20816	49	31
32	.77944	19	.17932	48	.79088	19	.20865	49	32
33	.77963	19	.17980	48	.79107	19	.20915	49	33
34	.77982	19	.18029	48	.79126	19	.20964	49	34
35	9.78002	19	10.18077	48	9.79145	18	10.21014	49	35
36	.78021	19	.18126	48	.79164	19	.21063	49	36
37	.78040	19	.18174	48	.79183	19	.21113	49	37
38	.78059	19	.18222	48	.79202	18	.21162	50	38
39	.78078	19	.18271	48	.79220	19	.21212	49	39
40	9.78098	19	10.18319	48	9.79239	19	10.21262	49	40
41	.78117	19	.18368	48	.79258	18	.21311	49	41
42	.78136	19	.18416	49	.79277	19	.21361	49	42
43	.78155	19	.18465	48	.79296	19	.21410	50	43
44	.78174	19	.18514	48	.79315	18	.21460	49	44
45	9.78194	19	10.18562	48	9.79333	19	10.21510	50	45
46	.78213	19	.18611	48	.79352	19	.21560	49	46
47	.78232	19	.18659	48	.79371	18	.21609	50	47
48	.78251	19	.18708	49	.79390	19	.21659	49	48
49	.78270	19	.18757	48	.79409	18	.21709	50	49
50	9.78289	19	10.18805	48	9.79427	19	10.21759	49	50
51	.78309	19	.18854	49	.79446	19	.21808	50	51
52	.78328	19	.18903	48	.79465	18	.21858	50	52
53	.78347	19	.18951	49	.79484	19	.21908	49	53
54	.78366	19	.19000	48	.79503	18	.21958	50	54
55	9.78385	19	10.19049	49	9.79521	19	10.22008	50	55
56	.78404	19	.19098	48	.79540	18	.22058	50	56
57	.78423	19	.19146	49	.79559	19	.22108	50	57
58	.78442	19	.19195	49	.79578	18	.22158	50	58
59	.78462	19	.19244	48	.79596	19	.22208	50	59
60	9.78481		10.19293		9.79615		10.22258		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	50	49
6	5.0	4.9
7	5.8	5.8
8	6.6	6.6
9	7.5	7.4
10	8.3	8.2
20	16.6	16.5
30	25.0	24.7
40	33.3	33.0
50	41.6	41.2

	49	48
6	4.9	4.8
7	5.7	5.6
8	6.5	6.4
9	7.3	7.3
10	8.1	8.1
20	16.3	16.1
30	24.5	24.2
40	32.6	32.3
50	40.8	40.4

	48	47
6	4.8	4.7
7	5.6	5.5
8	6.4	6.3
9	7.2	7.1
10	8.0	7.9
20	16.0	15.8
30	24.0	23.7
40	32.0	31.6
50	40.0	39.6

	19	19
6	1.9	1.9
7	2.3	2.2
8	2.6	2.5
9	2.9	2.8
10	3.2	3.1
20	6.5	6.3
30	9.7	9.5
40	13.0	12.6
50	16.2	15.8

	18
6	1.8
7	2.1
8	2.4
9	2.8
10	3.1
20	6.1
30	9.2
40	12.3
50	15.4

P. P.

′	68° Lg. Vers.	D	68° Log. Exs.	D	69° Lg. Vers.	D	69° Log. Exs.	D	′
0	9.79615	18	10.22258	50	9.80728	18	10.25295	51	0
1	.79634	19	.22308	50	.80747	18	.25347	51	1
2	.79653	18	.22358	50	.80765	18	.25398	51	2
3	.79671	18	.22408	50	.80783	18	.25449	51	3
4	.79690	19	.22458	50	.80802	18	.25501	51	4
5	9.79709	18	10.22508	50	9.80820	18	10.25552	51	5
6	.79727	19	.22558	50	.80839	18	.25604	51	6
7	.79746	18	.22608	50	.80857	18	.25655	51	7
8	.79765	18	.22658	50	.80875	18	.25707	51	8
9	.79783	19	.22708	50	.80894	18	.25758	51	9
10	9.79802	18	10.22759	50	9.80912	18	10.25810	51	10
11	.79821	18	.22809	50	.80930	18	.25861	51	11
12	.79839	19	.22859	50	.80949	18	.25913	51	12
13	.79858	18	.22909	50	.80967	18	.25964	51	13
14	.79877	18	.22960	50	.80985	18	.26016	51	14
15	9.79895	18	10.23010	50	9.81003	18	10.26067	52	15
16	.79914	19	.23060	50	.81022	18	.26119	51	16
17	.79933	18	.23110	50	.81040	18	.26171	51	17
18	.79951	18	.23161	50	.81058	18	.26222	52	18
19	.79970	18	.23211	50	.81077	18	.26274	51	19
20	9.79988	19	10.23262	50	9.81095	18	10.26326	52	20
21	.80007	18	.23312	50	.81113	18	.26378	51	21
22	.80026	18	.23362	50	.81131	18	.26429	52	22
23	.80044	18	.23413	50	.81150	18	.26481	52	23
24	.80063	18	.23463	50	.81168	18	.26533	52	24
25	9.80081	19	10.23514	50	9.81186	18	10.26585	51	25
26	.80100	18	.23564	50	.81204	18	.26637	52	26
27	.80119	18	.23615	50	.81223	18	.26689	52	27
28	.80137	18	.23666	50	.81241	18	.26741	52	28
29	.80156	18	.23716	50	.81259	18	.26793	52	29
30	9.80174	18	10.23767	50	9.81277	8	10.26845	52	30
31	.80193	18	.23817	51	.81295	18	.26897	52	31
32	.80211	18	.23868	50	.81314	18	.26949	52	32
33	.80230	18	.23919	50	.81332	18	.27001	52	33
34	.80248	19	.23969	51	.81350	18	.27053	52	34
35	9.80267	18	10.24020	50	9.81368	18	10.27105	52	35
36	.80286	18	.24071	51	.81386	18	.27157	52	36
37	.80304	18	.24122	50	.81405	18	.27209	52	37
38	.80323	18	.24172	51	.81423	18	.27261	52	38
39	.80341	18	.24223	51	.81441	18	.27314	52	39
40	9.80360	18	10.24274	50	9.81459	18	10.27366	52	40
41	.80378	18	.24325	51	.81477	18	.27418	52	41
42	.80397	18	.24376	51	.81495	18	.27470	52	42
43	.80415	18	.24427	51	.81513	18	.27523	52	43
44	.80434	18	.24478	51	.81532	18	.27575	52	44
45	9.80452	18	10.24529	51	9.81550	18	10.22627	52	45
46	.80470	18	.24580	51	.81568	18	.27680	52	46
47	.80489	18	.24631	51	.81586	18	.27732	52	47
48	.80507	18	.24682	51	.81604	18	.27785	52	48
49	.80526	18	.24733	51	.81622	18	.27837	52	49
50	9.80544	18	10.24784	51	9.81640	18	10.27890	52	50
51	.80563	18	.24835	51	.81658	18	.27942	52	51
52	.80587	18	.24886	51	.81676	18	.27995	52	52
53	.80600	18	.24937	51	.81695	18	.28047	52	53
54	.80618	18	.24988	51	.81713	18	.28100	52	54
55	9.80636	18	10.25039	51	9.81731	18	10.28152	53	55
56	.80655	18	.25090	51	.81749	18	.28205	52	56
57	.80673	18	.25142	51	.81767	18	.28258	52	57
58	.80692	18	.25193	51	.81785	18	.28310	53	58
59	.80710	18	.25244	51	.81803	18	.28363	52	59
60	9.80728		10.25295		9.81821		10.28416		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	53	52
6	5.3	5.2
7	6.2	6.1
8	7.0	7.0
9	7.9	7.9
10	8.8	8.7
20	17.6	17.5
30	26.5	26.2
40	35.3	35.0
50	44.1	43.7

	52	51
6	5.2	5.1
7	6.0	6.0
8	6.9	6.8
9	7.8	7.7
10	8.6	8.6
20	17.3	17.1
30	26.0	25.7
40	34.6	34.3
50	43.3	42.9

	51	50
6	5.1	5.0
7	5.9	5.9
8	6.8	6.7
9	7.6	7.6
10	8.5	8.4
20	17.0	16.8
30	25.5	25.2
40	34.0	33.6
50	42.5	42.1

	50
6	5.0
7	5.8
8	6.6
9	7.5
10	8.3
20	16.6
30	25.0
40	33.3
50	41.6

	19	18
6	1.9	1.8
7	2.2	2.1
8	2.5	2.4
9	2.8	2.8
10	3.1	3.1
20	6.3	6.1
30	9.5	9.2
40	12.6	12.3
50	15.8	15.4

	18
6	1.8
7	2.1
8	2.4
9	2.7
10	3.0
20	6.0
30	9.0
40	12.0
50	15.0

′	70° Lg. Vers.	D	70° Log. Exs.	D	71° Lg. Vers.	D	71° Log. Exs.	D	′
0	9.81821	18	10.28416	53	9.82894	17	10.31629	54	0
1	.81839	18	.28469	52	.82911	17	.31684	54	1
2	.81857	18	.28521	53	.82929	18	.31738	54	2
3	.81875	18	.28574	53	.82947	17	.31793	54	3
4	.81893	18	.28627	52	.82964	18	.31847	54	4
5	9.81911	18	10.28680	53	9.82982	17	10.31902	54	5
6	.81929	18	.28733	53	.83000	17	.31956	54	6
7	.81947	18	.28786	53	.83017	18	.32011	55	7
8	.81965	18	.28839	53	.83035	17	.32066	54	8
9	.81983	18	.28892	53	.83053	17	.32120	54	9
10	9.82001	18	10.28945	53	9.83070	18	10.32175	55	10
11	.82019	18	.28998	53	.83088	17	.32230	54	11
12	.82037	18	.29051	53	.83106	17	.32284	55	12
13	.82055	18	.29104	53	.83123	17	.32339	54	13
14	.82073	18	.29157	53	.83141	18	.32394	55	14
15	9.82091	17	10.29210	53	9.83159	17	10.32449	55	15
16	.82109	18	.29263	53	.83176	17	.32504	54	16
17	.82127	18	.29316	53	.83194	17	.32558	55	17
18	.82145	18	.29370	53	.83211	18	.32613	55	18
19	.82163	18	.29423	53	.83229	17	.32668	55	19
20	9.82181	18	10.29476	53	9.83247	17	10.32723	55	20
21	.82199	18	.29529	53	.83264	17	.32778	55	21
22	.82217	18	.29583	53	.83282	17	.32833	55	22
23	.82235	17	.29636	53	.83299	18	.32888	55	23
24	.82252	18	.29689	53	.83317	17	.32944	55	24
25	9.82270	18	10.29743	53	9.83335	17	10.32999	55	25
26	.82288	18	.29796	53	.83352	17	.33054	55	26
27	.82306	18	.29850	53	.83370	17	.33109	55	27
28	.82324	17	.29903	53	.83387	17	.33164	55	28
29	.82342	18	.29957	53	.83405	17	.33220	55	29
30	9.82360	18	10.30010	53	9.83422	18	10.33275	55	30
31	.82378	18	.30064	53	.83440	18	.33330	55	31
32	.82396	17	.30117	54	.83458	17	.33385	55	32
33	.82413	18	.30171	53	.83475	17	.33441	55	33
34	.82431	18	.30225	53	.83493	17	.33496	55	34
35	9.82449	17	10.30278	54	9.83510	17	10.33552	55	35
36	.82467	18	.30332	53	.83528	17	.33607	55	36
37	.82485	18	.30386	54	.83545	17	.33663	55	37
38	.82503	17	.30440	53	.83563	17	.33718	55	38
39	.82520	18	.30493	54	.83580	17	.33774	55	39
40	9.82538	18	10.30547	53	9.83598	17	10.33829	56	40
41	.82556	17	.30601	54	.83615	17	.33885	55	41
42	.82574	18	.30655	54	.83633	17	.33941	55	42
43	.82592	17	.30709	54	.83650	17	.33996	56	43
44	.82609	18	.30763	54	.83668	17	.34052	55	44
45	9.82627	18	10.30817	54	9.83685	17	10.34108	56	45
46	.82645	17	.30871	54	.83703	17	.34164	56	46
47	.82663	18	.30925	54	.83720	17	.34220	55	47
48	.82681	17	.30979	54	.83737	17	.34275	56	48
49	.82698	18	.31033	54	.83755	17	.34331	56	49
50	9.82716	17	10.31087	54	9.83772	17	10.34387	56	50
51	.82734	18	.31141	54	.83790	17	.34443	56	51
52	.82752	17	.31195	54	.83807	17	.34499	56	52
53	.82769	18	.31249	54	.83825	17	.34555	56	53
54	.82787	17	.31303	54	.83842	17	.34611	56	54
55	9.82805	18	10.31358	54	9.83859	17	10.34667	56	55
56	.82823	17	.31412	54	.83877	17	.34723	56	56
57	.82840	18	.31466	54	.83894	17	.34780	56	57
58	.82858	17	.31521	54	.83912	17	.34836	56	58
59	.82876	18	.31575	54	.83929	17	.34892	56	59
60	9.82894		10.31629		9.83946		10.34948		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	56	56
6	5.6	5.6
7	6.6	6.5
8	7.5	7.4
9	8.5	8.4
10	9.4	9.3
20	18.8	18.6
30	28.2	28.0
40	37.6	37.3
50	47.1	46.6

	55	55
6	5.5	5.5
7	6.5	6.4
8	7.4	7.3
9	8.3	8.2
10	9.2	9.1
20	18.5	18.3
30	27.7	27.5
40	37.0	36.6
50	46.2	45.8

	54	54
6	5.4	5.4
7	6.3	6.3
8	7.2	7.2
9	8.2	8.1
10	9.1	9.0
20	18.1	18.0
30	27.2	27.0
40	36.3	36.0
50	45.4	45.0

	53	53
6	5.3	5.3
7	6.2	6.2
8	7.1	7.0
9	8.0	7.9
10	8.9	8.8
20	17.8	17.6
30	26.7	26.5
40	35.6	35.3
50	44.6	44.1

	52
6	5.2
7	6.1
8	7.0
9	7.9
10	8.7
20	17.5
30	26.2
40	35.0
50	43.7

	18	17	17
6	1.8	1.7	1.7
7	2.1	2.0	2.0
8	2.4	2.3	2.2
9	2.7	2.6	2.5
10	3.0	2.9	2.8
20	6.0	5.8	5.6
30	9.0	8.7	8.5
40	12.0	11.6	11.3
50	15.0	14.6	14.1

P. P.

′	72° Lg. Vers.	D	72° Log. Exs.	D	73° Lg. Vers.	D	73° Log. Exs.	D	′
0	9.83946	17	10.34948	56	9.84980	17	10.38387	58	0
1	.83964	17	.35005	56	.84997	17	.38445	58	1
2	.83981	17	.35061	56	.85014	17	.38504	58	2
3	.83999	17	.35117	56	.85031	17	.38562	58	3
4	.84016	17	.35174	56	.85049	17	.38621	58	4
5	9.84033	17	10.35230	56	9.85066	17	10.38679	58	5
6	.84051	17	.35286	56	.85083	17	.38738	58	6
7	.84068	17	.35343	56	.85100	17	.38796	59	7
8	.84085	17	.35399	57	.85117	17	.38855	58	8
9	.84103	17	.35456	56	.85134	17	.38914	59	9
10	9.84120	17	10.35513	56	9.85151	17	10.38973	58	10
11	.84137	17	.35569	56	.85168	17	.39031	59	11
12	.84155	17	.35626	57	.85185	17	.39090	59	12
13	.84172	17	.35683	56	.85202	17	.39149	58	13
14	.84189	17	.35739	57	.85219	17	.39208	59	14
15	9.84207	17	10.35796	56	9.85236	17	10.39267	59	15
16	.84224	17	.35853	57	.85253	17	.39326	59	16
17	.84241	17	.35910	57	.85270	17	.39385	59	17
18	.84259	17	.35967	56	.85287	17	.39444	59	18
19	.84276	17	.36023	57	.85304	17	.39503	59	19
20	9.84293	17	10.36080	57	9.85321	17	10.39562	59	20
21	.84310	17	.36137	57	.85338	17	.39621	59	21
22	.84328	17	.36194	57	.85355	17	.39681	59	22
23	.84345	17	.36251	57	.85372	17	.39740	59	23
24	.84362	17	.36308	57	.85389	16	.39799	59	24
25	9.84380	17	10.36366	57	9.85405	17	10.39859	59	25
26	.84397	17	.36423	57	.85422	17	.39918	59	26
27	.84414	17	.36480	57	.85439	17	.39977	59	27
28	.84431	17	.36537	57	.85456	17	.40037	59	28
29	.84449	17	.36594	57	.85473	17	.40096	59	29
30	9.84466	17	10.36652	57	9.85490	17	10.40156	60	30
31	.84483	17	.36709	57	.85507	16	.40216	59	31
32	.84500	17	.36766	57	.85524	17	.40275	59	32
33	84517	17	.36824	57	.85541	17	.40335	60	33
34	.84535	17	.36881	57	.85558	17	.40395	59	34
35	9.84552	17	10.36938	57	9.85575	17	10.40454	60	35
36	.84569	17	.36996	58	.85592	16	.40514	59	36
37	.84586	17	.37054	57	.85608	17	.40574	60	37
38	.84603	17	.37111	57	.85625	17	.40634	60	38
39	.84620	17	.37169	57	.85642	17	.40694	60	39
40	9.84638	17	10.37226	57	9.85659	16	10.40754	60	40
41	.84655	17	.37284	58	.85676	17	.40814	60	41
42	.84672	17	.37342	57	.85693	17	.40874	60	42
43	.84689	17	.37399	58	.85710	16	.40934	60	43
44	.84706	17	.37457	58	.85726	17	.40994	60	44
45	9.84724	17	10.37515	57	9.85743	17	10.41054	60	45
46	.84741	17	.37573	58	.85760	16	.41114	60	46
47	.84758	17	.37631	58	.85777	17	.41174	60	47
48	.84775	17	.37689	58	.85794	17	.41235	60	48
49	.84792	17	.37747	58	.85811	16	.41295	60	49
50	9.84809	17	10.37805	58	9.85827	17	10.41355	60	50
51	.84826	17	.37863	58	.85844	17	.41416	60	51
52	.84844	17	.37921	58	.85861	16	.41476	60	52
53	.84861	17	.37979	58	.85878	17	.41537	60	53
54	.84878	17	.38037	58	.85895	16	.41597	60	54
55	9.84895	17	10.38095	58	9.85911	17	10.41658	61	55
56	.84912	17	.38153	58	.85928	17	.41719	60	56
57	.84929	17	.38212	58	.85945	16	.41779	60	57
58	.84946	17	.38270	58	.85962	17	.41840	61	58
59	.84963	17	.38328	58	.85979	16	.41901	61	59
60	9.84980		10.38387		9.85995		10.41962		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	61	60
6	6.1	6.0
7	7.1	7.0
8	8.1	8.0
9	9.1	9.1
10	10.1	10.1
20	20.3	20.1
30	30.5	30.2
40	40.6	40.3
50	50.8	50.4

	60	59
6	6.0	5.9
7	7.0	6.9
8	8.0	7.9
9	9.0	8.9
10	10.0	9.9
20	20.0	19.8
30	30.0	29.7
40	40.0	39.6
50	50.0	49.6

	59	58
6	5.9	5.8
7	6.9	6.8
8	7.8	7.8
9	8.8	8.8
10	9.8	9.7
20	19.6	19.5
30	29.5	29.2
40	39.3	39.0
50	49.1	48.7

	58	57
6	5.8	5.7
7	6.7	6.7
8	7.7	7.6
9	8.7	8.6
10	9.6	9.6
20	19.3	19.1
30	29.0	28.7
40	38.6	38.3
50	48.3	47.9

	57	56
6	5.7	5.6
7	6.6	6.6
9	7.6	7.5
9	8.5	8.5
10	9.5	9.4
20	19.0	18.8
30	28.5	28.2
40	38.0	37.6
50	47.5	47.1

	17	17	16
6	1.7	1.7	1.6
7	2.0	2.0	1.9
8	2.3	2.2	2.2
9	2.6	2.5	2.5
10	2.9	2.8	2.7
20	5.8	5.6	5.5
30	8.7	8.5	8.2
40	11.6	11.3	11.0
50	14.6	14.1	13.7

P. P.

′	74° Lg. Vers.	D	74° Log. Exs.	D	75° Lg. Vers.	D	75° Log. Exs.	D	′
0	9.85995	17	10.41962	60	9.86992	16	10.45693	63	0
1	.86012	16	.42022	61	.87009	16	.45756	63	1
2	.86029	17	.42083	61	.87025	16	.45820	64	2
3	.86046	16	.42144	61	.87042	16	.45884	63	3
4	.86062	17	.42205	61	.87058	16	.45947	64	4
5	9.86079	16	10.42266	61	9.87074	16	10.46011	64	5
6	.86096	17	.42327	61	.87091	16	.46075	64	6
7	.86113	16	.42388	61	.87107	16	.46139	64	7
8	.86129	17	.42450	61	.87124	16	.46203	64	8
9	.86146	16	.42511	61	.87140	16	.46267	64	9
10	9.86163	16	10.42572	61	9.87157	16	10.46331	64	10
11	.86179	17	.42633	61	.87173	16	.46395	64	11
12	.86196	16	.42695	61	.87189	16	.46460	64	12
13	.86213	17	.42756	61	.87206	16	.46524	64	13
14	.86230	16	.42817	61	.87222	16	.46588	64	14
15	9.86246	16	10.42879	61	9.87239	16	10.46652	64	15
16	.86263	17	.42940	61	.87255	16	.46717	64	16
17	.86280	16	.43002	61	.87271	16	.46781	64	17
18	.86296	16	.43063	61	.87288	16	.46846	64	18
19	.86313	17	.43125	62	.87304	16	.46910	64	19
20	9.86330	16	10.43187	61	9.87320	16	10.46975	64	20
21	.86346	16	.43249	62	.87337	16	.47040	65	21
22	.86363	17	.43310	61	.87353	16	.47104	64	22
23	.86380	16	.43372	62	.87370	16	.47169	65	23
24	.86396	16	.43434	61	.87386	16	.47234	64	24
25	9.86413	17	10.43496	62	9.87402	16	10.47299	65	25
26	.86430	16	.43558	62	.87419	16	.47364	65	26
27	.86446	16	.43620	62	.87435	16	.47429	65	27
28	.86463	16	.43682	62	.87451	16	.47494	65	28
29	.86479	17	.43744	62	.87468	16	.47559	65	29
30	9.86496	16	10.43806	62	9.87484	16	10.47624	65	30
31	.86513	16	.43868	62	.87500	16	.47689	65	31
32	.86529	16	.43931	62	.87516	16	.47754	65	32
33	.86546	16	.43993	62	.87533	16	.47820	65	33
34	.86562	17	.44055	62	.87549	16	.47885	65	34
35	9.86579	16	10.44118	62	9.87565	16	10.47950	65	35
36	.86596	16	.44180	62	.87582	16	.48016	65	36
37	.86612	16	.44242	62	.87598	16	.48081	65	37
38	.86629	16	.44305	62	.87614	16	.48147	65	38
39	.86645	16	.44368	63	.87631	16	.48213	66	39
40	9.86662	16	10.44430	62	9.87647	16	10.48278	65	40
41	.86678	17	.44493	62	.87653	16	.48344	65	41
42	.86695	16	.44556	63	.87679	16	.48410	66	42
43	.86712	16	.44618	62	.87696	16	.48476	66	43
44	.86728	16	.44681	63	.87712	16	.48542	66	44
45	9.86745	16	10.44744	62	9.87728	16	10.48607	65	45
46	.86761	16	.44807	63	.87744	16	.48674	66	46
47	.86778	16	.44870	63	.87761	16	.48740	66	47
48	.86794	16	.44933	63	.87777	16	.48806	66	48
49	.86811	16	.44996	63	.87793	16	.48872	66	49
50	9.86827	16	10.45059	63	9.87809	16	10.48938	66	50
51	.86844	16	.45122	63	.87825	16	.49004	66	51
52	.86860	16	.45185	63	.87842	16	.49071	66	52
53	.86877	16	.45248	63	.87858	16	.49137	66	53
54	.86893	16	.45312	63	.87874	16	.49204	66	54
55	9.86910	16	10.45375	63	9.87890	16	10.49270	66	55
56	.86926	16	.45439	63	.87906	16	.49337	66	56
57	.86943	16	.45502	63	.87923	16	.49403	66	57
58	.86959	16	.45565	63	.87939	16	.49470	67	58
59	.86976	16	.45629	64	.87955	16	.49537	66	59
60	9.86992		10.45693		9.87971		10.49604		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	67	66	66
6	6.7	6.6	6.6
7	7.8	7.7	7.7
8	8.9	8.8	8.8
9	10.0	10.0	9.9
10	11.1	11.1	11.0
20	22.3	22.1	22.0
30	33.5	33.2	33.0
40	44.6	44.3	44.0
50	55.8	55.4	55.0

	65	65	64
6	6.5	6.5	6.4
7	7.6	7.6	7.5
8	8.7	8.6	8.6
9	9.8	9.7	9.7
10	10.9	10.8	10.7
20	21.8	21.6	21.5
30	32.7	32.5	32.2
40	43.6	43.3	43.0
50	54.6	54.1	53.7

	64	63	63
6	6.4	6.3	6.3
7	7.4	7.4	7.3
8	8.5	8.4	8.4
9	9.6	9.5	9.4
10	10.6	10.6	10.5
20	21.3	21.1	21.0
30	32.0	31.7	31.5
40	42.6	42.3	42.0
50	53.3	52.9	52.5

	62	62	61
6	6.2	6.2	6.1
7	7.3	7.2	7.2
8	8.3	8.2	8.2
9	9.4	9.3	9.2
10	10.4	10.3	10.2
20	20.8	20.6	20.5
30	31.2	31.0	30.7
40	41.6	41.3	41.0
50	52.1	51.6	51.2

	61	60
6	6.1	6.0
7	7.1	7.0
8	8.1	8.0
9	9.1	9.1
10	10.1	10.1
20	20.3	20.1
30	30.5	30.2
40	40.6	40.3
50	50.8	50.4

	17	16	16
6	1.7	1.6	1.6
7	2.0	1.9	1.8
8	2.2	2.2	2.1
9	2.5	2.5	2.4
10	2.8	2.7	2.6
20	5.6	5.5	5.3
30	8.5	8.2	8.0
40	11.3	11.0	10.6
50	14.1	13.7	13.3

P. P.

	76°				77°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.87971	16	10.49604	66	9.88933	16	10.53724	70	0
1	.87987	16	.49670	67	.88949	15	.53794	71	1
2	.88003	16	.49737	67	.88964	16	.53865	70	2
3	.88020	16	.49804	67	.88980	16	.53936	71	3
4	.88036	16	.49871	67	.88996	16	.54007	71	4
5	9.88052	16	10.49939	67	9.89012	15	10.54078	71	5
6	.88068	16	.50006	67	.89028	16	.54149	71	6
7	.88084	16	.50073	67	.89044	16	.54220	71	7
8	.88100	16	.50140	67	.89060	15	.54291	71	8
9	.88116	16	.50208	67	.89075	16	.54362	71	9
10	9.88133	16	10.50275	67	9.89091	16	10.54433	71	10
11	.88149	16	.50342	67	.89107	15	.54505	71	11
12	.88165	16	.50410	67	.89123	16	.54576	71	12
13	.88181	16	.50477	68	.89139	16	.54647	72	13
14	.88197	16	.50545	67	.89155	15	.54719	71	14
15	9.88213	16	10.50613	68	9.89170	16	10.54791	71	15
16	.88229	16	.50681	67	.89186	15	.54862	72	16
17	.88245	16	.50748	68	.89202	16	.54934	71	17
18	.88261	16	.50816	68	.89218	16	.55006	72	18
19	.88277	16	.50884	68	.89234	15	.55078	72	19
20	9.88294	16	10.50952	68	9.89249	16	10.55150	72	20
21	.88310	16	.51020	68	.89265	15	.55222	72	21
22	.88326	16	.51088	68	.89281	16	.55294	72	22
23	.88342	16	.51157	68	.89297	15	.55366	72	23
24	.88358	16	.51225	68	.89312	16	.55438	72	24
25	9.88374	16	10.51293	68	9.89328	15	10.55511	72	25
26	.88390	16	.51361	68	.89344	16	.55583	72	26
27	.88406	16	.51430	68	.89360	16	.55655	73	27
28	.88422	16	.51498	68	.89376	15	.55728	72	28
29	.88438	16	.51567	69	.89391	15	.55801	72	29
30	9.88454	16	10.51636	68	9.89407	16	10.55873	73	30
31	.88470	16	.51704	68	.89423	15	.55946	72	31
32	.88486	16	.51773	69	.89438	16	.56019	73	32
33	.88502	16	.51842	69	.89454	15	.56092	73	33
34	.88518	16	.51911	69	.89470	16	.56165	73	34
35	9.88534	16	10.51980	69	9.89486	15	10.56238	73	35
36	.88550	16	.52049	69	.89501	16	.56311	73	36
37	.88566	16	.52118	69	.89517	15	.56384	73	37
38	.88582	16	.52187	69	.89533	15	.56457	73	38
39	.88598	16	.52256	69	.89548	16	.56531	73	39
40	9.88614	16	10.52325	69	9.89564	15	10.56604	73	40
41	.88630	16	.52394	69	.89580	16	.56678	73	41
42	.88646	15	.52464	69	.89596	15	.56751	74	42
43	.88662	16	.52533	69	.89611	15	.56825	73	43
44	.88678	16	.52603	69	.89627	16	.56899	74	44
45	9.88694	16	10.52672	70	9.89643	15	10.56973	74	45
46	.88710	16	.52742	69	.89658	15	.57047	73	46
47	.88726	16	.52812	69	.89674	16	.57120	74	47
48	.88742	16	.52881	70	.89690	15	.57195	74	48
49	.88758	16	.52951	70	.89705	15	.57269	74	49
50	9.88774	16	10.53021	70	9.89721	16	10.57343	74	50
51	.88790	15	.53091	70	.89737	15	.57417	74	51
52	.88805	16	.53161	70	.89752	15	.57491	74	52
53	.88821	16	.53231	70	.89768	15	.57566	74	53
54	.88837	16	.53301	70	.89783	16	.57640	75	34
55	9.88853	16	10.53372	70	9.89799	15	10.57715	74	55
56	.88869	15	.53442	70	.89815	15	.57790	74	56
57	.88885	16	.53512	70	.89830	15	.57864	75	57
58	.88901	16	.53583	70	.89846	16	.57939	75	58
59	.88917	16	.53653	70	.89862	15	.58014	75	59
60	9.88933		10.53724		9.89877		10.58089		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	75	74	73
6	7.5	7.4	7.3
7	8.7	8.6	8.5
8	10.0	9.8	9.7
9	11.2	11.1	10.9
10	12.5	12.3	12.1
20	25.0	24.6	24.3
30	37.5	37.0	36.5
40	50.0	49.3	48.6
50	62.5	61.6	60.8

	72	71	70
6	7.2	7.1	7.0
7	8.4	8.3	8.2
8	9.6	9.4	9.4
9	10.8	10.6	10.6
10	12.0	11.8	11.7
20	24.0	23.6	23.3
30	36.0	35.5	35.2
40	48.0	47.3	47.0
50	60.0	59.1	58.7

	69	68	67
6	6.9	6.8	6.7
7	8.0	7.9	7.8
8	9.2	9.0	8.9
9	10.3	10.2	10.0
10	11.5	11.3	11.1
20	23.0	22.6	22.3
30	34.5	34.0	33.5
40	46.0	45.3	44.6
50	57.5	56.6	55.8

	66	0
6	6.6	0.0
7	7.7	0.0
8	8.8	0.0
9	9.9	0.1
10	11.0	0.1
20	22.0	0.1
30	33.0	0.2
40	44.0	0.3
50	55.0	0.4

	16	16	15
6	1.6	1.6	1.5
7	1.9	1.8	1.8
8	2.2	2.1	2.0
9	2.5	2.4	2.3
10	2.7	2.6	2.6
20	5.5	5.3	5.1
30	8.2	8.0	7.7
40	11.0	10.6	10.3
50	13.7	13.3	12.9

P. P.

	78°				79°				
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′
0	9.89877	15	10.58089	75	9.90805	15	10.62745	80	0
1	.89893	15	.58164	75	.90820	15	.62825	80	1
2	.89908	15	.58239	75	.90835	15	.62906	80	2
3	.89924	15	.58315	75	.90851	15	.62986	81	3
4	.89939	16	.58390	75	.90866	15	.63067	80	4
5	9.89955	15	10.58465	75	9.90881	15	10.63148	81	5
6	.89971	15	.58541	75	.90897	15	.63229	81	6
7	.89986	15	.58616	76	.90912	15	.63310	81	7
8	.90002	15	.58692	75	.90927	15	.63391	81	8
9	.90017	15	.58768	76	.90943	15	.63472	81	9
10	9.90033	15	10.58844	76	9.90958	15	10.63553	81	10
11	.90048	15	.58920	75	.90973	15	.63634	81	11
12	.90064	16	.58995	75	.90988	15	.63716	81	12
13	.90080	15	.59072	76	.91004	15	.63797	81	13
14	.90095	15	.59148	76	.91019	15	.63879	82	14
15	9.90111	15	10.59224	76	9.91034	15	10.63961	82	15
16	.90126	15	.59300	76	.91049	15	.64043	82	16
17	.90142	15	.59377	76	.91065	15	.64125	82	17
18	.90157	15	.59453	76	.91080	15	.64207	82	18
19	.90173	15	.59530	76	.91095	15	.64289	82	19
20	9.90188	15	10.59606	77	9.91110	15	10.64371	82	20
21	.90204	15	.59683	76	.91126	15	.64453	82	21
22	.90219	15	.59760	77	.91141	15	.64536	82	22
23	.90235	15	.59837	77	.91156	15	.64618	83	23
24	.90250	15	.59914	77	.91171	15	.64701	82	24
25	9.90266	15	10.59991	77	9.91187	15	10.64784	83	25
26	.90281	15	.60068	77	.91202	15	.64867	83	26
27	.90297	15	.60145	77	.91217	15	.64950	83	27
28	.90312	15	.60223	77	.91232	15	.65033	83	28
29	.90328	15	.60300	77	.91247	15	.65116	83	29
30	9.90343	15	10.60378	77	9.91263	15	10.65199	83	30
31	.90359	15	.60455	77	.91278	15	.65283	83	31
32	.90374	15	.60533	78	.91293	15	.65366	83	32
33	.90389	15	.60611	77	.91308	15	.65450	84	33
34	.90405	15	.60688	78	.91323	15	.65534	83	34
35	9.90420	15	10.60766	78	9.91338	15	10.65617	84	35
36	.90436	15	.60844	78	.91354	15	.65701	84	36
37	.90451	15	.60923	78	.91369	15	.65785	84	37
38	.90467	15	.61001	78	.91384	15	.65870	84	38
39	.90482	15	.61079	78	.91399	15	.65954	84	39
40	9.90497	15	10.61158	78	9.91414	15	10.66038	84	40
41	.90513	15	.61236	78	.91429	15	.66123	84	41
42	.90528	15	.61315	78	.91445	15	.66207	84	42
43	.90544	15	.61393	79	.91460	15	.66292	85	43
44	.90559	15	.61472	78	.91475	15	.66377	85	44
45	9.90574	15	10.61551	79	9.91490	15	10.66462	85	45
46	.90590	15	.61630	79	.91505	15	.66547	85	46
47	.90605	15	.61709	79	.91520	15	.66632	85	47
48	.90621	15	.61788	79	.91535	15	.66717	85	48
49	.90636	15	.61867	79	.91550	15	.66803	85	49
50	9.90651	15	10.61947	79	9.91565	15	10.66888	85	50
51	.90667	15	.62026	79	.91581	15	.66974	85	51
52	.90682	15	.62105	80	.91596	15	.67059	86	52
53	.90697	15	.62185	79	.91611	15	.67145	86	53
54	.90713	15	.62265	80	.91626	15	.67231	86	54
55	9.90728	15	10.62345	79	9.91641	15	10.67317	86	55
56	.90744	15	.62424	80	.91656	15	.67403	86	56
57	.90759	15	.62504	80	.91671	15	.67490	86	57
58	.90774	15	.62585	80	.91686	15	.67576	86	58
59	.90790	15	.62665	80	.91701	15	.67663	86	59
60	9.90805		10.62745		9.91716		10.67749		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	86	85	84
6	8.6	8.5	8.4
7	10.0	9.9	9.8
8	11.4	11.3	11.2
9	12.9	12.7	12.6
10	14.3	14.1	14.0
20	28.6	28.3	28.0
30	43.0	42.5	42.0
40	57.3	56.6	56.0
50	71.6	70.8	70.0

	83	82	81
6	8.3	8.2	8.1
7	9.7	9.5	9.4
8	11.0	10.9	10.8
9	12.4	12.3	12.1
10	13.8	13.6	13.5
20	27.6	27.3	27.0
30	41.5	41.0	40.5
40	55.3	54.6	54.0
50	69.1	68.3	67.5

	80	79	78
6	8.0	7.9	7.8
7	9.3	9.2	9.1
8	10.6	10.5	10.4
9	12.0	11.8	11.7
10	13.3	13.1	13.0
20	26.6	26.3	26.0
30	40.0	39.5	39.0
40	53.3	52.6	52.0
50	66.6	65.8	65.0

	77	76	75
6	7.7	7.6	7.5
7	9.0	8.8	8.7
8	10.2	10.1	10.0
9	11.5	11.4	11.2
10	12.8	12.6	12.5
20	25.6	25.3	25.0
30	38.5	38.0	37.5
40	51.3	50.6	50.0
50	64.1	63.3	62.5

	0
6	0.0
7	0.0
8	0.0
9	0.1
10	0.1
20	0.1
30	0.2
40	0.3
50	0.4

	16	15	15
6	1.6	1.5	1.5
7	1.8	1.8	1.7
8	2.1	2.0	2.0
9	2.4	2.3	2.2
10	2.6	2.6	2.5
20	5.3	5.1	5.0
30	8.0	7.7	7.5
40	10.6	10.3	10.0
50	13.3	12.9	12.5

P. P.

′	80° Lg. Vers.	D	80° Log. Exs.	D	81° Lg. Vers.	D	81° Log. Exs.	D	′
0	9.91716	15	10.67749	86	9.92612	14	10.73178	95	0
1	.91731	15	.67836	87	.92626	15	.73273	94	1
2	.91746	15	.67923	87	.92641	14	.73368	95	2
3	.91761	15	.68010	87	.92656	15	.73463	95	3
4	.91776	15	.68097	87	.92671	15	.73558	95	4
5	9.91791	15	10.68184	87	9.92686	14	10.73653	95	5
6	.91807	15	.68272	87	.92700	15	.73748	95	6
7	.91822	15	.68359	87	.92715	14	.73844	96	7
8	.91837	15	.68447	87	.92730	15	.73940	95	8
9	.91852	15	.68534	88	.92745	14	.74035	96	9
10	9.91867	15	10.68622	88	9.92759	15	10.74131	96	10
11	.91882	15	.68710	88	.92774	14	.74227	96	11
12	.91897	15	.68798	88	.92789	15	.74324	96	12
13	.91912	15	.68886	88	.92804	14	.74420	96	13
14	.91927	15	.68975	88	.92818	15	.74517	96	14
15	9.91942	15	10.69063	88	9.92833	14	10.74613	97	15
16	.91957	15	.69152	88	.92848	14	.74710	97	16
17	.91972	15	.69240	89	.92862	15	.74807	97	17
18	.91987	15	.69329	89	.92877	14	.74905	97	18
19	.92002	14	.69418	89	.92892	15	.75002	97	19
20	9.92016	15	10.69507	89	9.92907	14	10.75099	98	20
21	.92031	15	.69596	89	.92921	14	.75197	97	21
22	.92046	15	.69686	89	.92936	15	.75295	98	22
23	.92061	15	.69775	89	.92951	14	.75393	98	23
24	.92076	15	.69865	90	.92965	15	.75491	98	24
25	9.92091	15	10.69955	89	9.92980	14	10.75589	98	25
26	.92106	15	.70044	90	.92995	14	.75688	98	26
27	.92121	15	.70134	90	.93009	15	.75786	99	27
28	.92136	14	.70224	90	.93024	14	.75885	99	28
29	.92151	15	.70315	90	.93039	14	.75984	99	29
30	9.92166	15	10.70405	90	9.93053	15	10.76083	99	30
31	.92181	15	.70495	91	.93068	14	.76182	99	31
32	.92196	15	.70586	90	.93083	14	.76282	100	32
33	.92211	15	.70677	91	.93097	15	.76382	99	33
34	.92226	14	.70768	91	.93112	14	.76481	100	34
35	9.92240	15	10.70859	91	9.93127	14	10.76581	100	35
36	.92255	15	.70950	91	.93141	14	.76681	100	36
37	.92270	15	.71041	91	.93156	15	.76782	100	37
38	.92285	15	.71133	91	.93171	14	.76882	100	38
39	.92300	14	.71224	91	.93185	14	.76983	100	39
40	9.92315	15	10.71316	92	9.93200	14	10.77083	101	40
41	.92330	15	.71408	92	.93214	15	.77184	101	41
42	.92345	15	.71500	92	.93229	14	.77286	101	42
43	.92360	14	.71592	92	.93244	14	.77387	101	43
44	.92374	15	.71684	92	.93258	14	.77488	101	44
45	9.92389	15	10.71776	92	9.93273	14	10.77590	102	45
46	.92404	14	.71869	92	.93287	15	.77692	102	46
47	.92419	15	.71961	93	.93302	14	.77794	102	47
48	.92434	15	.72054	92	.93317	14	.77896	102	48
49	.92449	14	.72147	93	.93331	14	.77998	102	49
50	9.92463	15	10.72240	93	9.93346	14	10.78101	102	50
51	.92478	15	.72333	93	.93360	14	.78203	103	51
52	.92493	14	.72427	93	.93375	14	.78306	103	52
53	.92508	15	.72520	93	.93389	15	.78409	103	53
54	.92523	15	.72614	93	.93404	14	.78513	103	54
55	9.92538	14	10.72707	94	9.93419	14	10.78616	104	55
56	.92552	15	.72801	94	.93433	14	.78720	103	56
57	.92567	15	.72895	94	.93448	14	.78823	104	57
58	.92582	14	.72990	94	.93462	14	.78927	104	58
59	.92597	15	.73084	94	.93477	14	.79031	104	59
60	9.92612		10.73178		9.93491		10.79136		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	90	80
6	9.0	8.0
7	10.5	9.3
8	12.0	10.6
9	13.5	12.0
10	15.0	13.3
20	30.0	26.6
30	45.0	40.0
40	60.0	53.3
50	75.0	66.6

	9	8
6	0.9	0.8
7	1.0	0.9
8	1.2	1.0
9	1.3	1.2
10	1.5	1.3
20	3.0	2.6
30	4.5	4.0
40	6.0	5.3
50	7.5	6.6

	7	6
6	0.7	0.6
7	0.8	0.7
8	0.0	0.8
9	1.0	0.9
10	1.1	1.0
20	2.3	2.0
30	3.5	3.0
40	4.6	4.0
50	5.8	5.0

	5	4
6	0.5	0.4
7	0.6	0.4
8	0.6	0.5
9	0.7	0.6
10	0.8	0.6
20	1.6	1.3
30	2.5	2.0
40	3.3	2.6
50	4.1	3.3

	15	15	14
6	1.5	1.5	1.4
7	1.8	1.7	1.7
8	2.0	2.0	1.9
9	2.3	2.2	2.2
10	2.6	2.5	2.4
20	5.1	5.0	4.8
30	7.7	7.5	7.2
40	10.3	10.0	9.6
50	12.9	12.5	12.1

P. P.

′	82° Lg. Vers.	D	82° Log. Exs.	D	83° Lg. Vers.	D	83° Log. Exs.	D	′
0	9.93491	14	10.79136	104	9.94356	14	10.85766	117	0
1	.93506	14	.79240	105	.94370	14	.85884	117	1
2	.93520	14	.79345	104	.94384	14	.86001	117	2
3	.93535	14	.79450	105	.94398	14	.86119	118	3
4	.93549	14	.79555	105	.94413	14	.86237	118	4
5	9.93564	14	10.79660	105	9.94427	14	10.86355	118	5
6	.93578	14	.79766	105	.94441	14	.86474	118	6
7	.93593	14	.79871	106	.94456	14	.86592	119	7
8	.93607	14	.79977	106	.94470	14	.86711	119	8
9	.93622	14	.80083	106	.94484	14	.86831	119	9
10	9.93636	14	10.80189	106	9.94498	14	10.86950	120	10
11	.93651	14	.80296	106	.94512	14	.87070	120	11
12	.93665	14	.80402	107	.94527	14	.87190	120	12
13	.93680	14	.80509	107	.94541	14	.87310	120	13
14	.93694	14	.80616	107	.94555	14	.87431	121	14
15	9.93709	14	10.80723	107	9.94569	14	10.87552	121	15
16	.93723	14	.80831	107	.94584	14	.87673	121	16
17	.93738	14	.80938	108	.94598	14	.87794	121	17
18	.93752	14	.81046	108	.94612	14	.87916	122	18
19	.93767	14	.81154	108	.94626	14	.88038	122	19
20	9.93781	14	10.81262	108	9.94640	14	10.88160	122	20
21	.93796	14	.81371	108	.94655	14	.88282	122	21
22	.93810	14	.81479	109	.94669	14	.88405	123	22
23	.93824	14	.81588	109	.94683	14	.88528	123	23
24	.93839	14	.81697	109	.94697	14	.88651	124	24
25	9.93853	14	10.81806	109	9.94711	14	10.88775	123	25
26	.93868	14	.81916	109	.94726	14	.88898	124	26
27	.93882	14	.82025	110	.94740	14	.89022	124	27
28	.93897	14	.82135	110	.94754	14	.89147	124	28
29	.93911	14	.82245	110	.94768	14	.89271	125	29
30	9.93925	14	10.82356	110	9.94782	14	10.89396	125	30
31	.93940	14	.82466	110	.94796	14	.89521	125	31
32	.93954	14	.82577	111	.94810	14	.89647	126	32
33	.93969	14	.82688	111	.94825	14	.89773	126	33
34	.93983	14	.82799	111	.94839	14	.89899	126	34
35	9.93997	14	10.82910	111	9.94853	14	10.90025	126	35
36	.94012	14	.83022	111	.94867	14	.90152	127	36
37	.94026	14	.83133	112	.94881	14	.90279	127	37
38	.94041	14	.83245	112	.94895	14	.90406	127	38
39	.94055	14	.83358	112	.94909	14	.90533	128	39
40	9.94069	14	10.83470	112	9.94923	14	10.90661	127	40
41	.94084	14	.83583	112	.94938	14	.90789	128	41
42	.94098	14	.83695	113	.94952	14	.90917	129	42
43	.94112	14	.83809	113	.94966	14	.91046	129	43
44	.94127	14	.83922	113	.94980	14	.91175	129	44
45	9.94141	14	10.84035	114	9.94994	14	10.91304	130	45
46	.94155	14	.84149	114	.95008	14	.91434	129	46
47	.94170	14	.84263	114	.95022	14	.91564	130	47
48	.94184	14	.84377	114	.95036	14	.91694	130	48
49	.94198	14	.84492	115	.95050	14	.91825	131	49
50	9.94213	14	10.84607	114	9.95064	14	10.91956	131	50
51	.94227	14	.84721	115	.95078	14	.92087	131	51
52	.94241	14	.84837	115	.95093	14	.92218	131	52
53	.94256	14	.84952	116	.95107	14	.92350	132	53
54	.94270	14	.85068	115	.95121	14	.92482	132	54
55	9.94284	14	10.85183	116	9.95135	14	10.92614	133	55
56	.94299	14	.85299	116	.95149	14	.92747	133	56
57	.94313	14	.85416	116	.95163	14	.92880	133	57
58	.94327	14	.85532	117	.95177	14	.93014	133	58
59	.94341	14	.85649	117	.95191	14	.93147	134	59
60	9.94356		10.85766		9.95205		10.93281		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	130	120
6	13.0	12.0
7	15.1	14.0
8	17.3	16.0
9	19.5	18.0
10	21.6	20.0
20	43.3	40.0
30	65.0	60.0
40	86.6	80.0
50	108.3	100.0

	110	100
6	11.0	10.0
7	12.8	11.6
8	14.6	13.3
9	16.5	15.0
10	18.3	16.6
20	36.6	33.3
30	55.0	50.0
40	73.3	66.6
50	91.6	83.3

	3	2
6	0.3	0.2
7	0.3	0.2
8	0.4	0.2
9	0.4	0.3
10	0.5	0.3
20	1.0	0.6
30	1.5	1.0
40	2.0	1.3
50	2.5	1.6

	1	0
6	0.1	0.0
7	0.1	0.0
8	0.1	0.0
9	0.1	0.1
10	0.1	0.1
20	0.3	0.1
30	0.5	0.2
40	0.6	0.3
50	0.8	0.4

	14	14
6	1.4	1.4
7	1.7	1.6
8	1.9	1.8
9	2.2	2.1
10	2.4	2.3
20	4.8	4.6
30	7.2	7.0
40	9.6	9.3
50	12.1	11.6

P. P.

′	84° Lg. Vers.	D	84° Log. Exs.	D	85° Lg. Vers.	D	85° Log. Exs.	D	′
0	9.95205	14	10.93281	134	9.96039	14	11.02010	158	0
1	.95219	14	.93416	135	.96053	13	.02168	159	1
2	.95233	14	.93551	135	.96067	14	.02327	159	2
3	.95247	14	.93686	135	.96081	14	.02487	159	3
4	.95261	14	.93821	135	.96095	13	.02646	160	4
5	9.95275	14	10.93957	136	9.96108	14	11.02807	161	5
6	.95289	14	.94093	136	.96122	13	.02968	161	6
7	.95303	14	.94229	137	.96136	14	.03129	161	7
8	.95317	14	.94366	137	.96150	13	.03291	162	8
9	.95331	14	.94503	137	.96163	14	.03453	163	9
10	9.95345	14	10.94641	137	9.96177	13	11.03616	163	10
11	.95359	13	.94778	138	.96191	14	.03780	164	11
12	.95373	14	.94917	138	.96205	13	.03944	164	12
13	.95387	14	.95055	139	.96218	14	.04108	165	13
14	.95401	14	.95194	139	.96232	13	.04273	165	14
15	9.95415	14	10.95333	139	9.96246	13	11.04438	166	15
16	.95429	14	.95473	140	.96259	14	.04604	167	16
17	.95443	14	.95613	140	.96273	13	.04771	167	17
18	.95457	14	.95753	140	.96287	14	.04938	167	18
19	.95471	14	.95894	141	.96301	13	.05106	168	19
20	9.95485	14	10.96035	141	9.96314	14	11.05274	169	20
21	.95499	14	.96176	142	.96328	13	.05443	169	21
22	.95513	14	.96318	142	.96342	13	.05612	169	22
23	.95527	13	.96461	142	.96355	14	.05782	170	23
24	.95540	14	.96603	143	.96369	13	.05952	171	24
25	9.95554	14	10.96746	143	9.96383	14	11.06123	171	25
26	.95568	14	.96889	144	.96397	13	.06295	172	26
27	.95582	14	.97033	144	.96410	13	.06467	173	27
28	.95596	14	.97177	144	.96424	14	.06640	173	28
29	.95610	14	.97322	145	.96438	13	.06813	174	29
30	9.95624	13	10.97467	145	9.96451	13	11.06987	174	30
31	.95638	14	.97612	145	.96465	14	.07161	175	31
32	.95652	14	.97758	146	.96479	13	.07336	176	32
33	.95666	14	.97904	146	.96492	13	.07512	176	33
34	.95680	13	.98050	147	.96506	13	.07688	177	34
35	9.95693	14	10.98197	147	9.96519	14	11.07865	177	35
36	.95707	14	.98345	147	.96533	13	.08043	178	36
37	.95721	14	.98492	148	.96547	13	.08221	179	37
38	.95735	14	.98640	149	.96560	14	.08400	179	38
39	.95749	13	.98789	149	.96574	13	.08579	180	39
40	9.95763	14	10.98938	149	9.96588	13	11.08759	180	40
41	.95777	14	.99087	150	.96601	13	.08940	181	41
42	.95791	13	.99237	150	.96615	14	.09121	182	42
43	.95804	14	.99387	151	.96629	13	.09303	182	43
44	.95818	14	.99538	151	.96642	13	.09486	183	44
45	9.95832	14	10.99689	151	9.96656	13	11.09669	184	45
46	.95846	13	.99841	152	.96669	13	.09853	185	46
47	.95860	14	10.99993	152	.96683	14	.10038	185	47
48	.95874	14	11.00145	153	.96697	13	.10223	186	48
49	.95888	13	.00298	153	.96710	13	.10409	186	49
50	9.95901	14	11.00451	154	9.96724	13	11.10595	187	50
51	.95915	13	.00605	154	.96737	13	.10783	188	51
52	.95929	14	.00759	155	.96751	13	.10971	189	52
53	.95943	14	.00914	155	.96764	14	.11160	189	53
54	.95957	13	.01069	155	.96778	13	.11349	190	54
55	9.95970	14	11.01225	156	9.96792	13	11.11539	191	55
56	.95984	14	.01381	156	.96805	13	.11730	191	56
57	.95998	13	.01537	157	.96819	13	.11922	192	57
58	.96012	14	.01694	157	.96832	13	.12114	193	58
59	.96026	13	.01852	158	.96846	13	.12307	193	59
60	9.96039		11.02010		9.96859		11.12501		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	190	180
6	19.0	18.0
7	22.1	21.0
8	25.3	24.0
9	28.5	27.0
10	31.6	30.0
20	63.3	60.0
30	95.0	90.0
40	126.6	120.0
50	158.3	150.0

	170	160
6	17.0	16.0
7	19.8	18.6
8	22.6	21.3
9	25.5	24.0
10	28.3	26.6
20	56.6	53.3
30	85.0	80.0
40	113.3	106.6
50	141.6	133.3

	150	140
6	15.0	14.0
7	17.5	16.3
8	20.0	18.6
9	22.5	21.0
10	25.0	23.3
20	50.0	46.6
30	75.0	70.0
40	100.0	93.3
50	125.0	116.6

	130	9	8
6	13.0	0.9	0.8
7	15.1	1.0	0.9
8	17.3	1.2	1.0
9	19.5	1.3	1.2
10	21.6	1.5	1.3
20	43.3	3.0	2.6
30	65.0	4.5	4.0
40	86.6	6.0	5.3
50	108.3	7.5	6.6

	7	6	5
6	0.7	0.6	0.5
7	0.8	0.7	0.6
8	0.9	0.8	0.6
9	1.0	0.9	0.7
10	1.1	1.0	0.8
20	2.3	2.0	1.6
30	3.5	3.0	2.5
40	4.6	4.0	3.3
50	5.8	5.0	4.1

	14	14	13
6	1.4	1.4	1.3
7	1.7	1.6	1.6
8	1.9	1.8	1.8
9	2.2	2.1	2.0
10	2.4	2.3	2.2
20	4.8	4.6	4.5
30	7.2	7.0	6.7
40	9.6	9.3	9.0
50	12.1	11.6	11.2

P. P.

TABLE VIII.—LOGARITHMIC VERSED SINES AND EXTERNAL SECANTS.

′	86° Lg. Vers.	D	86° Log. Exs.	D	87° Lg. Vers.	D	87° Log. Exs.	D	′
0	9.96859	13	11.12501	195	9.97665	13	11.25785	255	0
1	.96837	14	.12696	195	.97679	13	.26040	256	1
2	.96887	13	.12891	196	.97692	13	.26297	257	2
3	.96900	13	.13087	196	.97705	13	.26554	259	3
4	.96914	13	.13284	198	.97718	13	.26814	260	4
5	9.96927	13	11.13482	198	9.97732	13	11.27074	262	5
6	.96941	13	.13680	199	.97745	13	.27336	263	6
7	.96954	13	.13879	200	.97758	13	.27599	265	7
8	.96968	13	.14079	201	.97772	13	.27864	266	8
9	.96981	13	.14280	201	.97785	13	.28131	267	9
10	9.96995	13	11.14482	202	9.97798	13	11.28398	269	10
11	.97008	13	.14684	203	.97811	13	.28668	270	11
12	.97022	13	.14887	204	.97825	13	.28938	272	12
13	.97035	13	.15092	205	.97838	13	.29211	274	13
14	.97049	13	.15297	205	.97851	13	.29485	275	14
15	9.97062	13	11.15502	206	9.97864	13	11.29760	277	15
16	.97076	13	.15709	208	.97978	13	.30037	278	16
17	.97089	13	.15917	208	.97891	13	.30316	280	17
18	.97103	13	.16125	209	.97904	13	.30596	282	18
19	.97116	13	.16334	210	.97917	13	.30878	283	19
20	9.97130	13	11.16544	211	9.97931	13	11.31162	285	20
21	.97143	13	.16755	212	.97944	13	.31447	287	21
22	.97157	13	.16967	213	.97957	13	.31734	288	22
23	.97170	13	.17180	214	.97970	13	.32023	290	23
24	.97183	13	.17394	214	.97984	13	.32313	292	24
25	9.97197	13	11.17609	215	9.97997	13	11.32606	294	25
26	.97210	13	.17824	216	.98010	13	.32900	296	26
27	.97224	13	.18041	218	.98023	13	.33196	298	27
28	.97237	13	.18259	218	.98036	13	.33494	299	28
29	.97251	13	.18477	219	.98050	13	.33793	301	29
30	9.97264	13	11.18697	220	9.98063	13	11.34095	303	30
31	.97277	13	.18917	221	.98076	13	.34398	305	31
32	.97291	13	.19138	222	.98089	13	.34704	307	32
33	.97304	13	.19361	223	.98102	13	.35011	309	33
34	.97318	13	.19584	224	.98116	13	.35321	311	34
35	9.97331	13	11.19809	225	9.98129	13	11.35632	313	35
36	.97345	13	.20034	227	.98142	13	.35946	315	36
37	.97358	13	.20261	227	.98155	13	.36261	318	37
38	.97371	13	.20489	228	.98168	13	.36579	320	38
39	.97385	13	.20717	230	.98181	13	.36899	322	39
40	9.97398	13	11.20947	230	9.98195	13	11.37221	324	40
41	.97412	13	.21178	232	.98208	13	.37546	326	41
42	.97425	13	.21410	233	.98221	13	.37872	328	42
43	.97438	13	.21643	234	.98234	13	.38201	331	43
44	.97452	13	.21877	235	.98247	13	.38532	333	44
45	9.97465	13	11.22112	236	9.98260	13	11.38866	335	45
46	.97478	13	.22349	237	.98273	13	.39201	338	46
47	.97492	13	.22586	239	.98287	13	.39540	340	47
48	.97505	13	.22825	239	.98300	13	.39880	343	48
49	.97519	13	.23065	241	.98313	13	.40224	345	49
50	9.97532	13	11.23303	242	9.98326	13	11.40569	348	50
51	.97545	13	.23548	243	.98339	13	.40918	351	51
52	.97559	13	.23792	245	.98352	13	.41269	353	52
53	.97572	13	.24037	246	.98365	13	.41622	356	53
54	.97585	13	.24283	247	.98378	13	.41979	359	54
55	9.97599	13	11.24530	248	9.98392	13	11.42338	361	55
56	.97612	13	.24778	250	.98405	13	.42699	364	56
57	.97625	13	.25028	251	.98418	13	.43064	367	57
58	.97639	13	.25279	252	.98431	13	.43431	370	58
59	.97652	13	.25531	254	.98444	13	.43802	373	59
60	9.97665		11.25785		9.98457		11.44175		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	250	240
6	25.0	24.0
7	29.1	28.0
8	33.3	32.0
9	37.5	36.0
10	41.6	40.0
20	83.3	80.0
30	125.0	120.0
40	166.6	160.0
50	208.3	200.0

	230	220
6	23.0	22.0
7	26.8	25.6
8	30.6	29.3
9	34.5	33.0
10	38.3	36.6
20	76.6	73.3
30	115.0	110.0
40	153.3	146.6
50	191.6	183.3

	210	200
6	21.0	20.0
7	24.5	23.3
8	28.0	26.6
9	31.5	30.0
10	35.0	33.3
20	70.0	66.6
30	105.0	100.0
40	140.0	133.3
50	175.0	166.6

	190	4	3
6	19.0	0.4	0.3
7	22.1	0.4	0.3
8	25.3	0.5	0.4
9	28.5	0.6	0.4
10	31.6	0.6	0.5
20	63.3	1.3	1.0
30	95.0	2.0	1.5
40	126.6	2.6	2.0
50	158.3	3.3	2.5

	2	1	0
6	0.2	0.1	0.0
7	0.2	0.1	0.0
8	0.2	0.1	0.0
9	0.3	0.1	0.1
10	0.3	0.1	0.1
20	0.6	0.3	0.1
30	1.0	0.5	0.2
40	1.3	0.6	0.3
50	1.6	0.8	0.4

	14	13	13
6	1.4	1.3	1.3
7	1.6	1.6	1.5
8	1.8	1.8	1.7
9	2.1	2.0	1.9
10	2.3	2.2	2.1
20	4.6	4.5	4.3
30	7.0	6.7	6.5
40	9.3	9.0	8.6
50	11.6	11.2	10.8

P. P.

′	88° Lg. Vers.	D	88° Log. Exs.	D	89° Lg. Vers.	D	89° Log. Exs.	D	′
0	9.98457	13	11.44175	376	9.99235	12	11.75050	742	0
1	.98470	13	.44551	379	.99248	13	.75792	755	1
2	.98483	13	.44931	382	.99261	13	.76547	768	2
3	.98496	13	.45313	386	.99274	13	.77316	781	3
4	.98509	13	.45699	389	.99287	12	.78097	795	4
5	9.98522	13	11.46088	392	9.99299	13	11.78892	809	5
6	.98535	13	.46480	395	.99312	13	.79702	825	6
7	.98548	13	.46876	399	.99325	12	.80527	840	7
8	.98562	13	.47275	402	.99338	13	.81367	856	8
9	.98575	13	.47677	406	.99351	12	.82223	872	9
10	9.98588	13	11.48083	409	9.99363	13	11.83095	890	10
11	.98601	13	.48493	413	.99376	13	.83986	908	11
12	.98614	13	.48906	417	.99389	12	.84894	927	12
13	.98627	13	.49323	420	.99402	13	.85821	947	13
14	.98640	13	.49743	425	.99415	13	.86768	967	14
15	9.98653	13	11.50168	428	9.99428	12	11.87735	989	15
16	.98666	13	.50597	432	.99440	13	.88724	1009	16
17	.98679	13	.51029	436	.99453	12	.89735	1034	17
18	.98692	13	.51466	440	.99466	13	.90769	1059	18
19	.98705	13	.51906	445	.99479	12	.91829	1085	19
20	9.98718	13	11.52351	449	9.99491	13	11.92914	1112	20
21	.98731	13	.52801	454	.99504	13	.94026	1140	21
22	.98744	13	.53255	458	.99517	12	.95167	1171	22
23	.98757	13	.53713	463	.99530	13	.96338	1203	23
24	.98770	13	.54176	467	.99543	12	.97541	1236	24
25	9.98783	13	11.54643	472	9.99555	13	11.98777	1271	25
26	.98796	13	.55116	477	.99568	12	12.00048	1309	26
27	.98809	13	.55593	482	.99581	13	.01358	1349	27
28	.98822	13	.56076	487	.99594	12	.02707	1391	28
29	.98835	13	.56563	492	.99606	13	.04098	1436	29
30	9.98848	13	11.57056	498	9.99619	12	12.05535	1485	30
31	.98861	13	.57554	504	.99632	13	.07020	1537	31
32	.98874	13	.58058	509	.99645	12	.08557	1592	32
33	.98887	13	.58567	515	.99657	13	.10149	1652	33
34	.98900	13	.59082	520	.99670	12	.11801	1716	34
35	9.98913	12	11.59602	527	9.99683	12	12.13517	1785	35
36	.98925	13	.60129	533	.99695	13	.15302	1861	36
37	.98938	13	.60662	539	.99708	12	.17163	1943	37
38	.98951	13	.61202	545	.99721	13	.19106	2033	38
39	.98964	13	.61747	552	.99734	12	.21139	2131	39
40	9.98977	13	11.62300	559	9.99746	13	12.23271	2240	40
41	.98990	13	.62859	566	.99759	12	.25511	2361	41
42	.99003	13	.63425	573	.99772	12	.27872	2495	42
43	.99016	12	.63998	581	.99784	13	.30367	2645	43
44	.99029	13	.64579	588	.99797	12	.33013	2815	44
45	9.99042	13	11.65167	595	9.99810	13	12.35828	3009	45
46	.99055	13	.65762	604	.99823	12	.38837	3231	46
47	.99068	13	.66366	611	.99835	12	.42068	3489	47
48	.99081	12	.66978	620	.99848	13	.45557	3791	48
49	.99093	13	.67598	628	.99861	12	.49349	4152	49
50	9.99106	13	11.68227	638	9.99873	12	12.53501	4588	50
51	.99119	13	.68865	646	.99886	13	.58089	5127	51
52	.99132	13	.69511	656	.99899	12	.63217	5812	52
53	.99145	12	.70168	666	.99911	12	.69029	6707	53
54	.99158	13	.70834	675	.99924	13	.75736	7931	54
55	9.99171	13	11.71509	686	9.99937	12	12.83667	9704	55
56	.99184	13	.72196	696	.99949	12	.93371	12506	56
57	.99197	12	.72892	707	.99962	12	13.05877	17621	57
58	.99209	13	.73600	719	.99974	13	.23499	30116	58
59	.99222	13	.74319	730	.99987	12	.53615		59
60	9.99235		11.75050		10.00000		Infinity		60
′	Lg. Vers.	D	Log. Exs.	D	Lg. Vers.	D	Log. Exs.	D	′

P. P.

	13	13
6	1.3	1.3
7	1.6	1.5
8	1.8	1.7
9	2.0	1.9
10	2.2	2.1
20	4.5	4.3
30	6.7	6.5
40	9.0	8.6
50	11.2	10.8

	12
6	1.2
7	1.4
8	1.6
9	1.9
10	2.1
20	4.1
30	6.2
40	8.3
50	10.4

TABLE IX.—NATURAL SINES, COSINES, TANGENTS, AND COTANGENTS.

′	0° Sin.	0° Cos.	0° Tan.	0° Cot.	1° Sin.	1° Cos.	1° Tan.	1° Cot.	′
0	.00000	One	.00000	Infinite	.01745	.99985	.01746	57.2900	60
1	.00029	One	.00029	3437.75	.01774	.99984	.01775	56.3506	59
2	.00058	One	.00058	1718.87	.01803	.99984	.01804	55.4415	58
3	.00087	One	.00087	1145.92	.01832	.99983	.01833	54.5613	57
4	.00116	One	.00116	859.436	.01862	.99983	.01862	53.7086	56
5	.00145	One	.00145	687.549	.01891	.99982	.01891	52.8821	55
6	.00175	One	.00175	572.957	.01920	.99982	.01920	52.0807	54
7	.00204	One	.00204	491.106	.01949	.99981	.01949	51.3032	53
8	.00233	One	.00233	429.718	.01978	.99980	.01978	50.5485	52
9	.00262	One	.00262	381.971	.02007	.99980	.02007	49.8157	51
10	.00291	One	.00291	343.774	.02036	.99979	.02036	49.1039	50
11	.00320	.99999	.00320	312.521	.02065	.99979	.02066	48.4121	49
12	.00349	.99999	.00349	286.478	.02094	.99978	.02095	47.7395	48
13	.00378	.99999	.00378	264.441	.02123	.99977	.02124	47.0853	47
14	.00407	.99999	.00407	245.552	.02152	.99977	.02153	46.4489	46
15	.00436	.99999	.00436	229.182	.02181	.99976	.02182	45.8294	45
16	.00465	.99999	.00465	214.858	.02211	.99976	.02211	45.2261	44
17	.00495	.99999	.00495	202.219	.02240	.99975	.02240	44.6386	43
18	.00524	.99999	.00524	190.984	.02269	.99974	.02269	44.0661	42
19	.00553	.99998	.00553	180.932	.02298	.99974	.02298	43.5081	41
20	.00582	.99998	.00582	171.885	.02327	.99973	.02328	42.9641	40
21	.00611	.99998	.00611	163.700	.02356	.99972	.02357	42.4335	39
22	.00640	.99998	.00640	156.259	.02385	.99972	.02386	41.9158	38
23	.00669	.99998	.00669	149.465	.02414	.99971	.02415	41.4106	37
24	.00698	.99998	.00698	143.237	.02443	.99970	.02444	40.9174	36
25	.00727	.99997	.00727	137.507	.02472	.99969	.02473	40.4358	35
26	.00756	.99997	.00756	132.219	.02501	.99969	.02502	39.9655	34
27	.00785	.99997	.00785	127.321	.02530	.99968	.02531	39.5059	33
28	.00814	.99997	.00815	122.774	.02560	.99967	.02560	39.0568	32
29	.00844	.99996	.00844	118.540	.02589	.99966	.02589	38.6177	31
30	.00873	.99996	.00873	114.589	.02618	.99966	.02619	38.1885	30
31	.00902	.99996	.00902	110.892	.02647	.99965	.02648	37.7686	29
32	.00931	.99996	.00931	107.426	.02676	.99964	.02677	37.3579	28
33	.00960	.99995	.00960	104.171	.02705	.99963	.02706	36.9560	27
34	.00989	.99995	.00989	101.107	.02734	.99963	.02735	36.5627	26
35	.01018	.99995	.01018	98.2179	.02763	.99962	.02764	36.1776	25
36	.01047	.99995	.01047	95.4895	.02792	.99961	.02793	35.8006	24
37	.01076	.99994	.01076	92.9085	.02821	.99960	.02822	35.4313	23
38	.01105	.99994	.01105	90.4633	.02850	.99959	.02851	35.0695	22
39	.01134	.99994	.01135	88.1436	.02879	.99959	.02881	34.7151	21
40	.01164	.99993	.01164	85.9398	.02908	.99958	.02910	34.3678	20
41	.01193	.99993	.01193	83.8435	.02938	.99957	.02939	34.0273	19
42	.01222	.99993	.01222	81.8470	.02967	.99956	.02968	33.6935	18
43	.01251	.99992	.01251	79.9434	.02996	.99955	.02997	33.3662	17
44	.01280	.99992	.01280	78.1263	.03025	.99954	.03026	33.0452	16
45	.01309	.99991	.01309	76.3900	.03054	.99953	.03055	32.7303	15
46	.01338	.99991	.01338	74.7292	.03083	.99952	.03084	32.4213	14
47	.01367	.99991	.01367	73.1390	.03112	.99952	.03114	32.1181	13
48	.01396	.99990	.01396	71.6151	.03141	.99951	.03143	31.8205	12
49	.01425	.99990	.01425	70.1533	.03170	.99950	.03172	31.5284	11
50	.01454	.99989	.01455	68.7501	.03199	.99949	.03201	31.2416	10
51	.01483	.99989	.01484	67.4019	.03228	.99948	.03230	30.9599	9
52	.01513	.99989	.01513	66.1055	.03257	.99947	.03259	30.6833	8
53	.01542	.99988	.01542	64.8580	.03286	.99946	.03288	30.4116	7
54	.01571	.99988	.01571	63.6567	.03316	.99945	.03317	30.1446	6
55	.01600	.99987	.01600	62.4992	.03345	.99944	.03346	29.8823	5
56	.01629	.99987	.01629	61.3829	.03374	.99943	.03376	29.6245	4
57	.01658	.99986	.01658	60.3058	.03403	.99942	.03405	29.3711	3
58	.01687	.99986	.01687	59.2659	.03432	.99941	.03434	29.1220	2
59	.01716	.99985	.01716	58.2612	.03461	.99940	.03463	28.8771	1
60	.01745	.99985	.01746	57.2900	.03490	.99939	.03492	28.6363	0
′	89° Cos.	89° Sin.	89° Cot.	89° Tan.	88° Cos.	88° Sin.	88° Cot.	88° Tan.	′

	2°				3°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.03490	.99939	.03492	28.6363	.05234	.99863	.05241	19.0811	60
1	.03519	.99938	.03521	28.3994	.05263	.99861	.05270	18.9755	59
2	.03548	.99937	.03550	28.1664	.05292	.99860	.05299	18.8711	58
3	.03577	.99936	.03579	27.9372	.05321	.99858	.05328	18.7678	57
4	.03606	.99935	.03609	27.7117	.05350	.99857	.05357	18.6656	56
5	.03635	.99934	.03638	27.4899	.05379	.99855	.05387	18.5645	55
6	.03664	.99933	.03667	27.2715	.05408	.99854	.05416	18.4645	54
7	.03693	.99932	.03696	27.0566	.05437	.99852	.05445	18.3655	53
8	.03723	.99931	.03725	26.8450	.05466	.99851	.05474	18.2677	52
9	.03752	.99930	.03754	26.6367	.05495	.99849	.05503	18.1708	51
10	.03781	.99929	.03783	26.4316	.05524	.99847	.05533	18.0750	50
11	.03810	.99927	.03812	26.2296	.05553	.99846	.05562	17.9802	49
12	.03839	.99926	.03842	26.0307	.05582	.99844	.05591	17.8863	48
13	.03868	.99925	.03871	25.8348	.05611	.99842	.05620	17.7934	47
14	.03897	.99924	.03900	25.6418	.05640	.99841	.05649	17.7015	46
15	.03926	.99923	.03929	25.4517	.05669	.99839	.05678	17.6106	45
16	.03955	.99922	.03958	25.2644	.05698	.99838	.05708	17.5205	44
17	.03984	.99921	.03987	25.0798	.05727	.99836	.05737	17.4314	43
18	.04013	.99919	.04016	24.8978	.05756	.99834	.05766	17.3432	42
19	.04042	.99918	.04046	24.7185	.05785	.99833	.05795	17.2558	41
20	.04071	.99917	.04075	24.5418	.05814	.99831	.05824	17.1693	40
21	.04100	.99916	.04104	24.3675	.05844	.99829	.05854	17.0837	39
22	.04129	.99915	.04133	24.1957	.05873	.99827	.05883	16.9990	38
23	.04159	.99913	.04162	24.0263	.05902	.99826	.05912	16.9150	37
24	.04188	.99912	.04191	23.8593	.05931	.99824	.05941	16.8319	36
25	.04217	.99911	.04220	23.6945	.05960	.99822	.05970	16.7496	35
26	.04246	.99910	.04250	23.5321	.05989	.99821	.05999	16.6681	34
27	.04275	.99909	.04279	23.3718	.06018	.99819	.06029	16.5874	33
28	.04304	.99907	.04308	23.2137	.06047	.99817	.06058	16.5075	32
29	.04333	.99906	.04337	23.0577	.06076	.99815	.06087	16.4283	31
30	.04362	.99905	.04366	22.9038	.06105	.99813	.06116	16.3499	30
31	.04391	.99904	.04395	22.7519	.06134	.99812	.06145	16.2722	29
32	.04420	.99902	.04424	22.6020	.06163	.99810	.06175	16.1952	28
33	.04449	.99901	.04454	22.4541	.06192	.99808	.06204	16.1190	27
34	.04478	.99900	.04483	22.3081	.06221	.99806	.06233	16.0435	26
35	.04507	.99898	.04512	22.1640	.06250	.99804	.06262	15.9687	25
36	.04536	.99897	.04541	22.0217	.06279	.99803	.06291	15.8945	24
37	.04565	.99896	.04570	21.8813	.06308	.99801	.06321	15.8211	23
38	.04594	.99894	.04599	21.7426	.06337	.99799	.06350	15.7483	22
39	.04623	.99893	.04628	21.6056	.06366	.99797	.06379	15.6762	21
40	.04653	.99892	.04658	21.4704	.06395	.99795	.06408	15.6048	20
41	.04682	.99890	.04687	21.3369	.06424	.99793	.06437	15.5340	19
42	.04711	.99889	.04716	21.2049	.06453	.99792	.06467	15.4638	18
43	.04740	.99888	.04745	21.0747	.06482	.99790	.06496	15.3943	17
44	.04769	.99886	.04774	20.9460	.06511	.99788	.06525	15.3254	16
45	.04798	.99885	.04803	20.8188	.06540	.99786	.06554	15.2571	15
46	.04827	.99883	.04833	20.6932	.06569	.99784	.06584	15.1893	14
47	.04856	.99882	.04862	20.5691	.06598	.99782	.06613	15.1222	13
48	.04885	.99881	.04891	20.4465	.06627	.99780	.06642	15.0557	12
49	.04914	.99879	.04920	20.3253	.06656	.99778	.06671	14.9898	11
50	.04943	.99878	.04949	20.2056	.06685	.99776	.06700	14.9244	10
51	.04972	.99876	.04978	20.0872	.06714	.99774	.06730	14.8596	9
52	.05001	.99875	.05007	19.9702	.06743	.99772	.06759	14.7954	8
53	.05030	.99873	.05037	19.8546	.06773	.99770	.06788	14.7317	7
54	.05059	.99872	.05066	19.7403	.06802	.99768	.06817	14.6685	6
55	.05088	.99870	.05095	19.6273	.06831	.99766	.06847	14.6059	5
56	.05117	.99869	.05124	19.5156	.06860	.99764	.06876	14.5438	4
57	.05146	.99867	.05153	19.4051	.06889	.99762	.06905	14.4823	3
58	.05175	.99866	.05182	19.2959	.06918	.99760	.06934	14.4212	2
59	.05205	.99864	.05212	19.1879	.06947	.99758	.06963	14.3607	1
60	.05234	.99863	.05241	19.0811	.06976	.99756	.06993	14.3007	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	87°				86°				

TABLE IX.—NATURAL SINES, COSINES, TANGENTS, AND COTANGENTS.

	4°				5°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.06976	.99756	.06993	14.3007	.08716	.99619	.08749	11.4301	60
1	.07005	.99754	.07022	14.2411	.08745	.99617	.08778	11.3919	59
2	.07034	.99752	.07051	14.1821	.08774	.99614	.08807	11.3540	58
3	.07063	.99750	.07080	14.1235	.08803	.99612	.08837	11.3163	57
4	.07092	.99748	.07110	14.0655	.08831	.99609	.08866	11.2789	56
5	.07121	.99746	.07139	14.0079	.08860	.99607	.08895	11.2417	55
6	.07150	.99744	.07168	13.9507	.08889	.99604	.08925	11.2048	54
7	.07179	.99742	.07197	13.8940	.08918	.99602	.08954	11.1681	53
8	.07208	.99740	.07227	13.8378	.08947	.99599	.08983	11.1316	52
9	.07237	.99738	.07256	13.7821	.08976	.99596	.09013	11.0954	51
10	.07266	.99736	.07285	13.7267	.09005	.99594	.09042	11.0594	50
11	.07295	.99734	.07314	13.6719	.09034	.99591	.09071	11.0237	49
12	.07324	.99731	.07344	13.6174	.09063	.99588	.09101	10.9882	48
13	.07353	.99729	.07373	13.5634	.09092	.99586	.09130	10.9529	47
14	.07382	.99727	.07402	13.5098	.09121	.99583	.09159	10.9178	46
15	.07411	.99725	.07431	13.4566	.09150	.99580	.09189	10.8829	45
16	.07440	.99723	.07461	13.4039	.09179	.99578	.09218	10.8483	44
17	.07469	.99721	.07490	13.3515	.09208	.99575	.09247	10.8139	43
18	.07498	.99719	.07519	13.2996	.09237	.99572	.09277	10.7797	42
19	.07527	.99716	.07548	13.2480	.09266	.99570	.09306	10.7457	41
20	.07556	.99714	.07578	13.1969	.09295	.99567	.09335	10.7119	40
21	.07585	.99712	.07607	13.1461	.09324	.99564	.09365	10.6783	39
22	.07614	.99710	.07636	13.0958	.09353	.99562	.09394	10.6450	38
23	.07643	.99708	.07665	13.0458	.09382	.99559	.09423	10.6118	37
24	.07672	.99705	.07695	12.9962	.09411	.99556	.09453	10.5789	36
25	.07701	.99703	.07724	12.9469	.09440	.99553	.09482	10.5462	35
26	.07730	.99701	.07753	12.8981	.09469	.99551	.09511	10.5136	34
27	.07759	.99699	.07782	12.8496	.09498	.99548	.09541	10.4813	33
28	.07788	.99696	.07812	12.8014	.09527	.99545	.09570	10.4491	32
29	.07817	.99694	.07841	12.7536	.09556	.99542	.09600	10.4172	31
30	.07846	.99692	.07870	12.7062	.09585	.99540	.09629	10.3854	30
31	.07875	.99689	.07899	12.6591	.09614	.99537	.09658	10.3538	29
32	.07904	.99687	.07929	12.6124	.09642	.99534	.09688	10.3224	28
33	.07933	.99685	.07958	12.5660	.09671	.99531	.09717	10.2913	27
34	.07962	.99683	.07987	12.5199	.09700	.99528	.09746	10.2602	26
35	.07991	.99680	.08017	12.4742	.09729	.99526	.09776	10.2294	25
36	.08020	.99678	.08046	12.4288	.09758	.99523	.09805	10.1988	24
37	.08049	.99676	.08075	12.3838	.09787	.99520	.09834	10.1683	23
38	.08078	.99673	.08104	12.3390	.09816	.99517	.09864	10.1381	22
39	.08107	.99671	.08134	12.2946	.09845	.99514	.09893	10.1080	21
40	.08136	.99668	.08163	12.2505	.09874	.99511	.09923	10.0780	20
41	.08165	.99666	.08192	12.2067	.09903	.99508	.09952	10.0483	19
42	.08194	.99664	.08221	12.1632	.09932	.99506	.09981	10.0187	18
43	.08223	.99661	.08251	12.1201	.09961	.99503	.10011	9.98931	17
44	.08252	.99659	.08280	12.0772	.09990	.99500	.10040	9.96007	16
45	.08281	.99657	.08309	12.0346	.10019	.99497	.10069	9.93101	15
46	.08310	.99654	.08339	11.9923	.10048	.99494	.10099	9.90211	14
47	.08339	.99652	.08368	11.9504	.10077	.99491	.10128	9.87338	13
48	.08368	.99649	.08397	11.9087	.10106	.99488	.10158	9.84482	12
49	.08397	.99647	.08427	11.8673	.10135	.99485	.10187	9.81641	11
50	.08426	.99644	.08456	11.8262	.10164	.99482	.10216	9.78817	10
51	.08455	.99642	.08485	11.7853	.10192	.99479	.10246	9.76009	9
52	.08484	.99639	.08514	11.7448	.10221	.99476	.10275	9.73217	8
53	.08513	.99637	.08544	11.7045	.10250	.99473	.10305	9.70441	7
54	.08542	.99635	.08573	11.6645	.10279	.99470	.10334	9.67680	6
55	.08571	.99632	.08602	11.6248	.10308	.99467	.10363	9.64935	5
56	.08600	.99630	.08632	11.5853	.10337	.99464	.10393	9.62205	4
57	.08629	.99627	.08661	11.5461	.10366	.99461	.10422	9.59490	3
58	.08658	.99625	.08690	11.5072	.10395	.99458	.10452	9.56791	2
59	.08687	.99622	.08720	11.4685	.10424	.99455	.10481	9.54106	1
60	.08716	.99619	.08749	11.4301	.10453	.99452	.10510	9.51436	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	85°				84°				

	6°				7°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.10453	.99452	.10510	9.51436	.12187	.99255	.12278	8.14435	60
1	.10482	.99449	.10540	9.48781	.12216	.99251	.12308	8.12481	59
2	.10511	.99446	.10569	9.46141	.12245	.99248	.12338	8.10536	58
3	.10540	.99443	.10599	9.43515	.12274	.99244	.12367	8.08600	57
4	.10569	.99440	.10628	9.40904	.12302	.99240	.12397	8.06674	56
5	.10597	.99437	.10657	9.38307	.12331	.99237	.12426	8.04756	55
6	.10626	.99434	.10687	9.35724	.12360	.99233	.12456	8.02848	54
7	.10655	.99431	.10716	9.33155	.12389	.99230	.12485	8.00948	53
8	.10684	.99428	.10746	9.30599	.12418	.99226	.12515	7.99058	52
9	.10713	.99424	.10775	9.28058	.12447	.99222	.12544	7.97176	51
10	.10742	.99421	.10805	9.25530	.12476	.99219	.12574	7.95302	50
11	.10771	.99418	.10834	9.23016	.12504	.99215	.12603	7.93438	49
12	.10800	.99415	.10863	9.20516	.12533	.99211	.12633	7.91582	48
13	.10829	.99412	.10893	9.18028	.12562	.99208	.12662	7.89734	47
14	.10858	.99409	.10922	9.15554	.12591	.99204	.12692	7.87895	46
15	.10887	.99406	.10952	9.13093	.12620	.99200	.12722	7.86064	45
16	.10916	.99402	.10981	9.10646	.12649	.99197	.12751	7.84242	44
17	.10945	.99399	.11011	9.08211	.12678	.99193	.12781	7.82428	43
18	.10973	.99396	.11040	9.05789	.12706	.99189	.12810	7.80622	42
19	.11002	.99393	.11070	9.03379	.12735	.99186	.12840	7.78825	41
20	.11031	.99390	.11099	9.00983	.12764	.99182	.12869	7.77035	40
21	.11060	.99386	.11128	8.98598	.12793	.99178	.12899	7.75254	39
22	.11089	.99383	.11158	8.96227	.12822	.99175	.12929	7.73480	38
23	.11118	.99380	.11187	8.93867	.12851	.99171	.12958	7.71715	37
24	.11147	.99377	.11217	8.91520	.12880	.99167	.12988	7.69957	36
25	.11176	.99374	.11246	8.89185	.12908	.99163	.13017	7.68208	35
26	.11205	.99370	.11276	8.86862	.12937	.99160	.13047	7.66466	34
27	.11234	.99367	.11305	8.84551	.12966	.99156	.13076	7.64732	33
28	.11263	.99364	.11335	8.82252	.12995	.99152	.13106	7.63005	32
29	.11291	.99360	.11364	8.79964	.13024	.99148	.13136	7.61287	31
30	.11320	.99357	.11394	8.77689	.13053	.99144	.13165	7.59575	30
31	.11349	.99354	.11423	8.75425	.13081	.99141	.13195	7.57872	29
32	.11378	.99351	.11452	8.73172	.13110	.99137	.13224	7.56176	28
33	.11407	.99347	.11482	8.70931	.13139	.99133	.13254	7.54487	27
34	.11436	.99344	.11511	8.68701	.13168	.99129	.13284	7.52806	26
35	.11465	.99341	.11541	8.66482	.13197	.99125	.13313	7.51132	25
36	.11494	.99337	.11570	8.64275	.13226	.99122	.13343	7.49465	24
37	.11523	.99334	.11600	8.62078	.13254	.99118	.13372	7.47806	23
38	.11552	.99331	.11629	8.59893	.13283	.99114	.13402	7.46154	22
39	.11580	.99327	.11659	8.57718	.13312	.99110	.13432	7.44509	21
40	.11609	.99324	.11688	8.55555	.13341	.99106	.13461	7.42871	20
41	.11638	.99320	.11718	8.53402	.13370	.99102	.13491	7.41240	19
42	.11667	.99317	.11747	8.51259	.13399	.99098	.13521	7.39616	18
43	.11696	.99314	.11777	8.49128	.13427	.99094	.13550	7.37999	17
44	.11725	.99310	.11806	8.47007	.13456	.99091	.13580	7.36389	16
45	.11754	.99307	.11836	8.44896	.13485	.99087	.13609	7.34786	15
46	.11783	.99303	.11865	8.42795	.13514	.99083	.13639	7.33190	14
47	.11812	.99300	.11895	8.40705	.13543	.99079	.13669	7.31600	13
48	.11840	.99297	.11924	8.38625	.13572	.99075	.13698	7.30018	12
49	.11869	.99293	.11954	8.36555	.13600	.99071	.13728	7.28442	11
50	.11898	.99290	.11983	8.34496	.13629	.99067	.13758	7.26873	10
51	.11927	.99286	.12013	8.32446	.13658	.99063	.13787	7.25310	9
52	.11956	.99283	.12042	8.30406	.13687	.99059	.13817	7.23754	8
53	.11985	.99279	.12072	8.28376	.13716	.99055	.13846	7.22204	7
54	.12014	.99276	.12101	8.26355	.13744	.99051	.13876	7.20661	6
55	.12043	.99272	.12131	8.24345	.13773	.99047	.13906	7.19125	5
56	.12071	.99269	.12160	8.22344	.13802	.99043	.13935	7.17594	4
57	.12100	.99265	.12190	8.20352	.13831	.99039	.13965	7.16071	3
58	.12129	.99262	.12219	8.18370	.13860	.99035	.13995	7.14553	2
59	.12158	.99258	.12249	8.16398	.13889	.99031	.14024	7.13042	1
60	.12187	.99255	.12278	8.14435	.13917	.99027	.14054	7.11537	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	83°				82°				

	8°				9°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.13917	.99027	.14054	7.11537	.15643	.98769	.15838	6.31375	60
1	.13946	.99023	.14084	7.10038	.15672	.98764	.15868	6.30189	59
2	.13975	.99019	.14113	7.08546	.15701	.98760	.15898	6.29007	58
3	.14004	.99015	.14143	7.07059	.15730	.98755	.15928	6.27829	57
4	.14033	.99011	.14173	7.05579	.15758	.98751	.15958	6.26655	56
5	.14061	.99006	.14202	7.04105	.15787	.98746	.15988	6.25486	55
6	.14090	.99002	.14232	7.02637	.15816	.98741	.16017	6.24321	54
7	.14119	.98998	.14262	7.01174	.15845	.98737	.16047	6.23160	53
8	.14148	.98994	.14291	6.99718	.15873	.98732	.16077	6.22003	52
9	.14177	.98990	.14321	6.98268	.15902	.98728	.16107	6.20851	51
10	.14205	.98986	.14351	6.96823	.15931	.98723	.16137	6.19703	50
11	.14234	.98982	.14381	6.95385	.15959	.98718	.16167	6.18559	49
12	.14263	.98978	.14410	6.93952	.15988	.98714	.16196	6.17419	48
13	.14292	.98973	.14440	6.92525	.16017	.98709	.16226	6.16283	47
14	.14320	.98969	.14470	6.91104	.16046	.98704	.16256	6.15151	46
15	.14349	.98965	.14499	6.89688	.16074	.98700	.16286	6.14023	45
16	.14378	.98961	.14529	6.88278	.16103	.98695	.16316	6.12899	44
17	.14407	.98957	.14559	6.86874	.16132	.98690	.16346	6.11779	43
18	.14436	.98953	.14588	6.85475	.16160	.98686	.16376	6.10664	42
19	.14464	.98948	.14618	6.84082	.16189	.98681	.16405	6.09552	41
20	.14493	.98944	.14648	6.82694	.16218	.98676	.16435	6.08444	40
21	.14522	.98940	.14678	6.81312	.16246	.98671	.16465	6.07340	39
22	.14551	.98936	.14707	6.79936	.16275	.98667	.16495	6.06240	38
23	.14580	.98931	.14737	6.78564	.16304	.98662	.16525	6.05143	37
24	.14608	.98927	.14767	6.77199	.16333	.98657	.16555	6.04051	36
25	.14637	.98923	.14796	6.75838	.16361	.98652	.16585	6.02962	35
26	.14666	.98919	.14826	6.74483	.16390	.98648	.16615	6.01878	34
27	.14695	.98914	.14856	6.73133	.16419	.98643	.16645	6.00797	33
28	.14723	.98910	.14886	6.71789	.16447	.98638	.16674	5.99720	32
29	.14752	.98906	.14915	6.70450	.16476	.98633	.16704	5.98646	31
30	.14781	.98902	.14945	6.69116	.16505	.98629	.16734	5.97576	30
31	.14810	.98897	.14975	6.67787	.16533	.98624	.16764	5.96510	29
32	.14838	.98893	.15005	6.66463	.16562	.98619	.16794	5.95448	28
33	.14867	.98889	.15034	6.65144	.16591	.98614	.16824	5.94390	27
34	.14896	.98884	.15064	6.63831	.16620	.98609	.16854	5.93335	26
35	.14925	.98880	.15094	6.62523	.16648	.98604	.16884	5.92283	25
36	.14954	.98876	.15124	6.61219	.16677	.98600	.16914	5.91236	24
37	.14982	.98871	.15153	6.59921	.16706	.98595	.16944	5.90191	23
38	.15011	.98867	.15183	6.58627	.16734	.98590	.16974	5.89151	22
39	.15040	.98863	.15213	6.57339	.16763	.98585	.17004	5.88114	21
40	.15069	.98858	.15243	6.56055	.16792	.98580	.17033	5.87080	20
41	.15097	.98854	.15272	6.54777	.16820	.98575	.17063	5.86051	19
42	.15126	.98849	.15302	6.53503	.16849	.98570	.17093	5.85024	18
43	.15155	.98845	.15332	6.52234	.16878	.98565	.17123	5.84001	17
44	.15184	.98841	.15362	6.50970	.16906	.98561	.17153	5.82982	16
45	.15212	.98836	.15391	6.49710	.16935	.98556	.17183	5.81966	15
46	.15241	.98832	.15421	6.48456	.16964	.98551	.17213	5.80953	14
47	.15270	.98827	.15451	6.47206	.16992	.98546	.17243	5.79944	13
48	.15299	.98823	.15481	6.45961	.17021	.98541	.17273	5.78938	12
49	.15327	.98818	.15511	6.44720	.17050	.98536	.17303	5.77936	11
50	.15356	.98814	.15540	6.43484	.17078	.98531	.17333	5.76937	10
51	.15385	.98809	.15570	6.42253	.17107	.98526	.17363	5.75941	9
52	.15414	.98805	.15600	6.41026	.17136	.98521	.17393	5.74949	8
53	.15442	.98800	.15630	6.39804	.17164	.98516	.17423	5.73960	7
54	.15471	.98796	.15660	6.38587	.17193	.98511	.17453	5.72974	6
55	.15500	.98791	.15689	6.37374	.17222	.98506	.17483	5.71992	5
56	.15529	.98787	.15719	6.36165	.17250	.98501	.17513	5.71013	4
57	.15557	.98782	.15749	6.34961	.17279	.98496	.17543	5.70037	3
58	.15586	.98778	.15779	6.33761	.17308	.98491	.17573	5.69064	2
59	.15615	.98773	.15809	6.32566	.17336	.98486	.17603	5.68094	1
60	.15643	.98769	.15838	6.31375	.17365	.98481	.17633	5.67128	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	81°				80°				

	10°				11°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.17365	.98481	.17633	5.67128	.19081	.98163	.19438	5.14455	60
1	.17393	.98476	.17663	5.66165	.19109	.98157	.19468	5.13658	59
2	.17422	.98471	.17693	5.65205	.19138	.98152	.19498	5.12862	58
3	.17451	.98466	.17723	5.64248	.19167	.98146	.19529	5.12069	57
4	.17479	.98461	.17753	5.63295	.19195	.98140	.19559	5.11279	56
5	.17508	.98455	.17783	5.62344	.19224	.98135	.19589	5.10490	55
6	.17537	.98450	.17813	5.61397	.19252	.98129	.19619	5.09704	54
7	.17565	.98445	.17843	5.60452	.19281	.98124	.19649	5.08921	53
8	.17594	.98440	.17873	5.59511	.19309	.98118	.19680	5.08139	52
9	.17623	.98435	.17903	5.58573	.19338	.98112	.19710	5.07360	51
10	.17651	.98430	.17933	5.57638	.19366	.98107	.19740	5.06584	50
11	.17680	.98425	.17963	5.56706	.19395	.98101	.19770	5.05809	49
12	.17708	.98420	.17993	5.55777	.19423	.98096	.19801	5.05037	48
13	.17737	.98414	.18023	5.54851	.19452	.98090	.19831	5.04267	47
14	.17766	.98409	.18053	5.53927	.19481	.98084	.19861	5.03499	46
15	.17794	.98404	.18083	5.53007	.19509	.98079	.19891	5.02734	45
16	.17823	.98399	.18113	5.52090	.19538	.98073	.19921	5.01971	44
17	.17852	.98394	.18143	5.51176	.19566	.98067	.19952	5.01210	43
18	.17880	.98389	.18173	5.50264	.19595	.98061	.19982	5.00451	42
19	.17909	.98383	.18203	5.49356	.19623	.98056	.20012	4.99695	41
20	.17937	.98378	.18233	5.48451	.19652	.98050	.20042	4.98940	40
21	.17966	.98373	.18263	5.47548	.19680	.98044	.20073	4.98188	39
22	.17995	.98368	.18293	5.46648	.19709	.98039	.20103	4.97438	38
23	.18023	.98362	.18323	5.45751	.19737	.98033	.20133	4.96690	37
24	.18052	.98357	.18353	5.44857	.19766	.98027	.20164	4.95945	36
25	.18081	.98352	.18384	5.43966	.19794	.98021	.20194	4.95201	35
26	.18109	.98347	.18414	5.43077	.19823	.98016	.20224	4.94460	34
27	.18138	.98341	.18444	5.42192	.19851	.98010	.20254	4.93721	33
28	.18166	.98336	.18474	5.41309	.19880	.98004	.20285	4.92984	32
29	.18195	.98331	.18504	5.40429	.19908	.97998	.20315	4.92249	31
30	.18224	.98325	.18534	5.39552	.19937	.97992	.20345	4.91516	30
31	.18252	.98320	.18564	5.38677	.19965	.97987	.20376	4.90785	29
32	.18281	.98315	.18594	5.37805	.19994	.97981	.20406	4.90056	28
33	.18309	.98310	.18624	5.36936	.20022	.97975	.20436	4.89330	27
34	.18338	.98304	.18654	5.36070	.20051	.97969	.20466	4.88605	26
35	.18367	.98299	.18684	5.35206	.20079	.97963	.20497	4.87882	25
36	.18395	.98294	.18714	5.34345	.20108	.97958	.20527	4.87162	24
37	.18424	.98288	.18745	5.33487	.20136	.97952	.20557	4.86444	23
38	.18452	.98283	.18775	5.32631	.20165	.97946	.20588	4.85727	22
39	.18481	.98277	.18805	5.31778	.20193	.97940	.20618	4.85013	21
40	.18509	.98272	.18835	5.30928	.20222	.97934	.20648	4.84300	20
41	.18538	.98267	.18865	5.30080	.20250	.97928	.20679	4.83590	19
42	.18567	.98261	.18895	5.29235	.20279	.97922	.20709	4.82882	18
43	.18595	.98256	.18925	5.28393	.20307	.97916	.20739	4.82175	17
44	.18624	.98250	.18955	5.27553	.20336	.97910	.20770	4.81471	16
45	.18652	.98245	.18986	5.26715	.20364	.97905	.20800	4.80769	15
46	.18681	.98240	.19016	5.25880	.20393	.97899	.20830	4.80068	14
47	.18710	.98234	.19046	5.25048	.20421	.97893	.20861	4.79370	13
48	.18738	.98229	.19076	5.24218	.20450	.97887	.20891	4.78673	12
49	.18767	.98223	.19106	5.23391	.20478	.97881	.20921	4.77978	11
50	.18795	.98218	.19136	5.22566	.20507	.97875	.20952	4.77286	10
51	.18824	.98212	.19166	5.21744	.20535	.97869	.20982	4.76595	9
52	.18852	.98207	.19197	5.20925	.20563	.97863	.21013	4.75906	8
53	.18881	.98201	.19227	5.20107	.20592	.97857	.21043	4.75219	7
54	.18910	.98196	.19257	5.19293	.20620	.97851	.21073	4.74534	6
55	.18938	.98190	.19287	5.18480	.20649	.97845	.21104	4.73851	5
56	.18967	.98185	.19317	5.17671	.20677	.97839	.21134	4.73170	4
57	.18995	.98179	.19347	5.16863	.20706	.97833	.21164	4.72490	3
58	.19024	.98174	.19378	5.16058	.20734	.97827	.21195	4.71813	2
59	.19052	.98168	.19408	5.15256	.20763	.97821	.21225	4.71137	1
60	.19081	.98163	.19438	5.14455	.20791	.97815	.21256	4.70463	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	79°				78°				

	12°				13°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.20791	.97815	.21256	4.70463	.22495	.97437	.23087	4.33148	60
1	.20820	.97809	.21286	4.69791	.22523	.97430	.23117	4.32573	59
2	.20848	.97803	.21316	4.69121	.22552	.97424	.23148	4.32001	58
3	.20877	.97797	.21347	4.68452	.22580	.97417	.23179	4.31430	57
4	.20905	.97791	.21377	4.67786	.22608	.97411	.23209	4.30860	56
5	.20933	.97784	.21408	4.67121	.22637	.97404	.23240	4.30291	55
6	.20962	.97778	.21438	4.66458	.22665	.97398	.23271	4.29724	54
7	.20990	.97772	.21469	4.65797	.22693	.97391	.23301	4.29159	53
8	.21019	.97766	.21499	4.65138	.22722	.97384	.23332	4.28595	52
9	.21047	.97760	.21529	4.64480	.22750	.97378	.23363	4.28032	51
10	.21076	.97754	.21560	4.63825	.22778	.97371	.23393	4.27471	50
11	.21104	.97748	.21590	4.63171	.22807	.97365	.23424	4.26911	49
12	.21132	.97742	.21621	4.62518	.22835	.97358	.23455	4.26352	48
13	.21161	.97735	.21651	4.61868	.22863	.97351	.23485	4.25795	47
14	.21189	.97729	.21682	4.61219	.22892	.97345	.23516	4.25239	46
15	.21218	.97723	.21712	4.60572	.22920	.97338	.23547	4.24685	45
16	.21246	.97717	.21743	4.59927	.22948	.97331	.23578	4.24132	44
17	.21275	.97711	.21773	4.59283	.22977	.97325	.23608	4.23580	43
18	.21303	.97705	.21804	4.58641	.23005	.97318	.23639	4.23030	42
19	.21331	.97698	.21834	4.58001	.23033	.97311	.23670	4.22481	41
20	.21360	.97692	.21864	4.57363	.23062	.97304	.23700	4.21933	40
21	.21388	.97686	.21895	4.56726	.23090	.97298	.23731	4.21387	39
22	.21417	.97680	.21925	4.56091	.23118	.97291	.23762	4.20842	38
23	.21445	.97673	.21956	4.55458	.23146	.97284	.23793	4.20298	37
24	.21474	.97667	.21986	4.54826	.23175	.97278	.23823	4.19756	36
25	.21502	.97661	.22017	4.54196	.23203	.97271	.23854	4.19215	35
26	.21530	.97655	.22047	4.53568	.23231	.97264	.23885	4.18675	34
27	.21559	.97648	.22078	4.52941	.23260	.97257	.23916	4.18137	33
28	.21587	.97642	.22108	4.52316	.23288	.97251	.23946	4.17600	32
29	.21616	.97636	.22139	4.51693	.23316	.97244	.23977	4.17064	31
30	.21644	.97630	.22169	4.51071	.23345	.97237	.24008	4.16530	30
31	.21672	.97623	.22200	4.50451	.23373	.97230	.24039	4.15997	29
32	.21701	.97617	.22231	4.49832	.23401	.97223	.24069	4.15465	28
33	.21729	.97611	.22261	4.49215	.23429	.97217	.24100	4.14934	27
34	.21758	.97604	.22292	4.48600	.23458	.97210	.24131	4.14405	26
35	.21786	.97598	.22322	4.47986	.23486	.97203	.24162	4.13877	25
36	.21814	.97592	.22353	4.47374	.23514	.97196	.24193	4.13350	24
37	.21843	.97585	.22383	4.46764	.23542	.97189	.24223	4.12825	23
38	.21871	.97579	.22414	4.46155	.23571	.97182	.24254	4.12301	22
39	.21899	.97573	.22444	4.45548	.23599	.97176	.24285	4.11778	21
40	.21928	.97566	.22475	4.44942	.23627	.97169	.24316	4.11256	20
41	.21956	.97560	.22505	4.44338	.23656	.97162	.24347	4.10736	19
42	.21985	.97553	.22536	4.43735	.23684	.97155	.24377	4.10216	18
43	.22013	.97547	.22567	4.43134	.23712	.97148	.24408	4.09699	17
44	.22041	.97541	.22597	4.42534	.23740	.97141	.24439	4.09182	16
45	.22070	.97534	.22628	4.41936	.23769	.97134	.24470	4.08666	15
46	.22098	.97528	.22658	4.41340	.23797	.97127	.24501	4.08152	14
47	.22126	.97521	.22689	4.40745	.23825	.97120	.24532	4.07639	13
48	.22155	.97515	.22719	4.40152	.23853	.97113	.24562	4.07127	12
49	.22183	.97508	.22750	4.39560	.23882	.97106	.24593	4.06616	11
50	.22212	.97502	.22781	4.38969	.23910	.97100	.24624	4.06107	10
51	.22240	.97496	.22811	4.38381	.23938	.97093	.24655	4.05599	9
52	.22268	.97489	.22842	4.37793	.23966	.97086	.24686	4.05092	8
53	.22297	.97483	.22872	4.37207	.23995	.97079	.24717	4.04586	7
54	.22325	.97476	.22903	4.36623	.24023	.97072	.24747	4.04081	6
55	.22353	.97470	.22934	4.36040	.24051	.97065	.24778	4.03578	5
56	.22382	.97463	.22964	4.35459	.24079	.97058	.24809	4.03076	4
57	.22410	.97457	.22995	4.34879	.24108	.97051	.24840	4.02574	3
58	.22438	.97450	.23026	4.34300	.24136	.97044	.24871	4.02074	2
59	.22467	.97444	.23056	4.33723	.24164	.97037	.24902	4.01576	1
60	.22495	.97437	.23087	4.33148	.24192	.97030	.24933	4.01078	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	77°				76°				

	14°				15°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.24192	.97030	.24933	4.01078	.25882	.96593	.26795	3.73205	60
1	.24220	.97023	.24964	4.00582	.25910	.96585	.26826	3.72771	59
2	.24249	.97015	.24995	4.00086	.25938	.96578	.26857	3.72338	58
3	.24277	.97008	.25026	3.99592	.25966	.96570	.26888	3.71907	57
4	.24305	.97001	.25056	3.99099	.25994	.96562	.26920	3.71476	56
5	.24333	.96994	.25087	3.98607	.26022	.96555	.26951	3.71046	55
6	.24362	.96987	.25118	3.98117	.26050	.96547	.26982	3.70616	54
7	.24390	.96980	.25149	3.97627	.26079	.96540	.27013	3.70188	53
8	.24418	.96973	.25180	3.97139	.26107	.96532	.27044	3.69761	52
9	.24446	.96966	.25211	3.96651	.26135	.96524	.27076	3.69335	51
10	.24474	.96959	.25242	3.96165	.26163	.96517	.27107	3.68909	50
11	.24503	.96952	.25273	3.95680	.26191	.96509	.27138	3.68485	49
12	.24531	.96945	.25304	3.95196	.26219	.96502	.27169	3.68061	48
13	.24559	.96937	.25335	3.94713	.26247	.96494	.27201	3.67638	47
14	.24587	.96930	.25366	3.94232	.26275	.96486	.27232	3.67217	46
15	.24615	.96923	.25397	3.93751	.26303	.96479	.27263	3.66796	45
16	.24644	.96916	.25428	3.93271	.26331	.96471	.27294	3.66376	44
17	.24672	.96909	.25459	3.92793	.26359	.96463	.27326	3.65957	43
18	.24700	.96902	.25490	3.92316	.26387	.96456	.27357	3.65538	42
19	.24728	.96894	.25521	3.91839	.26415	.96448	.27388	3.65121	41
20	.24756	.96887	.25552	3.91364	.26443	.96440	.27419	3.64705	40
21	.24784	.96880	.25583	3.90890	.26471	.96433	.27451	3.64289	39
22	.24813	.96873	.25614	3.90417	.26500	.96425	.27482	3.63874	38
23	.24841	.96866	.25645	3.89945	.26528	.96417	.27513	3.63461	37
24	.24869	.96858	.25676	3.89474	.26556	.96410	.27545	3.63048	36
25	.24897	.96851	.25707	3.89004	.26584	.96402	.27576	3.62636	35
26	.24925	.96844	.25738	3.88536	.26612	.96394	.27607	3.62224	34
27	.24954	.96837	.25769	3.88068	.26640	.96386	.27638	3.61814	33
28	.24982	.96829	.25800	3.87601	.26668	.96379	.27670	3.61405	32
29	.25010	.96822	.25831	3.87136	.26696	.96371	.27701	3.60996	31
30	.25038	.96815	.25862	3.86671	.26724	.96363	.27732	3.60588	30
31	.25066	.96807	.25893	3.86208	.26752	.96355	.27764	3.60181	29
32	.25094	.96800	.25924	3.85745	.26780	.96347	.27795	3.59775	28
33	.25122	.96793	.25955	3.85284	.26808	.96340	.27826	3.59370	27
34	.25151	.96786	.25986	3.84824	.26836	.96332	.27858	3.58966	26
35	.25179	.96778	.26017	3.84364	.26864	.96324	.27889	3.58562	25
36	.25207	.96771	.26048	3.83906	.26892	.96316	.27921	3.58160	24
37	.25235	.96764	.26079	3.83449	.26920	.96308	.27952	3.57758	23
38	.25263	.96756	.26110	3.82992	.26948	.96301	.27983	3.57357	22
39	.25291	.96749	.26141	3.82537	.26976	.96293	.28015	3.56957	21
40	.25320	.96742	.26172	3.82083	.27004	.96285	.28046	3.56557	20
41	.25348	.96734	.26203	3.81630	.27032	.96277	.28077	3.56159	19
42	.25376	.96727	.26235	3.81177	.27060	.96269	.28109	3.55761	18
43	.25404	.96719	.26266	3.80726	.27088	.96261	.28140	3.55364	17
44	.25432	.96712	.26297	3.80276	.27116	.96253	.28172	3.54968	16
45	.25460	.96705	.26328	3.79827	.27144	.96246	.28203	3.54573	15
46	.25488	.96697	.26359	3.79378	.27172	.96238	.28234	3.54179	14
47	.25516	.96690	.26390	3.78931	.27200	.96230	.28266	3.53785	13
48	.25545	.96682	.26421	3.78485	.27228	.96222	.28297	3.53393	12
49	.25573	.96675	.26452	3.78040	.27256	.96214	.28329	3.53001	11
50	.25601	.96667	.26483	3.77595	.27284	.96206	.28360	3.52609	10
51	.25629	.96660	.26515	3.77152	.27312	.96198	.28391	3.52219	9
52	.25657	.96653	.26546	3.76709	.27340	.96190	.28423	3.51829	8
53	.25685	.96645	.26577	3.76268	.27368	.96182	.28454	3.51441	7
54	.25713	.96638	.26608	3.75828	.27396	.96174	.28486	3.51053	6
55	.25741	.96630	.26639	3.75388	.27424	.96166	.28517	3.50666	5
56	.25769	.96623	.26670	3.74950	.27452	.96158	.28549	3.50279	4
57	.25798	.96615	.26701	3.74512	.27480	.96150	.28580	3.49894	3
58	.25826	.96608	.26733	3.74075	.27508	.96142	.28612	3.49509	2
59	.25854	.96600	.26764	3.73640	.27536	.96134	.28643	3.49125	1
60	.25882	.96593	.26795	3.73205	.27564	.96126	.28675	3.48741	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	75°				74°				

′	16°				17°				′
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.27564	.96126	.28675	3.48741	.29237	.95630	.30573	3.27085	60
1	.27592	.96118	.28706	3.48359	.29265	.95622	.30605	3.26745	59
2	.27620	.96110	.28738	3.47977	.29293	.95613	.30637	3.26406	58
3	.27648	.96102	.28769	3.47596	.29321	.95605	.30669	3.26067	57
4	.27676	.96094	.28800	3.47216	.29348	.95596	.30700	3.25729	56
5	.27704	.96086	.28832	3.46837	.29376	.95588	.30732	3.25392	55
6	.27731	.96078	.28864	3.46458	.29404	.95579	.30764	3.25055	54
7	.27759	.96070	.28895	3.46080	.29432	.95571	.30796	3.24719	53
8	.27787	.96062	.28927	3.45703	.29460	.95562	.30828	3.24383	52
9	.27815	.96054	.28958	3.45327	.29487	.95554	.30860	3.24049	51
10	.27843	.96046	.28990	3.44951	.29515	.95545	.30891	3.23714	50
11	.27871	.96037	.29021	3.44576	.29543	.95536	.30923	3.23381	49
12	.27899	.96029	.29053	3.44202	.29571	.95528	.30955	3.23048	48
13	.27927	.96021	.29084	3.43829	.29599	.95519	.30987	3.22715	47
14	.27955	.96013	.29116	3.43456	.29626	.95511	.31019	3.22384	46
15	.27983	.96005	.29147	3.43084	.29654	.95502	.31051	3.22053	45
16	.28011	.95997	.29179	3.42713	.29682	.95493	.31083	3.21722	44
17	.28039	.95989	.29210	3.42343	.29710	.95485	.31115	3.21392	43
18	.28067	.95981	.29242	3.41973	.29737	.95476	.31147	3.21063	42
19	.28095	.95972	.29274	3.41604	.29765	.95467	.31178	3.20734	41
20	.28123	.95964	.29305	3.41236	.29793	.95459	.31210	3.20406	40
21	.28150	.95956	.29337	3.40869	.29821	.95450	.31242	3.20079	39
22	.28178	.95948	.29368	3.40502	.29849	.95441	.31274	3.19752	38
23	.28206	.95940	.29400	3.40136	.29876	.95433	.31306	3.19426	37
24	.28234	.95931	.29432	3.39771	.29904	.95424	.31338	3.19100	36
25	.28262	.95923	.29463	3.39406	.29932	.95415	.31370	3.18775	35
26	.28290	.95915	.29495	3.39042	.29960	.95407	.31402	3.18451	34
27	.28318	.95907	.29526	3.38679	.29987	.95398	.31434	3.18127	33
28	.28346	.95898	.29558	3.38317	.30015	.95389	.31466	3.17804	32
29	.28374	.95890	.29590	3.37955	.30043	.95380	.31498	3.17481	31
30	.28402	.95882	.29621	3.37594	.30071	.95372	.31530	3.17159	30
31	.28429	.95874	.29653	3.37234	.30098	.95363	.31562	3.16838	29
32	.28457	.95865	.29685	3.36875	.30126	.95354	.31594	3.16517	28
33	.28485	.95857	.29716	3.36516	.30154	.95345	.31626	3.16197	27
34	.28513	.95849	.29748	3.36158	.30182	.95337	.31658	3.15877	26
35	.28541	.95841	.29780	3.35800	.30209	.95328	.31690	3.15558	25
36	.28569	.95832	.29811	3.35443	.30237	.95319	.31722	3.15240	24
37	.28597	.95824	.29843	3.35087	.30265	.95310	.31754	3.14922	23
38	.28625	.95816	.29875	3.34732	.30292	.95301	.31786	3.14605	22
39	.28652	.95807	.29906	3.34377	.30320	.95293	.31818	3.14288	21
40	.28680	.95799	.29938	3.34023	.30348	.95284	.31850	3.13972	20
41	.28708	.95791	.29970	3.33670	.30376	.95275	.31882	3.13656	19
42	.28736	.95782	.30001	3.33317	.30403	.95266	.31914	3.13341	18
43	.28764	.95774	.30033	3.32965	.30431	.95257	.31946	3.13027	17
44	.28792	.95766	.30065	3.32614	.30459	.95248	.31978	3.12713	16
45	.28820	.95757	.30097	3.32264	.30486	.95240	.32010	3.12400	15
46	.28847	.95749	.30128	3.31914	.30514	.95231	.32042	3.12087	14
47	.28875	.95740	.30160	3.31565	.30542	.95222	.32074	3.11775	13
48	.28903	.95732	.30192	3.31216	.30570	.95213	.32106	3.11464	12
49	.28931	.95724	.30224	3.30868	.30597	.95204	.32139	3.11153	11
50	.28959	.95715	.30255	3.30521	.30625	.95195	.32171	3.10842	10
51	.28987	.95707	.30287	3.30174	.30653	.95186	.32203	3.10532	9
52	.29015	.95698	.30319	3.29829	.30680	.95177	.32235	3.10223	8
53	.29042	.95690	.30351	3.29483	.30708	.95168	.32267	3.09914	7
54	.29070	.95681	.30382	3.29139	.30736	.95159	.32299	3.09606	6
55	.29098	.95673	.30414	3.28795	.30763	.95150	.32331	3.09298	5
56	.29126	.95664	.30446	3.28452	.30791	.95142	.32363	3.08991	4
57	.29154	.95656	.30478	3.28109	.30819	.95133	.32396	3.08685	3
58	.29182	.95647	.30509	3.27767	.30846	.95124	.32428	3.08379	2
59	.29209	.95639	.30541	3.27426	.30874	.95115	.32460	3.08073	1
60	.29237	.95630	.30573	3.27085	.30902	.95106	.32492	3.07768	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	73°				72°				

′	18° Sin.	18° Cos.	18° Tan.	18° Cot.	19° Sin.	19° Cos.	19° Tan.	19° Cot.	′
0	.30902	.95106	.32492	3.07768	.32557	.94552	.34433	2.90421	60
1	.30929	.95097	.32524	3.07464	.32584	.94542	.34465	2.90147	59
2	.30957	.95088	.32556	3.07160	.32612	.94533	.34498	2.89873	58
3	.30985	.95079	.32588	3.06857	.32639	.94523	.34530	2.89600	57
4	.31012	.95070	.32621	3.06554	.32667	.94514	.34563	2.89327	56
5	.31040	.95061	.32653	3.06252	.32694	.94504	.34596	2.89055	55
6	.31068	.95052	.32685	3.05950	.32722	.94495	.34628	2.88783	54
7	.31095	.95043	.32717	3.05649	.32749	.94485	.34661	2.88511	53
8	.31123	.95033	.32749	3.05349	.32777	.94476	.34693	2.88240	52
9	.31151	.95024	.32782	3.05049	.32804	.94466	.34726	2.87970	51
10	.31178	.95015	.32814	3.04749	.32832	.94457	.34758	2.87700	50
11	.31206	.95006	.32846	3.04450	.32859	.94447	.34791	2.87430	49
12	.31233	.94997	.32878	3.04152	.32887	.94438	.34824	2.87161	48
13	.31261	.94988	.32911	3.03854	.32914	.94428	.34856	2.86892	47
14	.31289	.94979	.32943	3.03556	.32942	.94418	.34889	2.86624	46
15	.31316	.94970	.32975	3.03260	.32969	.94409	.34922	2.86356	45
16	.31344	.94961	.33007	3.02963	.32997	.94399	.34954	2.86089	44
17	.31372	.94952	.33040	3.02667	.33024	.94390	.34987	2.85822	43
18	.31399	.94943	.33072	3.02372	.33051	.94380	.35020	2.85555	42
19	.31427	.94933	.33104	3.02077	.33079	.94370	.35052	2.85289	41
20	.31454	.94924	.33136	3.01783	.33106	.94361	.35085	2.85023	40
21	.31482	.94915	.33169	3.01489	.33134	.94351	.35118	2.84758	39
22	.31510	.94906	.33201	3.01196	.33161	.94342	.35150	2.84494	38
23	.31537	.94897	.33233	3.00903	.33189	.94332	.35183	2.84229	37
24	.31565	.94888	.33266	3.00611	.33216	.94322	.35216	2.83965	36
25	.31593	.94878	.33298	3.00319	.33244	.94313	.35248	2.83702	35
26	.31620	.94869	.33330	3.00028	.33271	.94303	.35281	2.83439	34
27	.31648	.94860	.33363	2.99738	.33298	.94293	.35314	2.83176	33
28	.31675	.94851	.33395	2.99447	.33326	.94284	.35346	2.82914	32
29	.31703	.94842	.33427	2.99158	.33353	.94274	.35379	2.82653	31
30	.31730	.94832	.33460	2.98868	.33381	.94264	.35412	2.82391	30
31	.31758	.94823	.33492	2.98580	.33408	.94254	.35445	2.82130	29
32	.31786	.94814	.33524	2.98292	.33436	.94245	.35477	2.81870	28
33	.31813	.94805	.33557	2.98004	.33463	.94235	.35510	2.81610	27
34	.31841	.94795	.33589	2.97717	.33490	.94225	.35543	2.81350	26
35	.31868	.94786	.33621	2.97430	.33518	.94215	.35576	2.81091	25
36	.31896	.94777	.33654	2.97144	.33545	.94206	.35608	2.80833	24
37	.31923	.94768	.33686	2.96858	.33573	.94196	.35641	2.80574	23
38	.31951	.94758	.33718	2.96573	.33600	.94186	.35674	2.80316	22
39	.31979	.94749	.33751	2.96288	.33627	.94176	.35707	2.80059	21
40	.32006	.94740	.33783	2.96004	.33655	.94167	.35740	2.79802	20
41	.32034	.94730	.33816	2.95721	.33682	.94157	.35772	2.79545	19
42	.32061	.94721	.33848	2.95437	.33710	.94147	.35805	2.79289	18
43	.32089	.94712	.33881	2.95155	.33737	.94137	.35838	2.79033	17
44	.32116	.94702	.33913	2.94872	.33764	.94127	.35871	2.78778	16
45	.32144	.94693	.33945	2.94591	.33792	.94118	.35904	2.78523	15
46	.32171	.94684	.33978	2.94309	.33819	.94108	.35937	2.78269	14
47	.32199	.94674	.34010	2.94028	.33846	.94098	.35969	2.78014	13
48	.32227	.94665	.34043	2.93748	.33874	.94088	.36002	2.77761	12
49	.32254	.94656	.34075	2.93468	.33901	.94078	.36035	2.77507	11
50	.32282	.94646	.34108	2.93189	.33929	.94068	.36068	2.77254	10
51	.32309	.94637	.34140	2.92910	.33956	.94058	.36101	2.77002	9
52	.32337	.94627	.34173	2.92632	.33983	.94049	.36134	2.76750	8
53	.32364	.94618	.34205	2.92354	.34011	.94039	.36167	2.76498	7
54	.32392	.94609	.34238	2.92076	.34038	.94029	.36199	2.76247	6
55	.32419	.94599	.34270	2.91799	.34065	.94019	.36232	2.75996	5
56	.32447	.94590	.34303	2.91523	.34093	.94009	.36265	2.75746	4
57	.32474	.94580	.34335	2.91246	.34120	.93999	.36298	2.75496	3
58	.32502	.94571	.34368	2.90971	.34147	.93989	.36331	2.75246	2
59	.32529	.94561	.34400	2.90696	.34175	.93979	.36364	2.74997	1
60	.32557	.94552	.34433	2.90421	.34202	.93969	.36397	2.74748	0
′	71° Cos.	71° Sin.	71° Cot.	71° Tan.	70° Cos.	70° Sin.	70° Cot.	70° Tan.	′

	20°				21°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.34202	.93969	.36397	2.74748	.35837	.93358	.38386	2.60509	60
1	.34229	.93959	.36430	2.74499	.35864	.93348	.38420	2.60283	59
2	.34257	.93949	.36463	2.74251	.35891	.93337	.38453	2.60057	58
3	.34284	.93939	.36496	2.74004	.35918	.93327	.38487	2.59831	57
4	.34311	.93929	.36529	2.73756	.35945	.93316	.38520	2.59606	56
5	.34339	.93919	.36562	2.73509	.35973	.93306	.38553	2.59381	55
6	.34366	.93909	.36595	2.73263	.36000	.93295	.38587	2.59156	54
7	.34393	.93899	.36628	2.73017	.36027	.93285	.38620	2.58932	53
8	.34421	.93889	.36661	2.72771	.36054	.93274	.38654	2.58708	52
9	.34448	.93879	.36694	2.72526	.36081	.93264	.38687	2.58484	51
10	.34475	.93869	.36727	2.72281	.36108	.93253	.38721	2.58261	50
11	.34503	.93859	.36760	2.72036	.36135	.93243	.38754	2.58038	49
12	.34530	.93849	.36793	2.71792	.36162	.93232	.38787	2.57815	48
13	.34557	.93839	.36826	2.71548	.36190	.93222	.38821	2.57593	47
14	.34584	.93829	.36859	2.71305	.36217	.93211	.38854	2.57371	46
15	.34612	.93819	.36892	2.71062	.36244	.93201	.38888	2.57150	45
16	.34639	.93809	.36925	2.70819	.36271	.93190	.38921	2.56928	44
17	.34666	.93799	.36958	2.70577	.36298	.93180	.38955	2.56707	43
18	.34694	.93789	.36991	2.70335	.36325	.93169	.38988	2.56487	42
19	.34721	.93779	.37024	2.70094	.36352	.93159	.39022	2.56266	41
20	.34748	.93769	.37057	2.69853	.36379	.93148	.39055	2.56046	40
21	.34775	.93759	.37090	2.69612	.36406	.93137	.39089	2.55827	39
22	.34803	.93748	.37123	2.69371	.36434	.93127	.39122	2.55608	38
23	.34830	.93738	.37157	2.69131	.36461	.93116	.39156	2.55389	37
24	.34857	.93728	.37190	2.68892	.36488	.93106	.39190	2.55170	36
25	.34884	.93718	.37223	2.68653	.36515	.93095	.39223	2.54952	35
26	.34912	.93708	.37256	2.68414	.36542	.93084	39257	2.54734	34
27	.34939	.93698	.37289	2.68175	.36569	.93074	.39290	2.54516	33
28	.34966	.93688	.37322	2.67937	.36596	.93063	.39324	2.54299	32
29	.34993	.93677	.37355	2.67700	.36623	.93052	.39357	2.54082	31
30	.35021	.93667	.37388	2.67462	.36650	.93042	.39391	2.53865	30
31	.35048	.93657	.37422	2.67225	.36677	.93031	.39425	2.53648	29
32	.35075	.93647	.37455	2.66989	.36704	.93020	.39458	2.53432	28
33	.35102	.93637	.37488	2.66752	.36731	.93010	.39492	2.53217	27
34	.35130	.93626	.37521	2.66516	.36758	.92999	.39526	2.53001	26
35	.35157	.93616	.37554	2.66281	.36785	.92988	.39559	2.52786	25
36	.35184	.93606	.37588	2.66046	.36812	.92978	.39593	2.52571	24
37	.35211	.93596	.37621	2.65811	.36839	.92967	.39626	2.52357	23
38	.35239	.93585	.37654	2.65576	.36867	.92956	.39660	2.52142	22
39	.35266	.93575	.37687	2.65342	.36894	.92945	.39694	2.51929	21
40	.35293	.93565	.37720	2.65109	.36921	.92935	.39727	2.51715	20
41	.35320	.93555	.37754	2.64875	.36948	.92924	.39761	2.51502	19
42	.35347	.93544	.37787	2.64642	.36975	.92913	.39795	2.51289	18
43	.35375	.93534	.37820	2.64410	.37002	.92902	.39829	2.51076	17
44	.35402	.93524	.37853	2.64177	.37029	.92892	.39862	2.50864	16
45	.35429	.93514	.37887	2.63945	.37056	.92881	.39896	2.50652	15
46	.35456	.93503	.37920	2.63714	.37083	.92870	.39930	2.50440	14
47	.35484	.93493	.37953	2.63483	.37110	.92859	.39963	2.50229	13
48	.35511	.93483	.37986	2.63252	.37137	.92849	.39997	2.50018	12
49	.35538	.93472	.38020	2.63021	.37164	.92838	.40031	2.49807	11
50	.35565	.93462	.38053	2.62791	.37191	.92827	.40065	2.49597	10
51	.35592	.93452	.38086	2.62561	.37218	.92816	.40098	2.49386	9
52	.35619	.93441	.38120	2.62332	.37245	.92805	.40132	2.49177	8
53	.35647	.93431	.38153	2.62103	.37272	.92794	.40166	2.48967	7
54	.35674	.93420	.38186	2.61874	.37299	.92784	.40200	2.48758	6
55	.35701	.93410	.38220	2.61646	.37326	.92773	.40234	2.48549	5
56	.35728	.93400	.38253	2.61418	.37353	.92762	.40267	2.48340	4
57	.35755	.93389	.38286	2.61190	.37380	.92751	.40301	2.48132	3
58	.35782	.93379	.38320	2.60963	.37407	.92740	.40335	2.47924	2
59	.35810	.93368	.38353	2.60736	.37434	.92729	.40369	2.47716	1
60	.35837	.93358	.38386	2.60509	.37461	.92718	.40403	2.47509	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	69°				68°				

	22°				23°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.37461	.92718	.40403	2.47509	.39073	.92050	.42447	2.35585	60
1	.37488	.92707	.40436	2.47302	.39100	.92039	.42482	2.35395	59
2	.37515	.92697	.40470	2.47095	.39127	.92028	.42516	2.35205	58
3	.37542	.92686	.40504	2.46888	.39153	.92016	.42551	2.35015	57
4	.37569	.92675	.40538	2.46682	.39180	.92005	.42585	2.34825	56
5	.37595	.92664	.40572	2.46476	.39207	.91994	.42619	2.34636	55
6	.37622	.92653	.40606	2.46270	.39234	.91982	.42654	2.34447	54
7	.37649	.92642	.40640	2.46065	.39260	.91971	.42688	2.34258	53
8	.37676	.92631	.40674	2.45860	.39287	.91959	.42722	2.34069	52
9	.37703	92620	.40707	2.45655	.39314	.91948	.42757	2.33881	51
10	.37730	.92609	.40741	2.45451	.39341	.91936	.42791	2.33693	50
11	.37757	.92598	.40775	2.45246	.39367	.91925	.42826	2.33505	49
12	.37784	.92587	.40809	2.45043	.39394	.91914	.42860	2.33317	48
13	.37811	.92576	.40843	2.44839	.39421	.91902	.42894	2.33130	47
14	.37838	.92565	.40877	2.44636	.39448	.91891	.42929	2.32943	46
15	.37865	.92554	.40911	2.44433	.39474	.91879	.42963	2.32756	45
16	.37892	.92543	.40945	2.44230	.39501	.91868	.42998	2.32570	44
17	.37919	.92532	.40979	2.44027	.39528	.91856	.43032	2.32383	43
18	.37946	.92521	.41013	2.43825	.39555	.91845	.43067	2.32197	42
19	.37973	.92510	.41047	2.43623	.39581	.91833	.43101	2.32012	41
20	.37999	.92499	.41081	2.43422	.39608	.91822	.43136	2.31826	40
21	.38026	.92488	.41115	2.43220	.39635	.91810	.43170	2.31641	39
22	.38053	.92477	.41149	2.43019	.39661	.91799	.43205	2.31456	38
23	.38080	.92466	.41183	2.42819	.39688	.91787	.43239	2.31271	37
24	.38107	.92455	.41217	2.42618	.39715	.91775	.43274	2.31086	36
25	.38134	.92444	.41251	2.42418	.39741	.91764	.43308	2.30902	35
26	.38161	.92432	.41285	2.42218	.39768	.91752	.43343	2.30718	34
27	.38188	.92421	.41319	2.42019	.39795	.91741	.43378	2.30534	33
28	.38215	.92410	.41353	2.41819	.39822	.91729	.43412	2.30351	32
29	.38241	.92399	.41387	2.41620	.39848	.91718	.43447	2.30167	31
30	.38268	.92388	.41421	2.41421	.39875	.91706	.43481	2.29984	30
31	.38295	.92377	.41455	2.41223	.39902	.91694	.43516	2.29801	29
32	.38322	.92366	.41490	2.41025	.39928	.91683	.43550	2.29619	28
33	.33349	.92355	.41524	2.40827	.39955	.91671	.43585	2.29437	27
34	.38376	.92343	.41558	2.40629	.39982	.91660	.43620	2.29254	26
35	.38403	.92332	.41592	2.40432	.40008	.91648	.43654	2.29073	25
36	.38430	.92321	.41626	2.40235	.40035	.91636	.43689	2.28891	24
37	.38456	.92310	.41660	2.40038	.40062	.91625	.43724	2.28710	23
38	.38483	.92299	.41694	2.39841	.40088	.91613	.43758	2.28528	22
39	.38510	.92287	.41728	2.39645	.40115	.91601	.43793	2.28348	21
40	.38537	.92276	.41763	2.39449	.40141	.91590	.43828	2.28167	20
41	.38564	.92265	.41797	2.39253	.40168	.91578	.43862	2.27987	19
42	.38591	.92254	.41831	2.39058	.40195	.91566	.43897	2.27806	18
43	.38617	.92243	.41865	2.38863	.40221	.91555	.43932	2.27626	17
44	.38644	.92231	.41899	2.38668	.40248	.91543	.43966	2.27447	16
45	.38671	.92220	.41933	2.38473	.40275	.91531	.44001	2.27267	15
46	.38698	.92209	.41968	2.38279	40301	.91519	.44036	2.27088	14
47	.38725	.92198	.42002	2.38084	.40328	.91508	.44071	2.26909	13
48	.38752	.92186	.42036	2.37891	.40355	.91496	.44105	2.26730	12
49	.38778	.92175	.42070	2.37697	.40381	.91484	.44140	2.26552	11
50	.38805	.92164	.42105	2.37504	.40408	.91472	.44175	2.26374	10
51	.38832	.92152	.42139	2.37311	.40434	.91461	.44210	2.26196	9
52	.38859	.92141	.42173	2.37118	.40461	.91449	.44244	2.26018	8
53	.38886	.92130	.42207	2.36925	.40488	.91437	.44279	2.25840	7
54	.38912	.92119	.42242	2.36733	.40514	.91425	.44314	2.25663	6
55	.38939	.92107	.42276	2.36541	.40541	.91414	.44349	2.25486	5
56	.38966	.92096	.42310	2.36349	.40567	.91402	.44384	2.25309	4
57	.38993	.92085	.42345	2.36158	.40594	.91390	.44418	2.25132	3
58	.39020	.92073	.42379	2.35967	.40621	.91378	.44453	2.24956	2
59	.39046	.92062	.42413	2.35776	.40647	.91366	.44488	2.24780	1
60	.39073	.92050	.42447	2.35585	.40674	.91355	.44523	2.24604	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	67°				66°				

′	24° Sin.	24° Cos.	24° Tan.	24° Cot.	25° Sin.	25° Cos.	25° Tan.	25° Cot.	′
0	.40674	.91355	.44523	2.24604	.42262	.90631	.46631	2.14451	60
1	.40700	.91343	.44558	2.24428	.42288	.90618	.46666	2.14288	59
2	.40727	.91331	.44593	2.24252	.42315	.90606	.46702	2.14125	58
3	.40753	.91319	.44627	2.24077	.42341	.90594	.46737	2.13963	57
4	.40780	.91307	.44662	2.23902	.42367	.90582	.46772	2.13801	56
5	.40806	.91295	.44697	2.23727	.42394	.90569	.46808	2.13639	55
6	.40833	.91283	.44732	2.23553	.42420	.90557	.46843	2.13477	54
7	.40860	.91272	.44767	2.23378	.42446	.90545	.46879	2.13316	53
8	.40886	.91260	.44802	2.23204	.42473	.90532	.46914	2.13154	52
9	.40913	.91248	.44837	2.23030	.42499	.90520	.46950	2.12993	51
10	.40939	.91236	.44872	2.22857	.42525	.90507	.46985	2.12832	50
11	.40966	.91224	.44907	2.22683	.42552	.90495	.47021	2.12671	49
12	.40992	.91212	.44942	2.22510	.42578	.90483	.47056	2.12511	48
13	.41019	.91200	.44977	2.22337	.42604	.90470	.47092	2.12350	47
14	.41045	.91188	.45012	2.22164	.42631	.90458	.47128	2.12190	46
15	.41072	.91176	.45047	2.21992	.42657	.90446	.47163	2.12030	45
16	.41098	.91164	.45082	2.21819	.42683	.90433	.47199	2.11871	44
17	.41125	.91152	.45117	2.21647	.42709	.90421	.47234	2.11711	43
18	.41151	.91140	.45152	2.21475	.42736	.90408	.47270	2.11552	42
19	.41178	.91128	.45187	2.21304	.42762	.90396	.47305	2.11392	41
20	.41204	.91116	.45222	2.21132	.42788	.90383	.47341	2.11233	40
21	.41231	.91104	.45257	2.20961	.42815	.90371	.47377	2.11075	39
22	.41257	.91092	.45292	2.20790	.42841	.90358	.47412	2.10916	38
23	.41284	.91080	.45327	2.20619	.42867	.90346	.47448	2.10758	37
24	.41310	.91068	.45362	2.20449	.42894	.90334	.47483	2.10600	36
25	.41337	.91056	.45397	2.20278	.42920	.90321	.47519	2.10442	35
26	.41363	.91044	.45432	2.20108	.42946	.90309	.47555	2.10284	34
27	.41390	.91032	.45467	2.19938	.42972	.90296	.47590	2.10126	33
28	.41416	.91020	.45502	2.19769	.42999	.90284	.47626	2.09969	32
29	.41443	.91008	.45538	2.19599	.43025	.90271	.47662	2.09811	31
30	.41469	.90996	.45573	2.19430	.43051	.90259	.47698	2.09654	30
31	.41496	.90984	.45608	2.19261	.43077	.90246	. 7733	2.09498	29
32	.41522	.90972	.45643	2.19092	.43104	.90233	.47769	2.09341	28
33	.41549	.90960	.45678	2.18923	.43130	.90221	.47805	2.09184	27
34	.41575	.90948	.45713	2.18755	.43156	.90208	.47840	2.09028	26
35	.41602	.90936	.45748	2.18587	.43182	.90196	.47876	2.08872	25
36	.41628	.90924	.45784	2.18419	.43209	.90183	.47912	2.08716	24
37	.41655	.90911	.45819	2.18251	.43235	.90171	.47948	2.08560	23
38	.41681	.90899	.45854	2.18084	.43261	.90158	.47984	2.08405	22
39	.41707	.90887	.45889	2.17916	.43287	.90146	.48019	2.08250	21
40	.41734	.90875	.45924	2.17749	.43313	.90133	.48055	2.08094	20
41	.41760	.90863	.45960	2.17582	.43340	.90120	.48091	2.07939	19
42	.41787	.90851	.45995	2.17416	.43366	.90108	.48127	2.07785	18
43	.41813	.90839	.46030	2.17249	.43392	.90095	.48163	2.07630	17
44	.41840	.90826	.46065	2.17083	.43418	.90082	.48198	2.07476	16
45	.41866	.90814	.46101	2.16917	.43445	.90070	.48234	2.07321	15
46	.41892	.90802	.46136	2.16751	.43471	.90057	.48270	2.07167	14
47	.41919	.90790	.46171	2.16585	.43497	.90045	.48306	2.07014	13
48	.41945	.90778	.46206	2.16420	.43523	.90032	.48342	2.06860	12
49	.41972	.90766	.46242	2.16255	.43549	.90019	.48378	2.06706	11
50	.41998	.90753	.46277	2.16090	.43575	.90007	.48414	2.06553	10
51	.42024	.90741	.46312	2.15925	.43602	.89994	.48450	2.06400	9
52	.42051	.90729	.46348	2.15760	.43628	.89981	.48486	2.06247	8
53	.42077	.90717	.46383	2.15596	.43654	.89968	.48521	2.06094	7
54	.42104	.90704	.46418	2.15432	.43680	.89956	.48557	2.05942	6
55	.42130	.90692	.46454	2.15268	.43706	.89943	.48593	2.05790	5
56	.42156	.90680	.46489	2.15104	.43733	.89930	.48629	2.05637	4
57	.42183	.90668	.46525	2.14940	.43759	.89918	.48665	2.05485	3
58	.42209	.90655	.46560	2.14777	.43785	.89905	.48701	2.05333	2
59	.42235	.90643	.46595	2.14614	.43811	.89892	.48737	2.05182	1
60	.42262	.90631	.46631	2.14451	.43837	.89879	.48773	2.05030	0
′	65° Cos.	65° Sin.	65° Cot.	65° Tan.	64° Cos.	64° Sin.	64° Cot.	64° Tan.	′

	26°				27°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.43837	.89879	.48773	2.05030	.45399	.89101	.50953	1.96261	60
1	.43863	.89867	.48809	2.04879	.45425	.89087	.50989	1.96120	59
2	.43889	.89854	.48845	2.04728	.45451	.89074	.51026	1.95979	58
3	.43916	.89841	.48881	2.04577	.45477	.89061	.51063	1.95838	57
4	.43942	.89828	.48917	2.04426	.45503	.89048	.51099	1.95698	56
5	.43968	.89816	.48953	2.04276	.45529	.89035	.51136	1.95557	55
6	.43994	.89803	.48989	2.04125	.45554	.89021	.51173	1.95417	54
7	.44020	.89790	.49026	2.03975	.45580	.89008	.51209	1.95277	53
8	.44046	.89777	.49062	2.03825	.45606	.88995	.51246	1.95137	52
9	.44072	.89764	.49098	2.03675	.45632	.88981	.51283	1.94997	51
10	.44098	.89752	.49134	2.03526	.45658	.88968	.51319	1.94858	50
11	.44124	.89739	.49170	2.03376	.45684	.88955	.51356	1.94718	49
12	.44151	.89726	.49206	2.03227	.45710	.88942	.51393	1.94579	48
13	.44177	.89713	.49242	2.03078	.45736	.88928	.51430	1.94440	47
14	.44203	.89700	.49278	2.02929	.45762	.88915	.51467	1.94301	46
15	.44229	.89687	.49315	2.02780	.45787	.88902	.51503	1.94162	45
16	.44255	.89674	.49351	2.02631	.45813	.88888	.51540	1.94023	44
17	.44281	.89662	.49387	2.02483	.45839	.88875	.51577	1.93885	43
18	.44307	.89649	.49423	2.02335	.45865	.88862	.51614	1.93746	42
19	.44333	.89636	.49459	2.02187	.45891	.88848	.51651	1.93608	41
20	.44359	.89623	.49495	2.02039	.45917	.88835	.51688	1.93470	40
21	.44385	.89610	.49532	2.01891	.45942	.88822	.51724	1.93332	39
22	.44411	.89597	.49568	2.01743	.45968	.88808	.51761	1.93195	38
23	.44437	.89584	.49604	2.01596	.45994	.88795	.51798	1.93057	37
24	.44464	.89571	.49640	2.01449	.46020	.88782	.51835	1.92920	36
25	.44490	.89558	.49677	2.01302	.46046	.88768	.51872	1.92782	35
26	.44516	.89545	.49713	2.01155	.46072	.88755	.51909	1.92645	34
27	.44542	.89532	.49749	2.01008	.46097	.88741	.51946	1.92508	33
28	.44568	.89519	.49786	2.00862	.46123	.88728	.51983	1.92371	32
29	.44594	.89506	.49822	2.00715	.46149	.88715	.52020	1.92235	31
30	.44620	.89493	.49858	2.00569	.46175	.88701	.52057	1.92098	30
31	.44646	.89480	.49894	2.00423	.46201	.88688	.52094	1.91962	29
32	.44672	.89467	.49931	2.00277	.46226	.88674	.52131	1.91826	28
33	.44698	.89454	.49967	2.00131	.46252	.88661	.52168	1.91690	27
34	.44724	.89441	.50004	1.99986	.46278	.88647	.52205	1.91554	26
35	.44750	.89428	.50040	1.99841	.46304	.88634	.52242	1.91418	25
36	.44776	.89415	.50076	1.99695	.46330	.88620	.52279	1.91282	24
37	.44802	.89402	.50113	1.99550	.46355	.88607	.52316	1.91147	23
38	.44828	.89389	.50149	1.99406	.46381	.88593	.52353	1.91012	22
39	.44854	.89376	.50185	1.99261	.46407	.88580	.52390	1.90876	21
40	.44880	.89363	.50222	1.99116	.46433	.88566	.52427	1.90741	20
41	.44906	.89350	.50258	1.98972	.46458	.88553	.52464	1.90607	19
42	.44932	.89337	.50295	1.98828	.46484	.88539	.52501	1.90472	18
43	.44958	.89324	.50331	1.98684	.46510	.88526	.52538	1.90337	17
44	.44984	.89311	.50368	1.98540	.46536	.88512	.52575	1.90203	16
45	.45010	.89298	.50404	1.98396	.46561	.88499	.52613	1.90069	15
46	.45036	.89285	.50441	1.98253	.46587	.88485	.52650	1.89935	14
47	.45062	.89272	.50477	1.98110	.46613	.88472	.52687	1.89801	13
48	.45088	.89259	.50514	1.97966	.46639	.88458	.52724	1.89667	12
49	.45114	.89245	.50550	1.97823	.46664	.88445	.52761	1.89533	11
50	.45140	.89232	.50587	1.97681	.46690	.88431	.52798	1.89400	10
51	.45166	.89219	.50623	1.97538	.46716	.88417	.52836	1.89266	9
52	.45192	.89206	.50660	1.97395	.46742	.88404	.52873	1.89133	8
53	.45218	.89193	.50696	1.97253	.46767	.88390	.52910	1.89000	7
54	.45243	.89180	.50733	1.97111	.46793	.88377	.52947	1.88867	6
55	.45269	.89167	.50769	1.96969	.46819	.88363	.52985	1.88734	5
56	.45295	.89153	.50806	1.96827	.46844	.88349	.53022	1.88602	4
57	.45321	.89140	.50843	1.96685	.46870	.88336	.53059	1.88469	3
58	.45347	.89127	.50879	1.96544	.46896	.88322	.53096	1.88337	2
59	.45373	.89114	.50916	1.96402	.46921	.88308	.53134	1.88205	1
60	.45399	.89101	.50953	1.96261	.46947	.88295	.53171	1.88073	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	63°				62°				

′	28° Sin.	Cos.	Tan.	Cot.	29° Sin.	Cos.	Tan.	Cot.	′
0	.46947	.88295	.53171	1.88073	.48481	.87462	.55431	1.80405	60
1	.46973	.88281	.53208	1.87941	.48506	.87448	.55469	1.80281	59
2	.46999	.88267	.53246	1.87809	.48532	.87434	.55507	1.80158	58
3	.47024	.88254	.53283	1.87677	.48557	.87420	.55545	1.80034	57
4	.47050	.88240	.53320	1.87546	.48583	.87406	.55583	1.79911	56
5	.47076	.88226	.53358	1.87415	.48608	.87391	.55621	1.79788	55
6	.47101	.88213	.53395	1.87283	.48634	.87377	.55659	1.79665	54
7	.47127	.88199	.53432	1.87152	.48659	.87363	.55697	1.79542	53
8	.47153	.88185	.53470	1.87021	.48684	.87349	.55736	1.79419	52
9	.47178	.88172	.53507	1.86891	.48710	.87335	.55774	1.79296	51
10	.47204	.88158	.53545	1.86760	.48735	.87321	.55812	1.79174	50
11	.47229	.88144	.53582	1.86630	.48761	.87306	.55850	1.79051	49
12	.47255	.88130	.53620	1.86499	.48786	.87292	.55888	1.78929	48
13	.47281	.88117	.53657	1.86369	.48811	.87278	.55926	1.78807	47
14	.47306	.88103	.53694	1.86239	.48837	.87264	.55964	1.78685	46
15	.47332	.88089	.53732	1.86109	.48862	.87250	.56003	1.78563	45
16	.47358	.88075	.53769	1.85979	.48888	.87235	.56041	1.78441	44
17	.47383	.88062	.53807	1.85850	.48913	.87221	.56079	1.78319	43
18	.47409	.88048	.53844	1.85720	.48938	.87207	.56117	1.78198	42
19	.47434	.88034	.53882	1.85591	.48964	.87193	.56156	1.78077	41
20	.47460	.88020	.53920	1.85462	.48989	.87178	.56194	1.77955	40
21	.47486	.88006	.53957	1.85333	.49014	.87164	.56232	1.77834	39
22	.47511	.87993	.53995	1.85204	.49040	.87150	.56270	1.77713	38
23	.47537	.87979	.54032	1.85075	.49065	.87136	.56309	1.77592	37
24	.47562	.87965	.54070	1.84946	.49090	.87121	.56347	1.77471	36
25	.47588	.87951	.54107	1.84818	.49116	.87107	.56385	1.77351	35
26	.47614	.87937	.54145	1.84689	.49141	.87093	.56424	1.77230	34
27	.47639	.87923	.54183	1.84561	.49166	.87079	.56462	1.77110	33
28	.47665	.87909	.54220	1.84433	.49192	.87064	.56501	1.76990	32
29	.47690	.87896	.54258	1.84305	.49217	.87050	.56539	1.76869	31
30	.47716	.87882	.54296	1.84177	.49242	.87036	.56577	1.76749	30
31	.47741	.87868	.54333	1.84049	.49268	.87021	.56616	1.76629	29
32	.47767	.87854	.54371	1.83922	.49293	.87007	.56654	1.76510	28
33	.47793	.87840	.54409	1.83794	.49318	.86993	.56693	1.76390	27
34	.47818	.87826	.54446	1.83667	.49344	.86978	.56731	1.76271	26
35	.47844	.87812	.54484	1.83540	.49369	.86964	.56769	1.76151	25
36	.47869	.87798	.54522	1.83413	.49394	.86949	.56808	1.76032	24
37	.47895	.87784	.54560	1.83286	.49419	.86935	.56846	1.75913	23
38	.47920	.87770	.54597	1.83159	.49445	.86921	.56885	1.75794	22
39	.47946	.87756	.54635	1.83033	.49470	.86906	.56923	1.75675	21
40	.47971	.87743	.54673	1.82906	.49495	.86892	.56962	1.75556	20
41	.47997	.87729	.54711	1.82780	.49521	.86878	.57000	1.75437	19
42	.48022	.87715	.54748	1.82654	.49546	.86863	.57039	1.75319	18
43	.48048	.87701	.54786	1.82528	.49571	.86849	.57078	1.75200	17
44	.48073	.87687	.54824	1.82402	.49596	.86834	.57116	1.75082	16
45	.48099	.87673	.54862	1.82276	.49622	.86820	.57155	1.74964	15
46	.48124	.87659	.54900	1.82150	.49647	.86805	.57193	1.74846	14
47	.48150	.87645	.54938	1.82025	.49672	.86791	.57232	1.74728	13
48	.48175	.87631	.54975	1.81899	.49697	.86777	.57271	1.74610	12
49	.48201	.87617	.55013	1.81774	.49723	.86762	.57309	1.74492	11
50	.48226	.87603	.55051	1.81649	.49748	.86748	.57348	1.74375	10
51	.48252	.87589	.55089	1.81524	.49773	.86733	.57386	1.74257	9
52	.48277	.87575	.55127	1.81399	.49798	.86719	.57425	1.74140	8
53	.48303	.87561	.55165	1.81274	.49824	.86704	.57464	1.74022	7
54	.48328	.87546	.55203	1.81150	.49849	.86690	.57503	1.73905	6
55	.48354	.87532	.55241	1.81025	.49874	.86675	.57541	1.73788	5
56	.48379	.87518	.55279	1.80901	.49899	.86661	.57580	1.73671	4
57	.48405	.87504	.55317	1.80777	.49924	.86646	.57619	1.73555	3
58	.48430	.87490	.55355	1.80653	.49950	.86632	.57657	1.73438	2
59	.48456	.87476	.55393	1.80529	.49975	.86617	.57696	1.73321	1
60	.48481	.87462	.55431	1.80405	.50000	.86603	.57735	1.73205	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	61°				60°				

	30°				31°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.50000	.86603	.57735	1.73205	.51504	.85717	.60086	1.66428	60
1	.50025	.86588	.57774	1.73089	.51529	.85702	.60126	1.66318	59
2	.50050	.86573	.57813	1.72973	.51554	.85687	.60165	1.66209	58
3	.50076	.86559	.57851	1.72857	.51579	.85672	.60205	1.66099	57
4	.50101	.86544	.57890	1.72741	.51604	.85657	.60245	1.65990	56
5	.50126	.86530	.57929	1.72625	.51628	.85642	.60284	1.65881	55
6	.50151	.86515	.57968	1.72509	.51653	.85627	.60324	1.65772	54
7	.50176	.86501	.58007	1.72393	.51678	.85612	.60364	1.65663	53
8	.50201	.86486	.58046	1.72278	.51703	.85597	.60403	1.65554	52
9	.50227	.86471	.58085	1.72163	.51728	.85582	.60443	1.65445	51
10	.50252	.86457	.58124	1.72047	.51753	.85567	.60483	1.65337	50
11	.50277	.86442	.58162	1.71932	.51778	.85551	.60522	1.65228	49
12	.50302	.86427	.58201	1.71817	.51803	.85536	.60562	1.65120	48
13	.50327	.86413	.58240	1.71702	.51828	.85521	.60602	1.65011	47
14	.50352	.86398	.58279	1.71588	.51852	.85506	.60642	1.64903	46
15	.50377	.86384	.58318	1.71473	.51877	.85491	.60681	1.64795	45
16	.50403	.86369	.58357	1.71358	.51902	.85476	.60721	1.64687	44
17	.50428	.86354	.58396	1.71244	.51927	.85461	.60761	1.64579	43
18	.50453	.86340	.58435	1.71129	.51952	.85446	.60801	1.64471	42
19	.50478	.86325	.58474	1.71015	.51977	.85431	.60841	1.64363	41
20	.50503	.86310	.58513	1.70901	.52002	.85416	.60881	1.64256	40
21	.50528	.86295	.58552	1.70787	.52026	.85401	.60921	1.64148	39
22	.50553	.86281	.58591	1.70673	.52051	.85385	.60960	1.64041	38
23	.50578	.86266	.58631	1.70560	.52076	.85370	.61000	1.63934	37
24	.50603	.86251	.58670	1.70446	.52101	.85355	.61040	1.63826	36
25	.50628	.86237	58709	1.70332	.52126	.85340	.61080	1.63719	35
26	.50654	.86222	.58748	1.70219	.52151	.85325	.61120	1.63612	34
27	.50679	.86207	.58787	1.70106	.52175	.85310	.61160	1.63505	33
28	.50704	.86192	.58826	1.69992	.52200	.85294	.61200	1.63398	32
29	.50729	.86178	.58865	1.69879	.52225	.85279	.61240	1.63292	31
30	.50754	.86163	.58905	1.69766	.52250	.85264	.61280	1.63185	30
31	.50779	.86148	.58944	1.69653	.52275	.85249	.61320	1.63079	29
32	.50804	.86133	.58983	1.69541	52299	.85234	.61360	1.62972	28
33	.50829	.86119	.59022	1.69428	.52324	.85218	.61400	1.62866	27
34	.50854	.86104	.59061	1.69316	.52349	.85203	.61440	1.62760	26
35	.50879	.86089	.59101	1.69203	.52374	.85188	.61480	1.62654	25
36	.50904	.86074	.59140	1.69091	.52399	.85173	.61520	1.62548	24
37	.50929	.86059	.59179	1.68979	.52423	.85157	.61561	1.62442	23
38	.50954	.86045	59218	1.68866	.52448	.85142	.61601	1.62336	22
39	.50979	.86030	.59258	1.68754	.52473	.85127	.61641	1.62230	21
40	.51004	.86015	.59297	1.68643	.52498	.85112	.61681	1.62125	20
41	.51029	.86000	.59336	1.68531	.52522	.85096	.61721	1.62019	19
42	.51054	85985	.59376	1.68419	.52547	.85081	.61761	1.61914	18
43	.51079	.85970	.59415	1.68308	.52572	.85066	.61801	1.61808	17
44	.51104	.85956	.59454	1.68196	.52597	.85051	.61842	1.61703	16
45	.51129	.85941	.59494	1.68085	.52621	.85035	.61882	1.61598	15
46	.51154	.85926	.59533	1.67974	.52646	.85020	.61922	1.61493	14
47	.51179	.85911	.59573	1.67863	.52671	.85005	.61962	1.61388	13
48	.51204	.85896	.59612	1.67752	.52696	.84989	.62003	1.61283	12
49	.51229	.85881	.59651	1.67641	.52720	.84974	.62043	1.61179	11
50	.51254	.85866	.59691	1.67530	.52745	.84959	.62083	1.61074	10
51	.51279	.85851	.59730	1.67419	.52770	.84943	.62124	1.60970	9
52	.51304	.85836	.59770	1.67309	.52794	.84928	.62164	1.60865	8
53	.51329	.85821	.59809	1.67198	.52819	.84913	.62204	1.60761	7
54	.51354	.85806	.59849	1.67088	.52844	.84897	.62245	1.60657	6
55	.51379	.85792	.59888	1.66978	.52869	.84882	.62285	1.60553	5
56	.51404	.85777	.59928	1.66867	.52893	.84866	.62325	1.60449	4
57	.51429	.85762	.59967	1.66757	.52918	.84851	.62366	1.60345	3
58	.51454	.85747	.60007	1.66647	.52943	.84836	.62406	1.60241	2
59	.51479	85732	.60046	1.66538	.52967	.84820	.62446	1.60137	1
60	.51504	.85717	.60086	1.66428	.52992	.84805	.62487	1.60033	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	59°				58°				

	32°				33°				
′	Sin.	Cos	Tan.	Cot	Sin.	Cos.	Tan.	Cot.	′
0	.52992	.84805	.62487	1.60033	.54464	.83867	.64941	1.53986	60
1	.53017	.84789	.62527	1.59930	.54488	.83851	.64982	1.53888	59
2	.53041	.84774	.62568	1.59826	.54513	.83835	.65024	1.53791	58
3	.53066	.84759	.62608	1.59723	.54537	.83819	.65065	1.53693	57
4	.53091	.84743	.62649	1.59620	.54561	.83804	.65106	1.53595	56
5	.53115	.84728	.62689	1.59517	.54586	.83788	.65148	1.53497	55
6	.53140	.84712	.62730	1.59414	.54610	.83772	.65189	1.53400	54
7	.53164	.84697	.62770	1.59311	.54635	.83756	.65231	1.53302	53
8	.53189	.84681	.62811	1.59208	.54659	.83740	.65272	1.53205	52
9	.53214	.84666	.62852	1.59105	.54683	.83724	.65314	1.53107	51
10	.53238	.84650	.62892	1.59002	.54708	.83708	.65355	1.53010	50
11	.53263	.84635	.62933	1.58900	.54732	.83692	.65397	1.52913	49
12	.53288	.84619	.62973	1.58797	.54756	.83676	.65438	1.52816	48
13	.53312	.84604	.63014	1.58695	.54781	.83660	.65480	1.52719	47
14	.53337	.84588	.63055	1.58593	.54805	.83645	.65521	1.52622	46
15	.53361	.84573	.63095	1.58490	.54829	.83629	.65563	1.52525	45
16	.53386	.84557	.63136	1.58388	.54854	.83613	.65604	1.52429	44
17	.53411	.84542	.63177	1.58286	.54878	.83597	.65646	1.52332	43
18	.53435	.84526	.63217	1.58184	.54902	.83581	.65688	1.52235	42
19	.53460	.84511	.63258	1.58083	.54927	.83565	.65729	1.52139	41
20	.53484	.84495	.63299	1.57981	.54951	.83549	.65771	1.52043	40
21	.53509	.84480	.63340	1.57879	.54975	.83533	.65813	1.51946	39
22	.53534	.84464	.63380	1.57778	.54999	.83517	.65854	1.51850	38
23	.53558	.84448	.63421	1.57676	.55024	.83501	.65896	1.51754	37
24	.53583	.84433	.63462	1.57575	.55048	.83485	.65938	1.51658	36
25	.53607	.84417	.63503	1.57474	.55072	.83469	.65980	1.51562	35
26	.53632	.84402	.63544	1.57372	.55097	.83453	.66021	1.51466	34
27	.53656	.84386	.63584	1.57271	.55121	.83437	.66063	1.51370	33
28	.53681	.84370	.63625	1.57170	.55145	.83421	.66105	1.51275	32
29	.53705	.84355	.63666	1.57069	.55169	.83405	.66147	1.51179	31
30	.53730	.84339	.63707	1.56969	.55194	.83389	.66189	1.51084	30
31	.53754	.84324	.63748	1.56868	.55218	.83373	.66230	1.50988	29
32	.53779	.84308	.63789	1.56767	.55242	.83356	.66272	1.50893	28
33	.53804	.84292	.63830	1.56667	.55266	.83340	.66314	1.50797	27
34	.53828	.84277	.63871	1.56566	.55291	.83324	.66356	1.50702	26
35	.53853	.84261	.63912	1.56466	.55315	.83308	.66398	1.50607	25
36	.53877	.84245	.63953	1.56366	.55339	.83292	.66440	1.50512	24
37	.53902	.84230	.63994	1.56265	.55363	.83276	.66482	1.50417	23
38	.53926	.84214	.64035	1.56165	.55388	.83260	.66524	1.50322	22
39	.53951	.84198	.64076	1.56065	.55412	.83244	.66566	1.50228	21
40	.53975	.84182	.64117	1.55966	.55436	.83228	.66608	1.50133	20
41	.54000	.84167	.64158	1.55866	.55460	.83212	.66650	1.50038	19
42	.54024	.84151	.64199	1.55766	.55484	.83195	.66692	1.49944	18
43	.54049	.84135	.64240	1.55666	.55509	.83179	.66734	1.49849	17
44	.54073	.84120	.64281	1.55567	.55533	.83163	.66776	1.49755	16
45	.54097	.84104	.64322	1.55467	.55557	.83147	.66818	1.49661	15
46	.54122	.84088	.64363	1.55368	.55581	.83131	.66860	1.49566	14
47	.54146	.84072	.64404	1.55269	.55605	.83115	.66902	1.49472	13
48	.54171	.84057	.64446	1.55170	.55630	.83098	.66944	1.49378	12
49	.54195	.84041	.64487	1.55071	.55654	.83082	.66986	1.49284	11
50	.54220	.84025	.64528	1.54972	.55678	.83066	.67028	1.49190	10
51	.54244	.84009	.64569	1.54873	.55702	.83050	.67071	1.49097	9
52	.54269	.83994	.64610	1.54774	.55726	.83034	.67113	1.49003	8
53	.54293	.83978	.64652	1.54675	.55750	.83017	.67155	1.48909	7
54	.54317	.83962	.64693	1.54576	.55775	.83001	.67197	1.48816	6
55	.54342	.83946	.64734	1.54478	.55799	.82985	.67239	1.48722	5
56	.54366	.83930	.64775	1.54379	.55823	.82969	.67282	1.48629	4
57	.54391	.83915	.64817	1.54281	.55847	.82953	.67324	1.48536	3
58	.54415	.83899	.64858	1.54183	.55871	.82936	.67366	1.48442	2
59	.54440	.83883	.64899	1.54085	.55895	.82920	.67409	1.48349	1
60	.54464	.83867	.64941	1.53986	.55919	.82904	.67451	1.48256	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	57°				56°				

′	34° Sin.	Cos.	Tan.	Cot.	35° Sin.	Cos.	Tan.	Cot.	′
0	.55919	.82904	.67451	1.48256	.57358	.81915	.70021	1.42815	60
1	.55943	.82887	.67493	1.48163	.57381	.81899	.70064	1.42726	59
2	.55968	.82871	.67536	1.48070	.57405	.81882	.70107	1.42638	58
3	.55992	.82855	.67578	1.47977	.57429	.81865	.70151	1.42550	57
4	.56016	.82839	.67620	1.47885	.57453	.81848	.70194	1.42462	56
5	.56040	.82822	.67663	1.47792	.57477	.81832	.70238	1.42374	55
6	.56064	.82806	.67705	1.47699	.57501	.81815	.70281	1.42286	54
7	.56088	.82790	.67748	1.47607	.57524	.81798	.70325	1.42198	53
8	.56112	.82773	.67790	1.47514	.57548	.81782	.70368	1.42110	52
9	.56136	.82757	.67832	1.47422	.57572	.81765	.70412	1.42022	51
10	.56160	.82741	.67875	1.47330	.57596	.81748	.70455	1.41934	50
11	.56184	.82724	.67917	1.47238	.57619	.81731	.70499	1.41847	49
12	.56208	.82708	.67960	1.47146	.57643	.81714	.70542	1.41759	48
13	.56232	.82692	.68002	1.47053	.57667	.81698	.70586	1.41672	47
14	.56256	.82675	.68045	1.46962	.57691	.81681	.70629	1.41584	46
15	.56280	.82659	.68088	1.46870	.57715	.81664	.70673	1.41497	45
16	.56305	.82643	.68130	1.46778	.57738	.81647	.70717	1.41409	44
17	.56329	.82626	.68173	1.46686	.57762	.81631	.70760	1.41322	43
18	.56353	.82610	.68215	1.46595	.57786	.81614	.70804	1.41235	42
19	.56377	.82593	.68258	1.46503	.57810	.81597	.70848	1.41148	41
20	.56401	.82577	.68301	1.46411	.57833	.81580	.70891	1.41061	40
21	.56425	.82561	.68343	1.46320	.57857	.81563	.70935	1.40974	39
22	.56449	.82544	.68386	1.46229	.57881	.81546	.70979	1.40887	38
23	.56473	.82528	.68429	1.46137	.57904	.81530	.71023	1.40800	37
24	.56497	.82511	.68471	1.46046	.57928	.81513	.71066	1.40714	36
25	.56521	.82495	.68514	1.45955	.57952	.81496	.71110	1.40627	35
26	.56545	.82478	.68557	1.45864	.57976	.81479	.71154	1.40540	34
27	.56569	.82462	.68600	1.45773	.57999	.81462	.71198	1.40454	33
28	.56593	.82446	.68642	1.45682	.58023	.81445	.71242	1.40367	32
29	.56617	.82429	.68685	1.45592	.58047	.81428	.71285	1.40281	31
30	.56641	.82413	.68728	1.45501	.58070	.81412	.71329	1.40195	30
31	.56665	.82396	.68771	1.45410	.58094	.81395	.71373	1.40109	29
32	.56689	.82380	.68814	1.45320	.58118	.81378	.71417	1.40022	28
33	.56713	.82363	.68857	1.45229	.58141	.81361	.71461	1.39936	27
34	.56736	.82347	.68900	1.45139	.58165	.81344	.71505	1.39850	26
35	.56760	.82330	.68942	1.45049	.58189	.81327	.71549	1.39764	25
36	.56784	.82314	.68985	1.44958	.58212	.81310	.71593	1.39679	24
37	.56808	.82297	.69028	1.44868	.58236	.81293	.71637	1.39593	23
38	.56832	.82281	.69071	1.44778	.58260	.81276	.71681	1.39507	22
39	.56856	.82264	.69114	1.44688	.58283	.81259	.71725	1.39421	21
40	.56880	.82248	.69157	1.44598	.58307	.81242	.71769	1.39336	20
41	.56904	.82231	.69200	1.44508	.58330	.81225	.71813	1.39250	19
42	.56928	.82214	.69243	1.44418	.58354	.81208	.71857	1.39165	18
43	.56952	.82198	.69286	1.44329	.58378	.81191	.71901	1.39079	17
44	.56976	.82181	.69329	1.44239	.58401	.81174	.71946	1.38994	16
45	.57000	.82165	.69372	1.44149	.58425	.81157	.71990	1.38909	15
46	.57024	.82148	.69416	1.44060	.58449	.81140	.72034	1.38824	14
47	.57047	.82132	.69459	1.43970	.58472	.81123	.72078	1.38738	13
48	.57071	.82115	.69502	1.43881	.58496	.81106	.72122	1.38653	12
49	.57095	.82098	.69545	1.43792	.58519	.81089	.72167	1.38568	11
50	.57119	.82082	.69588	1.43703	.58543	.81072	.72211	1.38484	10
51	.57143	.82065	.69631	1.43614	.58567	.81055	.72255	1.38399	9
52	.57167	.82048	.69675	1.43525	.58590	.81038	.72299	1.38314	8
53	.57191	.82032	.69718	1.43436	.58614	.81021	.72344	1.38229	7
54	.57215	.82015	.69761	1.43347	.58637	.81004	.72388	1.38145	6
55	.57238	.81999	.69804	1.43258	.58661	.80987	.72432	1.38060	5
56	.57262	.81982	.69847	1.43169	.58684	.80970	.72477	1.37976	4
57	.57286	.81965	.69891	1.43080	.58708	.80953	.72521	1.37891	3
58	.57310	.81949	.69934	1.42992	.58731	.80936	.72565	1.37807	2
59	.57334	.81932	.69977	1.42903	.58755	.80919	.72610	1.37722	1
60	.57358	.81915	.70021	1.42815	.58779	.80902	.72654	1.37638	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	55°				54°				

′	36°				37°				′
	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	
0	.58779	.80902	.72654	1.37638	.60182	.79864	.75355	1.32704	60
1	.58802	.80885	.72699	1.37554	.60205	.79846	.75401	1.32624	59
2	.58826	.80867	.72743	1.37470	.60228	.79829	.75447	1.32544	58
3	.58849	.80850	.72788	1.37386	.60251	.79811	.75492	1.32464	57
4	.58873	.80833	.72832	1.37302	.60274	.79793	.75538	1.32384	56
5	.58896	.80816	.72877	1.37218	.60298	.79776	.75584	1.32304	55
6	.58920	.80799	.72921	1.37134	.60321	.79758	.75629	1.32224	54
7	.58943	.80782	.72966	1.37050	.60344	.79741	.75675	1.32144	53
8	.58967	.80765	.73010	1.36967	.60367	.79723	.75721	1.32064	52
9	.58990	.80748	.73055	1.36883	.60390	.79706	.75767	1.31984	51
10	.59014	.80730	.73100	1.36800	.60414	.79688	.75812	1.31904	50
11	.59037	.80713	.73144	1.36716	.60437	.79671	.75858	1.31825	49
12	.59061	.80696	.73189	1.36633	.60460	.79653	.75904	1.31745	48
13	.59084	.80679	.73234	1.36549	.60483	.79635	.75950	1.31666	47
14	.59108	.80662	.73278	1.36466	.60506	.79618	.75996	1.31586	46
15	.59131	.80644	.73323	1.36383	.60529	.79600	.76042	1.31507	45
16	.59154	.80627	.73368	1.36300	.60553	.79583	.76088	1.31427	44
17	.59178	.80610	.73413	1.36217	.60576	.79565	.76134	1.31348	43
18	.59201	.80593	.73457	1.36134	.60599	.79547	.76180	1.31269	42
19	.59225	.80576	.73502	1.36051	.60622	.79530	.76226	1.31190	41
20	.59248	.80558	.73547	1.35968	.60645	.79512	.76272	1.31110	40
21	.59272	.80541	.73592	1.35885	.60668	.79494	.76318	1.31031	39
22	.59295	.80524	.73637	1.35802	.60691	.79477	.76364	1.30952	38
23	.59318	.80507	.73681	1.35719	.60714	.79459	.76410	1.30873	37
24	.59342	.80489	.73726	1.35637	.60738	.79441	.76456	1.30795	36
25	.59365	.80472	.73771	1.35554	.60761	.79424	.76502	1.30716	35
26	.59389	.80455	.73816	1.35472	.60784	.79406	.76548	1.30637	34
27	.59412	.80438	.73861	1.35389	.60807	.79388	.76594	1.30558	33
28	.59436	.80420	.73906	1.35307	.60830	.79371	.76640	1.30480	32
29	.59459	.80403	.73951	1.35224	.60853	.79353	.76686	1.30401	31
30	.59482	.80386	.73996	1.35142	.60876	.79335	.76733	1.30323	30
31	.59506	.80368	.74041	1.35060	.60899	.79318	.76779	1.30244	29
32	.59529	.80351	.74086	1.34978	.60922	.79300	.76825	1.30166	28
33	.59552	.80334	.74131	1.34896	.60945	.79282	.76871	1.30087	27
34	.59576	.80316	.74176	1.34814	.60968	.79264	.76918	1.30009	26
35	.59599	.80299	.74221	1.34732	.60991	.79247	.76964	1.29931	25
36	.59622	.80282	.74267	1.34650	.61015	.79229	.77010	1.29853	24
37	.59646	.80264	.74312	1.34568	.61038	.79211	.77057	1.29775	23
38	.59669	.80247	.74357	1.34487	.61061	.79193	.77103	1.29696	22
39	.59693	.80230	.74402	1.34405	.61084	.79176	.77149	1.29618	21
40	.59716	.80212	.74447	1.34323	.61107	.79158	.77196	1.29541	20
41	.59739	.80195	.74492	1.34242	.61130	.79140	.77242	1.29463	19
42	.59763	.80178	.74538	1.34160	.61153	.79122	.77289	1.29385	18
43	.59786	.80160	.74583	1.34079	.61176	.79105	.77335	1.29307	17
44	.59809	.80143	.74628	1.33998	.61199	.79087	.77382	1.29229	16
45	.59832	.80125	.74674	1.33916	.61222	.79069	.77428	1.29152	15
46	.59856	.80108	.74719	1.33835	.61245	.79051	.77475	1.29074	14
47	.59879	.80091	.74764	1.33754	.61268	.79033	.77521	1.28997	13
48	.59902	.80073	.74810	1.33673	.61291	.79016	.77568	1.28919	12
49	.59926	.80056	.74855	1.33592	.61314	.78998	.77615	1.28842	11
50	.59949	.80038	.74900	1.33511	.61337	.78980	.77661	1.28764	10
51	.59972	.80021	.74946	1.33430	.61360	.78962	.77708	1.28687	9
52	.59995	.80003	.74991	1.33349	.61383	.78944	.77754	1.28610	8
53	.60019	.79986	.75037	1.33268	.61406	.78926	.77801	1.28533	7
54	.60042	.79968	.75082	1.33187	.61429	.78908	.77848	1.28456	6
55	.60065	.79951	.75128	1.33107	.61451	.78891	.77895	1.28379	5
56	.60089	.79934	.75173	1.33026	.61474	.78873	.77941	1.28302	4
57	.60112	.79916	.75219	1.32946	.61497	.78855	.77988	1.28225	3
58	.60135	.79899	.75264	1.32865	.61520	.78837	.78035	1.28148	2
59	.60158	.79881	.75310	1.32785	.61543	.78819	.78082	1.28071	1
60	.60182	.79864	.75355	1.32704	.61566	.78801	.78129	1.27994	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	
	53°				52°				

	38°				39°				
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	·61566	·78801	·78129	1·27994	·62932	·77715	·80978	1·23490	60
1	·61589	·78783	·78175	1·27917	·62955	·77696	·81027	1·23416	59
2	·61612	·78765	·78222	1·27841	·62977	·77678	·81075	1·23343	58
3	·61635	·78747	·78269	1·27764	·63000	·77660	·81123	1·23270	57
4	·61658	·78729	·78316	1·27688	·63022	·77641	·81171	1·23196	56
5	·61681	·78711	·78363	1·27611	·63045	·77623	·81220	1·23123	55
6	·61704	·78694	·78410	1·27535	·63068	·77605	·81268	1·23050	54
7	·61726	·78676	·78457	1·27458	·63090	77586	·81316	1·22977	53
8	·61749	·78658	·78504	1·27382	·63113	·77568	·81364	1·22904	52
9	·61772	·78640	·78551	1·27306	·63135	·77550	·81413	1·22831	51
10	·61795	·78622	·78598	1·27230	·63158	·77531	·81461	1·22758	50
11	·61818	·78604	·78645	1·27153	·63180	·77513	·81510	1·22685	49
12	·61841	·78586	·78692	1·27077	·63203	·77494	·81558	1·22612	48
13	·61864	·78568	·78739	1·27001	·63225	·77476	·81606	1·22539	47
14	·61887	·78550	·78786	1·26925	·63248	·77458	·81655	1·22467	46
15	·61909	·78532	·78834	1·26849	·63271	·77439	·81703	1·22394	45
16	·61932	·78514	·78881	1·26774	·63293	·77421	·81752	1·22321	44
17	·61955	·78496	·78928	1·26698	·63316	·77402	·81800	1·22249	43
18	·61978	·78478	·78975	1·26622	·63338	·77384	·81849	1·22176	42
19	·62001	·78460	·79022	1·26546	·63361	·77366	·81898	1·22104	41
20	·62024	·78442	·79070	1·26471	·63383	·77347	·81946	1·22031	40
21	·62046	·78424	·79117	1·26395	·63406	·77329	·81995	1·21959	39
22	·62069	·78405	·79164	1·26319	·63428	·77310	·82044	1·21886	38
23	·62092	·78387	·79212	1·26244	·63451	·77292	·82093	1·21814	37
24	·62115	·78369	·79259	1·26169	·63473	·77273	·82141	1·21742	36
25	·62138	·78351	·79306	1·26093	·63496	·77255	·82190	1·21670	35
26	·62160	·78333	·79354	1·26018	·63518	·77236	·82238	1·21598	34
27	·62183	·78315	·79401	1·25943	·63540	·77218	·82287	1·21526	33
28	·62206	·78297	·79449	1·25867	·63563	·77199	·82336	1·21454	32
29	·62229	·78279	·79496	1·25792	·63585	·77181	·82385	1·21382	31
30	·62251	·78261	·79544	1·25717	·63608	·77162	·82434	1·21310	30
31	·62274	·78243	·79591	1·25642	·63630	·77144	·82483	1·21238	29
32	·62297	·78225	·79639	1·25567	·63653	·77125	·82531	1·21166	28
33	·62320	·78206	·79686	1·25492	·63675	·77107	·82580	1·21094	27
34	·62342	·78188	·79734	1·25417	·63698	·77088	·82629	1·21023	26
35	·62365	·78170	·79781	1·25343	·63720	·77070	·82678	1·20951	25
36	·62388	·78152	·79829	1·25268	·63742	·77051	·82727	1·20879	24
37	·62411	·78134	·79877	1·25193	·63765	·77033	·82776	1·20808	23
38	·62433	·78116	·79924	1·25118	·63787	·77014	·82825	1·20736	22
39	·62456	·78098	·79972	1·25044	·63810	·76996	·82874	1·20665	21
40	·62479	·78079	·80020	1·24969	·63832	·76977	·82923	1·20593	20
41	·62502	·78061	·80067	1·24895	·63854	·76959	·82972	1·20522	19
42	·62524	·78043	·80115	1·24820	·63877	·76940	·83022	1·20451	18
43	·62547	·78025	·80163	1·24746	·63899	·76921	·83071	1·20379	17
44	·62570	·78007	·80211	1·24672	·63922	·76903	·83120	1·20308	16
45	·62592	·77988	·80258	1·24597	·63944	·76884	·83169	1·20237	15
46	·62615	·77970	·80306	1·24523	·63966	·76866	·83218	1·20166	14
47	·62638	·77952	·80354	1·24449	·63989	·76847	·83268	1·20095	13
48	·62660	·77934	·80402	1·24375	·64011	·76828	·83317	1·20024	12
49	·62683	·77916	·80450	1·24301	·64033	·76810	·83366	1·19953	11
50	·62706	·77897	·80498	1·24227	·64056	·76791	·83415	1·19882	10
51	·62728	·77879	·80546	1·24153	·64078	·76772	·83465	1·19811	9
52	·62751	·77861	·80594	1·24079	·64100	·76754	·83514	1·19740	8
53	·62774	·77843	·80642	1·24005	·64123	·76735	·83564	1·19669	7
54	·62796	·77824	·80690	1·23931	·64145	·76717	·83613	1·19599	6
55	·62819	·77806	·80738	1·23858	·64167	·76698	·83662	1·19528	5
56	·62842	·77788	·80786	1·23784	·64190	·76679	·83712	1·19457	4
57	·62864	·77769	·80834	1·23710	·64212	·76661	·83761	1·19387	3
58	·62887	·77751	·80882	1·23637	·64234	·76642	·83811	1·19316	2
59	·62909	·77733	·80930	1·23563	·64256	·76623	·83860	1·19246	1
60	·62932	·77715	80978	1·23490	·64279	·76604	·83910	1·19175	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	51°				50°				

TABLE IX.—NATURAL SINES, COSINES, TANGENTS, AND COTANGENTS.

′	40° Sin.	40° Cos.	40° Tan.	40° Cot.	41° Sin.	41° Cos.	41° Tan.	41° Cot.	′
0	.64279	.76604	.83910	1.19175	.65606	.75471	.86929	1.15037	60
1	.64301	.76586	.83960	1.19105	.65628	.75452	.86980	1.14969	59
2	.64323	.76567	.84009	1.19035	.65650	.75433	.87031	1.14902	58
3	.64346	.76548	.84059	1.18964	.65672	.75414	.87082	1.14834	57
4	.64368	.76530	.84108	1.18894	.65694	.75395	.87133	1.14767	56
5	.64390	.76511	.84158	1.18824	.65716	.75375	.87184	1.14699	55
6	.64412	.76492	.84208	1.18754	.65738	.75356	.87236	1.14632	54
7	.64435	.76473	.84258	1.18684	.65759	.75337	.87287	1.14565	53
8	.64457	.76455	.84307	1.18614	.65781	.75318	.87338	1.14498	52
9	.64479	.76436	.84357	1.18544	.65803	.75299	.87389	1.14430	51
10	.64501	.76417	.84407	1.18474	.65825	.75280	.87441	1.14363	50
11	.64524	.76398	.84457	1.18404	.65847	.75261	.87492	1.14296	49
12	.64546	.76380	.84507	1.18334	.65869	.75241	.87543	1.14229	48
13	.64568	.76361	.84556	1.18264	.65891	.75222	.87595	1.14162	47
14	.64590	.76342	.84606	1.18194	.65913	.75203	.87646	1.14095	46
15	.64612	.76323	.84656	1.18125	.65935	.75184	.87698	1.14028	45
16	.64635	.76304	.84706	1.18055	.65956	.75165	.87749	1.13961	44
17	.64657	.76286	.84756	1.17986	.65978	.75146	.87801	1.13894	43
18	.64679	.76267	.84806	1.17916	.66000	.75126	.87852	1.13828	42
19	.64701	.76248	.84856	1.17846	.66022	.75107	.87904	1.13761	41
20	.64723	.76229	.84906	1.17777	.66044	.75088	.87955	1.13694	40
21	.64746	.76210	.84956	1.17708	.66066	.75069	.88007	1.13627	39
22	.64768	.76192	.85006	1.17638	.66088	.75050	.88059	1.13561	38
23	.64790	.76173	.85057	1.17569	.66109	.75030	.88110	1.13494	37
24	.64812	.76154	.85107	1.17500	.66131	.75011	.88162	1.13428	36
25	.64834	.76135	.85157	1.17430	.66153	.74992	.88204	1.13361	35
26	.64856	.76116	.85207	1.17361	.66175	.74973	.88265	1.13295	34
27	.64878	.76097	.85257	1.17292	.66197	.74953	.88317	1.13228	33
28	.64901	.76078	.85308	1.17223	.66218	.74934	.88369	1.13162	32
29	.64923	.76059	.85358	1.17154	.66240	.74915	.88421	1.13096	31
30	.64945	.76041	.85408	1.17085	.66262	.74896	.88473	1.13029	30
31	.64967	.76022	.85458	1.17016	.66284	.74876	.88524	1.12963	29
32	.64989	.76003	.85509	1.16947	.66306	.74857	.88576	1.12897	28
33	.65011	.75984	.85559	1.16878	.66327	.74838	.88628	1.12831	27
34	.65033	.75965	.85609	1.16809	.66349	.74818	.88680	1.12765	26
35	.65055	.75946	.85660	1.16741	.66371	.74799	.88732	1.12699	25
36	.65077	.75927	.85710	1.16672	.66393	.74780	.88784	1.12633	24
37	.65100	.75908	.85761	1.16603	.66414	.74760	.88836	1.12567	23
38	.65122	.75889	.85811	1.16535	.66436	.74741	.88888	1.12501	22
39	.65144	.75870	.85862	1.16466	.66458	.74722	.88940	1.12435	21
40	.65166	.75851	.85912	1.16398	.66480	.74703	.88992	1.12369	20
41	.65188	.75832	.85963	1.16329	.66501	.74683	.89045	1.12303	19
42	.65210	.75813	.86014	1.16261	.66523	.74664	.89097	1.12238	18
43	.65232	.75794	.86064	1.16192	.66545	.74644	.89149	1.12172	17
44	.65254	.75775	.86115	1.16124	.66566	.74625	.89201	1.12106	16
45	.65276	.75756	.86166	1.16056	.66588	.74606	.89253	1.12041	15
46	.65298	.75738	.86216	1.15987	.66610	.74586	.89306	1.11975	14
47	.65320	.75719	.86267	1.15919	.66632	.74567	.89358	1.11909	13
48	.65342	.75700	.86318	1.15851	.66653	.74548	.89410	1.11844	12
49	.65364	.75680	.86368	1.15783	.66675	.74528	.89463	1.11778	11
50	.65386	.75661	.86419	1.15715	.66697	.74509	.89515	1.11713	10
51	.65408	.75642	.86470	1.15647	.66718	.74489	.89567	1.11648	9
52	.65430	.75623	.86521	1.15579	.66740	.74470	.89620	1.11582	8
53	.65452	.75604	.86572	1.15511	.66762	.74451	.89672	1.11517	7
54	.65474	.75585	.86623	1.15443	.66783	.74431	.89725	1.11452	6
55	.65496	.75566	.86674	1.15375	.66805	.74412	.89777	1.11387	5
56	.65518	.75547	.86725	1.15308	.66827	.74392	.89830	1.11321	4
57	.65540	.75528	.86776	1.15240	.66848	.74373	.89883	1.11256	3
58	.65562	.75509	.86827	1.15172	.66870	.74353	.89935	1.11191	2
59	.65584	.75490	.86878	1.15104	.66891	.74334	.89988	1.11126	1
60	.65606	.75471	.86929	1.15037	.66913	.74314	.90040	1.11061	0
′	49° Cos.	49° Sin.	49° Cot.	49° Tan.	48° Cos.	48° Sin.	48° Cot.	48° Tan.	′

′	42°				43°				′
′	Sin.	Cos.	Tan.	Cot.	Sin.	Cos.	Tan.	Cot.	′
0	.66913	.74314	.90040	1.11061	.68200	.73135	.93252	1.07237	60
1	.66935	.74295	.90093	1.10996	.68221	.73116	.93306	1.07174	59
2	.66956	.74276	.90146	1.10931	.68242	.73096	.93360	1.07112	58
3	.66978	.74256	.90199	1.10867	.68264	.73076	.93415	1.07049	57
4	.66999	.74237	.90251	1.10802	.68285	.73056	.93469	1.06987	56
5	.67021	.74217	.90304	1.10737	.68306	.73036	.93524	1.06925	55
6	.67043	.74198	.90357	1.10672	.68327	.73016	.93578	1.06862	54
7	.67064	.74178	.90410	1.10607	.68349	.72996	.93633	1.06800	53
8	.67086	.74159	.90463	1.10543	.68370	.72976	.93688	1.06738	52
9	.67107	.74139	.90516	1.10478	.68391	.72957	.93742	1.06676	51
10	.67129	.74120	.90569	1.10414	.68412	.72937	.93797	1.06613	50
11	.67151	.74100	.90621	1.10349	.68434	.72917	.93852	1.06551	49
12	.67172	.74080	.90674	1.10285	.68455	.72897	.93906	1.06489	48
13	.67194	.74061	.90727	1.10220	.68476	.72877	.93961	1.06427	47
14	.67215	.74041	.90781	1.10156	.68497	.72857	.94016	1.06365	46
15	.67237	.74022	.90834	1.10091	.68518	.72837	.94071	1.06303	45
16	.67258	.74002	.90887	1.10027	.68539	.72817	.94125	1.06241	44
17	.67280	.73983	.90940	1.09963	.68561	.72797	.94180	1.06179	43
18	.67301	.73963	.90993	1.09899	.68582	.72777	.94235	1.06117	42
19	.67323	.73944	.91046	1.09834	.68603	.72757	.94290	1.06056	41
20	.67344	.73924	.91099	1.09770	.68624	.72737	.94345	1.05994	40
21	.67366	.73904	.91153	1.09706	.68645	.72717	.94400	1.05932	39
22	.67387	.73885	.91206	1.09642	.68666	.72697	.94455	1.05870	38
23	.67409	.73865	.91259	1.09578	.68688	.72677	.94510	1.05809	37
24	.67430	.73846	.91313	1.09514	.68709	.72657	.94565	1.05747	36
25	.67452	.73826	.91366	1.09450	.68730	.72637	.94620	1.05685	35
26	.67473	.73806	.91419	1.09386	.68751	.72617	.94676	1.05624	34
27	.67495	.73787	.91473	1.09322	.68772	.72597	.94731	1.05562	33
28	.67516	.73767	.91526	1.09258	.68793	.72577	.94786	1.05501	32
29	.67538	.73747	.91580	1.09195	.68814	.72557	.94841	1.05439	31
30	.67559	.73728	.91633	1.09131	.68835	.72537	.94896	1.05378	30
31	.67580	.73708	.91687	1.09067	.68857	.72517	.94952	1.05317	29
32	.67602	.73688	.91740	1.09003	.68878	.72497	.95007	1.05255	28
33	.67623	.73669	.91794	1.08940	.68899	.72477	.95062	1.05194	27
34	.67645	.73649	.91847	1.08876	.68920	.72457	.95118	1.05133	26
35	.67666	.73629	.91901	1.08813	.68941	.72437	.95173	1.05072	25
36	.67688	.73610	.91955	1.08749	.68962	.72417	.95229	1.05010	24
37	.67709	.73590	.92008	1.08686	.68983	.72397	.95284	1.04949	23
38	.67730	.73570	.92062	1.08622	.69004	.72377	.95340	1.04888	22
39	.67752	.73551	.92116	1.08559	.69025	.72357	.95395	1.04827	21
40	.67773	.73531	.92170	1.08496	.69046	.72337	.95451	1.04766	20
41	.67795	.73511	.92224	1.08432	.69067	.72317	.95506	1.04705	19
42	.67816	.73491	.92277	1.08369	.69088	.72297	.95562	1.04644	18
43	.67837	.73472	.92331	1.08306	.69109	.72277	.95618	1.04583	17
44	.67859	.73452	.92385	1.08243	.69130	.72257	.95673	1.04522	16
45	.67880	.73432	.92439	1.08179	.69151	.72236	.95729	1.04461	15
46	.67901	.73413	.92493	1.08116	.69172	.72216	.95785	1.04401	14
47	.67923	.73393	.92547	1.08053	.69193	.72196	.95841	1.04340	13
48	.67944	.73373	.92601	1.07990	.69214	.72176	.95897	1.04279	12
49	.67965	.73353	.92655	1.07927	.69235	.72156	.95952	1.04218	11
50	.67987	.73333	.92709	1.07864	.69256	.72136	.96008	1.04158	10
51	.68008	.73314	.92763	1.07801	.69277	.72116	.96064	1.04097	9
52	.68029	.73294	.92817	1.07738	.69298	.72095	.96120	1.04036	8
53	.68051	.73274	.92872	1.07676	.69319	.72075	.96176	1.03976	7
54	.68072	.73254	.92926	1.07613	.69340	.72055	.96232	1.03915	6
55	.68093	.73234	.92980	1.07550	.69361	.72035	.96288	1.03855	5
56	.68115	.73215	.93034	1.07487	.69382	.72015	.96344	1.03794	4
57	.68136	.73195	.93088	1.07425	.69403	.71995	.96400	1.03734	3
58	.68157	.73175	.93143	1.07362	.69424	.71974	.96457	1.03674	2
59	.68179	.73155	.93197	1.07299	.69445	.71954	.96513	1.03613	1
60	.68200	.73135	.93252	1.07237	.69466	.71934	.96569	1.03553	0
′	Cos.	Sin.	Cot.	Tan.	Cos.	Sin.	Cot.	Tan.	′
	47°				46°				

44° | 44°

′	Sin.	Cos.	Tan.	Cot.	′	′	Sin.	Cos.	Tan.	Cot.	′
0	.69466	.71934	.96569	1.03553	60	30	.70091	.71325	.98270	1.01761	30
1	.69487	.71914	.96625	1.03493	59	31	.70112	.71305	.98327	1.01702	29
2	.69508	.71894	.96681	1.03433	58	32	.70132	.71284	.98384	1.01642	28
3	.69529	.71873	.96738	1.03372	57	33	.70153	.71264	.98441	1.01583	27
4	.69549	.71853	.96794	1.03312	56	34	.70174	.71243	.98499	1.01524	26
5	.69570	.71833	.96850	1.03252	55	35	.70195	.71223	.98556	1.01465	25
6	.69591	.71813	.96907	1.03192	54	36	.70215	.71203	.98613	1.01406	24
7	.69612	.71792	.96963	1.03132	53	37	.70236	.71182	.98671	1.01347	23
8	.69633	.71772	.97020	1.03072	52	38	.70257	.71162	.98728	1.01288	22
9	.69654	.71752	.97076	1.03012	51	39	.70277	.71141	.98786	1.01229	21
10	.69675	.71732	.97133	1.02952	50	40	.70298	.71121	98843	1.01170	20
11	.69696	.71711	.97189	1.02892	49	41	.70319	.71100	.98901	1.01112	19
12	.69717	.71691	.97246	1.02832	48	42	.70339	.71080	.98958	1.01053	18
13	.69737	.71671	.97302	1.02772	47	43	.70360	.71059	.99016	1.00994	17
14	.69758	.71650	.97359	1.02713	46	44	.70381	.71039	.99073	1.00935	16
15	.69779	.71630	.97416	1.02653	45	45	.70401	.71019	.99131	1.00876	15
16	.69800	.71610	.97472	1.02593	44	46	.70422	.70998	.99189	1.00818	14
17	.69821	.71590	.97529	1.02533	43	47	70443	.70978	.99247	1.00759	13
18	.69842	.71569	.97586	1.02474	42	48	.70463	.70957	.99304	1.00701	12
19	.69862	.71549	.97643	1.02414	41	49	.70484	70937	.99362	1.00642	11
20	.69883	.71529	.97700	1.02355	40	50	.70505	.70916	.99420	1.00583	10
21	.69904	.71508	.97756	1.02295	39	51	.70525	.70896	.99478	1.00525	9
22	.69925	.71488	.97813	1.02236	38	52	.70546	.70875	.99536	1.00467	8
23	.69946	.71468	.97870	1.02176	37	53	.70567	.70855	.99594	1.00408	7
24	.69966	.71447	.97927	1.02117	36	54	.70587	.70834	.99652	1.00350	6
25	.69987	.71427	.97984	1.02057	35	55	.70608	.70813	.99710	1.00291	5
26	.70008	.71407	98041	1.01998	34	56	.70628	.70793	.99768	1.00233	4
27	.70029	.71386	.98098	1.01939	33	57	.70649	.70772	.99826	1.00175	3
28	.70049	.71366	.98155	1.01879	32	58	.70670	.70752	.99884	1.00116	2
29	.70070	.71345	.98213	1.01820	31	59	.70690	.70731	.99942	1.00058	1
30	.70091	.71325	.98270	1.01761	30	60	.70711	.70711	1.00000	1.00000	0
′	Cos.	Sin.	Cot.	Tan.	′	′	Cos.	Sin.	Cot.	Tan.	′

45° | 45°

′	0° Vers.	0° Ex. sec.	1° Vers.	1° Ex. sec.	2° Vers.	2° Ex. sec.	3° Vers.	3° Ex. sec.	′
0	.00000	.00000	.00015	.00015	.00061	.00061	.00137	.00137	0
1	.00000	.00000	.00016	.00016	.00062	.00062	.00139	.00139	1
2	.00000	.00000	.00016	.00016	.00063	.00063	.00140	.00140	2
3	.00000	.00000	.00017	.00017	.00064	.00064	.00142	.00142	3
4	.00000	.00000	.00017	.00017	.00065	.00065	.00143	.00143	4
5	.00000	.00000	.00018	.00018	.00066	.00066	.00145	.00145	5
6	.00000	.00000	.00018	.00018	.00067	.00067	.00146	.00147	6
7	.00000	.00000	.00019	.00019	.00068	.00068	.00148	.00148	7
8	.00000	.00000	.00020	.00020	.00069	.00069	.00150	.00150	8
9	.00000	.00000	.00020	.00020	.00070	.00070	.00151	.00151	9
10	.00000	.00000	.00021	.00021	.00071	.00072	.00153	.00153	10
11	.00001	.00001	.00021	.00021	.00073	.00073	.00154	.00155	11
12	.00001	.00001	.00022	.00022	.00074	.00074	.00156	.00156	12
13	.00001	.00001	.00023	.00023	.00075	.00075	.00158	.00158	13
14	.00001	.00001	.00023	.00023	.00076	.00076	.00159	.00159	14
15	.00001	.00001	.00024	.00024	.00077	.00077	.00161	.00161	15
16	.00001	.00001	.00024	.00024	.00078	.00078	.00162	.00163	16
17	.00001	.00001	.00025	.00025	.00079	.00079	.00164	.00164	17
18	.00001	.00001	.00026	.00026	.00081	.00081	.00166	.00166	18
19	.00002	.00002	.00026	.00026	.00082	.00082	.00168	.00168	19
20	.00002	.00002	.00027	.00027	.00083	.00083	.00169	.00169	20
21	.00002	.00002	.00028	.00028	.00084	.00084	.00171	.00171	21
22	.00002	.00002	.00028	.00028	00085	.00085	.00173	.00173	22
23	.00002	.00002	.00029	.00029	.00087	.00087	.00174	.00175	23
24	.00002	.00002	.00030	.00030	.00088	.00088	.00176	.00176	24
25	.00003	.00003	.00031	.00031	.00089	.00089	.00178	.00178	25
26	00003	.00003	.00031	.00031	.00090	.00090	.00179	.00180	26
27	.00003	.00003	.00032	.00032	.00091	.00091	.00181	.00182	27
28	.00003	.00003	.00033	.00033	.00093	.00093	.00183	.00183	28
29	.00004	.00004	00034	.00034	.00094	.00094	.00185	.00185	29
30	.00004	.00004	.00034	.00034	00095	.00095	.00187	.00187	30
31	.00004	.00004	.00035	.00035	.00096	.00097	00188	.00189	31
32	.00004	.00004	.00036	.00036	.00098	.00098	.00190	.00190	32
33	.00005	.00005	.00037	.00037	.00099	.00099	.00192	.00192	33
34	.00005	.00005	.00037	.00037	.00100	.00100	.00194	.00194	34
35	.00005	.00005	.00038	.00038	.00102	.00102	.00196	.00196	35
36	.00005	.00005	.00039	.00039	.00103	.00103	.00197	.00198	36
37	.00006	.00006	.00040	.00040	.00104	.00104	.00199	.00200	37
38	.00006	00006	.00041	.00041	.00106	.00106	.00201	.00201	38
39	.00006	.00006	.00041	.00041	.00107	.00107	.00203	.00203	39
40	.00007	.00007	.00042	.00042	.00108	.00108	.00205	.00205	40
41	.00007	.00007	.00043	.00043	.00110	.00110	.00207	.00207	41
42	.00007	.00007	.00044	.00044	.00111	.00111	.00208	.00209	42
43	.00008	.00008	.00045	.00045	.00112	.00113	.00210	.00211	43
44	.00008	.00008	.00046	.00046	.00114	.00114	.00212	.00213	44
45	.00009	.00009	.00047	.00047	.00115	.00115	.00214	00215	45
46	00009	.00009	00048	.00048	.00117	.00117	.00216	.00216	46
47	.00009	.00009	.00048	.00048	.00118	.00118	.00218	.00218	47
47	.00010	.00010	.00049	.00049	.00119	.00120	.00220	.00220	48
49	00010	.00010	.00050	.00050	.00121	.00121	.00222	.00222	49
50	.00011	.00011	.00051	.00051	.00122	.00122	.00224	.00224	50
51	.00011	.00011	.00052	.00052	.00124	.00124	.00226	.00226	51
52	.00011	.00011	.00053	.00053	.00125	.00125	.00228	.00228	52
53	.00012	.00012	.00054	.00054	.00127	.00127	.00230	.00230	53
54	.00012	.00012	.00055	.00055	.00128	.00128	.00232	.00232	54
55	.00013	.00013	.00056	.00056	.00130	.00130	.00234	.00234	55
56	.00013	.00013	.00057	.00057	.00131	.00131	.00236	.00236	56
57	.00014	.00014	.00058	.00058	.00133	00133	.00238	.00238	57
58	.00014	.00014	.00059	.00059	.00134	.00134	.00240	.00240	58
59	.00015	.00015	.00060	00060	.00136	.00136	.00242	.00242	59
60	.00015	.00015	.00061	.00061	.00137	.00137	.00244	.00244	60

TABLE X.—NATURAL VERSED SINES AND EXTERNAL SECANTS.

′	4° Vers.	4° Ex. sec.	5° Vers.	5° Ex. sec.	6° Vers.	6° Ex. sec.	7° Vers.	7° Ex. sec.	′
0	.00244	.00244	.00381	.00382	.00548	.00551	.00745	.00751	0
1	.00246	.00246	.00383	.00385	.00551	.00554	.00749	.00755	1
2	.00248	.00248	.00386	.00387	.00554	.00557	.00752	.00758	2
3	.00250	.00250	.00388	.00390	.00557	.00560	.00756	.00762	3
4	.00252	.00252	.00391	.00392	.00560	.00563	.00760	.00765	4
5	.00254	.00254	.00393	.00395	.00563	.00566	.00763	.00769	5
6	.00256	.00257	.00396	.00397	.00566	.00569	.00767	.00773	6
7	.00258	.00259	.00398	.00400	.00569	.00573	.00770	.00776	7
8	.00260	.00261	.00401	.00403	.00572	.00576	.00774	.00780	8
9	.00262	00263	.00404	.00405	.00576	.00579	.00778	.00784	9
10	.00264	.00265	.00406	.00408	.00579	.00582	.00781	.00787	10
11	.00266	.00267	.00409	.00411	.00582	.00585	.00785	.00791	11
12	.00269	.00269	.00412	.00413	.00585	.00588	.00789	.00795	12
13	.00271	.00271	.00414	.00416	00588	.00592	00792	.00799	13
14	00273	.00274	.00417	.00419	.00591	.00595	.00796	.00802	14
15	.00275	.00276	.00420	.00421	00594	.00598	.00800	.00806	15
16	.00277	.00278	.00422	.00424	.00598	.00601	.00803	.00810	16
17	.00279	.00280	.00425	.00427	.00601	.00604	.00807	.00813	17
18	.00281	.00282	.00428	.00429	.00604	.00608	.00811	.00817	18
19	.00284	.00284	.00430	.00432	.00607	.00611	.00814	.00821	19
20	.00286	.00287	.00433	.00435	.00610	00614	.00818	.00825	20
21	.00288	.00289	.00436	.00438	.00614	.00617	.00822	.00828	21
22	.00290	.00291	.00438	.00440	.00617	.00621	.00825	.00832	22
23	.00293	.00293	.00441	.00443	.00620	.00624	.00829	.00836	23
24	.00295	.00296	.00444	.00446	.00623	.00627	.00833	.00840	24
25	.00297	.00298	.00447	.00449	.00626	.00630	.00837	.00844	25
26	.00299	.00300	.00449	.00451	.00630	.00634	.00840	.00848	26
27	.00301	.00302	.00452	.00454	.00633	.00637	.00844	.00851	27
28	.00304	.00305	.00455	.00457	.00636	.00640	.00848	.00855	28
29	.00306	.00307	.00458	.00460	.00640	.00644	.00852	.00859	29
30	.00308	.00309	.00460	.00463	.00643	.00647	.00856	.00863	30
31	.00311	.00312	.00463	.00465	.00646	.00650	00859	.00867	31
32	.00313	.00314	.00466	.00468	.00649	.00654	.00863	.00871	32
33	.00315	.00316	.00469	.00471	.00653	.00657	.00867	.00875	33
34	.00317	.00318	.00472	.00474	.00656	.00660	.00871	.00878	34
35	.00320	.00321	.00474	.00477	.00659	.00664	.00875	.00882	35
36	.00322	.00323	.00477	.00480	.00663	.00667	.00878	.00886	36
37	.00324	.00326	.00480	.00482	.00666	.00671	.00882	.00890	37
38	.00327	.00328	.00483	.00485	.00669	.00674	.00886	.00894	38
39	.00329	.00330	.00486	.00488	.00673	.00677	.00890	.00898	39
40	.00332	.00333	.00489	.00491	.00676	.00681	.00894	.00902	40
41	.00334	.00335	.00492	.00494	.00680	.00684	.00898	.00906	41
42	.00336	.00337	.00494	.00497	.00683	.00688	.00902	.00910	42
43	.00339	.00340	.00497	.00500	.00686	.00691	.00906	.00914	43
44	.00341	.00342	.00500	.00503	.00690	.00695	.00909	.00918	44
45	.00343	.00345	.00503	.00506	.00693	.00698	.00913	.00922	45
46	.00346	.00347	.00506	.00509	00607	.00701	00917	.00926	46
47	.00348	.00350	.00509	.00512	.00700	.00705	00921	.00930	47
48	00351	.00352	.00512	.00515	.00703	.00708	00925	.00934	48
49	00353	.00354	.00515	.00518	.00707	.00712	.00929	.00938	49
50	.00356	.00357	.00518	.00521	.00710	.00715	.00933	.00942	50
51	.00358	.00359	.00521	.00524	.00714	.00719	00937	.00946	51
52	.00361	.00362	.00524	.00527	.00717	.00722	.00941	.00950	52
53	.00363	.00364	.00527	.00530	.00721	.00726	.00945	.00954	53
54	.00365	.00367	.00530	.00533	.00724	.00730	.00949	.00958	54
55	.00368	.00369	.00533	.00536	.00728	.00733	.00953	.00962	55
56	.00370	.00372	.00536	.00539	.00731	.00737	.00957	.00966	56
57	.00373	.00374	.00539	.00542	.00735	.00740	.00961	.00970	57
58	.00375	.00377	.00542	.00545	.00738	.00744	.00965	.00975	58
59	.00378	.00379	.00545	00548	.00742	.00747	.00969	.00979	59
60	.00381	.00382	00548	.00551	.00745	.00751	.00973	.00983	60

	8°		9°		10°		11°		
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.00973	.00983	.01231	.01247	.01519	.01543	.01837	.01872	0
1	.00977	.00987	.01236	.01251	.01524	.01548	.01843	.01877	1
2	.00981	.00991	.01240	.01256	.01529	.01553	.01848	.01883	2
3	.00985	.00995	.01245	.01261	.01534	.01558	.01854	.01889	3
4	.00989	.00999	.01249	.01265	.01540	.01564	.01860	.01895	4
5	00994	.01004	.01254	.01270	.01545	.01569	.01865	.01901	5
6	.00998	.01008	.01259	.01275	.01550	.01574	01871	.01906	6
7	.01002	.01012	.01263	.01279	.01555	.01579	.01876	.01912	7
8	.01006	.01016	.01268	.01284	.01560	.01585	.01882	.01918	8
9	.01010	.01020	.01272	.01289	.01565	.01590	.01888	.01924	9
10	.01014	.01024	.01277	.01294	.01570	.01595	.01893	.01930	10
11	.01018	.01029	.01282	.01298	.01575	.01601	.01899	.01936	11
12	.01022	.01033	.01286	.01303	.01580	.01606	.01904	.01941	12
13	.01027	.01037	.01291	.01308	.01586	.01611	.01910	.01947	13
14	.01031	.01041	.01296	.01313	.01591	.01616	.01916	.01953	14
15	.01035	.01046	.01300	.01318	.01596	.01622	.01921	.01959	15
16	.01039	.01050	.01305	.01322	.01601	.01627	.01927	.01965	16
17	.01043	.01054	.01310	.01327	.01606	.01633	.01933	.01971	17
18	.01047	.01059	.01314	.01332	.01612	.01638	.01939	.01977	18
19	.01052	.01063	.01319	.01337	.01617	.01643	.01944	.01983	19
20	.01056	.01067	.01324	.01342	.01622	.01649	.01950	.01989	20
21	.01060	.01071	.01329	.01346	.01627	.01654	.01956	.01995	21
22	.01064	.01076	.01333	.01351	.01632	.01659	.01961	.02001	22
23	.01069	.01080	.01338	.01356	.01638	.01665	.01967	.02007	23
24	.01073	.01084	.01343	.01361	.01643	.01670	.01973	.02013	24
25	.01077	.01089	.01348	.01366	.01648	.01676	.01979	.02019	25
26	.01081	.01093	.01352	.01371	.01653	.01681	.01984	.02025	26
27	.01086	.01097	.01357	.01376	.01659	.01687	.01990	.02031	27
28	.01090	.01102	.01362	.01381	.01664	.01692	.01996	.02037	28
29	.01094	.01106	.01367	.01386	.01669	.01698	.02002	.02043	29
30	.01098	.01111	.01371	.01391	.01675	.01703	.02008	.02049	30
31	.01103	.01115	.01376	.01395	.01680	.01709	.02013	.02055	31
32	.01107	.01119	.01381	.01400	.01685	.01714	.02019	.02061	32
33	.01111	.01124	.01386	.01405	.01690	.01720	.02025	.02067	33
34	.01116	.01128	.01391	.01410	.01696	.01725	.02031	.02073	34
35	.01120	.01133	.01396	.01415	.01701	.01731	.02037	.02079	35
36	.01124	.01137	.01400	.01420	.01706	.01736	.02042	.02085	36
37	.01129	.01142	.01405	.01425	.01712	.01742	.02048	.02091	37
38	.01133	.01146	.01410	.01430	.01717	.01747	.02054	.02097	38
39	.01137	.01151	.01415	.01435	.01723	.01753	.02060	.02103	39
40	.01142	.01155	.01420	.01440	.01728	.01758	.02066	.02110	40
41	.01146	.01160	.01425	.01445	01733	.01764	.02072	.02116	41
42	.01151	.01164	.01430	01450	.01739	.01769	.02078	.02122	42
43	.01155	.01169	.01435	.01455	.01744	.01775	.02084	.02128	43
44	.01159	01173	.01439	.01461	.01750	.01781	.02090	.02134	44
45	.01164	.01178	.01444	.01466	.01755	01786	.02095	.02140	45
46	.01168	.01182	.01449	.01471	.01760	.01792	.02101	.02146	46
47	.01173	.01187	.01454	.01476	01766	.01798	.02107	.02153	47
48	.01177	.01191	.01459	.01481	.01771	.01803	.02113	.02159	48
49	.01182	.01196	.01464	.01486	.01777	.01809	.02119	.02165	49
50	.01186	.01200	.01469	.01491	.01782	.01815	.02125	.02171	50
51	.01191	.01205	.01474	.01496	.01788	.01820	.02131	.02178	51
52	.01195	.01209	.01479	.01501	.01793	.01826	.02137	.02184	52
53	.01200	.01214	.01484	.01506	.01799	.01832	.02143	.02190	53
54	.01204	.01219	.01489	.01512	.01804	.01837	.02149	.02196	54
55	.01209	.01223	.01494	.01517	.01810	.01843	.02155	.02203	55
56	.01213	.01228	.01499	.01522	.01815	.01849	.02161	.02209	56
57	.01218	.01233	.01504	.01527	.01821	.01854	.02167	.02215	57
58	.01222	.01237	.01509	.01532	.01826	.01860	.02173	.02221	58
59	.01227	.01242	.01514	.01537	.01832	.01866	.02179	.02228	59
60	01231	.01247	.01519	.01543	.01837	.01872	.02185	.02234	60

′	12° Vers.	12° Ex. sec.	13° Vers.	13° Ex. sec.	14° Vers.	14° Ex. sec.	15° Vers.	15° Ex. sec.	′
0	.02185	.02234	.02563	.02630	.02970	.03061	.03407	.03528	0
1	.02191	.02240	.02570	.02637	.02977	.03069	.03415	.03536	1
2	.02197	.02247	.02576	.02644	.02985	.03076	.03422	.03544	2
3	.02203	.02253	.02583	.02651	.02992	.03084	.03430	.03552	3
4	.02210	.02259	.02589	.02658	.02999	.03091	.03438	.03560	4
5	.02216	.02266	.02596	.02665	.03006	.03099	.03445	.03568	5
6	.02222	.02272	.02602	.02672	.03013	.03106	.03453	.03576	6
7	.02228	.02279	.02609	.02679	.03020	.03114	03460	.03584	7
8	.02234	.02285	.02616	.02686	.03027	.03121	.03468	.03592	8
9	.02240	.02291	.02622	.02693	.03034	.03129	.03476	.03601	9
10	.02246	.02298	.02629	.02700	.03041	.03137	.03483	.03609	10
11	.02252	.02304	.02635	.02707	.03048	.03144	.03491	.03617	11
12	.02258	.02311	.02642	.02714	.03055	.03152	.03498	.03625	12
13	.02265	.02317	.02649	.02721	.03063	.03159	.03506	.03633	13
14	.02271	.02323	.02655	.02728	.03070	.03167	.03514	.03642	14
15	.02277	.02330	.02662	.02735	.03077	.03175	.03521	.03650	15
16	.02283	.02336	.02669	.02742	.03084	.03182	.03529	.03658	16
17	.02289	.02343	.02675	.02749	.03091	.03190	.03537	.03666	17
18	.02295	.02349	.02682	.02756	.03098	.03198	.03544	.03674	18
19	.02302	.02356	.02689	.02763	.03106	.03205	.03552	.03683	19
20	.02308	.02362	.02696	.02770	.03113	.03213	.03560	.03691	20
21	.02314	.02369	.02702	.02777	.03120	.03221	.03567	.03699	21
22	.02320	.02375	.02709	.02784	.03127	.03228	.03575	.03708	22
23	.02327	.02382	.02716	.02791	.03134	.03236	.03583	.03716	23
24	.02333	.02388	.02722	.02799	.03142	.03244	.03590	.03724	24
25	.02339	.02395	.02729	.02806	.03149	.03251	.03598	.03732	25
26	.02345	.02402	.02736	.02813	.03156	.03259	.03606	.03741	26
27	.02352	.02408	.02743	.02820	.03163	.03267	.03614	.03749	27
28	.02358	.02415	.02749	.02827	.03171	.03275	.03621	.03758	28
29	.02364	.02421	.02756	.02834	.03178	.03282	.03629	.03766	29
30	.02370	.02428	.02763	.02842	.03185	.03290	.03637	.03774	30
31	.02377	.02435	.02770	.02849	.03193	.03298	.03645	.03783	31
32	.02383	.02441	.02777	.02856	.03200	.03306	.03653	.03791	32
33	.02389	.02448	.02783	.02863	.03207	.03313	.03660	.03799	33
34	.02396	.02454	.02790	.02870	.03214	.03321	.03668	.03808	34
35	.02402	.02461	.02797	.02878	.03222	.03329	.03676	.03816	35
36	.02408	.02468	.02804	.02885	.03229	.03337	.03684	.03825	36
37	.02415	.02474	.02811	.02892	.03236	.03345	.03692	.03833	37
38	.02421	.02481	.02818	.02899	.03244	.03353	.03699	.03842	38
39	.02427	.02488	.02824	.02907	.03251	.03360	.03707	.03850	39
40	.02434	.02494	.02831	.02914	.03258	.03368	03715	.03858	40
41	.02440	.02501	.02838	.02921	.03266	.03376	.03723	.03867	41
42	.02447	.02508	.02845	.02928	.03273	.03384	.03731	.03875	42
43	.02453	.02515	02852	.02936	.03281	.03392	.03739	.03884	43
44	.02459	.02521	.02859	.02943	.03288	.03400	.03747	.03892	44
45	.02466	.02528	.02866	.02950	.03295	.03408	.03754	.03901	45
46	.02472	.02535	.02873	.02958	.03303	.03416	.03762	.03909	46
47	.02479	.02542	.02880	.02965	.03310	.03424	.03770	.03918	47
48	.02485	.02548	.02887	.02972	.03318	.03432	.03778	.03927	48
49	.02492	.02555	.02894	.02980	.03325	.03439	.03786	.03935	49
50	.02498	.02562	.02900	.02987	.03333	.03447	.03794	.03944	50
51	.02504	.02569	.02907	.02994	.03340	.03455	.03802	.03952	51
52	.02511	.02576	.02914	.03002	.03347	.03463	.03810	.03961	52
53	.02517	.02582	.02921	.03009	.03355	.03471	.03818	.03969	53
54	.02524	.02589	.02928	.03017	.03362	.03479	.03826	.03978	54
55	.02530	.02596	.02935	.03024	.03370	.03487	.03834	.03987	55
56	.02537	.02603	.02942	.03032	.03377	.03495	.03842	.03995	56
57	.02543	.02610	.02949	.03039	.03385	.03503	.03850	.04004	57
58	.02550	.02617	.02956	.03046	.03392	.03512	.03858	.04013	58
59	.02556	.02624	.02963	.03054	.03400	.03520	.03866	.04021	59
60	.02563	.02630	.02970	.03061	03407	.03528	.03874	.04030	60

′	16° Vers.	16° Ex. sec.	17° Vers.	17° Ex. sec.	18° Vers.	18° Ex. sec.	19° Vers.	19° Ex. sec	′
0	.03874	.04030	.04370	.04569	.04894	.05146	.05448	.05762	0
1	.03882	.04039	.04378	.04578	.04903	.05156	.05458	.05773	1
2	.03890	.04047	.04387	.04588	.04912	.05166	.05467	.05783	2
3	.03898	.04056	.04395	.04597	.04921	.05176	.05477	.05794	3
4	.03906	.04065	.04404	.04606	.04930	.05186	.05486	.05805	4
5	.03914	.04073	.04412	.04616	.04939	.05196	.05496	.05815	5
6	.03922	.04082	.04421	.04625	.04948	.05206	.05505	.05826	6
7	.03930	.04091	.04429	04635	.04957	.05216	.05515	.05836	7
8	.03938	.04100	.04438	.04644	.04967	.05226	.05524	.05847	8
9	.03946	.04108	.04446	.04653	.04976	.05236	.05534	.05858	9
10	.03954	.04117	.04455	.04663	.04985	.05246	.05543	.05869	10
11	.03963	.04126	.04464	.04672	.04994	.05256	.05553	.05879	11
12	.03971	.04135	.04472	.04682	.05003	.05266	.05562	.05890	12
13	.03979	.04144	.04481	.04691	.05012	.05276	.05572	.05901	13
14	.03987	.04152	.04489	.04700	.05021	.05286	.05582	.05911	14
15	.03995	.04161	.04498	.04710	.05030	.05297	.05591	.05922	15
16	.04003	.04170	.04507	.04719	.05039	.05307	.05601	.05933	16
17	.04011	.04179	.04515	.04729	.05048	.05317	.05610	.05944	17
18	.04019	.04188	.04524	.04738	.05057	.05327	.05620	.05955	18
19	.04028	.04197	.04533	.04748	.05067	.05337	.05630	.05965	19
20	.04036	.04206	.04541	.04757	.05076	.05347	.05639	.05976	20
21	.04044	.04214	.04550	.04767	.05085	.05357	.05649	.05987	21
22	.04052	.04223	.04559	.04776	.05094	.05367	.05658	.05998	22
23	04060	.04232	.04567	.04786	.05103	.05378	.05668	.06009	23
24	.04069	.04241	.04576	.04795	.05112	.05388	.05678	.06020	24
25	.04077	.04250	.04585	.04805	.05122	.05398	.05687	.06030	25
26	.04085	.04259	.04593	.04815	.05131	.05408	.05697	.06041	26
27	.04093	.04268	.04602	.04824	.05140	.05418	05707	.06052	27
28	04102	.04277	.04611	04834	.05149	.05429	.05716	.06063	28
29	.04110	.04286	.04620	.04843	.05158	.05439	.05726	.06074	29
30	.04118	.04295	.04628	.04853	.05168	.05449	.05736	.06085	30
31	.04126	.04304	.04637	.04863	.05177	.05460	.05746	.06096	31
32	.04135	.04313	.04646	.04872	.05186	.05470	.05755	.06107	32
33	.04143	.04322	04655	.04882	.05195	.05480	.05765	.06118	33
34	.04151	.04331	.04663	.04891	.05205	.05490	.05775	.06129	34
35	.04159	.04340	.04672	.04901	.05214	.05501	.05785	.06140	35
36	.04168	.04349	.04681	.04911	.05223	.05511	.05794	.06151	36
37	.04176	.04358	.04690	04920	.05232	.05521	.05804	.06162	37
38	.04184	.04367	.04699	.04930	.05242	.05532	.05814	.06173	38
39	.04193	.04376	.04707	.04940	.05251	.05542	.05824	.06184	39
40	.04201	.04385	.04716	.04950	.05260	.05552	.05833	.06195	40
41	.04209	.04394	.04725	.04959	.05270	.05563	.05843	.06206	41
42	.04218	.04403	.04734	.04969	.05279	.05573	.05853	.06217	42
43	.04226	.04413	.04743	.04979	.05288	.05584	.05863	.06228	43
44	.04234	.04422	.04752	.04989	.05298	.05594	.05873	.06239	44
45	.04243	.04431	.04760	.04998	.05307	.05604	.05882	.06250	45
46	.04251	.04440	.04769	.05008	.05316	.05615	.05892	.06261	46
47	.04260	.04449	.04778	.05018	.05326	.05625	.05902	.06272	47
48	.04268	.04458	.04787	.05028	.05335	.05636	.05912	.06283	48
49	.04276	.04468	.04796	.05038	.05344	.05646	.05922	.06295	49
50	.04285	.04477	.04805	.05047	.05354	.05657	.05932	.06306	50
51	.04293	.04486	.04814	.05057	.05363	.05667	.05942	.06317	51
52	.04302	.04495	.04823	.05067	.05373	.05678	.05951	.06328	52
53	.04310	.04504	.04832	.05077	.05382	.05688	.05961	.06339	53
54	.04319	.04514	.04841	.05087	.05391	.05699	.05971	.06350	54
55	.04327	.04523	.04850	.05097	.05401	.05709	.05981	.06362	55
56	.04336	.04532	.04858	.05107	.05410	.05720	.05991	.06373	56
57	.04344	.04541	.04867	.05116	.05420	.05730	.06001	.06384	57
58	.04353	.04551	.04876	.05126	.05429	.05741	.06011	.06395	58
59	.04361	.04560	04885	.05136	.05439	.05751	.06021	.06407	59
60	.04370	.04569	.04894	.05146	.05448	.05762	.06031	.06418	60

′	20° Vers.	20° Ex. sec.	21° Vers.	21° Ex. sec.	22° Vers.	22° Ex. sec.	23° Vers.	23° Ex. sec.	′
0	.06031	.06418	.06642	.07115	.07282	.07853	.07950	.08636	0
1	.06041	.06429	.06652	.07126	.07293	.07866	.07961	.08649	1
2	.06051	.06440	.06663	.07138	.07303	.07879	.07972	.08663	2
3	.06061	.06452	.06673	.07150	.07314	.07892	.07984	.08676	3
4	.06071	06463	.06684	.07162	.07325	.07904	.07995	.08690	4
5	.06081	.06474	.06694	.07174	.07336	.07917	.08006	.08703	5
6	.06091	.06486	.06705	.07186	.07347	07930	.08018	.08717	6
7	.06101	06497	.06715	.07199	.07358	.07943	.08029	.08730	7
8	.06111	.06508	.06726	.07211	.07369	.07955	.08041	.08744	8
9	06121	.06520	.06736	.07223	.07380	.07968	.08052	.08757	9
10	.06131	.06531	06747	.07235	.07391	.07981	.08064	.08771	10
11	.06141	.06542	.06757	.07247	.07402	.07994	.08075	.08784	11
12	.06151	.06554	.06768	.07259	.07413	.08006	.08086	.08798	12
13	.06161	.06565	.06778	.07271	.07424	.08019	.08098	.08811	13
14	.06171	.06577	.06789	.07283	.07435	.08032	.08109	.08825	14
15	.06181	.06588	.06799	.07295	.07446	.08045	.08121	.08839	15
16	.06191	.06600	.06810	.07307	.07457	.08058	.08132	.08852	16
17	.06201	.06611	.06820	.07320	.07468	.08071	.08144	.08866	17
18	.06211	.06622	.06831	.07332	.07479	.08084	.08155	.08880	18
19	.06221	.06634	.06841	.07344	.07490	.08097	.08167	.08893	19
20	.06231	.06645	.06852	.07356	.07501	.08109	.08178	.08907	20
21	.06241	.06657	.06863	.07368	.07512	.08122	.08190	.08921	21
22	.06252	.06668	.06873	.07380	.07523	.08135	.08201	08934	22
23	.06262	.06680	.06884	.07393	.07534	.08148	.08213	.08948	23
24	.06272	.06691	.06894	.07405	.07545	.08161	.08225	.08962	24
25	.06282	.06703	.06905	.07417	.07556	.08174	.08236	.08975	25
26	.06292	.06715	.06916	.07429	.07568	.08087	08248	.08989	26
27	.06302	.06726	.06926	.07442	.07579	.08200	.08259	.09003	27
28	.06312	.06738	.06937	.07454	.07590	.08213	.08271	.09017	28
29	.06323	.06749	.06948	.07466	.07601	.08226	.08282	.09030	29
30	.06333	.06761	.06958	.07479	.07612	.08239	.08294	.09044	30
31	.06343	.06773	.06969	.07491	.07623	.08252	.08306	.09058	31
32	.06353	.06784	.06980	.07503	.07634	.08265	.08317	.09072	32
33	.06363	.06796	.06990	.07516	.07645	.08278	.08329	.09086	33
34	.06374	.06807	.07001	.07528	.07657	.08291	.08340	.09099	34
35	.06384	.06819	.07012	.07540	.07668	.08305	.08352	.09113	35
36	.06394	.06831	.07022	.07553	.07679	.08318	.08364	.09127	36
37	.06404	.06843	.07033	.07565	.07690	.08331	.08375	.09141	37
38	.06415	.06854	.07044	.07578	.07701	.08344	.08387	.09155	38
39	.06425	.06866	.07055	.07590	.07713	.08357	.08399	.09169	39
40	.06435	.06878	.07065	.07602	.07724	.08370	.08410	.09183	40
41	.06445	.06889	.07076	.07615	.07735	.08383	.08422	.09197	41
42	.06456	.06901	.07087	.07627	.07746	08397	08434	.09211	42
43	.06466	.06913	.07098	.07640	.07757	.08410	.08445	.09224	43
44	.06476	.06925	.07108	.07652	.07769	.08423	.08457	.09238	44
45	06486	.06936	.07119	.07665	07780	.08436	.08469	.09252	45
46	.06497	.06948	.07130	.07677	.07791	.08449	.08481	.09266	46
47	.06507	.06960	.07141	.07690	.07802	.08463	.08492	.09280	47
48	.06517	.06972	.07151	.07702	07814	08476	.08504	.09294	48
49	.06528	06984	.07162	.07715	.07825	.08489	.08516	09308	49
50	.06538	.06995	.07173	.07727	.07836	.08503	.08528	.09323	50
51	.06548	.07007	.07184	.07740	07848	.08516	.08539	.09337	51
52	.06559	.07019	.07195	.07752	07859	.08529	.08551	.09351	52
53	06569	.07031	.07206	.07765	.07870	.08542	.08563	.09365	53
54	.06580	.07043	.07216	.07778	.07881	.08556	.08575	09379	54
55	.06590	.07055	.07227	.07790	.07893	.08569	.08586	.09393	55
56	.06600	.07067	.07238	.07803	.07904	.08582	.08598	.09407	56
57	.06611	.07079	.07249	.07816	.07915	.08596	.08610	.09421	57
58	.06621	.07091	.07260	.07828	.07927	.08069	.08622	.09435	58
59	.06632	.07103	.07271	.07841	.07938	.08623	.08634	.09449	59
60	06642	.07115	.07282	.07853	.07950	.08636	.08645	.09464	60

′	24° Vers.	24° Ex. sec.	25° Vers.	25° Ex. sec.	26° Vers.	26° Ex. sec.	27° Vers.	27° Ex. sec.	′
0	08645	.09464	.09369	.10338	.10121	.11260	.10899	.12233	0
1	.08657	.09478	.09382	.10353	.10133	.11276	.10913	.12249	1
2	.08669	.09492	.09394	.10368	.10146	.11292	.10926	.12266	2
3	.08681	.09506	.09406	.10383	.10159	.11308	.10939	.12283	3
4	.08693	.09520	.09418	.10398	.10172	.11323	.10952	.12299	4
5	.08705	.09535	.09431	.10413	.10184	.11339	.10965	.12316	5
6	.08717	.09549	.09443	.10428	.10197	11355	.10979	.12333	6
7	.08728	.09563	.09455	.10443	.10210	.11371	.10992	.12349	7
8	.08740	.09577	09468	.10458	.10223	.11387	.11005	.12366	8
9	.08752	.09592	.09480	.10473	.10236	.11403	.11019	.12383	9
10	.08764	.09606	.09493	.10488	.10248	.11419	.11032	.12400	10
11	.08776	.09620	.09505	.10503	.10261	.11435	.11045	.12416	11
12	.08788	.09635	.09517	.10518	.10274	.11451	.11058	.12433	12
13	.08800	.09649	.09530	.10533	.10287	.11467	11072	.12450	13
14	.08812	.09663	.09542	.10549	.10300	.11483	.11085	.12467	14
15	.08824	.09678	09554	.10564	.10313	.11499	.11098	.12484	15
16	.08836	.09692	.09567	.10579	.10326	11515	.11112	.12501	16
17	.08848	.09707	.09579	.10594	.10338	.11531	.11125	.12518	17
18	.08860	.09721	.09592	.10609	.10351	.11547	.11138	.12534	18
19	.08872	.09735	.09604	.10625	.10364	.11563	.11152	.12551	19
20	.08884	.09750	.09617	.10640	.10377	.11579	.11165	.12568	20
21	.08896	.09764	.09629	.10655	.10390	.11595	.11178	.12585	21
22	.08908	.09779	.09642	.10670	.10403	.11611	.11192	.12602	22
23	.08920	.09793	.09654	.10686	.10416	.11627	.11205	.12619	23
24	.08932	.09808	.09666	.10701	10429	.11643	.11218	12636	24
25	.08944	.09822	.09679	.10716	.10442	.11659	.11232	.12653	25
26	.08956	.09837	.09691	.10731	.10455	.11675	.11245	.12670	26
27	.08968	.09851	.09704	.10747	.10468	.11691	.11259	.12687	27
28	.08980	.09866	.09716	.10762	.10481	.11708	.11272	.12704	28
29	.08992	.09880	.09729	.10777	.10494	.11724	.11285	.12721	29
30	.09004	.09895	.09741	.10793	.10507	.11740	.11299	.12738	30
31	.09016	.09909	.09754	.10808	.10520	.11756	.11312	.12755	31
32	.09028	.09924	.09767	.10824	.10533	.11772	.11326	.12772	32
33	.09040	.09939	.09779	.10839	.10546	.11789	.11339	.12789	33
34	.09052	.09953	.09792	.10854	.10559	.11805	.11353	.12807	34
35	.09064	.09968	.09804	.10870	.10572	.11821	.11366	.12824	35
36	.09076	.09982	09817	.10885	.10585	.11838	.11380	.12841	36
37	.09089	.09997	09829	.10901	.10598	.11854	.11393	.12858	37
38	.09101	.10012	.09842	.10916	.10611	.11870	.11407	.12875	38
39	.09113	.10026	.09854	.10932	.10624	.11886	.11420	.12892	39
40	.09125	.10041	.09867	.10947	.10637	.11903	.11434	.12910	40
41	.09137	.10055	.09880	.10963	.10650	.11919	.11447	.12927	41
42	.09149	.10071	.09892	.10978	.10663	.11936	.11461	.12944	42
43	.09161	.10085	.09905	.10994	.10676	.11952	.11474	.12961	43
44	.09174	.10100	.09918	.11009	.10689	.11968	.11488	.12979	44
45	.09186	.10115	.09930	.11025	.10702	.11985	.11501	.12996	45
46	.09198	.10130	.09943	.11041	.10715	.12001	.11515	.13013	46
47	.09210	.10144	.09955	.11056	.10728	.12018	.11528	.13031	47
48	.09222	.10159	.09968	.11072	.10741	.12034	.11542	.13048	48
49	.09234	.10174	.09981	.11087	.10755	.12051	.11555	.13065	49
50	.09247	.10189	.09993	.11103	.10768	.12067	.11569	.13083	50
51	.09259	.10204	.10006	.11119	.10781	.12084	.11583	.13100	51
52	.09271	.10218	.10019	.11134	10794	.12100	.11596	.13117	52
53	.09283	.10233	.10032	.11150	.10807	.12117	11610	.13135	53
54	.09296	.10248	.10044	.11166	10820	.12133	.11623	.13152	54
55	.09308	.10263	.10057	.11181	.10833	.12150	.11637	.13170	55
56	.09320	.10278	.10070	.11197	.10847	.12166	.11651	.13187	56
57	.09332	.10293	.10082	.11213	.10860	.12183	.11664	.13205	57
58	.09345	.10308	.10095	.11229	.10873	.12199	.11678	.13222	58
59	.09357	.10323	.10108	.11244	.10886	.12216	.11692	.13240	59
60	.09369	.10338	.10121	.11260	.10899	.12233	.11705	.13257	60

TABLE X.—NATURAL VERSED SINES AND EXTERNAL SECANTS.

′	28° Vers.	28° Ex. sec.	29° Vers.	29° Ex. sec.	30° Vers.	30° Ex. sec.	31° Vers.	31° Ex. sec.	′
0	.11705	.13257	.12538	.14335	.13397	.15470	.14283	.16663	0
1	.11719	.13275	.12552	.14354	.13412	.15489	.14298	.16684	1
2	.11733	.13292	.12566	.14372	.13427	.15509	.14313	.16704	2
3	.11746	.13310	.12580	.14391	.13441	.15528	.14328	.16725	3
4	.11760	.13327	.12595	.14409	.13456	.15548	.14343	.16745	4
5	.11774	.13345	.12609	.14428	.13470	.15567	.14358	.16766	5
6	.11787	.13362	.12623	.14446	.13485	.15587	.14373	.16786	6
7	.11801	.13380	.12637	.14465	.13499	.15606	.14388	.16806	7
8	.11815	.13398	.12651	.14483	.13514	.15626	.14403	.16827	8
9	.11828	.13415	.12665	.14502	.13529	.15645	.14418	.16848	9
10	.11842	.13433	.12679	.14521	.13543	.15665	.14433	.16868	10
11	.11856	.13451	.12694	.14539	.13558	.15684	.14449	.16889	11
12	.11870	.13468	.12708	.14558	.13573	.15704	.14464	.16909	12
13	.11883	.13486	.12722	.14576	.13587	.15724	.14479	.16930	13
14	.11897	.13504	.12736	.14595	.13602	.15743	.14494	.16950	14
15	.11911	.13521	.12750	.14614	.13616	.15763	.14509	.16971	15
16	.11925	.13539	.12765	.14632	.13631	.15782	.14524	.16992	16
17	.11938	.13557	.12779	.14651	.13646	.15802	.14539	.17012	17
18	.11952	.13575	.12793	.14670	.13660	.15822	.14554	.17033	18
19	.11966	.13593	.12807	.14689	.13675	.15841	.14569	.17054	19
20	.11980	.13610	.12822	.14707	.13690	.15861	.14584	.17075	20
21	.11994	.13628	.12836	.14726	.13705	.15881	.14599	.17095	21
22	.12007	.13646	.12850	.14745	.13719	.15901	.14615	.17116	22
23	.12021	.13664	.12864	.14764	.13734	.15920	.14630	.17137	23
24	.12035	.13682	.12879	.14782	.13749	.15940	.14645	.17158	24
25	.12049	.13700	.12893	.14801	.13763	.15960	.14660	.17178	25
26	.12063	.13718	.12907	.14820	.13778	.15980	.14675	.17199	26
27	.12077	.13735	.12921	.14839	.13793	.16000	.14690	.17220	27
28	.12091	.13753	.12936	.14858	.13808	.16019	.14706	.17241	28
29	.12104	.13771	.12950	.14877	.13822	.16039	.14721	.17262	29
30	.12118	.13789	.12964	.14896	.13837	.16059	.14736	.17283	30
31	.12132	.13807	.12979	.14914	.13852	.16079	.14751	.17304	31
32	.12146	.13825	.12993	.14933	.13867	.16099	.14766	.17325	32
33	.12160	.13843	.13007	.14952	.13881	.16119	.14782	.17346	33
34	.12174	.13861	.13022	.14971	.13896	.16139	.14797	.17367	34
35	.12188	.13879	.13036	.14990	.13911	.16159	.14812	.17388	35
36	.12202	.13897	.13051	.15009	.13926	.16179	.14827	.17409	36
37	.12216	.13916	.13065	.15028	.13941	.16199	.14843	.17430	37
38	.12230	.13934	.13079	.15047	.13955	.16219	.14858	.17451	38
39	.12244	.13952	.13094	.15066	.13970	.16239	.14873	.17472	39
40	.12257	.13970	.13108	.15085	.13985	.16259	.14888	.17493	40
41	.12271	.13988	.13122	.1510[illegible]	.14000	.16279	.14904	.17514	41
42	.12285	.14006	.13137	.15124	.14015	.16299	.14919	.17535	42
43	.12299	.14024	.13151	.15143	.14030	.16319	.14934	.17556	43
44	.12313	.14042	.13166	.15162	.14044	.16339	.14949	.17577	44
45	.12327	.14061	.13180	.15181	.14059	.16359	.14965	.17598	45
46	.12341	.14079	.13195	.15200	.14074	.16380	.14980	.17620	46
47	.12355	.14097	.13209	.15219	.14089	.16400	.14995	.17641	47
48	.12369	.14115	.13223	.15239	.14104	.16420	.15011	.17662	48
49	.12383	.14134	.13238	.15258	.14119	.16440	.15026	.17683	49
50	.12397	.14152	.13252	.15277	.14134	.16460	.15041	.17704	50
51	.12411	.14170	.13267	.15296	.14149	.16481	.15057	.17726	51
52	.12425	.14188	.13281	.15315	.14164	.16501	.15072	.17747	52
53	.12439	.14207	.13296	.15335	.14179	.16521	.15087	.17768	53
54	.12454	.14225	.13310	.15354	.14194	.16541	.15103	.17790	54
55	.12468	.14243	.13325	.15373	.14208	.16562	.15118	.17811	55
56	.12482	.14262	.13339	.15393	.14223	.16582	.15134	.17832	56
57	.12496	.14280	.13354	.15412	.14238	.16602	.15149	.17854	57
58	.12510	.14299	.13368	.15431	.14253	.16623	.15164	.17875	58
59	.12524	.14317	.13383	.15451	.14268	.16643	.15180	.17896	59
60	.12538	.14335	.13397	.15470	.14283	.16663	.15195	.17918	60

	32°		33°		34°		35°		
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.15195	.17918	.16133	.19236	.17096	.20622	.18085	.22077	0
1	.15211	.17939	.16149	.19259	.17113	.20645	.18101	.22102	1
2	.15226	.17961	.16165	.19281	.17129	.20669	.18118	.22127	2
3	.15241	.17982	.16181	.19304	.17145	.20693	.18135	.22152	3
4	.15257	.18004	.16196	.19327	.17161	.20717	.18152	.22177	4
5	.15272	.18025	.16212	.19349	.17178	.20740	.18168	.22202	5
6	.15288	.18047	.16228	.19372	.17194	.20764	.18185	.22227	6
7	.15303	.18068	.16244	.19394	.17210	.20788	.18202	.22252	7
8	.15319	.18090	.16260	.19417	.17227	.20812	.18218	.22277	8
9	.15334	.18111	.16276	.19440	.17243	.20836	.18235	.22302	9
10	.15350	.18133	.16292	.19463	.17259	.20859	.18252	.22327	10
11	.15365	.18155	.16308	.19485	.17276	.20883	.18269	.22352	11
12	.15381	.18176	.16324	.19508	.17292	.20907	.18286	.22377	12
13	.15396	.18198	.16340	.19531	.17308	.20931	.18302	.22402	13
14	.15412	.18220	.16355	.19554	.17325	.20955	.18319	.22428	14
15	.15427	.18241	.16371	.19576	.17341	.20979	.18336	.22453	15
16	.15443	.18263	.16387	.19599	.17357	.21003	.18353	.22478	16
17	.15458	.18285	.16403	.19622	.17374	.21027	.18369	.22503	17
18	.15474	.18307	.16419	.19645	.17390	.21051	.18386	.22528	18
19	.15489	.18328	.16435	.19668	.17407	.21075	.18403	.22554	19
20	.15505	.18350	.16451	.19691	.17423	.21099	.18420	.22579	20
21	.15520	.18372	.16467	.19713	.17439	.21123	.18437	.22604	21
22	.15536	.18394	.16483	.19736	.17456	.21147	.18454	.22629	22
23	.15552	.18416	.16499	.19759	.17472	.21171	.18470	.22655	23
24	.15567	.18437	.16515	.19782	.17489	.21195	.18487	.22680	24
25	.15583	.18459	.16531	.19805	.17505	.21220	.18504	.22706	25
26	.15598	.18481	.16547	.19828	.17522	.21244	.18521	.22731	26
27	.15614	.18503	.16563	.19851	.17538	.21268	.18538	.22756	27
28	.15630	.18525	.16579	.19874	.17554	.21292	.18555	.22782	28
29	.15645	.18547	.16595	.19897	.17571	.21316	.18572	.22807	29
30	.15661	.18569	.16611	.19920	.17587	.21341	.18588	.22833	30
31	.15676	.18591	.16627	.19944	.17604	.21365	.18605	.22858	31
32	.15692	.18613	.16644	.19967	.17620	.21389	.18622	.22884	32
33	.15708	.18635	.16660	.19990	.17637	.21414	.18639	.22909	33
34	.15723	.18657	.16676	.20013	.17658	.21438	.18656	.22935	34
35	.15739	.18679	.16692	.20036	.17670	.21462	.18673	.22960	35
36	.15755	.18701	.16708	.20059	.17686	.21487	.18690	.22986	36
37	.15770	.18723	.16724	.20083	.17703	.21511	.18707	.23012	37
38	.15786	.18745	.16740	.20106	.17719	.21535	.18724	.23037	38
39	.15802	.18767	.16756	.20129	.17736	.21560	.18741	.23063	39
40	.15818	.18790	.16772	.20152	.17752	.21584	.18758	.23089	40
41	.15833	.18812	.16788	.20176	.17769	.21609	.18775	.23114	41
42	.15849	.18834	.16805	.20199	.17786	.21633	.18792	.23140	42
43	.15865	.18856	.16821	.20222	.17802	.21658	.18809	.23166	43
44	.15880	.18878	.16837	.20246	.17819	.21682	.18826	.23192	44
45	.15896	.18901	.16853	.20269	.17835	.21707	.18843	.23217	45
46	.15912	.18923	.16869	.20292	.17852	.21731	.18860	.23243	46
47	.15928	.18945	.16885	.20316	.17868	.21756	.18877	.23269	47
48	.15943	.18967	.16902	.20339	.17885	.21781	.18894	.23295	48
49	.15959	.18990	.16918	.20363	.17902	.21805	.18911	.23321	49
50	.15975	.19012	.16934	.20386	.17918	.21830	.18928	.23347	50
51	.15991	.19034	.16950	.20410	.17935	.21855	.18945	.23373	51
52	.16006	.19057	.16966	.20433	.17952	.21879	.18962	.23399	52
53	.16022	.19079	.16983	.20457	.17968	.21904	.18979	.23424	53
54	.18038	.19102	.16999	.20480	.17985	.21929	.18996	.23450	54
55	.16054	.19124	.17015	.20504	.18001	.21953	.19013	.23476	55
56	.16070	.19146	.17031	.20527	.18018	.21978	.19030	.23502	56
57	.16085	.19169	.17047	.20551	.18035	.22003	.19047	.23529	57
58	.16101	.19191	.17064	.20575	.18051	.22028	.19064	.23555	58
59	.16117	.19214	.17080	.20598	.18068	.22053	.19081	.23581	59
60	.16133	.19236	.17096	.20622	.18085	.22077	.19098	.23607	60

TABLE X.—NATURAL VERSED SINES AND EXTERNAL SECANTS

	36°		37°		38°		39°		
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.19098	.23607	.20136	.25214	.21199	.26902	.22285	.28676	**0**
1	.19115	.23633	.20154	.25241	.21217	.26931	.22304	.28706	1
2	.19133	.23659	.20171	.25269	.21235	.26960	.22322	.28737	2
3	.19150	.23685	.20189	.25296	.21253	.26988	.22340	.28767	3
4	.19167	.23711	.20207	.25324	.21271	.27017	.22359	.28797	4
5	.19184	.23738	.20224	.25351	.21289	.27046	.22377	.28828	5
6	.19201	.23764	.20242	.25379	.21307	.27075	.22395	.28858	6
7	.19218	.23790	.20259	.25406	.21324	.27104	.22414	.28889	7
8	.19235	.23816	.20277	.25434	.21342	.27133	.22432	.28919	8
9	.19252	.23843	.20294	.25462	.21360	.27162	.22450	.28950	9
10	.19270	.23869	.20312	.25489	.21378	.27191	.22469	.28980	**10**
11	.19287	.23895	.20329	.25517	.21396	.27221	.22487	.29011	11
12	.19304	.23922	.20347	.25545	.21414	.27250	.22506	.29042	12
13	.19321	.23948	.20365	.25572	.21432	.27279	.22524	.29072	13
14	.19338	.23975	.20382	.25600	.21450	.27308	.22542	.29103	14
15	.19356	.24001	.20400	.25628	.21468	.27337	.22561	.29133	15
16	.19373	.24028	.20417	.25656	.21486	.27366	.22579	.29164	16
17	.19390	.24054	.20435	.25683	.21504	.27396	.22598	.29195	17
18	.19407	.24081	.20453	.25711	.21522	.27425	.22616	.29226	18
19	.19424	.24107	.20470	.25739	.21540	.27454	.22634	.29256	19
20	.19442	.24134	.20488	.25767	.21558	.27483	.22653	.29287	**20**
21	.19459	.24160	.20506	.25795	.21576	.27513	.22671	.29318	21
22	.19476	.24187	.20523	.25823	.21595	.27542	.22690	.29349	22
23	.19493	.24213	.20541	.25851	.21613	.27572	.22708	.29380	23
24	.19511	.24240	.20559	.25879	.21631	.27601	.22727	.29411	24
25	.19528	.24267	.20576	.25907	.21649	.27630	.22745	.29442	25
26	.19545	.24293	.20594	.25935	.21667	.27660	.22764	.29473	26
27	.19562	.24320	.20612	.25963	.21685	.27689	.22782	.29504	27
28	.19580	.24347	.20629	.25991	.21703	.27719	.22801	.29535	28
29	.19597	.24373	.20647	.26019	.21721	.27748	.22819	.29566	29
30	.19614	.24400	.20665	.26047	.21739	.27778	.22838	.29597	**30**
31	.19632	.24427	.20682	.26075	.21757	.27807	.22856	.29628	31
32	.19649	.24454	.20700	.26104	.21775	.27837	.22875	.29659	32
33	.19666	.24481	.20718	.26132	.21794	.27867	.22893	.29690	33
34	.19684	.24508	.20736	.26160	.21812	.27896	.22912	.29721	34
35	.19701	.24534	.20753	.26188	.21830	.27926	.22930	.29752	35
36	.19718	.24561	.20771	.26216	.21848	.27956	.22949	.29784	36
37	.19736	.24588	.20789	.26245	.21866	.27985	.22967	.29815	37
38	.19753	.24615	.20807	.26273	.21884	.28015	.22986	.29846	38
39	.19770	.24642	.20824	.26301	.21902	.28045	.23004	.29877	39
40	.19788	.24669	.20842	.26330	.21921	.28075	.23023	.29909	**40**
41	.19805	.24696	.20860	.26358	.21939	.28105	.23041	.29940	41
42	.19822	.24723	.20878	.26387	.21957	.28134	.23060	.29971	42
43	.19840	.24750	.20895	.26415	.21975	.28164	.23079	.30003	43
44	.19857	.24777	.20913	.26443	.21993	.28194	.23097	.30034	44
45	.19875	.24804	.20931	.26472	.22012	.28224	.23116	.30066	45
46	.19892	.24832	.20949	.26500	.22030	.28254	.23134	.30097	46
47	.19909	24859	.20967	.26529	.22048	.28284	.23153	.30129	47
48	.19927	.24886	.20985	.26557	.22066	.28314	.23172	.30160	48
49	.19944	.24913	.21002	.26586	.22084	.28344	.23190	.30192	49
50	.19962	.24940	.21020	.26615	.22103	.28374	.23209	.30223	**50**
51	.19979	.24967	.21038	.26643	.22121	.28404	.23228	.30255	51
52	.19997	.24995	.21056	.26672	.22139	.28434	.23246	.30287	52
53	.20014	.25022	.21074	.26701	.22157	.28464	.23265	.30318	53
54	.20032	.25049	.21092	.26729	.22176	.28495	.23283	.30350	54
55	.20049	.25077	.21109	.26758	.22194	.28525	.23302	.30382	55
56	.20066	.25104	.21127	.26787	.22212	.28555	.23321	.30413	56
57	.20084	.25131	.21145	.26815	.22231	.28585	.23339	.30445	57
58	.20101	.25159	.21163	.26844	.22249	.28615	.23358	.30477	58
59	.20119	.25186	.21181	.26873	.22267	.28646	.23377	.30509	59
60	.20136	.25214	.21199	.26902	.22285	.28676	.23396	.30541	**60**

TABLE X.—NATURAL VERSED SINES AND EXTERNAL SECANTS.

	40°		41°		42°		43°		
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.23396	.30541	.24529	.32501	.25686	.34563	.26865	.36733	0
1	.23414	.30573	.24548	.32535	.25705	.34599	.26884	.36770	1
2	.23433	.30605	.24567	.32568	.25724	.34634	.26904	.36807	2
3	.23452	.30636	.24586	.32602	.25744	.34669	.26924	.36844	3
4	.23470	.30668	.24605	.32636	.25763	.34704	.26944	.36881	4
5	.23489	.30700	.24625	.32669	.25783	.34740	.26964	.36919	5
6	.23508	.30732	.24644	.32703	.25802	.34775	.26984	.36956	6
7	.23527	.30764	.24663	.32737	.25822	.34811	.27004	.36993	7
8	.23545	.30796	.24682	.32770	.25841	.34846	.27024	.37030	8
9	.23564	.30829	.24701	.32804	.25861	.34882	.27043	.37068	9
10	.23583	.30861	.24720	.32838	.25880	.34917	.27063	.37105	10
11	.23602	.30893	.24739	.32872	.25900	.34953	.27083	.37143	11
12	.23620	.30925	.24759	.32905	.25920	.34988	.27103	.37180	12
13	.23639	.30957	.24778	.32939	.25939	.35024	.27123	.37218	13
14	.23658	.30989	.24797	.32973	.25959	.35060	.27143	.37255	14
15	.23677	.31022	.24816	.33007	.25978	.35095	.27163	.37293	15
16	.23696	.31054	.24835	.33041	.25998	.35131	.27183	.37330	16
17	.23714	.31086	.24854	.33075	.26017	.35167	.27203	.37368	17
18	.23733	.31119	.24874	.33109	.26037	.35203	.27223	.37406	18
19	.23752	.31151	.24893	.33143	.26056	.35238	.27243	.37443	19
20	.23771	.31183	.24912	.33177	.26076	.35274	.27263	.37481	20
21	.23790	.31216	.24931	.33211	.26096	.35310	.27283	.37519	21
22	.23808	.31248	.24950	.33245	.26115	.35346	.27303	.37556	22
23	.23827	.31281	.24970	.33279	.26135	.35382	.27323	.37594	23
24	.23846	.31313	.24989	.33314	.26154	.35418	.27343	.37632	24
25	.23865	.31346	.25008	.33348	.26174	.35454	.27363	.37670	25
26	.23884	.31378	.25027	.33382	.26194	.35490	.27383	.37708	26
27	.23903	.31411	.25047	.33416	.26213	.35526	.27403	.37746	27
28	.23922	.31443	.25066	.33451	.26233	.35562	.27423	.37784	28
29	.23941	.31476	.25085	.33485	.26253	.35598	.27443	.37822	29
30	.23959	.31509	.25104	.33519	.26272	.35634	.27463	.37860	30
31	.23978	.31541	.25124	.33554	.26292	.35670	.27483	.37898	31
32	.23997	.31574	.25143	.33588	.26312	.35707	.27503	.37936	32
33	.24016	.31607	.25162	.33622	.26331	.35743	.27523	.37974	33
34	.24035	.31640	.25182	.33657	.26351	.35779	.27543	.38012	34
35	.24054	.31672	.25201	.33691	.26371	.35815	.27563	.38051	35
36	.24073	.31705	.25220	.33726	.26390	.35852	.27583	.38089	36
37	.24092	.31738	.25240	.33760	.26410	.35888	.27603	.38127	37
38	.24111	.31771	.25259	.33795	.26430	.35924	.27623	.38165	38
39	.24130	.31804	.25278	.33830	.26449	.35961	.27643	.38204	39
40	.24149	.31837	.25297	.33864	.26469	.35997	.27663	.38242	40
41	.24168	.31870	.25317	.33899	.26489	.36034	.27683	.38280	41
42	.24187	.31903	.25336	.33934	.26509	.36070	.27703	.38319	42
43	.24206	.31936	.25356	.33968	.26528	.36107	.27723	.38357	43
44	.24225	.31969	.25375	.34003	.26548	.36143	.27743	.38396	44
45	.24244	.32002	.25394	.34038	.26568	.36180	.27764	.38434	45
46	.24262	.32035	.25414	.34073	.26588	.36217	.27784	.38473	46
47	.24281	.32068	.25433	.34108	.26607	.36253	.27804	.38512	47
48	.24300	.32101	.25452	.34142	.26627	.36290	.27824	.38550	48
49	.24320	.32134	.25472	.34177	.26647	.36327	.27844	.38589	49
50	.24339	.32168	.25491	.34212	.26667	.36363	.27864	.38628	50
51	.24358	.32201	.25511	.34247	.26686	.36400	.27884	.38666	51
52	.24377	.32234	.25530	.34282	.26706	.36437	.27905	.38705	52
53	.24396	.32267	.25549	.34317	.26726	.36474	.27925	.38744	53
54	.24415	.32301	.25569	.34352	.26746	.36511	.27945	.38783	54
55	.24434	.32334	.25588	.34387	.26766	.36548	.27965	.38822	55
56	.24453	.32368	.25608	.34423	.26785	.36585	.27985	.38860	56
57	.24472	.32401	.25627	.34458	.26805	.36622	.28005	.38899	57
58	.24491	.32434	.25647	.34493	.26825	.36659	.28026	.38938	58
59	.24510	.32468	.25666	.34528	.26845	.36696	.28046	.38977	59
60	.24529	.32501	.25686	.34563	.26865	.36733	.28066	.39016	60

TABLE X.—NATURAL VERSED SINES AND EXTERNAL SECANTS.

	44°		45°		46°		47°		
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.28066	.39016	.29289	.41421	.30534	.43956	.31800	.46628	0
1	.28086	.39055	.29310	.41463	.30555	.43999	.31821	.46674	1
2	.28106	.39095	.29330	.41504	.30576	.44042	.31843	.46719	2
3	.28127	.39134	.29351	.41545	.30597	.44086	.31864	.46765	3
4	.28147	.39173	.29372	.41586	.30618	.44129	.31885	.46811	4
5	.28167	.39212	.29392	.41627	.30639	.44173	.31907	.46857	5
6	.28187	.39251	.29413	.41669	.30660	.44217	.31928	.46903	6
7	.28208	.39291	.29433	.41710	.30681	.44260	.31949	.46949	7
8	.28228	.39330	.29454	.41752	.30702	.44304	.31971	.46995	8
9	.28248	.39369	.29475	.41793	.30723	.44347	.31992	.47041	9
10	.28268	.39409	.29495	.41835	.30744	.44391	.32013	.47087	10
11	.28289	.39448	.29516	.41876	.30765	.44435	.32035	.47134	11
12	.28309	.39487	.29537	.41918	.30786	.44479	.32056	.47180	12
13	.28329	.39527	.29557	.41959	.30807	.44523	.32077	.47226	13
14	.28350	.39566	.29578	.42001	.30828	.44567	.32099	.47272	14
15	.28370	.39606	.29599	.42042	.30849	.44610	.32120	.47319	15
16	.28390	.39646	.29619	.42084	.30870	.44654	.32141	.47365	16
17	.28410	.39685	.29640	.42126	.30891	.44698	.32163	.47411	17
18	.28431	.39725	.29661	.42168	.30912	.44742	.32184	.47458	18
19	.28451	.39764	.29681	.42210	.30933	.44787	.32205	.47504	19
20	.28471	.39804	.29702	.42251	.30954	.44831	.32227	.47551	20
21	.28492	.39844	.29723	.42293	.30975	.44875	.32248	.47598	21
22	.28512	.39884	.29743	.42335	.30996	.44919	.32270	.47644	22
23	.28532	.39924	.29764	.42377	.31017	.44963	.32291	.47691	23
24	.28553	.39963	.29785	.42419	.31038	.45007	.32312	.47738	24
25	.28573	.40003	.29805	.42461	.31059	.45052	.32334	.47784	25
26	.28593	.40043	.29826	.42503	.31080	.45096	.32355	.47831	26
27	.28614	.40083	.29847	.42545	.31101	.45141	.32377	.47878	27
28	.28634	.40123	.29868	.42587	.31122	.45185	.32398	.47925	28
29	.28655	.40163	.29888	.42630	.31143	.45229	.32420	.47972	29
30	.28675	.40203	.29909	.42672	.31165	.45274	.32441	.48019	30
31	.28695	.40243	.29930	.42714	.31186	.45319	.32462	.48066	31
32	.28716	.40283	.29951	.42756	.31207	.45363	.32484	.48113	32
33	.28736	.40324	.29971	.42799	.31228	.45408	.32505	.48160	33
34	.28757	.40364	.29992	.42841	.31249	.45452	.32527	.48207	34
35	.28777	.40404	.30013	.42883	.31270	.45497	.32548	.48254	35
36	.28797	.40444	.30034	.42926	.31291	.45542	.32570	.48301	36
37	.28818	.40485	.30054	.42968	.31312	.45587	.32591	.48349	37
38	.28838	.40525	.30075	.43011	.31334	.45631	.32613	.48396	38
39	.28859	.40565	.30096	.43053	.31355	.45676	.32634	.48443	39
40	.28879	.40606	.30117	.43096	.31376	.45721	.32656	.48491	40
41	.28900	.40646	.30138	.43139	.31397	.45766	.32677	.48538	41
42	.28920	.40687	.30158	.43181	.31418	.45811	.32699	.48586	42
43	.28941	.40727	.30179	.43224	.31439	.45856	.32720	.48633	43
44	.28961	.40768	.30200	.43267	.31461	.45901	.32742	.48681	44
45	.28981	.40808	.30221	.43310	.31482	.45946	.32763	.48728	45
46	.29002	.40849	.30242	.43352	.31503	.45992	.32785	.48776	46
47	.29022	.40890	.30263	.43395	.31524	.46037	.32806	.48824	47
48	.29043	.40930	.30283	.43438	.31545	.46082	.32828	.48871	48
49	.29063	.40971	.30304	.43481	.31567	.46127	.32849	.48919	49
50	.29084	.41012	.30325	.43524	.31588	.46173	.32871	.48967	50
51	.29104	.41053	.30346	.43567	.31609	.46218	.32893	.49015	51
52	.29125	.41093	.30367	.43610	.31630	.46263	.32914	.49063	52
53	.29145	.41134	.30388	.43653	.31651	.46309	.32936	.49111	53
54	.29166	.41175	.30409	.43696	.31673	.46354	.32957	.49159	54
55	.29187	.41216	.30430	.43739	.31694	.46400	.32979	.49207	55
56	.29207	.41257	.30451	.43783	.31715	.46445	.33001	.49255	56
57	.29228	.41298	.30471	.43826	.31736	.46491	.33022	.49303	57
58	.29248	.41339	.30492	.43869	.31758	.46537	.33044	.49351	58
59	.29269	.41380	.30513	.43912	.31779	.46582	.33065	.49399	59
60	.29289	.41421	.30534	.43956	.31800	.46628	.33087	.49448	60

TABLE X.—NATURAL VERSED SINES AND EXTERNAL SECANTS.

	48°		49°		50°		51°		
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.33087	.49448	.34394	.52425	.35721	.55572	.37068	.58902	0
1	.33109	.49496	.34416	.52476	.35744	.55626	.37091	.58959	1
2	.33130	.49544	.34438	.52527	.35766	.55680	.37113	.59016	2
3	.33152	.49593	.34460	.52579	.35788	.55734	.37136	.59073	3
4	.33173	.49641	.34482	.52630	.35810	.55789	.37158	.59130	4
5	.33195	.49690	.34504	.52681	.35833	.55843	.37181	.59188	5
6	.33217	.49738	.34526	.52732	.35855	.55897	.37204	.59245	6
7	.33238	.49787	.34548	.52784	.35877	.55951	.37226	.59302	7
8	.33260	.49835	.34570	.52835	.35900	.56005	.37249	.59360	8
9	.33282	.49884	.34592	.52886	.35922	.56060	.37272	.59418	9
10	.33303	.49933	.34614	.52938	.35944	.56114	.37294	.59475	10
11	.33325	.49981	.34636	.52989	.35967	.56169	.37317	.59533	11
12	.33347	.50030	.34658	.53041	.35989	.56223	.37340	.59590	12
13	.33368	.50079	.34680	.53092	.36011	.56278	.37362	.59648	13
14	.33390	.50128	.34702	.53144	.36034	.56332	.37385	.59706	14
15	.33412	.50177	.34724	.53196	.36056	.56387	.37408	.59764	15
16	.33434	.50226	.34746	.53247	.36078	.56442	.37430	.59822	16
17	.33455	.50275	.34768	.53299	.36101	.56497	.37453	.59880	17
18	.33477	.50324	.34790	.53351	.36123	.56551	.37476	.59938	18
19	.33499	.50373	.34812	.53403	.36146	.56606	.37498	.59996	19
20	.33520	.50422	.34834	.53455	.36168	.56661	.37521	.60054	20
21	.33542	.50471	.34856	.53507	.36190	.56716	.37544	.60112	21
22	.33564	.50521	.34878	.53559	.36213	.56771	.37567	.60171	22
23	.33586	.50570	.34900	.53611	.36235	.56826	.37589	.60229	23
24	.33607	.50619	.34923	.53663	.36258	.56881	.37612	.60287	24
25	.33629	.50669	.34945	.53715	.36280	.56937	.37635	.60346	25
26	.33651	.50718	.34967	.53768	.36302	.56992	.37658	.60404	26
27	.33673	.50767	.34989	.53820	.36325	.57047	.37680	.60463	27
28	.33694	.50817	.35011	.53872	.36347	.57103	.37703	.60521	28
29	.33716	.50866	.35033	.53924	.36370	.57158	.37726	.60580	29
30	.33738	.50916	.35055	.53977	.36392	.57213	.37749	.60639	30
31	.33760	.50966	.35077	.54029	.36415	.57269	.37771	.60698	31
32	.33782	.51015	.35099	.54082	.36437	.57324	.37794	.60756	32
33	.33803	.51065	.35122	.54134	.36460	.57380	.37817	.60815	33
34	.33825	.51115	.35144	.54187	.36482	.57436	.37840	.60874	34
35	.33847	.51165	.35166	.54240	.36504	.57491	.37862	.60933	35
36	.33869	.51215	.35188	.54292	.36527	.57547	.37885	.60992	36
37	.33891	.51265	.35210	.54345	.36549	.57603	.37908	.61051	37
38	.33912	.51314	.35232	.54398	.36572	.57659	.37931	.61111	38
39	.33934	.51364	.35254	.54451	.36594	.57715	.37954	.61170	39
40	.33956	.51415	.35277	.54504	.36617	.57771	.37976	.61229	40
41	.33978	.51465	.35299	.54557	.36639	.57827	.37999	.61288	41
42	.34000	.51515	.35321	.54610	.36662	.57883	.38022	.61348	42
43	.34022	.51565	.35343	.54663	.36684	.57939	.38045	.61407	43
44	.34044	.51615	.35365	.54716	.36707	.57995	.38068	.61467	44
45	.34065	.51665	.35388	.54769	.36729	.58051	.38091	.61526	45
46	.34087	.51716	.35410	.54822	.36752	.58108	.38113	.61586	46
47	.34109	.51766	.35432	.54876	.36775	.58164	.38136	.61646	47
48	.34131	.51817	.35454	.54929	.36797	.58221	.38159	.61705	48
49	.34153	.51867	.35476	.54982	.36820	.58277	.38182	.61765	49
50	.34175	.51918	.35499	.55036	.36842	.58333	.38205	.61825	50
51	.34197	.51968	.35521	.55089	.36865	.58390	.38228	.61885	51
52	.34219	.52019	.35543	.55143	.36887	.58447	.38251	.61945	52
53	.34241	.52069	.35565	.55196	.36910	.58503	.38274	.62005	53
54	.34262	.52120	.35588	.55250	.36932	.58560	.38296	.62065	54
55	.34284	.52171	.35610	.55303	.36955	.58617	.38319	.62125	55
56	.34306	.52222	.35632	.55357	.36978	.58674	.38342	.62185	56
57	.34328	.52273	.35654	.55411	.37000	.58731	.38365	.62246	57
58	.34350	.52323	.35677	.55465	.37023	.58788	.38388	.62306	58
59	.34372	.52374	.35699	.55518	.37045	.58845	.38411	.62366	59
60	.34394	.52425	.35721	.55572	.37068	.58902	.38434	.62427	60

	52°		53°		54°		55°		
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.38434	.62427	.39819	.66164	.41221	.70130	.42642	.74345	0
1	.38457	.62487	.39842	.66228	.41245	.70198	.42666	.74417	1
2	.38480	.62548	.39865	.66292	.41269	.70267	.42690	.74490	2
3	.38503	.62609	.39888	.66357	.41292	.70335	.42714	.74562	3
4	.38526	.62669	.39911	.66421	.41316	.70403	.42738	.74635	4
5	.38549	.62730	.39935	.66486	.41339	.70472	.42762	.74708	5
6	.38571	.62791	.39958	.66550	.41363	.70540	.42785	.74781	6
7	.38594	.62852	.39981	.66615	.41386	.70609	.42809	.74854	7
8	.38617	.62913	.40005	.66679	.41410	.70677	.42833	.74927	8
9	.38640	.62974	.40028	.66744	.41433	.70746	.42857	.75000	9
10	.38663	.63035	.40051	.66809	.41457	.70815	.42881	.75073	10
11	.38686	.63096	.40074	.66873	.41481	.70884	.42905	.75146	11
12	.38709	.63157	.40098	.66938	.41504	.70953	.42929	.75219	12
13	.38732	.63218	.40121	.67003	.41528	.71022	.42953	.75293	13
14	.38755	.63279	.40144	.67068	.41551	.71091	.42976	.75366	14
15	.38778	.63341	.40168	.67133	.41575	.71160	.43000	.75440	15
16	.38801	.63402	.40191	.67199	.41599	.71229	.43024	.75513	16
17	.38824	.63464	.40214	.67264	.41622	.71298	.43048	.75587	17
18	.38847	.63525	.40237	.67329	.41646	.71368	.43072	.75661	18
19	.38870	.63587	.40261	.67394	.41670	.71437	.43096	.75734	19
20	.38893	.63648	.40284	.67460	.41693	.71506	.43120	.75808	20
21	.38916	.63710	.40307	.67525	.41717	.71576	.43144	.75882	21
22	.38939	.63772	.40331	.67591	.41740	.71646	.43168	.75956	22
23	.38962	.63834	.40354	.67656	.41764	.71715	.43192	.76031	23
24	.38985	.63895	.40378	.67722	.41788	.71785	.43216	.76105	24
25	.39009	.63957	.40401	.67788	.41811	.71855	.43240	.76179	25
26	.39032	.64019	.40424	.67853	.41835	.71925	.43264	.76253	26
27	.39055	.64081	.40448	.67919	.41859	.71995	.43287	.76328	27
28	.39078	.64144	.40471	.67985	.41882	.72065	.43311	.76402	28
29	.39101	.64206	.40494	.68051	.41906	.72135	.43335	.76477	29
30	.39124	.64268	.40518	.68117	.41930	.72205	.43359	.76552	30
31	.39147	.64330	.40541	.68183	.41953	.72275	.43383	.76626	31
32	.39170	.64393	.40565	.68250	.41977	.72346	.43407	.76701	32
33	.39193	.64455	.40588	.68316	.42001	.72416	.43431	.76776	33
34	.39216	.64518	.40611	.68382	.42024	.72487	.43455	.76851	34
35	.39239	.64580	.40635	.68449	.42048	.72557	.43479	.76926	35
36	.39262	.64643	.40658	.68515	.42072	.72628	.43503	.77001	36
37	.39286	.64705	.40682	.68582	.42096	.72698	.43527	.77077	37
38	.39309	.64768	.40705	.68648	.42119	.72769	.43551	.77152	38
39	.39332	.64831	.40728	.68715	.42143	.72840	.43575	.77227	39
40	.39355	.64894	.40752	.68782	.42167	.72911	.43599	.77303	40
41	.39378	.64957	.40775	.68848	.42191	.72982	.43623	.77378	41
42	.39401	.65020	.40799	.68915	.42214	.73053	.43647	.77454	42
43	.39424	.65083	.40822	.68982	.42238	.73124	.43671	.77530	43
44	.39447	.65146	.40846	.69049	.42262	.73195	.43695	.77606	44
45	.39471	.65209	.40869	.69116	.42285	.73267	.43720	.77681	45
46	.39494	.65272	.40893	.69183	.42309	.73338	.43744	.77757	46
47	.39517	.65336	.40916	.69250	.42333	.73409	.43768	.77833	47
48	.39540	.65399	.40939	.69318	.42357	.73481	.43792	.77910	48
49	.39563	.65462	.40963	.69385	.42381	.73552	.43816	.77986	49
50	.39586	.65526	.40986	.69452	.42404	.73624	.43840	.78062	50
51	.39610	.65589	.41010	.69520	.42428	.73696	.43864	.78138	51
52	.39633	.65653	.41033	.69587	.42452	.73768	.43888	.78215	52
53	.39656	.65717	.41057	.69655	.42476	.73840	.43912	.78291	53
54	.39679	.65780	.41080	.69723	.42499	.73911	.43936	.78368	54
55	.39702	.65844	.41104	.69790	.42523	.73983	.43960	.78445	55
56	.39726	.65908	.41127	.69858	.42547	.74056	.43984	.78521	56
57	.39749	.65972	.41151	.69926	.42571	.74128	.44008	.78598	57
58	.39772	.66036	.41174	.69994	.42595	.74200	.44032	.78675	58
59	.39795	.66100	.41198	.70062	.42619	.74272	.44057	.78752	59
60	.39819	.66164	.41221	.70130	.42642	.74345	.44081	.78829	60

′	56° Vers.	56° Ex. sec.	57° Vers.	57° Ex. sec.	58° Vers.	58° Ex. sec.	59° Vers.	59° Ex. sec.	′
0	.44081	.78829	.45536	.83608	.47008	.88708	.48496	.94160	0
1	.44105	.78906	.45560	.83690	.47033	.88796	.48521	.94254	1
2	.44129	.78984	.45585	.83773	.47057	.88884	.48546	.94349	2
3	.44153	.79061	.45609	.83855	.47082	.88972	.48571	.94443	3
4	.44177	.79138	.45634	.83938	.47107	.89060	.48596	.94537	4
5	.44201	.79216	.45658	.84020	.47131	.89148	.48621	.94632	5
6	.44225	.79293	.45683	.84103	.47156	.89237	.48646	.94726	6
7	.44250	.79371	.45707	.84186	.47181	.89325	.48671	.94821	7
8	.44274	.79449	.45731	.84269	.47206	.89414	.48696	.94916	8
9	.44298	.79527	.45756	.84352	.47230	.89503	.48721	.95011	9
10	.44322	.79604	.45780	.84435	.47255	.89591	.48746	.95106	10
11	.44346	.79682	.45805	.84518	.47280	.89680	.48771	.95201	11
12	.44370	.79761	.45829	.84601	.47304	.89769	.48796	.95296	12
13	.44395	.79839	.45854	.84685	.47329	.89858	.48821	.95392	13
14	.44419	.79917	.45878	.84768	.47354	.89948	.48846	.95487	14
15	.44443	.79995	.45903	.84852	.47379	.90037	.48871	.95583	15
16	.44467	.80074	.45927	.84935	.47403	.90126	.48896	.95678	16
17	.44491	.80152	.45951	.85019	.47428	.90216	.48921	.95774	17
18	.44516	.80231	.45976	.85103	.47453	.90305	.48946	.95870	18
19	.44540	.80309	.46000	.85187	.47478	.90395	.48971	.95966	19
20	.44564	.80388	.46025	.85271	.47502	.90485	.48996	.96062	20
21	.44588	.80467	.46049	.85355	.47527	.90575	.49021	.96158	21
22	.44612	.80546	.46074	.85439	.47552	.90665	.49046	.96255	22
23	.44637	.80625	.46098	.85523	.47577	.90755	.49071	.96351	23
24	.44661	.80704	.46123	.85608	.47601	.90845	.49096	.96448	24
25	.44685	.80783	.46147	.85692	.47626	.90935	.49121	.96544	25
26	.44709	.80862	.46172	.85777	.47651	.91026	.49146	.96641	26
27	.44734	.80942	.46196	.85861	.47676	.91116	.49171	.96738	27
28	.44758	.81021	.46221	.85946	.47701	.91207	.49196	.96835	28
29	.44782	.81101	.46246	.86031	.47725	.91297	.49221	.96932	29
30	.44806	.81180	.46270	.86116	.47750	.91388	.49246	.97029	30
31	.44831	.81260	.46295	.86201	.47775	.91479	.49271	.97127	31
32	.44855	.81340	.46319	.86286	.47800	.91570	.49296	.97224	32
33	.44879	.81419	.46344	.86371	.47825	.91661	.49321	.97322	33
34	.44903	.81499	.46368	.86457	.47849	.91752	.49346	.97420	34
35	.44928	.81579	.46393	.86542	.47874	.91844	.49372	.97517	35
36	.44952	.81659	.46417	.86627	.47899	.91935	.49397	.97615	36
37	.44976	.81740	.46442	.86713	.47924	.92027	.49422	.97713	37
38	.45001	.81820	.46466	.86799	.47949	.92118	.49447	.97811	38
39	.45025	.81900	.46491	.86885	.47974	.92210	.49472	.97910	39
40	.45049	.81981	.46516	.86970	.47998	.92302	.49497	.98008	40
41	.45073	.82061	.46540	.87056	.48023	.92394	.49522	.98107	41
42	.45098	.82142	.46565	.87142	.48048	.92486	.49547	.98205	42
43	.45122	.82222	.46589	.87229	.48073	.92578	.49572	.98304	43
44	.45146	.82303	.46614	.87315	.48098	.92670	.49597	.98403	44
45	.45171	.82384	.46639	.87401	.48123	.92762	.49623	.98502	45
46	.45195	.82465	.46663	.87488	.48148	.92855	.49648	.98601	46
47	.45219	.82546	.46688	.87574	.48172	.92947	.49673	.98700	47
48	.45244	.82627	.46712	.87661	.48197	.93040	.49698	.98799	48
49	.45268	.82709	.46737	.87748	.48222	.93133	.49723	.98899	49
50	.45292	.82790	.46762	.87834	.48247	.93226	.49748	.98998	50
51	.45317	.82871	.46786	.87921	.48272	.93319	.49773	.99098	51
52	.45341	.82953	.46811	.88008	.48297	.93412	.49799	.99198	52
53	.45365	.83034	.46836	.88095	.48322	.93505	.49824	.99298	53
54	.45390	.83116	.46860	.88183	.48347	.93598	.49849	.99398	54
55	.45414	.83198	.46885	.88270	.48372	.93692	.49874	.99498	55
56	.45439	.83280	.46909	.88357	.48396	.93785	.49899	.99598	56
57	.45463	.83362	.46934	.88445	.48421	.93879	.49924	.99698	57
58	.45487	.83444	.46959	.88532	.48446	.93973	.49950	.99799	58
59	.45512	.83526	.46983	.88620	.48471	.94066	.49975	.99899	59
60	.45536	.83608	.47008	.88708	.48496	.94160	.50000	1.00000	60

′	60° Vers.	60° Ex. sec.	61° Vers.	61° Ex. sec.	62° Vers.	62° Ex. sec.	63° Vers.	63° Ex. sec.	′
0	.50000	1.00000	.51519	1.06267	.53053	1.13005	.54601	1.20269	0
1	.50025	1.00101	.51544	1.06375	.53079	1.13122	.54627	1.20395	1
2	.50050	1.00202	.51570	1.06483	.53104	1.13239	.54653	1.20521	2
3	.50076	1.00303	.51595	1.06592	.53130	1.13356	.54679	1.20647	3
4	.50101	1.00404	.51621	1.06701	.53156	1.13473	.54705	1.20773	4
5	.50126	1.00505	.51646	1.06809	.53181	1.13590	.54731	1.20900	5
6	.50151	1.00607	.51672	1.06918	.53207	1.13707	.54757	1.21026	6
7	.50176	1.00708	.51697	1.07027	.53233	1.13825	.54782	1.21153	7
8	.50202	1.00810	.51723	1.07137	.53258	1.13942	.54808	1.21280	8
9	.50227	1.00912	.51748	1.07246	.53284	1.14060	.54834	1.21407	9
10	.50252	1.01014	.51774	1.07356	.53310	1.14178	.54860	1.21535	10
11	.50277	1.01116	.51799	1.07465	.53336	1.14296	.54886	1.21662	11
12	.50303	1.01218	.51825	1.07575	.53361	1.14414	.54912	1.21790	12
13	.50328	1.01320	.51850	1.07685	.53387	1.14533	.54938	1.21918	13
14	.50353	1.01422	.51876	1.07795	.53413	1.14651	.54964	1.22045	14
15	.50378	1.01525	.51901	1.07905	.53439	1.14770	.54990	1.22174	15
16	.50404	1.01628	.51927	1.08015	.53464	1.14889	.55016	1.22302	16
17	.50429	1.01730	.51952	1.08126	.53490	1.15008	.55042	1.22430	17
18	.50454	1.01833	.51978	1.08236	.53516	1.15127	.55068	1.22559	18
19	.50479	1.01936	.52003	1.08347	.53542	1.15246	.55094	1.22688	19
20	.50505	1.02039	.52029	1.08458	.53567	1.15366	.55120	1.22817	20
21	.50530	1.02143	.52054	1.08569	.53593	1.15485	.55146	1.22946	21
22	.50555	1.02246	.52080	1.08680	.53619	1.15605	.55172	1.23075	22
23	.50581	1.02349	.52105	1.08791	.53645	1.15725	.55198	1.23205	23
24	.50606	1.02453	.52131	1.08903	.53670	1.15845	.55224	1.23334	24
25	.50631	1.02557	.52156	1.09014	.53696	1.15965	.55250	1.23464	25
26	.50656	1.02661	.52182	1.09126	.53722	1.16085	.55276	1.23594	26
27	.50682	1.02765	.52207	1.09238	.53748	1.16206	.55302	1.23724	27
28	.50707	1.02869	.52233	1.09350	.53774	1.16326	.55328	1.23855	28
29	.50732	1.02973	.52259	1.09462	.53799	1.16447	.55354	1.23985	29
30	.50758	1.03077	.52284	1.09574	.53825	1.16568	.55380	1.24116	30
31	.50783	1.03182	.52310	1.09686	.53851	1.16689	.55406	1.24247	31
32	.50808	1.03286	.52335	1.09799	.53877	1.16810	.55432	1.24378	32
33	.50834	1.03391	.52361	1.09911	.53903	1.16932	.55458	1.24509	33
34	.50859	1.03496	.52386	1.10024	.53928	1.17053	.55484	1.24640	34
35	.50884	1.03601	.52412	1.10137	.53954	1.17175	.55510	1.24772	35
36	.50910	1.03706	.52438	1.10250	.53980	1.17297	.55536	1.24903	36
37	.50935	1.03811	.52463	1.10363	.54006	1.17419	.55563	1.25035	37
38	.50960	1.03916	.52489	1.10477	.54032	1.17541	.55589	1.25167	38
39	.50986	1.04022	.52514	1.10590	.54058	1.17663	.55615	1.25300	39
40	.51011	1.04128	.52540	1.10704	.54083	1.17786	.55641	1.25432	40
41	.51036	1.04233	.52566	1.10817	.54109	1.17909	.55667	1.25565	41
42	.51062	1.04339	.52591	1.10931	.54135	1.18031	.55693	1.25697	42
43	.51087	1.04445	.52617	1.11045	.54161	1.18154	.55719	1.25830	43
44	.51113	1.04551	.52642	1.11159	.54187	1.18277	.55745	1.25963	44
45	.51138	1.04658	.52668	1.11274	.54213	1.18401	.55771	1.26097	45
46	.51163	1.04764	.52694	1.11388	.54238	1.18524	.55797	1.26230	46
47	.51189	1.04870	.52719	1.11503	.54264	1.18648	.55823	1.26364	47
48	.51214	1.04977	.52745	1.11617	.54290	1.18772	.55849	1.26498	48
49	.51239	1.05084	.52771	1.11732	.54316	1.18895	.55876	1.26632	49
50	.51265	1.05191	.52796	1.11847	.54342	1.19019	.55902	1.26766	50
51	.51290	1.05298	.52822	1.11963	.54368	1.19144	.55928	1.26900	51
52	.51316	1.05405	.52848	1.12078	.54394	1.19268	.55954	1.27035	52
53	.51341	1.05512	.52873	1.12193	.54420	1.19393	.55980	1.27169	53
54	.51366	1.05619	.52899	1.12309	.54446	1.19517	.56006	1.27304	54
55	.51392	1.05727	.52924	1.12425	.54471	1.19642	.56032	1.27439	55
56	.51417	1.05835	.52950	1.12540	.54497	1.19767	.56058	1.27574	56
57	.51443	1.05942	.52976	1.12657	.54523	1.19892	.56084	1.27710	57
58	.51468	1.06050	.53001	1.12773	.54549	1.20018	.56111	1.27845	58
59	.51494	1.06158	.53027	1.12889	.54575	1.20143	.56137	1.27981	59
60	.51519	1.06267	.53053	1.13005	.54601	1.20269	.56163	1.28117	60

	64°		65°		66°		67°		
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.56163	1.28117	.57738	1.36620	.59326	1.45859	.60927	1.55930	0
1	.56189	1.28253	.57765	1.36768	.59353	1.46020	.60954	1.56106	1
2	.56215	1.28390	.57791	1.36916	.59379	1.46181	.60980	1.56282	2
3	.56241	1.28526	.57817	1.37064	.59406	1.46342	.61007	1.56458	3
4	.56267	1.28663	.57844	1.37212	.59433	1.46504	.61034	1.56634	4
5	.56294	1.28800	.57870	1.37361	.59459	1.46665	.61061	1.56811	5
6	.56320	1.28937	.57896	1.37509	.59486	1.46827	.61088	1.56988	6
7	.56346	1.29074	.57923	1.37658	.59512	1.46989	.61114	1.57165	7
8	.56372	1.29211	.57949	1.37808	.59539	1.47152	.61141	1.57342	8
9	.56398	1.29349	.57976	1.37957	.59566	1.47314	.61168	1.57520	9
10	.56425	1.29487	.58002	1.38107	.59592	1.47477	.61195	1.57698	10
11	.56451	1.29625	.58028	1.38256	.59619	1.47640	.61222	1.57876	11
12	.56477	1.29763	.58055	1.38406	.59645	1.47804	.61248	1.58054	12
13	.56503	1.29901	.58081	1.38556	.59672	1.47967	.61275	1.58233	13
14	.56529	1.30040	.58108	1.38707	.59699	1.48131	.61302	1.58412	14
15	.56555	1.30179	.58134	1.38857	.59725	1.48295	.61329	1.58591	15
16	.56582	1.30318	.58160	1.39008	.59752	1.48459	.61356	1.58771	16
17	.56608	1.30457	.58187	1.39159	.59779	1.48624	.61383	1.58950	17
18	.56634	1.30596	.58213	1.39311	.59805	1.48789	.61409	1.59130	18
19	.56660	1.30735	.58240	1.39462	.59832	1.48954	.61436	1.59311	19
20	.56687	1.30875	.58266	1.39614	.59859	1.49119	.61463	1.59491	20
21	.56713	1.31015	.58293	1.39766	.59885	1.49284	.61490	1.59672	21
22	.56739	1.31155	.58319	1.39918	.59912	1.49450	.61517	1.59853	22
23	.56765	1.31295	.58345	1.40070	.59938	1.49616	.61544	1.60035	23
24	.56791	1.31436	.58372	1.40222	.59965	1.49782	.61570	1.60217	24
25	.56818	1.31576	.58398	1.40375	.59992	1.49948	.61597	1.60399	25
26	.56844	1.31717	.58425	1.40528	.60018	1.50115	.61624	1.60581	26
27	.56870	1.31858	.58451	1.40681	.60045	1.50282	.61651	1.60763	27
28	.56896	1.31999	.58478	1.40835	.60072	1.50449	.61678	1.60946	28
29	.56923	1.32140	.58504	1.40988	.60098	1.50617	.61705	1.61129	29
30	.56949	1.32282	.58531	1.41142	.60125	1.50784	.61732	1.61313	30
31	.56975	1.32424	.58557	1.41296	.60152	1.50952	.61759	1.61496	31
32	.57001	1.32566	.58584	1.41450	.60178	1.51120	.61785	1.61680	32
33	.57028	1.32708	.58610	1.41605	.60205	1.51289	.61812	1.61864	33
34	.57054	1.32850	.58637	1.41760	.60232	1.51457	.61839	1.62049	34
35	.57080	1.32993	.58663	1.41914	.60259	1.51626	.61866	1.62234	35
36	.57106	1.33135	.58690	1.42070	.60285	1.51795	.61893	1.62419	36
37	.57133	1.33278	.58716	1.42225	.60312	1.51965	.61920	1.62604	37
38	.57159	1.33422	.58743	1.42380	.60339	1.52134	.61947	1.62790	38
39	.57185	1.33565	.58769	1.42536	.60365	1.52304	.61974	1.62976	39
40	.57212	1.33708	.58796	1.42692	.60392	1.52474	.62001	1.63162	40
41	.57238	1.33852	.58822	1.42848	.60419	1.52645	.62027	1.63348	41
42	.57264	1.33996	.58849	1.43005	.60445	1.52815	.62054	1.63535	42
43	.57291	1.34140	.58875	1.43162	.60472	1.52986	.62081	1.63722	43
44	.57317	1.34284	.58902	1.43318	.60499	1.53157	.62108	1.63909	44
45	.57343	1.34429	.58928	1.43476	.60526	1.53329	.62135	1.64097	45
46	.57369	1.34573	.58955	1.43633	.60552	1.53500	.62162	1.64285	46
47	.57396	1.34718	.58981	1.43790	.60579	1.53672	.62189	1.64473	47
48	.57422	1.34863	.59008	1.43948	.60606	1.53845	.62216	1.64662	48
49	.57448	1.35009	.59034	1.44106	.60633	1.54017	.62243	1.64851	49
50	.57475	1.35154	.59061	1.44264	.60659	1.54190	.62270	1.65040	50
51	.57501	1.35300	.59087	1.44423	.60686	1.54363	.62297	1.65229	51
52	.57527	1.35446	.59114	1.44582	.60713	1.54536	.62324	1.65419	52
53	.57554	1.35592	.59140	1.44741	.60740	1.54709	.62351	1.65609	53
54	.57580	1.35738	.59167	1.44900	.60766	1.54883	.62378	1.65799	54
55	.57606	1.35885	.59194	1.45059	.60793	1.55057	.62405	1.65989	55
56	.57633	1.36031	.59220	1.45219	.60820	1.55231	.62431	1.66180	56
57	.57659	1.36178	.59247	1.45378	.60847	1.55405	.62458	1.66371	57
58	.57685	1.36325	.59273	1.45539	.60873	1.55580	.62485	1.66563	58
59	.57712	1.36473	.59300	1.45699	.60900	1.55755	.62512	1.66755	59
60	.57738	1.36620	.59326	1.45859	.60927	1.55930	.62539	1.66947	60

′	68°		69°		70°		71°		′
′	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	′
0	.62539	1.66947	.64163	1.79043	.65798	1.92380	.67443	2.07155	0
1	.62566	1.67139	.64190	1.79254	.65825	1.92614	.67471	2.07415	1
2	.62593	1.67332	.64218	1.79466	.65853	1.92849	.67498	2.07675	2
3	.62620	1.67525	.64245	1.79679	.65880	1.93083	.67526	2.07936	3
4	.62647	1.67718	.64272	1.79891	.65907	1.93318	.67553	2.08197	4
5	.62674	1.67911	.64299	1.80104	.65935	1.93554	.67581	2.08459	5
6	.62701	1.68105	.64326	1.80318	.65962	1.93790	.67608	2.08721	6
7	.62728	1.68299	.64353	1.80531	.65989	1.94026	.67636	2.08983	7
8	.62755	1.68494	.64381	1.80746	.66017	1.94263	.67663	2.09246	8
9	.62782	1.68689	.64408	1.80960	.66044	1.94500	.67691	2.09510	9
10	.62809	1.68884	.64435	1.81175	.66071	1.94737	.67718	2.09774	10
11	.62836	1.69079	.64462	1.81390	.66099	1.94975	.67746	2.10038	11
12	.62863	1.69275	.64489	1.81605	.66126	1.95213	.67773	2.10303	12
13	.62890	1.69471	.64517	1.81821	.66154	1.95452	.67801	2.10568	13
14	.62917	1.69667	.64544	1.82037	.66181	1.95691	.67829	2.10834	14
15	.62944	1.69864	.64571	1.82254	.66208	1.95931	.67856	2.11101	15
16	.62971	1.70061	.64598	1.82471	.66236	1.96171	.67884	2.11367	16
17	.62998	1.70258	.64625	1.82688	.66263	1.96411	.67911	2.11635	17
18	.63025	1.70455	.64653	1.82906	.66290	1.96652	.67939	2.11903	18
19	.63052	1.70653	.64680	1.83124	.66318	1.96893	.67966	2.12171	19
20	.63079	1.70851	.64707	1.83342	.66345	1.97135	.67994	2.12440	20
21	.63106	1.71050	.64734	1.83561	.66373	1.97377	.68021	2.12709	21
22	.63133	1.71249	.64761	1.83780	.66400	1.97619	.68049	2.12979	22
23	.63161	1.71448	.64789	1.83999	.66427	1.97862	.68077	2.13249	23
24	.63188	1.71647	.64816	1.84219	.66455	1.98106	.68104	2.13520	24
25	.63215	1.71847	.64843	1.84439	.66482	1.98349	.68132	2.13791	25
26	.63242	1.72047	.64870	1.84659	.66510	1.98594	.68159	2.14063	26
27	.63269	1.72247	.64898	1.84880	.66537	1.98838	.68187	2.14335	27
28	.63296	1.72448	.64925	1.85102	.66564	1.99083	.68214	2.14608	28
29	.63323	1.72649	.64952	1.85323	.66592	1.99329	.68242	2.14881	29
30	.63350	1.72850	.64979	1.85545	.66619	1.99574	.68270	2.15155	30
31	.63377	1.73052	.65007	1.85767	.66647	1.99821	.68297	2.15429	31
32	.63404	1.73254	.65034	1.85990	.66674	2.00067	.68325	2.15704	32
33	.63431	1.73456	.65061	1.86213	.66702	2.00315	.68352	2.15979	33
34	.63458	1.73659	.65088	1.86437	.66729	2.00562	.68380	2.16255	34
35	.63485	1.73862	.65116	1.86661	.66756	2.00810	.68408	2.16531	35
36	.63512	1.74065	.65143	1.86885	.66784	2.01059	.68435	2.16808	36
37	.63539	1.74269	.65170	1.87109	.66811	2.01308	.68463	2.17085	37
38	.63566	1.74473	.65197	1.87334	.66839	2.01557	.68490	2.17363	38
39	.63594	1.74677	.65225	1.87560	.66866	2.01807	.68518	2.17641	39
40	.63621	1.74881	.65252	1.87785	.66894	2.02057	.68546	2.17920	40
41	.63648	1.75086	.65279	1.88011	.66921	2.02308	.68573	2.18199	41
42	.63675	1.75292	.65306	1.88238	.66949	2.02559	.68601	2.18479	42
43	.63702	1.75497	.65334	1.88465	.66976	2.02810	.68628	2.18759	43
44	.63729	1.75703	.65361	1.88692	.67003	2.03062	.68656	2.19040	44
45	.63756	1.75909	.65388	1.88920	.67031	2.03315	.68684	2.19322	45
46	.63783	1.76116	.65416	1.89148	.67058	2.03568	.68711	2.19604	46
47	.63810	1.76323	.65443	1.89376	.67086	2.03821	.68739	2.19886	47
48	.63838	1.76530	.65470	1.89605	.67113	2.04075	.68767	2.20169	48
49	.63865	1.76737	.65497	1.89834	.67141	2.04329	.68794	2.20453	49
50	.63892	1.76945	.65525	1.90063	.67168	2.04584	.68822	2.20737	50
51	.63919	1.77154	.65552	1.90293	.67196	2.04839	.68849	2.21021	51
52	.63946	1.77362	.65579	1.90524	.67223	2.05094	.68877	2.21306	52
53	.63973	1.77571	.65607	1.90754	.67251	2.05350	.68905	2.21592	53
54	.64000	1.77780	.65634	1.90986	.67278	2.05607	.68932	2.21878	54
55	.64027	1.77990	.65661	1.91217	.67306	2.05864	.68960	2.22165	55
56	.64055	1.78200	.65689	1.91449	.67333	2.06121	.68988	2.22452	56
57	.64082	1.78410	.65716	1.91681	.67361	2.06379	.69015	2.22740	57
58	.64109	1.78621	.65743	1.91914	.67388	2.06637	.69043	2.23028	58
59	.64136	1.78832	.65771	1.92147	.67416	2.06896	.69071	2.23317	59
60	.64163	1.79043	.65798	1.92380	.67443	2.07155	.69098	2.23607	60

′	72° Vers.	72° Ex. sec.	73° Vers.	73° Ex. sec.	74° Vers.	74° Ex. sec.	75° Vers.	75° Ex. sec.	′
0	.69098	2.23607	.70763	2.42030	.72436	2.62796	.74118	2.86370	0
1	.69126	2.23897	.70791	2.42356	.72464	2.63164	.74146	2.86790	1
2	.69154	2.24187	.70818	2.42683	.72492	2.63533	.74174	2.87211	2
3	.69181	2.24478	.70846	2.43010	.72520	2.63903	.74202	2.87633	3
4	.69209	2.24770	.70874	2.43337	.72548	2.64274	.74231	2.88056	4
5	.69237	2.25062	.70902	2.43666	.72576	2.64645	.74259	2.88479	5
6	.69264	2.25355	.70930	2.43995	.72604	2.65018	.74287	2.88904	6
7	.69292	2.25648	.70958	2.44324	.72632	2.65391	.74315	2.89330	7
8	.69320	2.25942	.70985	2.44655	.72660	2.65765	.74343	2.89756	8
9	.69347	2.26237	.71013	2.44986	.72688	2.66140	.74371	2.90184	9
10	.69375	2.26531	.71041	2.45317	.72716	2.66515	.74399	2.90613	10
11	.69403	2.26827	.71069	2.45650	.72744	2.66892	.74427	2.91042	11
12	.69430	2.27123	.71097	2.45983	.72772	2.67269	.74455	2.91473	12
13	.69458	2.27420	.71125	2.46316	.72800	2.67647	.74484	2.91904	13
14	.69486	2.27717	.71153	2.46651	.72828	2.68025	.74512	2.92337	14
15	.69514	2.28015	.71180	2.46986	.72856	2.68405	.74540	2.92770	15
16	.69541	2.28313	.71208	2.47321	.72884	2.68785	.74568	2.93204	16
17	.69569	2.28612	.71236	2.47658	.72912	2.69167	.74596	2.93640	17
18	.69597	2.28912	.71264	2.47995	.72940	2.69549	.74624	2.94076	18
19	.69624	2.29212	.71292	2.48333	.72968	2.69931	.74652	2.94514	19
20	.69652	2.29512	.71320	2.48671	.72996	2.70315	.74680	2.94952	20
21	.69680	2.29814	.71348	2.49010	.73024	2.70700	.74709	2.95392	21
22	.69708	2.30115	.71375	2.49350	.73052	2.71085	.74737	2.95832	22
23	.69735	2.30418	.71403	2.49691	.73080	2.71471	.74765	2.96274	23
24	.69763	2.30721	.71431	2.50032	.73108	2.71858	.74793	2.96716	24
25	.69791	2.31024	.71459	2.50374	.73136	2.72246	.74821	2.97160	25
26	.69818	2.31328	.71487	2.50716	.73164	2.72635	.74849	2.97604	26
27	.69846	2.31633	.71515	2.51060	.73192	2.73024	.74878	2.98050	27
28	.69874	2.31939	.71543	2.51404	.73220	2.73414	.74906	2.98497	28
29	.69902	2.32244	.71571	2.51748	.73248	2.73806	.74934	2.98944	29
30	.69929	2.32551	.71598	2.52094	.73276	2.74198	.74962	2.99393	30
31	.69957	2.32858	.71626	2.52440	.73304	2.74591	.74990	2.99843	31
32	.69985	2.33166	.71654	2.52787	.73332	2.74984	.75018	3.00293	32
33	.70013	2.33474	.71682	2.53134	.73360	2.75379	.75047	3.00745	33
34	.70040	2.33783	.71710	2.53482	.73388	2.75775	.75075	3.01198	34
35	.70068	2.34092	.71738	2.53831	.73416	2.76171	.75103	3.01652	35
36	.70096	2.34403	.71766	2.54181	.73444	2.76568	.75131	3.02107	36
37	.70124	2.34713	.71794	2.54531	.73472	2.76966	.75159	3.02563	37
38	.70151	2.35025	.71822	2.54883	.73500	2.77365	.75187	3.03020	38
39	.70179	2.35336	.71850	2.55235	.73529	2.77765	.75216	3.03479	39
40	.70207	2.35649	.71877	2.55587	.73557	2.78166	.75244	3.03938	40
41	.70235	2.35962	.71905	2.55940	.73585	2.78568	.75272	3.04398	41
42	.70263	2.36276	.71933	2.56294	.73613	2.78970	.75300	3.04860	42
43	.70290	2.36590	.71961	2.56649	.73641	2.79374	.75328	3.05322	43
44	.70318	2.36905	.71989	2.57005	.73669	2.79778	.75356	3.05786	44
45	.70346	2.37221	.72017	2.57361	.73697	2.80183	.75385	3.06251	45
46	.70374	2.37537	.72045	2.57718	.73725	2.80589	.75413	3.06717	46
47	.70401	2.37854	.72073	2.58076	.73753	2.80996	.75441	3.07184	47
48	.70429	2.38171	.72101	2.58434	.73781	2.81404	.75469	3.07652	48
49	.70457	2.38489	.72129	2.58794	.73809	2.81813	.75497	3.08121	49
50	.70485	2.38808	.72157	2.59154	.73837	2.82223	.75526	3.08591	50
51	.70513	2.39128	.72185	2.59514	.73865	2.82633	.75554	3.09063	51
52	.70540	2.39448	.72213	2.59876	.73893	2.83045	.75582	3.09535	52
53	.70568	2.39768	.72241	2.60238	.73921	2.83457	.75610	3.10009	53
54	.70596	2.40089	.72269	2.60601	.73950	2.83871	.75639	3.10484	54
55	.70624	2.40411	.72296	2.60965	.73978	2.84285	.75667	3.10960	55
56	.70652	2.40734	.72324	2.61330	.74006	2.84700	.75695	3.11437	56
57	.70679	2.41057	.72352	2.61695	.74034	2.85116	.75723	3.11915	57
58	.70707	2.41381	.72380	2.62061	.74062	2.85533	.75751	3.12394	58
59	.70735	2.41705	.72408	2.62428	.74090	2.85951	.75780	3.12875	59
60	.70763	2.42030	.72436	2.62796	.74118	2.86370	.75808	3.13357	60

′	76° Vers.	76° Ex. sec.	77° Vers.	77° Ex. sec.	78° Vers.	78° Ex. sec.	79° Vers.	79° Ex. sec.	′
0	.75808	3.13357	.77505	3.44541	.79209	3.80973	.80919	4.24084	0
1	.75836	3.13839	.77533	3.45102	.79237	3.81633	.80948	4.24870	1
2	.75864	3.14323	.77562	3.45664	.79266	3.82294	.80976	4.25658	2
3	.75892	3.14809	.77590	3.46228	.79294	3.82956	.81005	4.26448	3
4	.75921	3.15295	.77618	3.46793	.79323	3.83621	.81033	4.27241	4
5	.75949	3.15782	.77647	3.47360	.79351	3.84288	.81062	4.28036	5
6	.75977	3.16271	.77675	3.47928	.79380	3.84956	.81090	4.28833	6
7	.76005	3.16761	.77703	3.48498	.79408	3.85627	.81119	4.29634	7
8	.76034	3.17252	.77732	3.49069	.79437	3.86299	.81148	4.30436	8
9	.76062	3.17744	.77760	3.49642	.79465	3.86973	.81176	4.31241	9
10	.76090	3.18238	.77788	3.50216	.79493	3.87649	.81205	4.32049	10
11	.76118	3.18733	.77817	3.50791	.79522	3.88327	.81233	4.32859	11
12	.76147	3.19228	.77845	3.51368	.79550	3.89007	.81262	4.33671	12
13	.76175	3.19725	.77874	3.51947	.79579	3.89689	.81290	4.34486	13
14	.76203	3.20224	.77902	3.52527	.79607	3.90373	.81319	4.35304	14
15	.76231	3.20723	.77930	3.53109	.79636	3.91058	.81348	4.36124	15
16	.76260	3.21224	.77959	3.53692	.79664	3.91746	.81376	4.36947	16
17	.76288	3.21726	.77987	3.54277	.79693	3.92436	.81405	4.37772	17
18	.76316	3.22229	.78015	3.54863	.79721	3.93128	.81433	4.38600	18
19	.76344	3.22734	.78044	3.55451	.79750	3.93821	.81462	4.39430	19
20	.76373	3.23239	.78072	3.56041	.79778	3.94517	.81491	4.40263	20
21	.76401	3.23746	.78101	3.56632	.79807	3.95215	.81519	4.41099	21
22	.76429	3.24255	.78129	3.57224	.79835	3.95914	.81548	4.41937	22
23	.76458	3.24764	.78157	3.57819	.79864	3.96616	.81576	4.42778	23
24	.76486	3.25275	.78186	3.58414	.79892	3.97320	.81605	4.43622	24
25	.76514	3.25787	.78214	3.59012	.79921	3.98025	.81633	4.44468	25
26	.76542	3.26300	.78242	3.59611	.79949	3.98733	.81662	4.45317	26
27	.76571	3.26814	.78271	3.60211	.79978	3.99443	.81691	4.46169	27
28	.76599	3.27330	.78299	3.60813	.80006	4.00155	.81719	4.47023	28
29	.76627	3.27847	.78328	3.61417	.80035	4.00869	.81748	4.47881	29
30	.76655	3.28366	.78356	3.62023	.80063	4.01585	.81776	4.48740	30
31	.76684	3.28885	.78384	3.62630	.80092	4.02303	.81805	4.49603	31
32	.76712	3.29406	.78413	3.63238	.80120	4.03024	.81834	4.50468	32
33	.76740	3.29929	.78441	3.63849	.80149	4.03746	.81862	4.51337	33
34	.76769	3.30452	.78470	3.64461	.80177	4.04471	.81891	4.52208	34
35	.76797	3.30977	.78498	3.65074	.80206	4.05197	.81919	4.53081	35
36	.76825	3.31503	.78526	3.65690	.80234	4.05926	.81948	4.53958	36
37	.76854	3.32031	.78555	3.66307	.80263	4.06657	.81977	4.54837	37
38	.76882	3.32560	.78583	3.66925	.80291	4.07390	.82005	4.55720	38
39	.76910	3.33090	.78612	3.67545	.80320	4.08125	.82034	4.56605	39
40	.76938	3.33622	.78640	3.68167	.80348	4.08863	.82063	4.57493	40
41	.76967	3.34154	.78669	3.68791	.80377	4.09602	.82091	4.58383	41
42	.76995	3.34689	.78697	3.69417	.80405	4.10344	.82120	4.59277	42
43	.77023	3.35224	.78725	3.70044	.80434	4.11088	.82148	4.60174	43
44	.77052	3.35761	.78754	3.70673	.80462	4.11835	.82177	4.61073	44
45	.77080	3.36299	.78782	3.71303	.80491	4.12583	.82206	4.61976	45
46	.77108	3.36839	.78811	3.71935	.80520	4.13334	.82234	4.62881	46
47	.77137	3.37380	.78839	3.72569	.80548	4.14087	.82263	4.63790	47
48	.77165	3.37923	.78868	3.73205	.80577	4.14842	.82292	4.64701	48
49	.77193	3.38466	.78896	3.73843	.80605	4.15599	.82320	4.65616	49
50	.77222	3.39012	.78924	3.74482	.80634	4.16359	.82349	4.66533	50
51	.77250	3.39558	.78953	3.75123	.80662	4.17121	.82377	4.67454	51
52	.77278	3.40106	.78981	3.75766	.80691	4.17886	.82406	4.68377	52
53	.77307	3.40656	.79010	3.76411	.80719	4.18652	.82435	4.69304	53
54	.77335	3.41206	.79038	3.77057	.80748	4.19421	.82463	4.70234	54
55	.77363	3.41759	.79067	3.77705	.80776	4.20193	.82492	4.71166	55
56	.77392	3.42312	.79095	3.78355	.80805	4.20966	.82521	4.72102	56
57	.77420	3.42867	.79123	3.79007	.80833	4.21742	.82549	4.73041	57
58	.77448	3.43424	.79152	3.79661	.80862	4.22521	.82578	4.73983	58
59	.77477	3.43982	.79180	3.80316	.80891	4.23301	.82607	4.74929	59
60	.77505	3.44541	.79209	3.80973	.80919	4.24084	.82635	4.75877	60

TABLE X.—NATURAL VERSED SINES AND EXTERNAL SECANTS.

′	80°		81°		82°		83°		′
	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	Vers.	Ex. sec.	
0	.82635	4.75877	.84357	5.39245	.86083	6.18530	.87813	7.20551	0
1	.82664	4.76829	.84385	5.40422	.86112	6.20020	.87842	7.22500	1
2	.82692	4.77784	.84414	5.41602	.86140	6.21517	.87871	7.24457	2
3	.82721	4.78742	.84443	5.42787	.86169	6.23019	.87900	7.26425	3
4	.82750	4.79703	.84471	5.43977	.86198	6.24529	.87929	7.28402	4
5	.82778	4.80667	.84500	5.45171	.86227	6.26044	.87957	7.30388	5
6	.82807	4.81635	.84529	5.46369	.86256	6.27563	.87986	7.32384	6
7	.82836	4.82606	.84558	5.47572	.86284	6.29095	.88015	7.34390	7
8	.82864	4.83581	.84586	5.48779	.86313	6.30630	.88044	7.36405	8
9	.82893	4.84558	.84615	5.49991	.86342	6.32171	.88073	7.38431	9
10	.82922	4.85539	.84644	5.51208	.86371	6.33719	.88102	7.40466	10
11	.82950	4.86524	.84673	5.52429	.86400	6.35274	.88131	7.42511	11
12	.82979	4.87511	.84701	5.53655	.86428	6.36835	.88160	7.44566	12
13	.83008	4.88502	.84730	5.54886	.86457	6.38403	.88188	7.46632	13
14	.83036	4.89497	.84759	5.56121	.86486	6.39978	.88217	7.48707	14
15	.83065	4.90495	.84788	5.57361	.86515	6.41560	.88246	7.50793	15
16	.83094	4.91496	.84816	5.58606	.86544	6.43148	.88275	7.52889	16
17	.83122	4.92501	.84845	5.59855	.86573	6.44743	.88304	7.54996	17
18	.83151	4.93509	.84874	5.61110	.86601	6.46346	.88333	7.57113	18
19	.83180	4.94521	.84903	5.62369	.86630	6.47955	.88362	7.59241	19
20	.83208	4.95536	.84931	5.63633	.86659	6.49571	.88391	7.61379	20
21	.83237	4.96555	.84960	5.64902	.86688	6.51194	.88420	7.63528	21
22	.83266	4.97577	.84989	5.66176	.86717	6.52825	.88448	7.65688	22
23	.83294	4.98603	.85018	5.67454	.86746	6.54462	.88477	7.67859	23
24	.83323	4.99633	.85046	5.68738	.86774	6.56107	.88506	7.70041	24
25	.83352	5.00666	.85075	5.70027	.86803	6.57759	.88535	7.72234	25
26	.83380	5.01703	.85104	5.71321	.86832	6.59418	.88564	7.74438	26
27	.83409	5.02743	.85133	5.72620	.86861	6.61085	.88593	7.76653	27
28	.83438	5.03787	.85162	5.73924	.86890	6.62759	.88622	7.78880	28
29	.83467	5.04834	.85190	5.75233	.86919	6.64441	.88651	7.81118	29
30	.83495	5.05886	.85219	5.76547	.86947	6.66130	.88680	7.83367	30
31	.83524	5.06941	.85248	5.77866	.86976	6.67826	.88709	7.85628	31
32	.83553	5.08000	.85277	5.79191	.87005	6.69530	.88737	7.87901	32
33	.83581	5.09062	.85305	5.80521	.87034	6.71242	.88766	7.90186	33
34	.83610	5.10129	.85334	5.81856	.87063	6.72962	.88795	7.92482	34
35	.83639	5.11199	.85363	5.83196	.87092	6.74689	.88824	7.94791	35
36	.83667	5.12273	.85392	5.84542	.87120	6.76424	.88853	7.97111	36
37	.83696	5.13350	.85420	5.85893	.87149	6.78167	.88882	7.99444	37
38	.83725	5.14432	.85449	5.87250	.87178	6.79918	.88911	8.01788	38
39	.83754	5.15517	.85478	5.88612	.87207	6.81677	.88940	8.04146	39
40	.83782	5.16607	.85507	5.89979	.87236	6.83443	.88969	8.06515	40
41	.83811	5.17700	.85536	5.91352	.87265	6.85218	.88998	8.08897	41
42	.83840	5.18797	.85564	5.92731	.87294	6.87001	.89027	8.11292	42
43	.83868	5.19898	.85593	5.94115	.87322	6.88792	.89055	8.13699	43
44	.83897	5.21004	.85622	5.95505	.87351	6.90592	.89084	8.16120	44
45	.83926	5.22113	.85651	5.96900	.87380	6.92400	.89113	8.18553	45
46	.83954	5.23226	.85680	5.98301	.87409	6.94216	.89142	8.20999	46
47	.83983	5.24343	.85708	5.99708	.87438	6.96040	.89171	8.23459	47
48	.84012	5.25464	.85737	6.01120	.87467	6.97873	.89200	8.25931	48
49	.84041	5.26590	.85766	6.02538	.87496	6.99714	.89229	8.28417	49
50	.84069	5.27719	.85795	6.03962	.87524	7.01565	.89258	8.30917	50
51	.84098	5.28853	.85823	6.05392	.87553	7.03423	.89287	8.33430	51
52	.84127	5.29991	.85852	6.06828	.87582	7.05291	.89316	8.35957	52
53	.84155	5.31133	.85881	6.08269	.87611	7.07167	.89345	8.38497	53
54	.84184	5.32279	.85910	6.09717	.87640	7.09052	.89374	8.41052	54
55	.84213	5.33429	.85939	6.11171	.87669	7.10946	.89403	8.43620	55
56	.84242	5.34584	.85967	6.12630	.87698	7.12849	.89431	8.46203	56
57	.84270	5.35743	.85996	6.14096	.87726	7.14760	.89460	8.48800	57
58	.84299	5.36906	.86025	6.15568	.87755	7.16681	.89489	8.51411	58
59	.84328	5.38073	.86054	6.17046	.87784	7.18612	.89518	8.54037	59
60	.84357	5.39245	.86083	6.18530	.87813	7.20551	.89547	8.56677	60

′	84° Vers.	84° Ex. sec.	85° Vers.	85° Ex. sec.	86° Vers.	86° Ex. sec.	′
0	.89547	8.56677	.91284	10.47371	.93024	13.33559	0
1	.89576	8.59332	.91313	10.51199	.93053	13.39547	1
2	.89605	8.62002	.91342	10.55052	.93082	13.45586	2
3	.89634	8.64687	.91371	10.58932	.93111	13.51676	3
4	.89663	8.67387	.91400	10.62837	.93140	13.57817	4
5	.89692	8.70103	.91429	10.66769	.93169	13.64011	5
6	.89721	8.72833	.91458	10.70728	.93198	13.70258	6
7	.89750	8.75579	.91487	10.74714	.93227	13.76558	7
8	.89779	8.78341	.91516	10.78727	.93257	13.82913	8
9	.89808	8.81119	.91545	10.82768	.93286	13.89323	9
10	.89836	8.83912	.91574	10.86837	.93315	13.95788	10
11	.89865	8.86722	.91603	10.90934	.93344	14.02310	11
12	.89894	8.89547	.91632	10.95060	.93373	14.08890	12
13	.89923	8.92389	.91661	10.99214	.93402	14.15527	13
14	.89952	8.95248	.91690	11.03397	.93431	14.22223	14
15	.89981	8.98123	.91719	1.07610	.93460	14.28979	15
16	.90010	9.01015	.91748	11.11852	.93489	14.35795	16
17	.90039	9.03923	.91777	11.16125	.93518	14.42672	17
18	.90068	9.06849	.91806	11.20427	.93547	14.49611	18
19	.90097	9.09792	.91835	11.24761	.93576	14.56614	19
20	.90126	9.12752	.91864	11.29125	.93605	14.63679	20
21	.90155	9.15730	.91893	11.33521	.93634	14.70810	21
22	.90184	9.18725	.91922	11.37948	.93663	14.78005	22
23	.90213	9.21739	.91951	11.42408	.93692	14.85268	23
24	.90242	9.24770	.91980	11.46900	.93721	14.92597	24
25	.90271	9.27819	.92009	11.51424	.93750	14.99995	25
26	.90300	9.30887	.92038	11.55982	.93779	15.07462	26
27	.90329	9.33973	.92067	11.60572	.93808	15.14999	27
28	.90358	9.37077	.92096	11.65197	.93837	15.22607	28
29	.90386	9.40201	.92125	11.69856	.93866	15.30287	29
30	.90415	9.43343	.92154	11.74550	.93895	15.38041	30
31	.90444	9.46505	.92183	11.79278	.93924	15.45869	31
32	.90473	9.49685	.92212	11.84042	.93953	15.53772	32
33	.90502	9.52886	.92241	11.88841	.93982	15.61751	33
34	.90531	9.56106	.92270	11.93677	.94011	15.69808	34
35	.90560	9.59346	.92299	11.98549	.94040	15.77944	35
36	.90589	9.62605	.92328	12.03458	.94069	15.86159	36
37	.90618	9.65885	.92357	12.08404	.94098	15.94456	37
38	.90647	9.69186	.92386	12.13388	.94127	16.02835	38
39	.90676	9.72507	.92415	12.18411	.94156	16.11297	39
40	.90705	9.75849	.92444	12.23472	.94186	16.19843	40
41	.90734	9.79212	.92473	12.28572	.94215	16.28476	41
42	.90763	9.82596	.92502	12.33712	.94244	16.37196	42
43	.90792	9.86001	.92531	12.38891	.94273	16.46005	43
44	.90821	9.89428	.92560	12.44112	.94302	16.54903	44
45	.90850	9.92877	.92589	12.49373	.94331	16.63893	45
46	.90879	9.96348	.92618	12.54676	.94360	16.72975	46
47	.90908	9.99841	.92647	12.60021	.94389	16.82152	47
48	.90937	10.03356	.92676	12.65408	.94418	16.91424	48
49	.90966	10.06894	.92705	12.70838	.94447	17.00794	49
50	.90995	10.10455	.92734	12.76312	.94476	17.10262	50
51	.91024	10.14039	.92763	12.81829	.94505	17.19830	51
52	.91053	10.17646	.92792	12.87391	.94534	17.29501	52
53	.91082	10.21277	.92821	12.92999	.94563	17.39274	53
54	.91111	10.24932	.92850	12.98651	.94592	17.49153	54
55	.91140	10.28610	.92879	13.04350	.94621	17.59139	55
56	.91169	10.32313	.92908	13.10096	.94650	17.69233	56
57	.91197	10.36040	.92937	13.15889	.94679	17.79438	57
58	.91226	10.39792	.92966	13.21730	.94708	17.89755	58
59	.91255	10.43569	.92995	13.27620	.94737	18.00185	59
60	.91284	10.47371	.93024	13.33559	.94766	18.10732	60

TABLE X.—NATURAL VERSED SINES AND EXTERNAL SECANTS.

′	87° Vers.	87° Ex. sec.	88° Vers.	88° Ex. sec.	89° Vers.	89° Ex. sec.	′
0	.94766	18.10732	.96510	27.65371	.98255	56.29869	0
1	.94795	18.21397	.96539	27.89440	.98284	57.26976	1
2	.94825	18.32182	.96568	28.13917	.98313	58.27431	2
3	.94854	18.43088	.96597	28.38812	.98342	59.31411	3
4	.94883	18.54119	.96626	28.64137	.98371	60.39105	4
5	.94912	18.65275	.96655	28.89903	.98400	61.50715	5
6	.94941	18.76560	.96684	29.16120	.98429	62.66460	6
7	.94970	18.87976	.96714	29.42802	.98458	63.86572	7
8	.94999	18.99524	.96743	29.69960	.98487	65.11304	8
9	.95028	19.11208	.96772	29.97607	.98517	66.40927	9
10	.95057	19.23028	.96801	30.25758	.98546	67.75736	10
11	.95086	19.34989	.96830	30.54425	.98575	69.16047	11
12	.95115	19.47093	.96859	30.83623	.98604	70.62205	12
13	.95144	19.59341	.96888	31.13366	.98633	72.14583	13
14	.95173	19.71737	.96917	31.43671	.98662	73.73586	14
15	.95202	19.84283	.96946	31.74554	.98691	75.39655	15
16	.95231	19.96982	.96975	32.06030	.98720	77.13274	16
17	.95260	20.09838	.97004	32.38118	.98749	78.94968	17
18	.95289	20.22852	.97033	32.70835	.98778	80.85315	18
19	.95318	20.36027	.97062	33.04199	.98807	82.84947	19
20	.95347	20.49368	.97092	33.38232	.98836	84.94561	20
21	.95377	20.62876	.97121	33.72952	.98866	87.14924	21
22	.95406	20.76555	.97150	34.08380	.98895	89.46886	22
23	.95435	20.90409	.97179	34.44539	.98924	91.91387	23
24	.95464	21.04440	.97208	34.81452	.98953	94.49471	24
25	.95493	21.18653	.97237	35.19141	.98982	97.22303	25
26	.95522	21.33050	.97266	35.57633	.99011	100.1119	26
27	.95551	21.47635	.97295	35.96953	.99040	103.1757	27
28	.95580	21.62413	.97324	36.37127	.99069	106.4311	28
29	.95609	21.77386	.97353	36.78185	.99098	109.8966	29
30	.95638	21.92559	.97382	37.20155	.99127	113.5930	30
31	.95667	22.07935	.97411	37.63068	.99156	117.5444	31
32	.95696	22.23520	.97440	38.06957	.99186	121.7780	32
33	.95725	22.39316	.97470	38.51855	.99215	126.3253	33
34	.95754	22.55328	.97499	38.97797	.99244	131.2223	34
35	.95783	22.71563	.97528	39.44820	.99278	136.5111	35
36	.95812	22.88022	.97557	39.92963	.99302	142.2406	36
37	.95842	23.04712	.97586	40.42266	.99331	148.4684	37
38	.95871	23.21637	.97615	40.92772	.99360	155.2623	38
39	.95900	23.38802	.97644	41.44525	.99389	162.7033	39
40	.95929	23.56212	.97673	41.97571	.99418	170.8883	40
41	.95958	23.73873	.97702	42.51961	.99447	179.9350	41
42	.95987	23.91790	.97731	43.07746	.99476	189.9868	42
43	.96016	24.09969	.97760	43.64980	.99505	201.2212	43
44	.96045	24.28414	.97789	44.23720	.99535	213.8600	44
45	.96074	24.47134	.97819	44.84026	.99564	228.1839	45
46	.96103	24.66132	.97848	45.45963	.99593	244.5540	46
47	.96132	24.85417	.97877	46.09596	.99622	263.4427	47
48	.96161	25.04994	.97906	46.74997	.99651	285.4795	48
49	.96190	25.24869	.97935	47.42241	.99680	311.5230	49
50	.96219	25.45051	.97964	48.11406	.99709	342.7752	50
51	.96248	25.65546	.97993	48.82576	.99738	380.9723	51
52	.96277	25.86360	.98022	49.55840	.99767	428.7187	52
53	.96307	26.07503	.98051	50.31290	.99796	490.1070	53
54	.96336	26.28981	.98080	51.09027	.99825	571.9581	54
55	.96365	26.50804	.98109	51.89156	.99855	686.5496	55
56	.96394	26.72978	.98138	52.71790	.99884	858.4369	56
57	.96423	26.95513	.98168	53.57046	.99913	1144.916	57
58	.96452	27.18417	.98197	54.45053	.99942	1717.874	58
59	.96481	27.41700	.98226	55.35946	.99971	3436.747	59
60	.96510	27.65371	.98255	56.29869	1.00000	Infinite	60

Temp. ° Fahr.	Inches. 26.0	26.5	27.0	27.5	28.0	28.5	29.0	29.5	30.0	30.5	31.0
45	−.039	−.039	−.040	−.041	−.042	−.042	−.043	−.044	−.045	−.045	−.046
46	.041	.042	.043	.043	.044	.045	.046	.046	.047	.048	.049
47	.043	.044	.045	.046	.047	.048	.048	.049	.050	.051	.052
48	.046	.047	.047	.048	.049	.050	.051	.052	.053	.053	.054
49	.048	.049	.050	.051	.052	.052	.054	.054	.055	.056	.057
50	.050	.051	.052	.053	.054	.055	.056	.057	.058	.059	.060
51	.053	.054	.055	.056	.057	.058	.059	.060	.061	.062	.063
52	.055	.056	.057	.058	.059	.060	.061	.062	.064	.065	.066
53	.057	.058	.060	.061	.062	.063	.064	.065	.066	.067	.068
54	.060	.061	.062	.063	.064	.065	.067	.068	.069	.070	.071
55	.062	.063	.064	.065	.066	.068	.069	.070	.071	.073	.074
56	.064	.065	.067	.068	.069	.070	.072	.073	.074	.075	.077
57	.067	.068	.069	.070	.072	.073	.075	.076	.077	.078	.080
58	.069	.070	.071	.073	.074	.076	.077	.078	.080	.081	.082
59	.072	.073	.074	.075	.077	.078	.080	.081	.083	.084	.085
60	.074	.076	.077	.078	.079	.081	.082	.084	.085	.086	.088
61	.076	.077	.079	.080	.082	.083	.085	.086	.088	.089	.091
62	.079	.080	.082	.083	.085	.086	.088	.089	.091	.092	.094
63	.081	.082	.084	.085	.087	.088	.090	.091	.093	.095	.096
64	.083	.085	.086	.088	.090	.091	.093	.094	.096	.097	.099
65	.086	.087	.089	.090	.092	.093	.095	.097	.099	.100	.102
66	.088	.089	.091	.093	.095	.096	.098	.099	.101	.103	.105
67	.090	.092	.094	.095	.097	.099	.101	.102	.104	.106	.108
68	.093	.094	.096	.098	.100	.101	.103	.105	.107	.108	.110
69	.095	.097	.099	.100	.102	.104	.106	.107	.110	.111	.113
70	.097	.099	.101	.103	.105	.106	.109	.110	.112	.114	.116
71	.100	.101	.103	.105	.107	.109	.111	.113	.115	.117	.119
72	.102	.104	.106	.108	.110	.112	.114	.116	.118	.120	.122
73	.104	.106	.108	.110	.112	.114	.116	.118	.120	.122	.124
74	.107	.109	.111	.113	.115	.117	.119	.121	.123	.125	.127
75	.109	.111	.113	.115	.117	.119	.122	.124	.126	.128	.130
76	.111	.113	.116	.118	.120	.122	.124	.126	.128	.130	.133
77	.114	.116	.118	.120	.122	.124	.127	.129	.131	.133	.136
78	.116	.118	.120	.122	.125	.127	.129	.131	.134	.136	.138
79	.118	.120	.123	.125	.127	.129	.132	.134	.137	.139	.141
80	.121	.123	.125	.127	.130	.132	.135	.137	.139	.141	.144
81	.123	.125	.128	.130	.132	.134	.137	.139	.142	.144	.147
82	.125	.128	.130	.132	.135	.137	.140	.142	.145	.147	.149
83	.128	.130	.133	.135	.138	.140	.142	.145	.147	.149	.152
84	.130	.132	.135	.138	.140	.142	.145	.147	.150	.152	.155
85	.132	.134	.137	.140	.143	.145	.148	.150	.153	.155	.158
86	.135	.137	.140	.142	.145	.148	.150	.153	.155	.158	.161
87	.137	.139	.142	.144	.148	.150	.153	.155	.158	.161	.163
88	.139	.142	.145	.147	.150	.152	.155	.158	.161	.163	.166
89	.142	.144	.147	.150	.153	.155	.158	.161	.164	.166	.169
90	.144	.147	.150	.153	.155	.158	.161	.164	.166	.169	.172
91	−.146	−.149	−.152	−.155	−.158	−.160	−.163	−.166	−.169	−.172	−.175

TABLE XII.—BAROMETRIC ELEVATIONS.*

B	A	Diff. for .01.	B	A	Diff. for .01.	B	A	Diff. for .01.
Inches.	Feet.	Feet.	Inches.	Feet.	Feet.	Inches.	Feet.	Feet.
20.0	11,047	−13.6	23.7	6,423	−11.5	27.4	2,470	−9.9
20.1	10,911	13.5	23.8	6,308	11.4	27.5	2,371	9.9
20.2	10,776	13.4	23.9	6,194	11.4	27.6	2,272	9.9
20.3	10,642	13.4	24.0	6,080	11.3	27.7	2,173	9.8
20.4	10,508	13.3	24.1	5,967	11.3	27.8	2,075	9.8
20.5	10,375	13.3	24.2	5,854	11.3	27.9	1,977	9.7
20.6	10,242	13.2	24.3	5,741	11.2	28.0	1,880	9.7
20.7	10,110	13.1	24.4	5,629	11.1	28.1	1,783	9.7
20.8	9,979	13.1	24.5	5,518	11.1	28.2	1 686	9.7
20.9	9,848	13.0	24.6	5,407	11.1	28.3	1,589	9.6
21.0	9,718	12.9	24.7	5,296	11.0	28.4	1,493	9.6
21.1	9,589	12.9	24.8	5,186	10.9	28.5	1,397	9.5
21.2	9,460	12.8	24.9	5,077	10.9	28.6	1,302	9.5
21.3	9,332	12.8	25.0	4,968	10.9	28.7	1,207	9.5
21.4	9,204	12.7	25.1	4,859	10.8	28.8	1,112	9.4
21.5	9,077	12.6	25.2	4,751	10.8	28.9	1,018	9.4
21.6	8,951	12.6	25.3	4,643	10.8	29.0	924	9.4
21.7	8,825	12.5	25.4	4,535	10.7	29.1	830	9.4
21.8	8,700	12.5	25.5	4,428	10.7	29.2	736	9.3
21.9	8,575	12.4	25.6	4,321	10.6	29.3	643	9.3
22.0	8,451	12.4	25.7	4,215	10.6	29.4	550	9.2
22.1	8,327	12.3	25.8	4,109	10.5	29.5	458	9.2
22.2	8,204	12.2	25.9	4,004	10.5	29.6	366	9.2
22.3	8,082	12.2	26.0	3 899	10.4	29.7	274	9.2
22.4	7,960	12.2	26.1	3,794	10.4	29.8	182	9.1
22.5	7,838	12.1	26.2	3 690	10.4	29.9	91	9.1
22.6	7,717	12.0	26.3	3,586	10.3	30.0	0	9.1
22.7	7,597	12.0	26.4	3,483	10.3	30.1	− 91	9.0
22.8	7,477	11.9	26.5	3,380	10.3	30.2	181	9.0
22.9	7,358	11.9	26.6	3,277	10.2	30.3	271	9.0
23.0	7,239	11.8	26.7	3,175	10.2	30.4	361	9.0
23.1	7,121	11.7	26.8	3,073	10.1	30.5	451	8.9
23.2	7,004	11.7	26.9	2 972	10.1	30.6	540	8.9
23.3	6,887	11.7	27.0	2.871	10 1	30.7	629	8.8
23.4	6,770	11.6	27.1	2 770	10.0	30.8	717	8.8
23.5	6,554	11.6	27.2	2,670	10.0	30.9	805	−8.8
23.6	6,538	−11.5	27.3	2,570	−10 0	31 0	−893	
23.7	6,423		27.4	2.470				

* Compiled from Report of U. S. C. & G. Survey for 1881, App. 10 Table XI.

TABLE XIII.—COEFFICIENTS FOR CORRECTIONS FOR TEMPERATURE AND HUMIDITY.*

$t+t'$	C	Diff. for 1°.	$t+t'$	C	Diff. for 1°.	$t+t'$	C	Diff. for 1°.
0°	− .1024	10.9	60°	− .0380	10.7	120°	+ .0262	10.6
10	.0915	10.9	70	.0273	10.7	130	.0368	10.4
20	.0806	10.8	80	.0166	10.8	140	.0472	10.3
30	.0698	10.6	90	− .0058	10.7	150	.0575	10.2
40	.0592	10.6	100	+ .0049	10.7	160	.0677	10.2
50	.0486	10.6	110	.0156	10.6	170	.0779	10.0
60	− .0380		120	+ .0262		180	+ .0879	

* Compiled from Report of U. S. C. & G. Survey for 1881, App. 10, Tables I, **IV.**

1 $\sin a = \frac{1}{\operatorname{cosec} a} = \frac{\tan a}{\sqrt{1+\tan^2 a}} = \sqrt{\frac{1-\cos 2a}{2}} = \frac{1}{\sqrt{1+\cot^2 a}}$

$= \cos a \tan a = \sqrt{1-\cos^2 a} = 2 \sin \tfrac{1}{2}a \cos \tfrac{1}{2}a$

$= \frac{1+\cos a}{\cot \frac{1}{2}a} = \frac{2 \tan \frac{1}{2}a}{1+\tan^2 \frac{1}{2}a} = \operatorname{vers} a \cot \tfrac{1}{2}a.$

2 $\cos a = \frac{1}{\sec a} = \frac{\cot a}{\sqrt{1+\cot^2 a}} = \frac{1}{\sqrt{1+\tan^2 a}}$

$= 1 - \operatorname{vers} a = \sin a \cot a = \sqrt{1-\sin^2 a} = 2 \cos^2 \tfrac{1}{2}a - 1$

$= \sin a \cot \tfrac{1}{2}a - 1 = \cos^2 \tfrac{1}{2}a - \sin^2 \tfrac{1}{2}a = 1 - 2 \sin^2 \tfrac{1}{2}a.$

3 $\tan a = \frac{1}{\cot a} = \frac{\sin a}{\cos a} = \frac{\sec a}{\operatorname{cosec} a} = \frac{1}{\sqrt{\operatorname{cosec}^2 a - 1}}$

$= \operatorname{vers} 2a \operatorname{cosec} 2a = \cot a - 2 \cot 2a = \sin a \sec a$

$= \frac{\sin 2a}{1+\cos 2a} = \operatorname{exsec} a \cot \tfrac{1}{2}a = \operatorname{exsec} 2a \cot 2a.$

4 $\cot a = \frac{1}{\tan a} = \frac{\cos a}{\sin a} = \frac{\sin 2a}{1-\cos 2a} = \frac{1+\cos 2a}{\sin 2a}$

$= \sqrt{\operatorname{cosec}^2 a - 1} = \cot \tfrac{1}{2}a - \operatorname{cosec} a.$

5 $\operatorname{vers} a = 1 - \cos a = \sin a \tan \tfrac{1}{2}a = 2 \sin^2 \tfrac{1}{2}a = \cos a \operatorname{exsec} a.$

6 $\operatorname{exsec} a = \sec a - 1 = \tan a \tan \tfrac{1}{2}a = \operatorname{vers} a \sec a.$

7 $\sin \tfrac{1}{2}a = \sqrt{\frac{\operatorname{vers} a}{2}} = \frac{\sin a}{2 \cos \frac{1}{2}a} = \frac{\operatorname{vers} a \cos \frac{1}{2}a}{\sin a}.$

8 $\cos \tfrac{1}{2}a = \sqrt{\frac{1+\cos a}{2}} = \frac{\sin a}{2 \sin \frac{1}{2}a} = \frac{\sin a \sin \frac{1}{2}a}{\operatorname{vers} a}.$

9 $\tan \tfrac{1}{2}a = \operatorname{vers} a \operatorname{cosec} a = \operatorname{cosec} a - \cot a = \frac{\tan a}{1+\sec a}.$

10 $\cot \tfrac{1}{2}a = \frac{1+\cos a}{\sin a} = \operatorname{cosec} a + \cot a = \frac{\tan a}{\operatorname{exsec} a} = \frac{1}{\operatorname{cosec} a - \cot a}.$

11 $\operatorname{vers} \tfrac{1}{2}a = 1 - \sqrt{\tfrac{1}{2}(1+\cos a)}.$

12 $\operatorname{exsec} \tfrac{1}{2}a = \frac{1}{\sqrt{\frac{1}{2}(1+\cos a)}} - 1.$

13 $\sin 2a \quad = 2 \sin a \cos a = \frac{2 \tan a}{1 + \tan^2 a}.$

14 $\cos 2a \quad = \cos^2 a - \sin^2 a = 1 - 2 \sin^2 a = 2 \cos^2 a - 1$

$$= \frac{1 - \tan^2 a}{1 + \tan^2 a}.$$

15 $\tan 2a \quad = \frac{2 \tan a}{1 - \tan^2 a}.$

16 $\cot 2a \quad = \frac{1}{2} \cot a - \frac{1}{2} \tan a = \frac{\cot^2 a - 1}{2 \cot a} = \frac{1 - \tan^2 a}{2 \tan a}.$

17 $\text{vers } 2a \quad = 2 \sin^2 a = 1 - \cos 2a = 2 \sin a \cos a \tan a.$

18 $\text{exsec } 2a = \frac{\tan 2a}{\cot a} = \frac{2 \tan^2 a}{1 - \tan^2 a} = \frac{2 \sin^2 a}{1 - 2 \sin^2 a}.$

19 $\sin (a \pm b) = \sin a \cos b \pm \cos a \sin b.$

20 $\cos (a \pm b) = \cos a \cos b \mp \sin a \sin b.$

21 $\sin a + \sin b = 2 \sin \frac{1}{2}(a+b) \cos \frac{1}{2}(a-b).$

22 $\sin a - \sin b = 2 \sin \frac{1}{2}(a-b) \cos \frac{1}{2}(a+b).$

23 $\cos a + \cos b = 2 \cos \frac{1}{2}(a+b) \cos \frac{1}{2}(a-b).$

24 $\cos a - \cos b = -2 \sin \frac{1}{2}(a+b) \sin \frac{1}{2}(a-b).$

Call the sides of any triangle A, B, C, and the opposite angles a, b, and c. Call $s = \frac{1}{2}(A + B + C)$.

25 $\tan \frac{1}{2}(a-b) = \frac{A-B}{A+B} \tan \frac{1}{2}(a+b) = \frac{A-B}{A+B} \cot \frac{1}{2}c.$

26 $C = (A+B) \frac{\cos \frac{1}{2}(a+b)}{\cos \frac{1}{2}(a-b)} = (A-B) \frac{\sin \frac{1}{2}(a+b)}{\sin \frac{1}{2}(a-b)}.$

27 $\sin \frac{1}{2}a = \sqrt{\frac{(s-B)(s-C)}{BC}}.$

28 $\cos \frac{1}{2}a = \sqrt{\frac{s(s-A)}{BC}}.$

29 $\text{vers } a = \frac{2(s-B)(s-C)}{BC}.$

30 $\text{Area } = \sqrt{s(s-A)(s-B)(s-C)} = A^2 \frac{\sin b \sin c}{2 \sin a}.$

		Logarithm.
Circumference of a circle (radius $= r$) $= 2\pi r$.		
Area of a circle $= \pi r^2$.		
Area of sector (length of arc $= l$) $= \frac{1}{2} lr$.		
" " " (angle of arc $= \alpha°$) $= \frac{\alpha}{360}\pi r^2$.		
Area of segment (chord $= c$, mid. ord. $= m$) $= \frac{2}{3} cm$ (approx.).		
Volume of a cone or pyramid = area of base × $\frac{1}{3}$ height.		
Area of a circle to radius 1 / Circumference of a circle to diameter 1 / Surface of a sphere to diameter 1 } $= \pi =$	3.1415927	0.497 1499
Volume of a sphere to radius $1 = 4\pi \div 3$ =	4.1887902	0.622 0886
Arc equal to radius expressed in degrees =	57.2957795	1.758 1226
Arc equal to radius expressed in minutes =	3437.7467708	3.536 2739
Arc equal to radius expressed in seconds =	206264.8062471	5.314 4251
Length of arc of 1°, radius unity	0.01745329	8.241 8774
Sine of one second = 0.0000048481		4.685 5749
Weight of one cubic foot of water at maximum density (therm. 39°.8 F., barom. 30″)	62.379	1.795 0384
Weight of one cubic foot of water at ordinary temperature (therm. 62° F.)	62.321	1.794 6349
Acceleration due to gravity at latitude of New York in feet per square second	32.15945	1.507 3086
1 yard (U. S. standard) $= \frac{3600}{3937}$ meter =	0.914402 m.	9.961 1371
1 foot =	0.304801 m.	9.484 0158
1 inch =	0.025400 m.	8.404 8346
1 meter =	3.28083 feet	0.515 9842
=	39.3700 inches	1.595 1654
1 pound (avoirdupois) =	0.453592 kilogr.	9.656 6659
1 kilogram =	2.20462 pounds	1.343 3341
1 bushel (U. S. standard) =	2150.420 cu. in.	
=	1.244 cu. ft.	
1 gallon (U. S. standard) =	231. cu. in.	
=	0.1337 cu. ft.	

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
1	1	1	1.0000000	1.0000000	1.000000000
2	4	8	1.4142136	1.2599210	.500000000
3	9	27	1.7320508	1.4422496	.333333333
4	16	64	2.0000000	1.5874011	.250000000
5	25	125	2.2360680	1.7099759	.200000000
6	36	216	2.4494897	1.8171206	.166666667
7	49	343	2.6457513	1.9129312	.142857143
8	64	512	2.8284271	2.0000000	.125000000
9	81	729	3.0000000	2.0800837	.111111111
10	100	1000	3.1622777	2.1544347	.100000000
11	121	1331	3.3166248	2.2239801	.090909091
12	144	1728	3.4641016	2.2894286	.083333333
13	169	2197	3.6055513	2.3513347	.076923077
14	196	2744	3.7416574	2.4101422	.071428571
15	225	3375	3.8729833	2.4662121	.066666667
16	256	4096	4.0000000	2.5198421	.062500000
17	289	4913	4.1231056	2.5712816	.058823529
18	324	5832	4.2426407	2.6207414	.055555556
19	361	6859	4.3588989	2.6684016	.052631579
20	400	8000	4.4721360	2.7144177	.050000000
21	441	9261	4.5825757	2.7589243	.047619048
22	484	10648	4.6904158	2.8020393	.045454545
23	529	12167	4.7958315	2.8438670	.043478261
24	576	13824	4.8989795	2.8844991	.041666667
25	625	15625	5.0000000	2.9240177	.040000000
26	676	17576	5.0990195	2.9624960	.038461538
27	729	19683	5.1961524	3.0000000	.037037037
28	784	21952	5.2915026	3.0365889	.035714286
29	841	24389	5.3851648	3.0723168	.034482759
30	900	27000	5.4772256	3.1072325	.033333333
31	961	29791	5.5677644	3.1413806	.032258065
32	1024	32768	5.6568542	3.1748021	.031250000
33	1089	35937	5.7445626	3.2075343	.030303030
34	1156	39304	5.8309519	3.2396118	.029411765
35	1225	42875	5.9160798	3.2710663	.028571429
36	1296	46656	6.0000000	3.3019272	.027777778
37	1369	50653	6.0827625	3.3322218	.027027027
38	1444	54872	6.1644140	3.3619754	.026315789
39	1521	59319	6.2449980	3.3912114	.025641026
40	1600	64000	6.3245553	3.4199519	.025000000
41	1681	68921	6.4031242	3.4482172	.024390244
42	1764	74088	6.4807407	3.4760266	.023809524
43	1849	79507	6.5574385	3.5033981	.023255814
44	1936	85184	6.6332496	3.5303483	.022727273
45	2025	91125	6.7082039	3.5568933	.022222222
46	2116	97336	6.7823300	3.5830479	.021739130
47	2209	103823	6.8556546	3.6088261	.021276600
48	2304	110592	6.9282032	3.6342411	.020833333
49	2401	117649	7.0000000	3.6593057	.020408163
50	2500	125000	7.0710678	3.6840314	.020000000
51	2601	132651	7.1414284	3.7084298	.019607843
52	2704	140608	7.2111026	3.7325111	.019230769
53	2809	148877	7.2801099	3.7562858	.018867925
54	2916	157464	7.3484692	3.7797631	.018518519
55	3025	166375	7.4161985	3.8029525	.018181818
56	3136	175616	7.4833148	3.8258624	.017857143
57	3249	185193	7.5498344	3.8485011	.017543860
58	3364	195112	7.6157731	3.8708766	.017241379
59	3481	205379	7.6811457	3.8929965	.016949153
60	3600	216000	7.7459667	3.9148676	.016666667

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
61	3721	226981	7·8102497	3·9364972	·016393443
62	3844	238328	7·8740079	3·9578915	·016129032
63	3969	250047	7·9372539	3·9790571	·015873016
64	4096	262144	8·0000000	4·0000000	·015625000
65	4225	274625	8·0622577	4·0207256	·015384615
66	4356	287496	8·1240384	4·0412401	·015151515
67	4489	300763	8·1853528	4·0615480	·014925373
68	4624	314432	8·2462113	4·0816551	·014705882
69	4761	328509	8·3066239	4·1015661	·014492754
70	4900	343000	8·3666003	4·1212853	·014285714
71	5041	357911	8·4261498	4·1408178	·014084507
72	5184	373248	8·4852814	4·1601676	·013888889
73	5329	389017	8·5440037	4·1793390	·013698630
74	5476	405224	8·6023253	4·1983364	·013513514
75	5625	421875	8·6602540	4·2171633	·013333333
76	5776	438976	8·7177979	4·2358236	·013157895
77	5929	456533	8·7749644	4·2543210	·012987013
78	6084	474552	8·8317609	4·2726586	·012820513
79	6241	493039	8·8881944	4·2908404	·012658228
80	6400	512000	8·9442719	4·3088695	·012500000
81	6561	531441	9·0000000	4·3267487	·012345679
82	6724	551368	9·0553851	4·3444815	·012195122
83	6889	571787	9·1104336	4·3620707	·012048193
84	7056	592704	9·1651514	4·3795191	·011904762
85	7225	614125	9·2195445	4·3968296	·011764706
86	7396	636056	9·2736185	4·4140049	·011627907
87	7569	658503	9·3273791	4·4310476	·011494253
88	7744	681472	9·3808315	4·4479602	·011363636
89	7921	704969	9·4339811	4·4647451	·011235955
90	8100	729000	9·4868330	4·4814047	·011111111
91	8281	753571	9·5393920	4·4979414	·010989011
92	8464	778688	9·5916630	4·5143574	·010869565
93	8649	804357	9·6436508	4·5306549	·010752688
94	8836	830584	9·6953597	4·5468359	·010638298
95	9025	857375	9·7467943	4·5629026	·010526316
96	9216	884736	9·7979590	4·5788570	·010416667
97	9409	912673	9·8488578	4·5947009	·010309278
98	9604	941192	9·8994949	4·6104363	·010204082
99	9801	970299	9·9498744	4·6260650	·010101010
100	10000	1000000	10·0000000	4·6415888	·010000000
101	10201	1030301	10·0498756	4·6570095	·009900990
102	10404	1061208	10·0995049	4·6723287	·009803922
103	10609	1092727	10·1488916	4·6875482	·009708738
104	10816	1124864	10·1980390	4·7026694	·009615385
105	11025	1157625	10·2469508	4·7176940	·009523810
106	11236	1191016	10·2956301	4·7326235	·009433962
107	11449	1225043	10·3440804	4·7474594	·009345794
108	11664	1259712	10·3923048	4·7622032	·009259259
109	11881	1295029	10·4403065	4·7768562	·009174312
110	12100	1331000	10·4880885	4·7914199	·009090909
111	12321	1367631	10·5356538	4·8058955	·009009009
112	12544	1404928	10·5830052	4·8202845	·008928571
113	12769	1442897	10·6301458	4·8345881	·008849558
114	12996	1481544	10·6770783	4·8488076	·008771930
115	13225	1520875	10·7238053	4·8629442	·008695652
116	13456	1560896	10·7703296	4·8769990	·008620690
117	13689	1601613	10·8166538	4·8909732	·008547009
118	13924	1643032	10·8627805	4·9048681	·008474576
119	14161	1685159	10·9087121	4·9186847	·008403361
120	14400	1728000	10·9544512	4·9324242	·008333333

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
121	14641	1771561	11.0000000	4.9460874	.008264463
122	14884	1815848	11.0453610	4.9596757	.008196721
123	15129	1860867	11.0905365	4.9731898	.008130081
124	15376	1906624	11.1355287	4.9866310	.008064516
125	15625	1953125	11.1803399	5.0000000	.008000000
126	15876	2000376	11.2249722	5.0132979	.007936508
127	16129	2048383	11.2694277	5.0265257	.007874016
128	16384	2097152	11.3137085	5.0396842	.007812500
129	16641	2146689	11.3578167	5.0527743	.007751938
130	16900	2197000	11.4017543	5.0657970	.007692308
131	17161	2248091	11.4455231	5.0787531	.007633588
132	17424	2299968	11.4891253	5.0916434	.007575758
133	17689	2352637	11.5325626	5.1044687	.007518797
134	17956	2406104	11.5758369	5.1172299	.007462687
135	18225	2460375	11.6189500	5.1299278	.007407407
136	18496	2515456	11.6619038	5.1425632	.007352941
137	18769	2571353	11.7046999	5.1551367	.007299270
138	19044	2628072	11.7473401	5.1676493	.007246377
139	19321	2685619	11.7898261	5.1801015	.007194245
140	19600	2744000	11.8321596	5.1924941	.007142857
141	19881	2803221	11.8743421	5.2048279	.007092199
142	20164	2863288	11.9163753	5.2171034	.007042254
143	20449	2924207	11.9582607	5.2293215	.006993007
144	20736	2985984	12.0000000	5.2414828	.006944444
145	21025	3048625	12.0415946	5.2535879	.006896552
146	21316	3112136	12.0830460	5.2656374	.006849315
147	21609	3176523	12.1243557	5.2776321	.006802721
148	21904	3241792	12.1655251	5.2895725	.006756757
149	22201	3307949	12.2065556	5.3014592	.006711409
150	22500	3375000	12.2474487	5.3132928	.006666667
151	22801	3442951	12.2882057	5.3250740	.006622517
152	23104	3511808	12.3288280	5.3368033	.006578947
153	23409	3581577	12.3693169	5.3484812	.006535948
154	23716	3652264	12.4096736	5.3601084	.006493506
155	24025	3723875	12.4498996	5.3716854	.006451613
156	24336	3796416	12.4899960	5.3832126	.006410256
157	24649	3869893	12.5299641	5.3946907	.006369427
158	24964	3944312	12.5698051	5.4061202	.006329114
159	25281	4019679	12.6095202	5.4175015	.006289308
160	25600	4096000	12.6491106	5.4288352	.006250000
161	25921	4173281	12.6885775	5.4401218	.006211180
162	26244	4251528	12.7279221	5.4513618	.006172840
163	26569	4330747	12.7671453	5.4625556	.006134969
164	26896	4410944	12.8062485	5.4737037	.006097561
165	27225	4492125	12.8452326	5.4848066	.006060606
166	27556	4574296	12.8840987	5.4958647	.006024096
167	27889	4657463	12.9228480	5.5068784	.005988024
168	28224	4741632	12.9614814	5.5178484	.005952381
169	28561	4826809	13.0000000	5.5287748	.005917160
170	28900	4913000	13.0384048	5.5396583	.005882353
171	29241	5000211	13.0766968	5.5504991	.005847953
172	29584	5088448	13.1148770	5.5612978	.005813953
173	29929	5177717	13.1529464	5.5720546	.005780347
174	30276	5268024	13.1909060	5.5827702	.005747126
175	30625	5359375	13.2287566	5.5934447	.005714286
176	30976	5451776	13.2664992	5.6040787	.005681818
177	31329	5545233	13.3041347	5.6146724	.005649718
178	31684	5639752	13.3416641	5.6252263	.005617978
179	32041	5735339	13.3790882	5.6357408	.005586592
180	32400	5832000	13.4164079	5.6462162	.005555556

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
181	32761	5929741	13·4536240	5·6566528	·005524862
182	33124	6028568	13·4907376	5·6670511	·005494505
183	33489	6128487	13·5277493	5·6774114	·005464481
184	33856	6229504	13·5646600	5·6877340	·005434783
185	34225	6331625	13·6014705	5·6980192	·005405405
186	34596	6434856	13·6381817	5·7082675	·005376344
187	34969	6539203	13·6747943	5·7184791	·005347594
188	35344	6644672	13·7113092	5·7286543	·005319149
189	35721	6751269	13·7477271	5·7387936	·005291005
190	36100	6859000	13·7840488	5·7488971	·005263158
191	36481	6967871	13·8202750	5·7589652	·005235602
192	36864	7077888	13·8564065	5·7689982	·005208333
193	37249	7189057	13·8924440	5·7789966	·005181347
194	37636	7301384	13·9283883	5·7889604	·005154639
195	38025	7414875	13·9642400	5·7988900	·005128205
196	38416	7529536	14·0000000	5·8087857	·005102041
197	38809	7645373	14·0356688	5·8186479	·005076142
198	39204	7762392	14·0712473	5·8284767	·005050505
199	39601	7880599	14·1067360	5·8382725	·005025126
200	40000	8000000	14·1421356	5·8480355	·005000000
201	40401	8120601	14·1774469	5·8577660	·004975124
202	40804	8242408	14·2126704	5·8674643	·004950495
203	41209	8365427	14·2478068	5·8771307	·004926108
204	41616	8489664	14·2828569	5·8867653	·004901961
205	42025	8615125	14·3178211	5·8963685	·004878049
206	42436	8741816	14·3527001	5·9059406	·004854369
207	42849	8869743	14·3874946	5·9154817	·004830918
208	43264	8998912	14·4222051	5·9249921	·004807692
209	43681	9129329	14·4568323	5·9344721	·004784689
210	44100	9261000	14·4913767	5·9439220	·004761905
211	44521	9393931	14·5258390	5·9533418	·004739336
212	44944	9528128	14·5602198	5·9627320	·004716981
213	45369	9663597	14·5945195	5·9720926	·004694836
214	45796	9800344	14·6287388	5·9814240	·004672897
215	46225	9938375	14·6628783	5·9907264	·004651163
216	46656	10077696	14·6969385	6·0000000	·004629630
217	47089	10218313	14·7309199	6·0092450	·004608295
218	47524	10360232	14·7648231	6·0184617	·004587156
219	47961	10503459	14·7986486	6·0276502	·004566210
220	48400	10648000	14·8323970	6·0368107	·004545455
221	48841	10793861	14·8660687	6·0459435	·004524887
222	49284	10941048	14·8996644	6·0550489	·004504505
223	49729	11089567	14·9331845	6·0641270	·004484305
224	50176	11239424	14·9666295	6·0731779	·004464286
225	50625	11390625	15·0000000	6·0822020	·004444444
226	51076	11543176	15·0332964	6·0911994	·004424779
227	51529	11697083	15·0665192	6·1001702	·004405286
228	51984	11852352	15·0996689	6·1091147	·004385965
229	52441	12008989	15·1327460	6·1180332	·004366812
230	52900	12167000	15·1657509	6·1269257	·004347826
231	53361	12326391	15·1986842	6·1357924	·004329004
232	53824	12487168	15·2315462	6·1446337	·004310345
233	54289	12649337	15·2643375	6·1534495	·004291845
234	54756	12812904	15·2970585	6·1622401	·004273504
235	55225	12977875	15·3297097	6·1710058	·004255319
236	55696	13144256	15·3622915	6·1797466	·004237288
237	56169	13312053	15·3948043	6·1884628	·004219409
238	56644	13481272	15·4272486	6·1971544	·004201681
239	57121	13651919	15·4596248	6·2058218	·004184100
240	57600	13824000	15·4919334	6·2144650	·004166667

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
241	58081	13997521	15·5241747	6·2230843	·004149378
242	58564	14172488	15·5563492	6·2316797	·004132231
243	59049	14348907	15·5884573	6·2402515	·004115226
244	59536	14526784	15·6204994	6·2487998	·004098361
245	60025	14706125	15·6524758	6·2573248	·004081633
246	60516	14886936	15·6843871	6·2658266	·004065041
247	61009	15069223	15·7162336	6·2743054	·004048583
248	61504	15252992	15·7480157	6·2827613	·004032258
249	62001	15438249	15·7797338	6·2911946	·004016064
250	62500	15625000	15·8113883	6·2996053	·004000000
251	63001	15813251	15·8429795	6·3079935	·003984064
252	63504	16003008	15·8745079	6·3163596	·003968254
253	64009	16194277	15·9059737	6·3247035	·003952569
254	64516	16387064	15·9373775	6·3330256	·003937008
255	65025	16581375	15·9687194	6·3413257	·003921569
256	65536	16777216	16·0000000	6·3496042	·003906250
257	66049	16974593	16·0312195	6·3578611	·003891051
258	66564	17173512	16·0623784	6·3660968	·003875969
259	67081	17373979	16·0934769	6·3743111	·003861004
260	67600	17576000	16·1245155	6·3825043	·003846154
261	68121	17779581	16·1554944	6·3906765	·003831418
262	68644	17984728	16·1864141	6·3988279	·003816794
263	69169	18191447	16·2172747	6·4069585	·003802281
264	69696	18399744	16·2480768	6·4150687	·003787879
265	70225	18609625	16·2788206	6·4231583	·003773585
266	70756	18821096	16·3095064	6·4312276	·003759398
267	71289	19034163	16·3401346	6·4392767	·003745318
268	71824	19248832	16·3707055	6·4473057	·003731343
269	72361	19465109	16·4012195	6·4553148	·003717472
270	72900	19683000	16·4316767	6·4633041	·003703704
271	73441	19902511	16·4620776	6·4712736	·003690037
272	73984	20123648	16·4924225	6·4792236	·003676471
273	74529	20346417	16·5227116	6·4871541	·003663004
274	75076	20570824	16·5529454	6·4950653	·003649635
275	75625	20796875	16·5831240	6·5029572	·003636364
276	76176	21024576	16·6132477	6·5108300	·003623188
277	76729	21253933	16·6433170	6·5186839	·003610108
278	77284	21484952	16·6733320	6·5265189	·003597122
279	77841	21717639	16·7032931	6·5343351	·003584229
280	78400	21952000	16·7332005	6·5421326	·003571429
281	78961	22188041	16·7630546	6·5499116	·003558719
282	79524	22425768	16·7928556	6·5576722	·003546099
283	80089	22665187	16·8226038	6·5654144	·003533569
284	80656	22906304	16·8522995	6·5731385	·003521127
285	81225	23149125	16·8819430	6·5808443	·003508772
286	81796	23393656	16·9115345	6·5885323	·003496503
287	82369	23639903	16·9410743	6·5962023	·003484321
288	82944	23887872	16·9705627	6·6038545	·003472222
289	83521	24137569	17·0000000	6·6114890	·003460208
290	84100	24389000	17·0293864	6·6191060	·003448276
291	84681	24642171	17·0587221	6·6267054	·003436426
292	85264	24897088	17·0880075	6·6342874	·003424658
293	85849	25153757	17·1172428	6·6418522	·003412969
294	86436	25412184	17·1464282	6·6493998	·003401361
295	87025	25672375	17·1755640	6·6569302	·003389831
296	87616	25934336	17·2046505	6·6644437	·003378378
297	88209	26198073	17·2336879	6·6719403	·003367003
298	88804	26463592	17·2626765	6·6794200	·003355705
299	89401	26730899	17·2916165	6·6868831	·003344482
300	90000	27000000	17·3205081	6·6943295	·003333333

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
301	90601	27270901	17·3493516	6·7017593	·003322259
302	91204	27543608	17·3781472	6·7091729	·003311258
303	91809	27818127	17·4068952	6·7165700	·003300330
304	92416	28094464	17·4355958	6·7239508	·003289474
305	93025	28372625	17·4642492	6·7313155	·003278689
306	93636	28652616	17·4928557	6·7386641	·003267974
307	94249	28934443	17·5214155	6·7459967	·003257329
308	94864	29218112	17·5499288	6·7533134	·003246753
309	95481	29503629	17·5783958	6·7606143	·003236246
310	96100	29791000	17·6068169	6·7678995	·003225806
311	96721	30080231	17·6351921	6·7751690	·003215434
312	97344	30371328	17·6635217	6·7824229	·003205128
313	97969	30664297	17·6918060	6·7896613	·003194888
314	98596	30959144	17·7200451	6·7968844	·003184713
315	99225	31255875	17·7482393	6·8040921	·003174603
316	99856	31554496	17·7763888	6·8112847	·003164557
317	100489	31855013	17·8044938	6·8184620	·003154574
318	101124	32157432	17·8325545	6·8256242	·003144654
319	101761	32461759	17·8605711	6·8327714	·003134796
320	102400	32768000	17·8885438	6·8399037	·003125000
321	103041	33076161	17·9164729	6·8470213	·003115265
322	103684	33386248	17·9443584	6·8541240	·003105590
323	104329	33698267	17·9722008	6·8612120	·003095975
324	104976	34012224	18·0000000	6·8682855	·003086420
325	105625	34328125	18·0277564	6·8753443	·003076923
326	106276	34645976	18·0554701	6·8823888	·003067485
327	106929	34965783	18·0831413	6·8894188	·003058104
328	107584	35287552	18·1107703	6·8964345	·003048780
329	108241	35611289	18·1383571	6·9034359	·003039514
330	108900	35937000	18·1659021	6·9104232	·003030303
331	109561	36264691	18·1934054	6·9173964	·003021148
332	110224	36594368	18·2208672	6·9243556	·003012048
333	110889	36926037	18·2482876	6·9313008	·003003003
334	111556	37259704	18·2756669	6·9382321	·002994012
335	112225	37595375	18·3030052	6·9451496	·002985075
336	112896	37933056	18·3303028	6·9520533	·002976190
337	113569	38272753	18·3575598	6·9589434	·002967359
338	114244	38614472	18·3847763	6·9658198	·002958580
339	114921	38958219	18·4119526	6·9726826	·002949853
340	115600	39304000	18·4390889	6·9795321	·002941176
341	116281	39651821	18·4661853	6·9863681	·002932551
342	116964	40001688	18·4932420	6·9931906	·002923977
343	117649	40353607	18·5202592	7·0000000	·002915452
344	118336	40707584	18·5472370	7·0067962	·002906977
345	119025	41063625	18·5741756	7·0135791	·002898551
346	119716	41421736	18·6010752	7·0203490	·002890173
347	120409	41781923	18·6279360	7·0271058	·002881844
348	121104	42144192	18·6547581	7·0338497	·002873563
349	121801	42508549	18·6815417	7·0405806	·002865330
350	122500	42875000	18·7082869	7·0472987	·002857143
351	123201	43243551	18·7349940	7·0540041	·002849003
352	123904	43614208	18·7616630	7·0606967	·002840909
353	124609	43986977	18·7882942	7·0673767	·002832861
354	125316	44361864	18·8148877	7·0740440	·002824859
355	126025	44738875	18·8414437	7·0806988	·002816901
356	126736	45118016	18·8679623	7·0873411	·002808989
357	127449	45499293	18·8944436	7·0939709	·002801120
358	128164	45882712	18·9208879	7·1005885	·002793296
359	128881	46268279	18·9472953	7·1071937	·002785515
360	129600	46656000	18·9736660	7·1137866	·002777778

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
361	130321	47045881	19·0000000	7·1203674	·002770083
362	131044	47437928	19·0262976	7·1269360	·002762431
363	131769	47832147	19·0525589	7·1334925	·002754821
364	132496	48228544	19·0787840	7·1400370	·002747253
365	133225	48627125	19·1049732	7·1465695	·002739726
366	133956	49027896	19·1311265	7·1530901	·002732240
367	134689	49430863	19·1572441	7·1595988	·002724796
368	135424	49836032	19·1833261	7·1660957	·002717391
369	136161	50243409	19·2093727	7·1725809	·002710027
370	136900	50653000	19·2353841	7·1790544	·002702703
371	137641	51064811	19·2613603	7·1855162	·002695418
372	138384	51478848	19·2873015	7·1919663	·002688172
373	139129	51895117	19·3132079	7·1984050	·002680965
374	139876	52313624	19·3390796	7·2048322	·002673797
375	140625	52734375	19·3649167	7·2112479	·002666667
376	141376	53157376	19·3907194	7·2176522	·002659574
377	142129	53582633	19·4164878	7·2240450	·002652520
378	142884	54010152	19·4422221	7·2304268	·002645503
379	143641	54439939	19·4679223	7·2367972	·002638522
380	144400	54872000	19·4935887	7·2431565	·002631579
381	145161	55306341	19·5192213	7·2495045	·002624672
382	145924	55742968	19·5448203	7·2558415	·002617801
383	146689	56181887	19·5703858	7·2621675	·002610966
384	147456	56623104	19·5959179	7·2684824	·002604167
385	148225	57066625	19·6214169	7·2747864	·002597403
386	148996	57512456	19·6468827	7·2810794	·002590674
387	149769	57960603	19·6723156	7·2873617	·002583979
388	150544	58411072	19·6977156	7·2936330	·002577320
389	151321	58863869	19·7230829	7·2998936	·002570694
390	152100	59319000	19·7484177	7·3061436	·002564103
391	152881	59776471	19·7737199	7·3123828	·002557545
392	153664	60236288	19·7989899	7·3186114	·002551020
393	154449	60698457	19·8242276	7·3248295	·002544529
394	155236	61162984	19·8494332	7·3310369	·002538071
395	156025	61629875	19·8746069	7·3372339	·002531646
396	156816	62099136	19·8997487	7·3434205	·002525253
397	157609	62570773	19·9248588	7·3495966	·002518892
398	158404	63044792	19·9499373	7·3557624	·002512563
399	159201	63521199	19·9749844	7·3619178	·002506266
400	160000	64000000	20·0000000	7·3680630	·002500000
401	160801	64481201	20·0249844	7·3741979	·002493766
402	161604	64964808	20·0499377	7·3803227	·002487562
403	162409	65450827	20·0748599	7·3864373	·002481390
404	163216	65939264	20·0997512	7·3925418	·002475248
405	164025	66430125	20·1246118	7·3986363	·002469136
406	164836	66923416	20·1494417	7·4047206	·002463054
407	165649	67419143	20·1742410	7·4107950	·002457002
408	166464	67917312	20·1990099	7·4168595	·002450980
409	167281	68417929	20·2237484	7·4229142	·002444988
410	168100	68921000	20·2484567	7·4289589	·002439024
411	168921	69426531	20·2731349	7·4349938	·002433090
412	169744	69934528	20·2977831	7·4410189	·002427184
413	170569	70444997	20·3224014	7·4470342	·002421308
414	171396	70957944	20·3469899	7·4530399	·002415459
415	172225	71473375	20·3715488	7·4590359	·002409639
416	173056	71991296	20·3960781	7·4650223	·002403846
417	173889	72511713	20·4205779	7·4709991	·002398082
418	174724	73034632	20·4450483	7·4769664	·002392344
419	175561	73560059	20·4694895	7·4829242	·002386635
420	176400	74088000	20·4939015	7·4888724	·002380952

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
421	177241	74618461	20.5182845	7.4948113	.002375297
422	178084	75151448	20.5426386	7.5007406	.002369668
423	178929	75686967	20.5669638	7.5066607	.002364066
424	179776	76225024	20.5912603	7.5125715	.002358491
425	180625	76765625	20.6155281	7.5184730	.002352941
426	181476	77308776	20.6397674	7.5243652	.002347418
427	182329	77854483	20.6639783	7.5302482	.002341920
428	183184	78402752	20.6881609	7.5361221	.002336449
429	184041	78953589	20.7123152	7.5419867	.002331002
430	184900	79507000	20.7364414	7.5478423	.002325581
431	185761	80062991	20.7605395	7.5536888	.002320186
432	186624	80621568	20.7846097	7.5595263	.002314815
433	187489	81182737	20.8086520	7.5653548	.002309469
434	188356	81746504	20.8326667	7.5711743	.002304147
435	189225	82312875	20.8566536	7.5769849	.002298851
436	190096	82881856	20.8806130	7.5827865	.002293578
437	190969	83453453	20.9045450	7.5885793	.002288330
438	191844	84027672	20.9284495	7.5943633	.002283105
439	192721	84604519	20.9523268	7.6001385	.002277904
440	193600	85184000	20.9761770	7.6059049	.002272727
441	194481	85766121	21.0000000	7.6116626	.002267574
442	195364	86350888	21.0237960	7.6174116	.002262443
443	196249	86938307	21.0475652	7.6231519	.002257336
444	197136	87528384	21.0713075	7.6288837	.002252252
445	198025	88121125	21.0950231	7.6346067	.002247191
446	198916	88716536	21.1187121	7.6403213	.002242152
447	199809	89314623	21.1423745	7.6460272	.002237136
448	200704	89915392	21.1660105	7.6517247	.002232143
449	201601	90518849	21.1896201	7.6574138	.002227171
450	202500	91125000	21.2132034	7.6630943	.002222222
451	203401	91733851	21.2367606	7.6687665	.002217295
452	204304	92345408	21.2602916	7.6744303	.002212389
453	205209	92959677	21.2837967	7.6800857	.002207506
454	206116	93576664	21.3072758	7.6857328	.002202643
455	207025	94196375	21.3307290	7.6913717	.002197802
456	207930	94818816	21.3541565	7.6970023	.002192982
457	208849	95443993	21.3775583	7.7026246	.002188184
458	209764	96071912	21.4009346	7.7082388	.002183406
459	210681	96702579	21.4242853	7.7138448	.002178649
460	211600	97336000	21.4476106	7.7194426	.002173913
461	212521	97972181	21.4709106	7.7250325	.002169197
462	213444	98611128	21.4941853	7.7306141	.002164502
463	214369	99252847	21.5174348	7.7361877	.002159827
464	215296	99897344	21.5406592	7.7417532	.002155172
465	216225	100544625	21.5638587	7.7473109	.002150538
466	217156	101194696	21.5870331	7.7528606	.002145923
467	218089	101847563	21.6101828	7.7584023	.002141328
468	219024	102503232	21.6333077	7.7639361	.002136752
469	219961	103161709	21.6564078	7.7694620	.002132196
470	220900	103823000	21.6794834	7.7749801	.002127660
471	221841	104487111	21.7025344	7.7804904	.002123142
472	222784	105154048	21.7255610	7.7859928	.002118644
473	223729	105823817	21.7435632	7.7914875	.002114165
474	224676	106496424	21.7715411	7.7969745	.002109705
475	225625	107171875	21.7944947	7.8024538	.002105263
476	226576	107850176	21.8174242	7.8079254	.002100840
477	227529	108531333	21.8403297	7.8133892	.002096436
478	228484	109215352	21.8632111	7.8188456	.002092050
479	229441	109902239	21.8860686	7.8242942	.002087683
480	230400	110592000	21.9089023	7.8297353	.002083333

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
481	231361	111284641	21.9317122	7.8351688	.002079002
482	232324	111980168	21.9544984	7.8405949	.002074689
483	233289	112678587	21.9772610	7.8460134	.002070393
484	234256	113379904	22.0000000	7.8514244	.002066116
485	235225	114084125	22.0227155	7.8568281	.002061856
486	236196	114791256	22.0454077	7.8622242	.002057613
487	237169	115501303	22.0680765	7.8676130	.002053388
488	238144	116214272	22.0907220	7.8729944	.002049180
489	239121	116930169	22.1133444	7.8783684	.002044990
490	240100	117649000	22.1359436	7.8837352	.002040816
491	241081	118370771	22.1585198	7.8890946	.002036660
492	242064	119095488	22.1810730	7.8944468	.002032520
493	243049	119823157	22.2036033	7.8997917	.002028398
494	244036	120553784	22.2261108	7.9051294	.002024291
495	245025	121287375	22.2485955	7.9104599	.002020202
496	246016	122023936	22.2710575	7.9157832	.002016129
497	247009	122763473	22.2934968	7.9210994	.002012072
498	248004	123505992	22.3159136	7.9264085	.002008032
499	249001	124251499	22.3383079	7.9317104	.002004008
500	250000	125000000	22.3606798	7.9370053	.002000000
501	251001	125751501	22.3830293	7.9422931	.001996008
502	252004	126506008	22.4053565	7.9475739	.001992032
503	253009	127263527	22.4276615	7.9528477	.001988072
504	254016	128024064	22.4499443	7.9581144	.001984127
505	255025	128787625	22.4722051	7.9633743	.001980198
506	256036	129554216	22.4944438	7.9686271	.001976285
507	257049	130323843	22.5166605	7.9738731	.001972387
508	258064	131096512	22.5388553	7.9791122	.001968504
509	259081	131872229	22.5610283	7.9843444	.001964637
510	260100	132651000	22.5831796	7.9895697	.001960784
511	261121	133432831	22.6053091	7.9947883	.001956947
512	262144	134217728	22.6274170	8.0000000	.001953125
513	263169	135005697	22.6495033	8.0052049	.001949318
514	264196	135796744	22.6715681	8.0104032	.001945525
515	265225	136590875	22.6936114	8.0155946	.001941748
516	266256	137388096	22.7156334	8.0207794	.001937984
517	267289	138188413	22.7376340	8.0259574	.001934236
518	268324	138991832	22.7596134	8.0311287	.001930502
519	269361	139798359	22.7815715	8.0362935	.001926782
520	270400	140608000	22.8035085	8.0414515	.001923077
521	271441	141420761	22.8254244	8.0466030	.001919386
522	272484	142236648	22.8473193	8.0517479	.001915709
523	273529	143055667	22.8691933	8.0568862	.001912046
524	274576	143877824	22.8910463	8.0620180	.001908397
525	275625	144703125	22.9128785	8.0671432	.001904762
526	276676	145531576	22.9346899	8.0722620	.001901141
527	277729	146363183	22.9564806	8.0773743	.001897533
528	278784	147197952	22.9782506	8.0824800	.001893939
529	279841	148035889	23.0000000	8.0875794	.001890359
530	280900	148877000	23.0217289	8.0926723	.001886792
531	281961	149721291	23.0434372	8.0977589	.001883239
532	283024	150568768	23.0651252	8.1028390	.001879699
533	284089	151419437	23.0867928	8.1079128	.001876173
534	285156	152273304	23.1084400	8.1129803	.001872659
535	286225	153130375	23.1300670	8.1180414	.001869159
536	287296	153990656	23.1516738	8.1230962	.001865672
537	288369	154854153	23.1732605	8.1281447	.001862197
538	289444	155720872	23.1948270	8.1331870	.001858736
539	290521	156590819	23.2163735	8.1382230	.001855288
540	291600	157464000	23.2379001	8.1432529	.001851852

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
541	292681	158340421	23.2594067	8.1482765	.001848429
542	293764	159220088	23.2808935	8.1532939	.001845018
543	294849	160103007	23.3023604	8.1583051	.001841621
544	295936	160989184	23.3238076	8.1633102	.001838235
545	297025	161878625	23.3452351	8.1683092	.001834862
546	298116	162771336	23.3666429	8.1733020	.001831502
547	299209	163667323	23.3880311	8.1782888	.001828154
548	300304	164566592	23.4093998	8.1832695	.001824818
549	301401	165469149	23.4307490	8.1882441	.001821494
550	302500	166375000	23.4520788	8.1932127	.001818182
551	303601	167284151	23.4733892	8.1981753	.001814882
552	304704	168196608	23.4946802	8.2031319	.001811594
553	305809	169112377	23.5159520	8.2080825	.001808318
554	306916	170031464	23.5372046	8.2130271	.001805054
555	308025	170953875	23.5584380	8.2179657	.001801802
556	309136	171879616	23.5796522	8.2228985	.001798561
557	310249	172808693	23.6008474	8.2278254	.001795332
558	311364	173741112	23.6220236	8.2327463	.001792115
559	312481	174676879	23.6431808	8.2376614	.001788909
560	313600	175616000	23.6643191	8.2425706	.001785714
561	314721	176558481	23.6854386	8.2474740	.001782531
562	315844	177504328	23.7065392	8.2523715	.001779359
563	316969	178453547	23.7276210	8.2572633	.001776199
564	318096	179406144	23.7486842	8.2621492	.001773050
565	319225	180362125	23.7697286	8.2670294	.001769912
566	320356	181321496	23.7907545	8.2719039	.001766784
567	321489	182284263	23.8117618	8.2767726	.001763668
568	322624	183250432	23.8327506	8.2816355	.001760563
569	323761	184220009	23.8537209	8.2864928	.001757469
570	324900	185193000	23.8746728	8.2913444	.001754386
571	326041	186169411	23.8956063	8.2961903	.001751313
572	327184	187149248	23.9165215	8.3010304	.001748252
573	328329	188132517	23.9374184	8.3058651	.001745201
574	329476	189119224	23.9582971	8.3106941	.001742160
575	330625	190109375	23.9791576	8.3155175	.001739130
576	331776	191102976	24.0000000	8.3203353	.001736111
577	332929	192100033	24.0208243	8.3251475	.001733102
578	334084	193100552	24.0416306	8.3299542	.001730104
579	335241	194104539	24.0624188	8.3347553	.001727116
580	336400	195112000	24.0831891	8.3395509	.001724138
581	337561	196122941	24.1039416	8.3443410	.001721170
582	338724	197137368	24.1246762	8.3491256	.001718213
583	339889	198155287	24.1453929	8.3539047	.001715266
584	341056	199176704	24.1660919	8.3586784	.001712329
585	342225	200201625	24.1867732	8.3634466	.001709402
586	343396	201230056	24.2074369	8.3682095	.001706485
587	344569	202262003	24.2280829	8.3729668	.001703578
588	345744	203297472	24.2487113	8.3777188	.001700680
589	346921	204336469	24.2693222	8.3824653	.001697793
590	348100	205379000	24.2899156	8.3872065	.001694915
591	349281	206425071	24.3104916	8.3919423	.001692047
592	350464	207474688	24.3310501	8.3966729	.001689189
593	351649	208527857	24.3515913	8.4013981	.001686341
594	352836	209584584	24.3721152	8.4061180	.001683502
595	354025	210644875	24.3926218	8.4108326	.001680672
596	355216	211708736	24.4131112	8.4155419	.001677852
597	356409	212776173	24.4335834	8.4202460	.001675042
598	357604	213847192	24.4540385	8.4249448	.001672241
599	358801	214921799	24.4744765	8.4296383	.001669449
600	360000	216000000	24.4948974	8.4343267	.001666667

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
601	361201	217081801	24.5153013	8.4390098	.001663894
602	362404	218167208	24.5356883	8.4436877	.001661130
603	363609	219256227	24.5560583	8.4483605	.001658375
604	364816	220348864	24.5764115	8.4530281	.001655629
605	366025	221445125	24.5967478	8.4576906	.001652893
606	367236	222545016	24.6170673	8.4623479	.001650165
607	368449	223648543	24.6373700	8.4670001	.001647446
608	369664	224755712	24.6576560	8.4716471	.001644737
609	370881	225866529	24.6779254	8.4762892	.001642036
610	372100	226981000	24.6981781	8.4809261	.001639344
611	373321	228099131	24.7184142	8.4855579	.001636661
612	374544	229220928	24.7386338	8.4901848	.001633987
613	375769	230346397	24.7588368	8.4948065	.001631321
614	376996	231475544	24.7790234	8.4994233	.001628664
615	378225	232608375	24.7991935	8.5040350	.001626016
616	379456	233744896	24.8193473	8.5086417	.001623377
617	380689	234885113	24.8394847	8.5132435	.001620746
618	381924	236029032	24.8596058	8.5178403	.001618123
619	383161	237176659	24.8797106	8.5224321	.001615509
620	384400	238328000	24.8997992	8.5270189	.001612903
621	385641	239483061	24.9198716	8.5316009	.001610306
622	386884	240641848	24.9399278	8.5361780	.001607717
623	388129	241804367	24.9599679	8.5407501	.001605136
624	389376	242970624	24.9799920	8.5453173	.001602564
625	390625	244140625	25.0000000	8.5498797	.001600000
626	391876	245314376	25.0199920	8.5544372	.001597444
627	393129	246491883	25.0399681	8.5589899	.001594896
628	394384	247673152	25.0599282	8.5635377	.001592357
629	395641	248858189	25.0798724	8.5680807	.001589825
630	396900	250047000	25.0998008	8.5726189	.001587302
631	398161	251239591	25.1197134	8.5771523	.001584786
632	399424	252435968	25.1396102	8.5816809	.001582278
633	400689	253636137	25.1594913	8.5862047	.001579779
634	401956	254840104	25.1793566	8.5907238	.001577287
635	403225	256047875	25.1992063	8.5952380	.001574803
636	404496	257259456	25.2190404	8.5997476	.001572327
637	405769	258474853	25.2388589	8.6042525	.001569859
638	407044	259694072	25.2586619	8.6087526	.001567398
639	408321	260917119	25.2784493	8.6132480	.001564945
640	409600	262144000	25.2982213	8.6177388	.001562500
641	410881	263374721	25.3179778	8.6222248	.001560062
642	412164	264609288	25.3377189	8.6267063	.001557632
643	413449	265847707	25.3574447	8.6311830	.001555210
644	414736	267089984	25.3771551	8.6356551	.001552795
645	416025	268336125	25.3968502	8.6401226	.001550388
646	417316	269586136	25.4165301	8.6445855	.001547988
647	418609	270840023	25.4361947	8.6490437	.001545595
648	419904	272097792	25.4558441	8.6534974	.001543210
649	421201	273359449	25.4754784	8.6579465	.001540832
650	422500	274625000	25.4950976	8.6623911	.001538462
651	423801	275894451	25.5147016	8.6668310	.001536098
652	425104	277167808	25.5342907	8.6712665	.001533742
653	426409	278445077	25.5538647	8.6756974	.001531394
654	427716	279726264	25.5734237	8.6801237	.001529052
655	429025	281011375	25.5929678	8.6845456	.001526718
656	430336	282300416	25.6124969	8.6889630	.001524390
657	431649	283593393	25.6320112	8.6933759	.001522070
658	432964	284890312	25.6515107	8.6977843	.001519757
659	434281	286191179	25.6709953	8.7021882	.001517451
660	435600	287496000	25.6904652	8.7065877	.001515152

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
661	436921	288804781	25·7099203	8·7109827	·001512859
662	438244	290117528	25·7293607	8·7153734	·001510574
663	439569	291434247	25·7487864	8·7197596	·001508296
664	440896	292754944	25·7681975	8·7241414	·001506024
665	442225	294079625	25·7875939	8·7285187	·001503759
666	443556	295408296	25·8069758	8·7328918	·001501502
667	444889	296740963	25·8263431	8·7372604	·001499250
668	446224	298077632	25·8456960	8·7416246	·001497006
669	447561	299418309	25·8650343	8·7459846	·001494768
670	448900	300763000	25·8843582	8·7503401	·001492537
671	450241	302111711	25·9036677	8·7546913	·001490313
672	451584	303464448	25·9229628	8·7590383	·001488095
673	452929	304821217	25·9422435	8·7633809	·001485884
674	454276	306182024	25·9615100	8·7677192	·001483680
675	455625	307546875	25·9807621	8·7720532	·001481481
676	456976	308915776	26·0000000	8·7763830	·001479290
677	458329	310288733	26·0192237	8·7807084	·001477105
678	459684	311665752	26·0384331	8·7850296	·001474926
679	461041	313046839	26·0576284	8·7893466	·001472754
680	462400	314432000	26·0768096	8·7936593	·001470588
681	463761	315821241	26·0959767	8·7979679	·001468429
682	465124	317214568	26·1151297	8·8022721	·001466276
683	466489	318611987	26·1342687	8·8065722	·001464129
684	467856	320013504	26·1533937	8·8108681	·001461988
685	469225	321419125	26·1725047	8·8151598	·001459854
686	470596	322828856	26·1916017	8·8194474	·001457726
687	471969	324242703	26·2106848	8 8237307	·001455604
688	473344	325660672	26·2297541	8·8280099	·001453488
689	474721	327082769	26·2488095	8·8322850	·001451379
690	476100	328509000	26·2678511	8·8365559	·001449275
691	477481	329939371	26·2868789	8·8408227	·001447178
692	478864	331373888	26·3058929	8·8450854	·001445087
693	480249	332812557	26·3248932	8·8493440	·001443001
694	481636	334255384	26·3438797	8·8535985	·001440922
695	483025	335702375	26·3628527	8·8578489	·001438849
696	484416	337153536	26·3818119	8·8620952	·001436782
697	485809	338608873	26·4007576	8·8663375	·001434720
698	487204	340068392	26·4196896	8·8705757	·001432665
699	488601	341532099	26·4386081	8·8748099	·001430615
700	490000	343000000	26·4575131	8·8790400	·001428571
701	491401	344472101	26·4764046	8·8832661	·001426534
702	492804	345948408	26·4952826	8·8874882	·001424501
703	494209	347428927	26·5141472	8·8917063	·001422475
704	495616	348913664	26·5329983	8·8959204	·001420455
705	497025	350402625	26·5518361	8·9001304	·001418440
706	498436	351895816	26·5706605	8·9043366	·001416431
707	499849	353393243	26·5894716	8·9085387	·001414427
708	501264	354894912	26·6082694	8·9127369	·001412429
709	502681	356400829	26·6270539	8·9169311	·001410437
710	504100	357911000	26·6458252	8·9211214	·001408451
711	505521	359425431	26·6645833	8·9253078	·001406470
712	506944	360944128	26·6833281	8·9294902	·001404494
713	508369	362467097	26·7020598	8·9336687	·001402525
714	509796	363994344	26·7207784	8·9378433	·001400560
715	511225	365525875	26·7394839	8·9420140	·001399501
716	512656	367061696	26·7581763	8·9461809	·001396648
717	514089	368601813	26·7768557	8·9503438	·001394700
718	515524	370146232	26·7955220	8·9545029	·001392758
719	516961	371694959	26·8141754	8·9586581	·001390821
720	518400	373248000	26·8328157	8·9628095	·001388889

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
721	519841	374805361	26.8514432	8.9669570	.001386963
722	521284	376367048	26.8700577	8.9711007	.001385042
723	522729	377933067	26.8886593	8.9752406	.001383126
724	524176	379503424	26.9072481	8.9793766	.001381215
725	525625	381078125	26.9258240	8.9835089	.001379310
726	527076	382657176	26.9443872	8.9876373	.001377410
727	528529	384240583	26.9629375	8.9917620	.001375516
728	529984	385828352	26.9814751	8.9958829	.001373626
729	531441	387420489	27.0000000	9.0000000	.001371742
730	532900	389017000	27.0185122	9.0041134	.001369863
731	534361	390617891	27.0370117	9.0082229	.001367989
732	535824	392223168	27.0554985	9.0123288	.001366120
733	537289	393832837	27.0739727	9.0164309	.001364256
734	538756	395446904	27.0924344	9.0205293	.001362398
735	540225	397065375	27.1108834	9.0246239	.001360544
736	541696	398688256	27.1293199	9.0287149	.001358696
737	543169	400315553	27.1477439	9.0328021	.001356852
738	544644	401947272	27.1661554	9.0368857	.001355014
739	546121	403583419	27.1845544	9.0409655	.001353180
740	547600	405224000	27.2029410	9.0450419	.001351351
741	549081	406869021	27.2213152	9.0491142	.001349528
742	550564	408518488	27.2396769	9.0531831	.001347709
743	552049	410172407	27.2580263	9.0572482	.001345895
744	553536	411830784	27.2763634	9.0613098	.001344086
745	555025	413493625	27.2946881	9.0653677	.001342282
746	556516	415160936	27.3130006	9.0694220	.001340483
747	558009	416832723	27.3313007	9.0734726	.001338688
748	559504	418508992	27.3495887	9.0775197	.001336898
749	561001	420189749	27.3678644	9.0815631	.001335113
750	562500	421875000	27.3861279	9.0856030	.001333333
751	564001	423564751	27.4043792	9.0896392	.001331558
752	565504	425259008	27.4226184	9.0936719	.001329787
753	567009	426957777	27.4408455	9.0977010	.001328021
754	568516	428661064	27.4590604	9.1017265	.001326260
755	570025	430368875	27.4772633	9.1057485	.001324503
756	571536	432081216	27.4954542	9.1097669	.001322751
757	573049	433798093	27.5136330	9.1137818	.001321004
758	574564	435519512	27.5317998	9.1177931	.001319261
759	576081	437245479	27.5499546	9.1218010	.001317523
760	577600	438976000	27.5680975	9.1258053	.001315789
761	579121	440711081	27.5862284	9.1298061	.001314060
762	580644	442450728	27.6043475	9.1338034	.001312336
763	582169	444194947	27.6224546	9.1377971	.001310616
764	583696	445943744	27.6405499	9.1417874	.001308901
765	585225	447697125	27.6586334	9.1457742	.001307190
766	586756	449455096	27.6767050	9.1497576	.001305483
767	588289	451217663	27.6947648	9.1537375	.001303781
768	589824	452984832	27.7128129	9.1577139	.001302083
769	591361	454756609	27.7308492	9.1616869	.001300390
770	592900	456533000	27.7488739	9.1656565	.001298701
771	594441	458314011	27.7668868	9.1696225	.001297017
772	595984	460099648	27.7848880	9.1735852	.001295337
773	597529	461889917	27.8028775	9.1775445	.001293661
774	599076	463684824	27.8208555	9.1815003	.001291990
775	600625	465484375	27.8388218	9.1854527	.001290323
776	602176	467288576	27.8567766	9.1894018	.001288660
777	603729	469097433	27.8747197	9.1933474	.001287001
778	605284	470910952	27.8926514	9.1972897	.001285347
779	606841	472729139	27.9105715	9.2012286	.001283697
780	608400	474552000	27.9284801	9.2051641	.001282051

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
781	609961	476379541	27·9463772	9·2090962	·001280410
782	611524	478211768	27·9642629	9·2130250	·001278772
783	613089	480048687	27·9821372	9·2169505	·001277139
784	614656	481890304	28·0000000	9·2208726	·001275510
785	616225	483736625	28·0178515	9·2247914	·001273885
786	617796	485587656	28·0356915	9·2287068	·001272265
787	619369	487443403	28·0535203	9·2326189	·001270648
788	620944	489303872	28·0713377	9·2365277	·001269036
789	622521	491169069	28·0891438	9·2404333	·001267427
790	624100	493039000	28·1069386	9·2443355	·001265823
791	625681	494913671	28·1247222	9·2482344	·001264223
792	627264	496793088	28·1424946	9·2521300	·001262626
793	628849	498677257	28·1602557	9·2560224	·001261034
794	630436	500566184	28·1780056	9·2599114	·001259446
795	632025	502459875	28·1957444	9·2637973	·001257862
796	633616	504358336	28·2134720	9·2676798	·001256281
797	635209	506261573	28·2311884	9·2715592	·001254705
798	636804	508169592	28·2488938	9·2754352	·001253133
799	638401	510082399	28·2665881	9·2793081	·001251564
800	640000	512000000	28·2842712	9·2831777	·001250000
801	641601	513922401	28·3019434	9·2870440	·001248439
802	643204	515849608	28·3196045	9·2909072	·001246883
803	644809	517781627	28·3372546	9·2947671	·001245330
804	646416	519718464	28·3548938	9·2986239	·001243781
805	648025	521660125	28·3725219	9·3024775	·001242236
806	649636	523606616	28·3901391	9·3063278	·001240695
807	651249	525557943	28·4077454	9·3101750	·001239157
808	652864	527514112	28·4253408	9·3140190	·001237624
809	654481	529475129	28·4429253	9·3178599	·001236094
810	656100	531441000	28·4604989	9·3216975	·001234568
811	657721	533411731	28·4780617	9·3255320	·001233046
812	659344	535387328	28·4956137	9·3293634	·001231527
813	660969	537367797	28·5131549	9·3331916	·001230012
814	662596	539353144	28·5306852	9·3370167	·001228501
815	664225	541343375	28·5482048	9·3408386	·001226994
816	665856	543338496	28·5657137	9·3446575	·001225490
817	667489	545338513	28·5832119	9·3484731	·001223990
818	669124	547343432	28·6006993	9·3522857	·001222494
819	670761	549353259	28·6181760	9·3560952	·001221001
820	672400	551368000	28·6356421	9·3599016	·001219512
821	674041	553387661	28·6530976	9·3637049	·001218027
822	675684	555412248	28·6705424	9·3675051	·001216545
823	677329	557441767	28·6879766	9·3713022	·001215067
824	678976	559476224	28·7054002	9·3750963	·001213592
825	680625	561515625	28·7228132	9·3788873	·001212121
826	682276	563559976	28·7402157	9·3826752	·001210654
827	683929	565609283	28·7576077	9·3864600	·001209190
828	685584	567663552	28·7749891	9·3902419	·001207729
829	687241	569722789	28·7923601	9·3940206	·001206273
830	688900	571787000	28·8097206	9·3977964	·001204819
831	690561	573856191	28·8270706	9·4015691	·001203369
832	692224	575930368	28·8444102	9·4053387	·001201923
833	693889	578009537	28·8617394	9·4091054	·001200480
834	695556	580093704	28·8790582	9·4128690	·001199041
835	697225	582182875	28·8963666	9·4166297	·001197605
836	698896	584277056	28·9136646	9·4203873	·001196172
837	700569	586376253	28·9309523	9·4241420	·001194743
838	702244	588480472	28·9482297	9·4278936	·001193317
839	703921	590589719	28·9654967	9·4316423	·001191895
840	705600	592704000	28·9827535	9·4353880	·001190476

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
841	707281	594823321	29.0000000	9.4391307	.001189061
842	708964	596947688	29.0172363	9.4428704	.001187648
843	710649	599077107	29.0344623	9.4466072	.001186240
844	712336	601211584	29.0516781	9.4503410	.001184834
845	714025	603351125	29.0688837	9.4540719	.001183432
846	715716	605495736	29.0860791	9.4577999	.001182033
847	717409	607645423	29.1032644	9.4615249	.001180638
848	719104	609800192	29.1204396	9.4652470	.001179245
849	720801	611960049	29.1376046	9.4689661	.001177856
850	722500	614125000	29.1547595	9.4726824	.001176471
851	724201	616295051	29.1719043	9.4763957	.001175088
852	725904	618470208	29.1890390	9.4801061	.001173709
853	727609	620650477	29.2061637	9.4838136	.001172333
854	729316	622835864	29.2232784	9.4875182	.001170960
855	731025	625026375	29.2403830	9.4912200	.001169591
856	732736	627222016	29.2574777	9.4949188	.001168224
857	734449	629422793	29.2745623	9.4986147	.001166861
858	736164	631628712	29.2916370	9.5023078	.001165501
859	737881	633839779	29.3087018	9.5059980	.001164144
860	739600	636056000	29.3257566	9.5096854	.001162791
861	741321	638277381	29.3428015	9.5133699	.001161440
862	743044	640503928	29.3598365	9.5170515	.001160093
863	744769	642735647	29.3768616	9.5207303	.001158749
864	746496	644972544	29.3938769	9.5244063	.001157407
865	748225	647214625	29.4108823	9.5280794	.001156069
866	749956	649461896	29.4278779	9.5317497	.001154734
867	751689	651714363	9.4448637	9.5354172	.001153403
868	753424	653972032	29.4618397	9.5390818	.001152074
869	755161	656234909	29.4788059	9.5427437	.001150748
870	756900	658503000	29.4957624	9.5464027	.001149425
871	758641	660776311	29.5127091	9.5500589	.001148106
872	760384	663054848	29.5296461	9.5537123	.001146789
873	762129	665338617	29.5465734	9.5573630	.001145475
874	763876	667627624	29.5634910	9.5610108	.001144165
875	765625	669921875	29.5803989	9.5646559	.001142857
876	767376	672221376	29.5972972	9.5682982	.001141553
877	769129	674526133	29.6141858	9.5719377	.001140251
878	770884	676836152	29.6310648	9.5755745	.001138952
879	772641	679151439	29.6479342	9.5792085	.001137656
880	774400	681472000	29.6647939	9.5828397	.001136364
881	776161	683797841	29.6816442	9.5864682	.001135074
882	777924	686128968	29.6984848	9.5900939	.001133787
883	779689	688465387	29.7153159	9.5937169	.001132503
884	781456	690807104	29.7321375	9.5973373	.001131222
885	783225	693154125	29.7489496	9.6009548	.001129944
886	784996	695506456	29.7657521	9.6045696	.001128668
887	786769	697864103	29.7825452	9.6081817	.001127396
888	788544	700227072	29.7993289	9.6117911	.001126126
889	790321	702595369	29.8161030	9.6153977	.001124859
890	792100	704969000	29.8328678	9.6190017	.001123596
891	793881	707347971	29.8496231	9.6226030	.001122334
892	795664	709732288	29.8663690	9.6262016	.001121076
893	797449	712121957	29.8831056	9.6297975	.001119821
894	799236	714516984	29.8998328	9.6333907	.001118568
895	801025	716917375	29.9165506	9.6369812	.001117318
896	802816	719323136	29.9332591	9.6405690	.001116071
897	804609	721734273	29.9499583	9.6441542	.001114827
898	806404	724150792	29.9666481	9.6477367	.001113586
899	808201	726572699	29.9833287	9.6513166	.001112347
900	810000	729000000	30.0000000	9.6548938	.001111111

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
901	811801	731432701	30.0166620	9.6584684	.001109878
902	813604	733870808	30.0333148	9.6620403	.001108647
903	815409	736314327	30.0499584	9.6656096	.001107420
904	817216	738763264	30.0665928	9.6691762	.001106195
905	819025	741217625	30.0832179	9.6727403	.001104972
906	820836	743677416	30.0998339	9.6763017	.001103753
907	822649	746142643	30.1164407	9.6798604	.001102536
908	824464	748613312	30.1330383	9.6834166	.001101322
909	826281	751089429	30.1496269	9.6869701	.001100110
910	828100	753571000	30.1662063	9.6905211	.001098901
911	829921	756058031	30.1827765	9.6940694	.001097695
912	831744	758550528	30.1993377	9.6976151	.001096491
913	833569	761048497	30.2158899	9.7011583	.001095290
914	835396	763551944	30.2324329	9.7046989	.001094092
915	837225	766060875	30.2489669	9.7082369	.001092896
916	839056	768575296	30.2654919	9.7117723	.001091703
917	840889	771095213	30.2820079	9.7153051	.001090513
918	842724	773620632	30.2985148	9.7188354	.001089325
919	844561	776151559	30.3150128	9.7223631	.001088139
920	846400	778688000	30.3315018	9.7258883	.001086957
921	848241	781229961	30.3479818	9.7294109	.001085776
922	850084	783777448	30.3644529	9.7329309	.001084599
923	851929	786330467	30.3809151	9.7364484	.001083423
924	853776	788889024	30.3973683	9.7399634	.001082251
925	855625	791453125	30.4138127	9.7434758	.001081081
926	857476	794022776	30.4302481	9.7469857	.001079914
927	859329	796597983	30.4466747	9.7504930	.001078749
928	861184	799178752	30.4630924	9.7539979	.001077586
929	863041	801765089	30.4795013	9.7575002	.001076426
930	864900	804357000	30.4959014	9.7610001	.001075269
931	866761	806954491	30.5122926	9.7644974	.001074114
932	868624	809557568	30.5286750	9.7679922	.001072961
933	870489	812166237	30.5450487	9.7714845	.001071811
934	872356	814780504	30.5614136	9.7749743	.001070664
935	874225	817400375	30.5777697	9.7784616	.001069519
936	876096	820025856	30.5941171	9.7819466	.001068376
937	877969	822656953	30.6104557	9.7854288	.001067236
938	879844	825293672	30.6267857	9.7889087	.001066098
939	881721	827936019	30.6431069	9.7923861	.001064963
940	883600	830584000	30.6594194	9.7958611	.001063830
941	885481	833237621	30.6757233	9.7993336	.001062699
942	887364	835896888	30.6920185	9.8028036	.001061571
943	889249	838561807	30.7083051	9.8062711	.001060445
944	891136	841232384	30.7245830	9.8097362	.001059322
945	893025	843908625	30.7408523	9.8131989	.001058201
946	894916	846590536	30.7571130	9.8166591	.001057082
947	896809	849278123	30.7733651	9.8201169	.001055966
948	898704	851971392	30.7896086	9.8235723	.001054852
949	900601	854670349	30.8058436	9.8270252	.001053741
950	902500	857375000	30.8220700	9.8304757	.001052632
951	904401	860085351	30.8382879	9.8339238	.001051525
952	906304	862801408	30.8544972	9.8373695	.001050420
953	908209	865523177	30.8706981	9.8408127	.001049318
954	910116	868250664	30.8868904	9.8442536	.001048218
955	912025	870983875	30.9030743	9.8476920	.001047120
956	913936	873722816	30.9192497	9.8511280	.001046025
957	915849	876467493	30.9354166	9.8545617	.001044932
958	917764	879217912	30.9515751	9.8579929	.001043841
959	919681	881974079	30.9677251	9.8614218	.001042753
960	921600	884736000	30.9838668	9.8648483	.001041667

No.	Squares.	Cubes.	Square Roots.	Cube Roots.	Reciprocals.
961	923521	887503681	31.0000000	9.8682724	.001040583
962	925444	890277128	31.0161248	9.8716941	.001039501
963	927369	893056347	31.0322413	9.8751135	.001038422
964	929296	895841344	31.0483494	9.8785305	.001037344
965	931225	898632125	31.0644491	9.8819451	.001036269
966	933156	901428696	31.0805405	9.8853574	.001035197
967	935089	904231063	31.0966236	9.8887673	.001034126
968	937024	907039232	31.1126984	9.8921749	.001033058
969	938961	909853209	31.1287648	9.8955801	.001031992
970	940900	912673000	31.1448230	9.8989830	.001030928
971	942841	915498611	31.1608729	9.9023835	.001029866
972	944784	918330048	31.1769145	9.9057817	.001028807
973	946729	921167317	31.1929479	9.9091776	.001027749
974	948676	924010424	31.2089731	9.9125712	.001026694
975	950625	926859375	31.2249900	9.9159624	.001025641
976	952576	929714176	31.2409987	9.9193513	.001024590
977	954529	932574833	31.2569992	9.9227379	.001023541
978	956484	935441352	31.2729915	9.9261222	.001022495
979	958441	938313739	31.2889757	9.9295042	.001021450
980	960400	941192000	31.3049517	9.9328839	.001020408
981	962361	944076141	31.3209195	9.9362613	.001019368
982	964324	946966168	31.3368792	9.9396363	.001018330
983	966289	949862087	31.3528308	9.9430092	.001017294
984	968256	952763904	31.3687743	9.9463797	.001016260
985	970225	955671625	31.3847097	9.9497479	.001015228
986	972196	958585256	31.4006369	9.9531138	.001014199
987	974169	961504803	31.4165561	9.9564775	.001013171
988	976144	964430272	31.4324673	9.9598389	.001012146
989	978121	967361669	31.4483704	9.9631981	.001011122
990	980100	970299000	31.4642654	9.9665549	.001010101
991	982081	973242271	31.4801525	9.9699095	.001009082
992	984064	976191488	31.4960315	9.9732619	.001008065
993	986049	979146657	31.5119025	9.9766120	.001007049
994	988036	982107784	31.5277655	9.9799599	.001006036
995	990025	985074875	31.5436206	9.9833055	.001005025
996	992016	988047936	31.5594677	9.9866488	.001004016
997	994009	991026973	31.5753068	9.9899900	.001003009
998	996004	994011992	31.5911380	9.9933289	.001002004
999	998001	997002999	31.6069613	9.9966656	.001001001
1000	1000000	1000000000	31.6227766	10.0000000	.001000000
1001	1002001	1003003001	31.6385840	10.0033322	.0009990010
1002	1004004	1006012008	31.6543836	10.0066622	.0009980040
1003	1006009	1009027027	31.6701752	10.0099899	.0009970090
1004	1008016	1012048064	31.6859590	10.0133155	.0009960159
1005	1010025	1015075125	31.7017349	10.0166389	.0009950249
1006	1012036	1018108216	31.7175030	10.0199601	.0009940358
1007	1014049	1021147343	31.7332633	10.0232791	.0009930487
1008	1016064	1024192512	31.7490157	10.0265958	.0009920635
1009	1018081	1027243729	31.7647603	10.0299104	.0009910803
1010	1020100	1030301000	31.7804972	10.0332228	.0009900990
1011	1022121	1033364331	31.7962262	10.0365330	.0009891197
1012	1024144	1036433728	31.8119474	10.0398410	.0009881423
1013	1026169	1039509197	31.8276609	10.0431469	.0009871668
1014	1028196	1042590744	31.8433666	10.0464506	.0009861933
1015	1030225	1045678375	31.8590646	10.0497521	.0009852217
1016	1032256	1048772096	31.8747549	10.0530514	.0009842520
1017	1034289	1051871913	31.8904374	10.0563485	.0009832842
1018	1036324	1054977832	31.9061123	10.0596435	.0009823183
1019	1038361	1058089859	31.9217794	10.0629364	.0009813543
1020	1040400	1061208000	31.9374388	10.0662271	.0009803922

TABLE XVII.—CUBIC YARDS PER 100 FEET OF LEVEL SECTIONS. SLOPE 1 : 1.

Depth, *d*	Base 12 feet.	Base 14 feet.	Base 16 feet.	Base 18 feet.	Base 20 feet.	Base 28 feet.	Base 30 feet.	Base 32 feet.
1	48	56	63	70	78	107	115	122
2	104	119	133	148	163	222	237	252
3	167	189	211	233	256	344	367	389
4	237	267	296	326	356	474	504	533
5	315	352	389	426	463	611	648	685
6	400	444	489	533	578	756	800	844
7	493	544	596	648	700	907	959	1011
8	593	652	711	770	830	1067	1126	1185
9	700	767	833	900	967	1233	1300	1367
10	815	889	963	1037	1111	1407	1481	1556
11	937	1019	1100	1181	1263	1589	1670	1752
12	1067	1156	1244	1333	1422	1778	1867	1956
13	1204	1300	1396	1493	1589	1974	2070	2167
14	1348	1452	1556	1659	1763	2178	2281	2385
15	1500	1611	1722	1833	1944	2389	2500	2611
16	1659	1778	1896	2015	2133	2607	2726	2844
17	1826	1952	2078	2204	2330	2833	2959	3085
18	2000	2133	2267	2400	2533	3067	3200	3333
19	2181	2322	2463	2604	2744	3307	3448	3589
20	2370	2519	2667	2815	2963	3556	3704	3852
21	2567	2722	2878	3033	3189	3811	3967	4122
22	2770	2933	3096	3259	3422	4074	4237	4400
23	2981	3152	3322	3493	3663	4344	4515	4685
24	3200	3378	3556	3733	3911	4622	4800	4978
25	3426	3611	3796	3981	4167	4907	5093	5278
26	3659	3852	4044	4237	4430	5200	5393	5585
27	3900	4100	4300	4500	4700	5500	5700	5900
28	4148	4356	4563	4770	4978	5807	6015	6222
29	4404	4619	4833	5048	5263	6122	6337	6552
30	4667	4889	5111	5333	5556	6444	6667	6889
31	4937	5167	5396	5626	5856	6774	7004	7233
32	5215	5452	5689	5926	6163	7111	7348	7585
33	5500	5744	5989	6233	6478	7456	7700	7944
34	5793	6044	6296	6548	6800	7807	8059	8311
35	6093	6352	6611	6870	7130	8167	8426	8685
36	6400	6667	6933	7200	7467	8533	8800	9067
37	6715	6989	7263	7537	7811	8907	9181	9456
38	7037	7319	7600	7881	8163	9289	9570	9852
39	7367	7656	7944	8233	8522	9678	9967	10256
40	7704	8000	8296	8593	8889	10074	10370	10667
41	8048	8352	8656	8959	9263	10478	10781	11085
42	8400	8711	9022	9333	9644	10889	11200	11511
43	8759	9078	9396	9715	10033	11307	11626	11944
44	9126	9452	9778	10104	10430	11733	12059	12385
45	9500	9833	10167	10500	10833	12167	12500	12833
46	9881	10222	10563	10904	11244	12607	12948	13289
47	10270	10619	10967	11315	11663	13056	13404	13752
48	10667	11022	11378	11733	12089	13511	13867	14222
49	11070	11433	11796	12159	12522	13974	14337	14700
50	11481	11852	12222	12593	12963	14444	14815	15185
51	11900	12278	12656	13033	13411	14922	15300	15678
52	12326	12711	13096	13481	13867	15407	15793	16178
53	12759	13152	13544	13937	14330	15900	16293	16685
54	13200	13600	14000	14400	14800	16400	16800	17200
55	13648	14056	14463	14870	15278	16907	17315	17722
56	14104	14519	14933	15348	15763	17422	17837	18252
57	14567	14989	15411	15833	16256	17944	18367	18789
58	15037	15467	15896	16326	16756	18474	18904	19333
59	15515	15952	16389	16826	17263	19011	19448	19885
60	16000	16444	16889	17333	17778	19556	20000	20444

TABLE XVII.—CUBIC YARDS PER 100 FEET OF LEVEL SECTIONS. SLOPE 1.5 : 1.

Depth *d*	Base 12 feet.	Base 14 feet.	Base 16 feet.	Base 18 feet.	Base 20 feet.	Base 28 feet.	Base 30 feet.	Base 32 feet.
1	50	57	65	72	80	109	117	124
2	111	126	141	156	170	230	244	259
3	183	206	228	250	272	361	383	406
4	267	296	326	356	385	504	533	563
5	361	398	435	472	509	657	694	731
6	467	511	556	600	644	822	867	911
7	583	635	687	739	791	998	1050	1102
8	711	770	830	889	948	1185	1244	1304
9	850	917	983	1050	1117	1383	1450	1517
10	1000	1074	1148	1222	1296	1593	1667	1741
11	1161	1243	1324	1406	1487	1813	1894	1976
12	1333	1422	1511	1600	1689	2044	2133	2222
13	1517	1613	1709	1806	1902	2287	2383	2480
14	1711	1815	1919	2022	2126	2541	2644	2748
15	1917	2028	2139	2250	2361	2806	2917	3028
16	2133	2252	2370	2489	2607	3081	3200	3319
17	2361	2487	2613	2739	2865	3369	3494	3620
18	2600	2733	2867	3000	3133	3667	3800	3933
19	2850	2991	3131	3272	3413	3976	4117	4257
20	3111	3259	3407	3556	3704	4296	4444	4593
21	3383	3539	3694	3850	4006	4628	4783	4939
22	3667	3830	3993	4156	4319	4970	5133	5296
23	3961	4131	4302	4472	4642	5324	5494	5665
24	4267	4444	4622	4800	4978	5689	5867	6044
25	4583	4769	4954	5139	5324	6065	6250	6435
26	4911	5104	5296	5489	5681	6452	6644	6837
27	5250	5450	5650	5850	6050	6850	7050	7250
28	5600	5807	6015	6222	6430	7259	7467	7674
29	5961	6176	6391	6606	6820	7680	7894	8109
30	6333	6556	6778	7000	7222	8111	8333	8556
31	6717	6946	7176	7406	7635	8554	8783	9013
32	7111	7348	7585	7822	8059	9007	9244	9481
33	7517	7761	8006	8250	8494	9472	9717	9961
34	7933	8185	8437	8689	8941	9948	10200	10452
35	8361	8620	8880	9139	9398	10435	10694	10954
36	8800	9067	9333	9600	9867	10933	11200	11467
37	9250	9524	9798	10072	10346	11443	11717	11991
38	9711	9993	10274	10556	10837	11963	12244	12526
39	10183	10472	10761	11050	11339	12494	12783	13072
40	10667	10963	11259	11556	11852	13037	13333	13630
41	11161	11465	11769	12072	12376	13591	13894	14198
42	11667	11978	12289	12600	12911	14156	14467	14778
43	12183	12502	12820	13139	13457	14731	15050	15369
44	12711	13037	13363	13689	14015	15319	15644	15970
45	13250	13583	13917	14250	14583	15917	16250	16583
46	13800	14141	14481	14822	15163	16526	16867	17207
47	14361	14709	15057	15406	15754	17146	17494	17843
48	14933	15289	15644	16000	16356	17778	18133	18489
49	15517	15880	16243	16606	16969	18420	18783	19146
50	16111	16481	16852	17222	17593	19074	19444	19815
51	16717	17094	17472	17850	18228	19739	20117	20494
52	17333	17719	18104	18489	18874	20415	20800	21185
53	17961	18354	18746	19139	19531	21102	21494	21887
54	18600	19000	19400	19800	20200	21800	22200	22600
55	19250	19657	20065	20472	20880	22509	22917	23324
56	19911	20326	20741	21156	21570	23230	23644	24059
57	20583	21006	21428	21850	22272	23961	24383	24805
58	21267	21696	22126	22556	22985	24704	25133	25563
59	21961	22398	22835	23272	23709	25457	25894	26331
60	22667	23111	23556	24000	24444	26222	26667	27111

TABLE XVII.—CUBIC YARDS PER 100 FEET OF LEVEL SECTIONS. CORRECTIVE *PERCENTAGE* FACTORS.

To be applied when cross-sections are *not* level. See § **95**.

Side slope = 1.5 : 1 or $\beta = 33°41'$.

Transverse surface slope.		b=12 feet and d=			b=20 feet and d=			b=30 feet and d=		
$\alpha°$	Per cent	10 feet.	20 feet.	50 feet.	10 feet.	20 feet.	50 feet.	10 feet.	20 feet.	50 feet.
		%	%	%	%	%	%	%	%	%
5	9	1.9	1.8	1.8	2.1	1.8	1.8	2.3	2.0	1.8
10	18	8.2	7.7	7.5	9.0	8.0	7.6	10.0	8.4	7.7
15	27	21	20	19	23	21	20	26	22	20
20	36	46	44	43	51	45	44	57	48	44
30	57	327	324	317	358	336	321	400	354	326

Side slope = 1 : 1 or $\beta = 45°$.

Transverse surface slope.		b=12 feet and d=			b=20 feet and d=			b=30 feet and d=		
$\alpha°$	Per cent	10 feet.	20 feet.	50 feet.	10 feet.	20 feet.	50 feet.	10 feet.	20 feet.	50 feet.
		%	%	%	%	%	%	%	%	%
5	9	0.9	0.8	0.8	1.0	0.9	0.8	1.2	0.9	0.8
10	18	3.7	3.4	3.2	4.3	3.6	3.3	5.0	4.0	3.4
15	27	9.0	8.2	7.8	10.3	8.7	8.0	12.1	9.5	8.2
20	36	18	16	15	20	17	16	24	19	16
30	57	58	53	50	67	56	51	78	61	53

TABLE XVIII.—ANNUAL CHARGE AGAINST A TIE, BASED ON THE ORIGINAL COST AND ASSUMED LIFE OF THE TIE; INTEREST COMPOUNDED AT 5%. (See § 217.)

Original cost of tie in cents.	Life of tie in years.																	
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20	7.34	5.64	4.62	3.94	3.46	3.09	2.81	2.59	2.41	2.26	2.13	2.02	1.93	1.85	1.77	1.71	1.65	1.60
25	9.18	7.05	5.77	4.92	4.32	3.87	3 52	3.24	3.01	2.82	2.66	2.53	2.41	2.31	2.22	2.14	2.07	2.01
30	11.02	8.46	6.93	5.91	5.18	4.64	4.22	3.89	3.61	3.38	3.19	3.03	2.89	2.77	2.66	2.57	2.48	2.41
35	12.85	9.87	8.08	6.90	6.05	5.42	4.92	4.53	4.21	3.95	3.73	3.54	3.37	3.23	3.10	2.99	2.90	2.81
40	14.69	11.28	9.24	7.88	6.91	6.19	5.63	5.18	4.81	4.51	4.26	4.04	3.85	3.79	3.55	3.42	3.31	3.21
45	16.52	12.69	10.39	8.87	7.78	6.96	6.33	5.83	5.42	5.08	4.79	4.55	4.34	4.15	3.99	3.85	3.72	3.61
50	18.36	14.10	11.55	9.85	8.64	7.74	7.03	6.48	6.02	5.64	5.32	5.05	4.82	4.61	4.43	4.28	4.14	4.01
55	20.20	15.51	12.70	10.84	9.51	8.51	7.74	7.12	6.62	6.21	5.86	5.56	5.30	5.07	4.88	4.71	4.55	4.41
60	22.03	16.92	13.86	11.82	10.37	9.28	8.44	7.77	7.22	6.77	6.39	6.06	5.78	5.54	5.32	5.13	4.96	4.81
65	23.87	18.33	15.01	12.81	11.23	10.06	9.14	8.42	7.83	7.33	6.92	6.57	6.26	6.00	5.77	5.56	5.38	5.22
70	25.70	19.74	16.17	13.79	12.10	10.83	9.85	9.07	8.43	7.90	7.45	7.07	6.74	6.46	6.21	5.99	5.79	5.62
75	27.54	21.15	17.32	14.78	12.96	11.60	10.55	9.72	9.03	8.46	7.98	7.58	7.22	6.92	6.65	6.42	6.20	6.02
80	29.38	22.56	18.48	15.76	13.83	12.38	11.25	10.36	9.63	9.03	8.52	8.08	7.71	7.38	7.10	6.84	6.62	6.42
85	31.21	23.97	19.63	16.75	14.69	13.15	11.96	11.01	10.23	9.59	9.05	8.59	8.19	7.84	7.54	7.27	7.03	6.82
90	33.05	25.38	20.79	17.73	15.55	13.92	12.66	11.66	10.84	10.15	9.58	9.09	8.67	8.30	7.98	7.70	7.45	7.22
95	34.88	26.79	21.94	18.71	16.42	14.70	13.37	12.30	11.44	10.72	10.12	9.60	9.15	8.76	8.42	8.12	7.86	7.62
100	36.72	28.20	23.10	19.70	17.28	15.47	14.07	12.95	12.04	11.28	10.65	10.10	9.63	9.23	8.87	8.55	8.27	8.02
For each 5 cents, add	1.836	1.410	1.155	.985	.864	.774	.703	.648	.602	.564	.532	.505	.482	.461	.443	.428	.414	.401

INDEX.

Numbers refer to sections except where specifically marked **pages (p.).**

LIBRARY OF CONGRESS
0 021 218 321 0