ELMENDORF

The Welding of Aluminum and the Strength of Aluminum Welds

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THE WELDING OF ALUMINUM
AND
THE STRENGTH OF ALUMINUM WELDS

BY

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Armin Elmendorf

ENTITLED The Welding of Aluminum and the Strength of

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IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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CONTENTS.

THE WELDING OF ALUMINUM AND THE STRENGTH OF ALUMINUM WELDS.

In number of distinct properties peculiar to the particular metal none of the metals extensively used in the industries approaches that of aluminum. Its extreme lightness, the facility with which it mixes with the other metals to form alloys, its high conductivity of both heat and electricity, its whiteness and capacity for resisting corrosion are familiar to all who ever had occasion to use the metal. One property, quite peculiar to the metal, is, however, not so well known to the layman. To the man in the shops who has to work with aluminum it is a source of much trouble. This is the avidity with which aluminum combines with oxygen ,even at atmospheric temperatures. This has made it almost impossible both to solder and to weld the metal. On the other hand, the film or thin coating of oxide formed on the surface when the metal is cold serves as a protective mantel against further oxidation and against corrosion by acidious fluids, giving aluminum a property of extreme importance and value in the industries.

The overcoming of the tendency to combine with atmospheric oxygen has perplexed many inventors who sought methods for soldering the metal. Scores of patents for aluminum solder have been issued, many solders have found commercial development by enthusiastic promoters, but to this day no solder has been placed upon the market that will give

a reliable and permanent joint. Mr. [illegible] Shoop, a Swiss authority on soldering and welding, has alone made over a thousand experiments to discover the magic combination of alloys or chemical ingredients for a flux which would accomplish this feat. After years of persistent endeavors he came to the conclusion that it was physically impossible.

(1) To the initiate in the art of welding aluminum the quickness with which it combines with oxygen and thereby develops the troublesome oxide film is soon made apparent. The metal upon being reduced to a molten state by the oxy-acetylene flame rolls up into globules which will not coalesce when they are brought together, but remain intact as originally formed. A similar phenomenon more familiar to most people is the formation into balls, of mercury when this metal is poured upon a flat surface. The film of oxide which is formed on the surface of mercury probably also accounts for separation into globules and the tendency to remain separated. A violent stirring of these globules, thereby disrupting the skin of oxide, brings the pure metal together and thereby effects a union. When the molten aluminum parts are stirred with a steel rod the same thing occurs, provided, of course, that the space in which the aluminum globules are confined is limited so that they will not scatter.

(2) The welding of aluminum thru mechanical means was accomplished with some success before the introduction of the oxy-acetylene process. By a method similar to that employed by the blacksmith in welding steel, the Heraeus Com-

pany of Hanan, Germany welded aluminum parts that were of a certain shape and size. The two pieces to be welded were first heated to a temperature of about 750 degrees Fahrenheit and then rapidly transferred to a hot anvil where a union was brought about by quickly hammering the two pieces together. This method is, of course, applicable to large castings only.

For more fragile castings which can not be struck with a hammer a union of two parts can only be accomplished by fusing the metal pieces at the point where they are to be joined. But a simple stirring of the molten metal as previously described is often not sufficient even for places where it is practicable, and with sheet metal and other light parts it is out of the question. Here chemical means must be resorted to to absorb or destroy the oxide coating.

(3) Mr. Shoop has made an extensive study of substances which will eliminate the oxide film so that a pure metallic aluminum surface is provided during the welding process. Such agents as glass powder and borax which simply exclude the air did not yield satifactory results, nor did the use of a very hot flame to reduce the oxide meet with success. A reagent to dissolve the oxide could not be avoided. He found that besides the solvent action on the oxide other requirements had to be fulfilled by the flux as follows: The melting point should be near that of aluminum. The evaporative point should be as high as possible so that the flux is stable under the influence of the flame. When fluid, the substance must spread over the hot aluminum surface as a thin enamel-like layer, cutting off any access of air to the surface.

Finally, the substance must be free from oxygen and must not have any tendency to combine with aluminum. In Shoop's experiments potassium bisulphate was first used. To $KHSO_4$ which has a melting point of 300 degrees F. he added K_2SO which has a melting point over 1000 degrees F. so that the melting point of the mixture was considerably higher than that of potassium bisulphate alone. Although this flux did act as was expected, it was not sufficiently effective for dissolving the oxide. He then tried substances with a pronounced etching effect on aluminum like potassium hydroxide, hydrofluoric acid, chlorates, etc. A really satisfactory solution of the problem was finally obtained by the use of alkali chlorides.

(4) Mr. Theo. Kautny, Editor of _Autogene Bearbeitung_ states that the alkali-chlorides may be replaced by alkali-bromides. A mixture in which such a substitution was made was patented in Switzerland by Mr. Shoop.. The latter seems to own most of the patent rights for successful aluminum fluxes. Mr. Kautny analyzed a commercial flux covered by one of these patents and found it to contain the following ingredients:

Sodium chloride (NaCl)	30%
Potassium chloride (KCl)	45%
Lithium chloride (LiCl)	15%
Potassium fluoride (KFl)	7%
Sodium disulphate (NaHSO)	3%

The addition of the fluorides serves, according to Mr.Kautny

the purpose of giving a more perfect fusion to the flux. The mixtures should be thoroughly pulverized to prevent the possible embedding of unfused grains of the ingredients having a higher melting point, and thereby weakening the weld.

The melting points of some of these constituents are higher than those of others in such a proportion that the melting point of the mixture lies below that of aluminum.

The success of such a flux depends mainly upon the fineness with which the ingredients are ground and the thoroughness with which they are mixed. The fluxes are hygroscopic and when exposed to the air for any length of time absorb moisture from it to such an extent that they may become quite mushy. When in this condition a flux can not be used for welding. However, if the water is added immediately before welding so that crystals have not had time to form, the flux may be used in the moistened state. Alcohol makes a better paste than does water but its addition must also immediately precede the welding operation as the paste cannot be preserved for future use. A convenient and practicable method for using the flux consists in filling a hollow rod of aluminum with the powder which is fused, together with the "filling-in" aluminum. Such rods have been placed upon the market in Germany.

(5) In welding aluminum something might be learned from the processes in vogue with other metals such as steel. A writer in the Scientific American Supplement* found that such

* Reference #5 in Bibliography.

substances as silicon and manganese increase the weldability of steel, while on the other hand their oxides hinder welding. He advances the theory that any iron oxide which is not removed by the slag forming substances in the steel or by fluxes is removed or reduced by the deoxidizing constituents of the steel. "The fundamental principle of the theory of welding steel, therefore, is that metallic contact of the minute particles of the welding surface is produced at the welding temperatures by the action of reducing agents contained in the steel." An alloy containing such elements as manganese, silicon or phosphorus if it can be made should yield some interesting results when applied to the welding of aluminum as a "filling-in" material.

(6) Quite essential to the strength of an autogenous weld in aluminum is a thorough hammering of the joint while the metal is still hot and the temperature near the point of fusion. Mr. Kautny in experimenting with aluminum welds found that the weld would often yield to stresses when it had not been hammered before the metal was allowed to cool, while if this procedure is carried out the metal will never yield at the weld but always out of it. His experiments were carried out in cast aluminum which meant, of course, that the metal in the joint was given a different physical structure than that of the stock. The weld became, thru beating, something more like rolled aluminum than the cast parts which were joined. This being the case it must result in giving the metal in the weld a higher tensile strength

than that of the cast body.

(7) The high heat conductivity of aluminum often presents another difficulty to the welding of the metal, especially in repair work. Work on it must be done rapidly to prevent a collapse of the metal adjoining the weld from overheating and bringing it up to the melting point. A mold may be placed under the part to support the metal in case it becomes soft thru overheating. The ratio of heat conductivity of aluminum to that of iron is given as 31.3 to 11.9. Kent gives 11,000,000 as the modulus of cast aluminum, and the shrinkage per foot as 17/64 inches in cooling from the melting point to atmospheric temperature. Using a distance of one inch, which may be assumed as the width of the weld, then the heating of the weld without heating the metal in the immediate neighborhood would result in a stress of 243,000 lb. per sq. in. which is obviously quite beyond the highest stress that any metal can withstand.

$$11,000,000 = \frac{P \times 12 \times 64}{17}$$

$$P = S = 243,000$$

The hypothetical condition of having one part of the metal at a fusing temperature and another part immediately adjoining it at atmospheric temperature does, of course, never happen in practice. But the rapidity with which the oxy-acetylene blow-pipe heats often results in heating the metal to the melting point at one place while the metal four or five inches away may be at atmospheric temperature. The stresses set up in the metal even under these conditions are higher than it can stand and a crack results. If the work consists

in the filling in of a crack previously developed the stresses resulting from the heating make it practically impossible to mend the fracture without extending the crack farther into the body of the piece.

(8) This trouble is eliminated in most cases by heating the whole piece to an even temperature by means of a gasoline torch or a charcoal bed. The extreme difference in temperture is thereby reduced and the stresses due to expension and contraction are brought down.

In welding sheet aluminum trouble is often experienced in burning holes into the thin metal. A seam such as that shown in Fig.1 having two rails of copper at the sides will prevent the melting of holes due to the action of the copper in conducting away the heat.

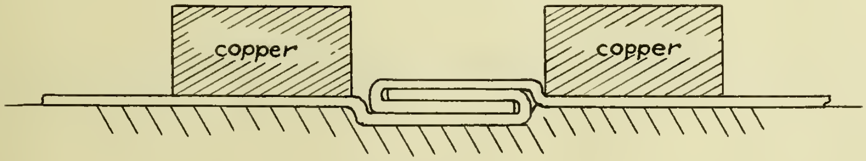


Fig. 1

For heavier sheet metal a butt joint such as that shown in Fig. 2 gives good results. It is necessary to use the regular welding flux for these joints.

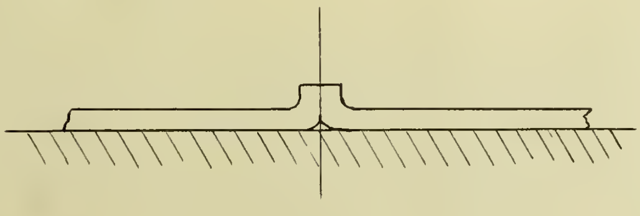


Fig. 2

(9) Welded aluminum wires have been tested as to electric conductivity. Experiments made by Professor J. Sahulka of Vienna show that the reduction of conductivity is practicable negligible. A wire 3meters in length and 4 millimeters in diameter gave an increase of about..006% in resistance on account of one joint. This testifies to the solidity of the weld and to the absence of foreign particles in the joint. As a consequence the metal will not decompose and can be safely used for cables.

(10) Tests have also been made to determine the effect of acids on aluminum. Nitric and sulphuric acids and their vapors attack aluminum only very slightly. According to Schoop the German Army workshops have for several years been using aluminum vessels for working with acids and the results have been very satisfactory. Vessels that were in use for two years were still giving good service, while in former experience with brass, copper,and bronze vessels these had to be replaced in the same time by new vessels. Besides having the advantage of lighter weight so that they can be easily handled a considerable saving in cost is effected since the vessels do not have to be renewed as often those previously installed made of other metals. The production of these vessels was made possible thru the introduction of the oxy-acetylene process of welding aluminum.

(11) Because aluminum can be welded its use for all kinds of kitchen and cooking utensils has spread. In hygienic and sanitary respects it approaches the precious metals. Chemists

are interested in the metal for large evaporating vessels and distilling coils. Breweries are replacing the vats and containers made of wood or enameled iron plates by aluminum containers. Sheet aluminum is especially well adapted for certain requirements in aeronautics. The automobile industry has a heavy demand for the metal for engine cases and transmission boxes. Aluminum is also useful for apparatus of the fat, glycerine, and stearine industries, for transportation vessels, for cooling and heating pipes, for extractive apparatus, etc. Its light weight and low cost make it a desirable metal for all these uses. Until the advent of the oxy-acetylene process of welding the metal its use was, however, very limited. Now, with the discovery of good fluxes and with the growth of skill in manipulating the blow-pipe the great range of use to which aluminum may be put is only being discovered.

The following illustrations show some of the uses to which aluminum has been put. The apparatus all required welding at some stage in its manufacture.

Figures 3,4,5,6 show aluminum vats. Figures 7 and 8 illustrate aluminum vessels used in the chemical industries, the former being constructed to withstand high pressures. Fig. 9 shows an aluminum vacuum vessel made of 0.27 metal. Figures 10 and 11 show vessels used in a candle factory. Fig. 12 shows a low pressure evaporator. Fig. 13 shows a milk container of 800 gallons capacity. Fig. 14 shows a continuous tube used in the hydrochloric acid industry. Fig. 15 pictures a group of welded aluminum tubes. Fig. 16 shows an aluminum evaporating pan. Figures 17 & 18 show large aluminum vessels.

Fig 3

Fig 4

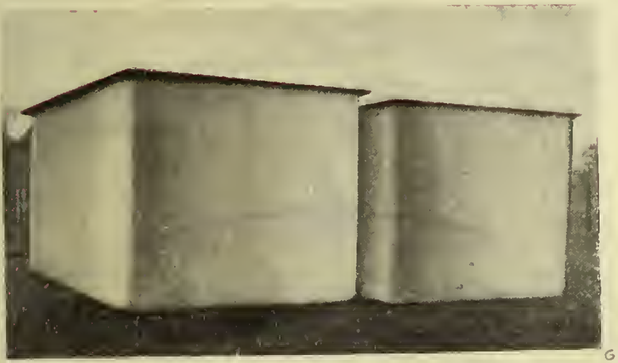


Fig 6

Fig 5

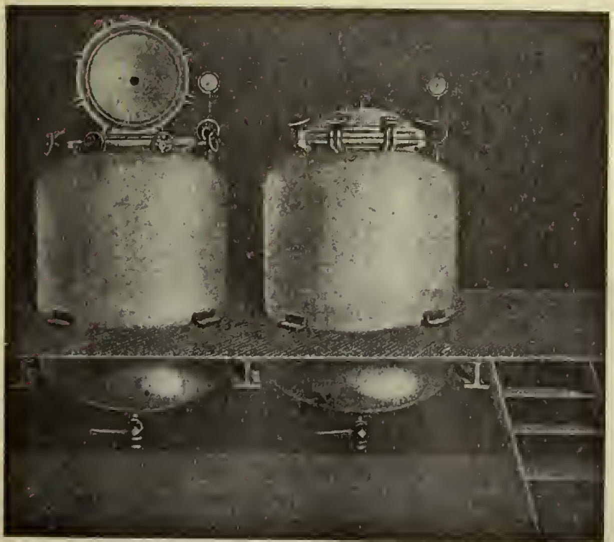


Fig 7

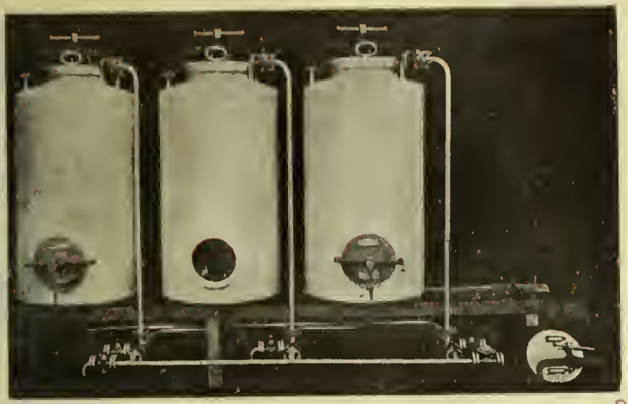


Fig 8

Fig 12

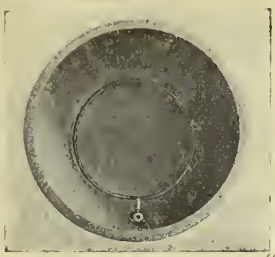


Fig 10

Fig 9

Fig 11

Fig 16

Fig 15

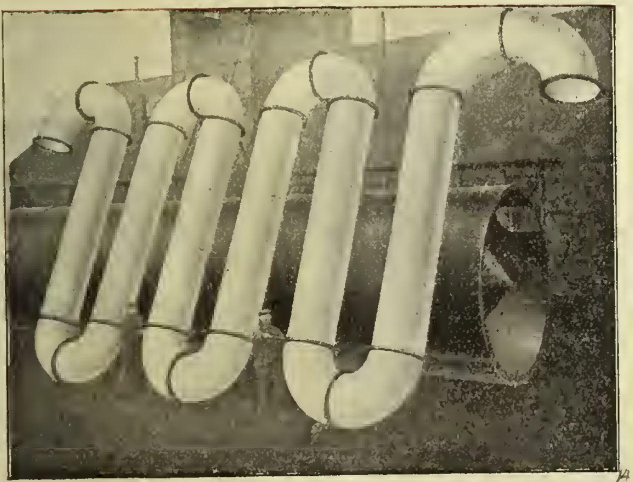


Fig 14

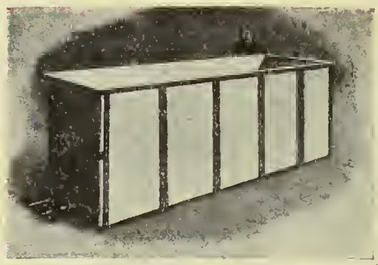


Fig 13

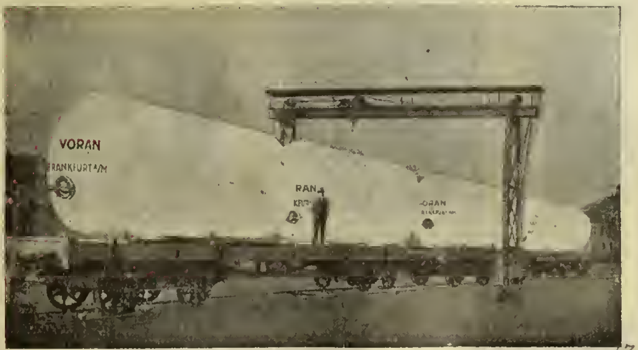


Fig 17

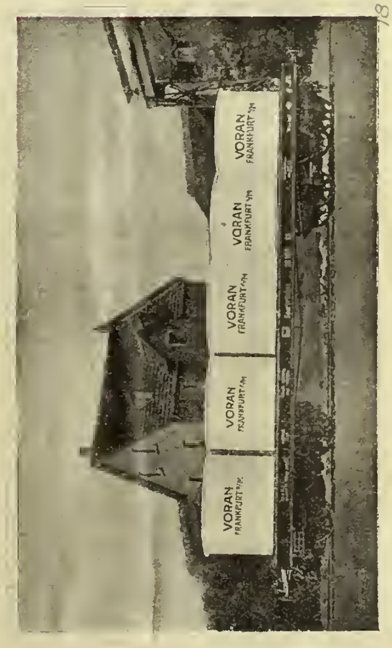


Fig 18

II TESTS ON WELDS.

(12) PURPOSE OF TESTS.

From the list of uses to which aluminum is put it is seen that the welds made are usually subjected to some stresses. In cases where there is a heating and cooling of different parts of a vessel these stresses may run quite high so that it is imperative that the welds be as strong, if possible, as the stock material welded. In places, such as engine crank cases, the stresses are not only high at times but there is a great repetition of stresses tending to bring about fatigue of the metal. A study of aluminum welds made by the oxy-acetylene process with a view of determining the actual and relative strength of the welds under tension, compression, and repetition of stresses should therefore be of considerable importance. Such was the purpose of the series of tests conducted in the Laboratory of Theoretical and Applied Mechanics of which the results follow.

(13) PREPARATION OF TEST PIECES.

As welding with the high temperatures of the oxy-acetylene blow-pipe amounts to nothing more than a local recasting of the metal, the metal in the weld will always be cast aluminum no matter whether the stock is rolled or drawn. The slight hammering that is usually done upon the weld can hardly effect the physical structure of the metal in the weld. Because the weld itself has all the properties of cast aluminum, the tests conducted were all made upon the cast metal.

For the fatigue tests on the unwelded aluminum, 7/8 inch rods slightly larger than the standard test pieces were used. These were subsequently turned down to the size shown in Fig. 19.

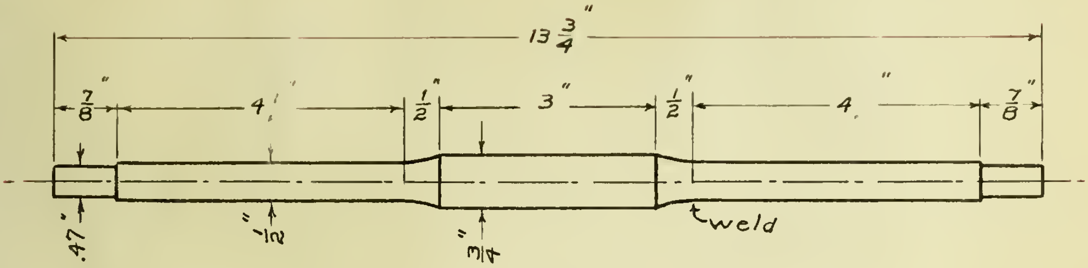


Fig 19

For fatigue tests on welded aluminum a central stick 7/8 inches in diameter and 4 inches long was used to which were welded two end rods 5/8 inches in diameter and 5 inches long as shown in Fig, 20.

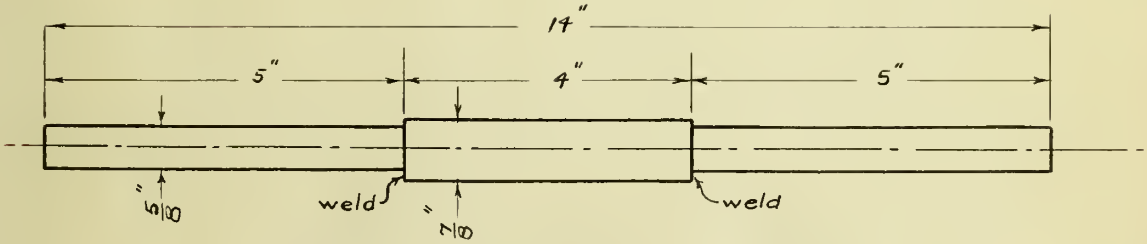


Fig 20

The whole was then turned down to the same size as the test pieces used for the fatigue tests of the unwelded aluminum. The particular dimensions of the central 3/4 inch stock chosen threw the weld at the section of maximum stress. These test pieces were welded by R. P. Rodgers, of Santa Monica, California who has had several years

experience with aluminum welding.

Another series of six test pieces for fatigue tests was welded by the Davis-Bournonville Company of New Jersey, dealers in oxy-acetylene equipment. The stock consisted of two pieces of cast aluminum 7/8 inches in diameter with ends turned, which were welded end to end. They were turned down to the general dimensions of the previous pieces except that the 3/4 inch section was extended so that the weld came at the section of maximum stress. Twenty pieces of 5/8 inch stock about 5 inches long were welded in pairs end to end to form 10 test pieces. Of these five were turned down to the dimensions given in Fig. 21 and five were left unfinished to be tested as they came from the welder.

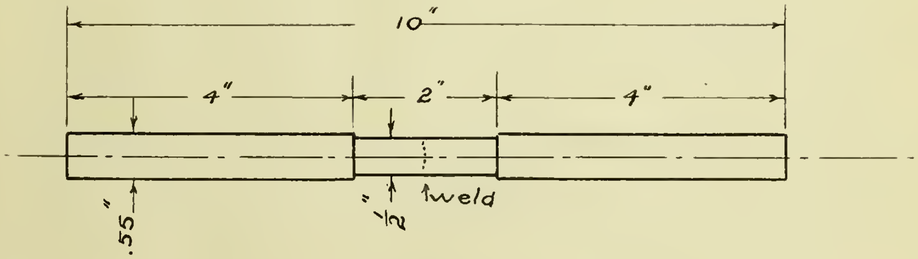


Fig 21

The castings were made in the foundry of the University of Illinois where the aluminum was melted in a brass furnace in which the flames came into direct contact with the metal. In the particular furnace it is difficult to regulate the temperature and to watch the melting, so that the trouble from blowholes caused by casting aluminum at too high a temperature could not be avoided. Some of the castings

made were quite honeycombed with pockets so that they had to be discarded. The best ones only were kept for the tests, but even they often showed flaws that were not visible until the surface had been cut away in the lathe. The metal used was Grade 12 bar aluminum from the U.S.Reduction Company of Chicago.

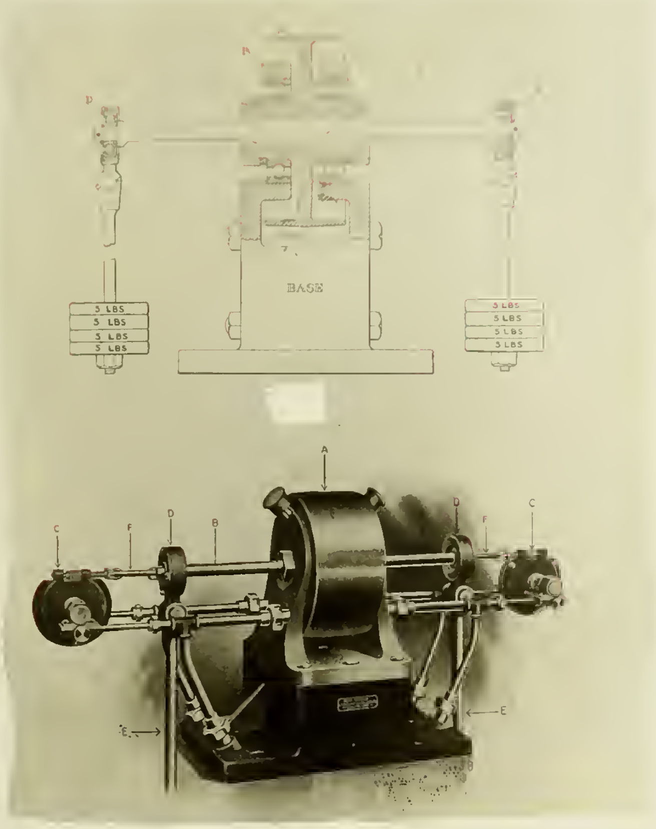
(14) DESCRIPTION OF TESTING MACHINES.

The White-Souther endurance testing machine made by the Souther Engineering Company of Hartford, Connecticut was used in all the fatigue tests. A description of the machine follows on the next page. For the tension and compression tests Riehle machines of 50,000 and 100,000 pounds capacity, respectively, were used.

The limits of 50 and 30 pounds, respectively, for the highest and lowest weight suspended from the fatigue test piece, were chosen, the former because the particular machine upon which the tests were made is not reliable for any number of repetitionsof stress below that recorded at the breaking with this load, and the latter because of the time limit. The number of repetitions of stress varied, roughly, between 5000 and 800,000.

(15) EQUATION GOVERNING REPITITION OF STRESS FOR UNWELDED ALUMINUM.

Equating the bending moment to the resisting moment and solving for S according to the equation derived thereby, namely, $S = Mc/I$, where M the product of the load and its



WHITE-SOUTHER ENDURANCE TESTING MACHINE

The load is applied at D where it hangs upon a collar in which the sleeve mounted upon the test piece turns upon roller bearings. The number of turns is indicated by the counter at C driven by a worm and worm wheel which receives its motion from the test piece B by means of a flexible connecting link F. The test piece C is fastened in a draw-in collet driven into the pulley A. A is turned by a belt from a motor at a constant speed of 1700 R.P.M.

moment arm in inches and I/c is the section modulus, gave the series of values for the stress recorded in the Log. Sheet, Table 1. The moment arm used was the distance from the action line of the load to the section at which failure occurred. The relation between the number of repetitions of stress and the magnitude of stress seems to be expressed by an exponential law.* If the logarithms of these two variables are plotted as coordinates the curve is a straight line whose slope is the exponent. As this gives a means of comparison with similar curves for other materials the logarithms of stress and repetition of stress were plotted rather than the direct magnitudes.

Ordinary aluminum castings are quite solid, while some of the castings used in the tests were weakened by blowholes so that all those that showed a flaw such as a cavity or foreign matter in the section at which failure occurred were eliminated in deciding upon the position of the curve through the points. Of the eighteen endurance tests made, eleven showed solid sections at the break. These eleven points are plotted on the accompanying curve sheet. A straight line seems to govern the relation between the logarithms of the magnitudes of the stress and repetition of stress.

Taking the simple straight line formula

$$x = k - my$$

and letting x = log of repetition of stress, y = magnitude of stress, we have,

$$\log R = k - m \log S \qquad \begin{cases} R = \text{number of repetitions} \\ S = \text{magnitude of stress.} \end{cases}$$

* See references # 4 and # 5

For the line thru the points plotted $m = 8.83$ and $k = 41.3$. The equation governing the relation between the stress and repetition of stress then is

$$\log R = 41.3 - 8.83 \log S \qquad (1)$$

This may also be put in the form

$$\log S = 4.68 - .113 \log R$$
$$\text{or} \qquad S = 48000\, R^{-.113} \qquad (2)$$

It is interesting to note that equation (1) is almost identical with the relation developed by Upton and Lewis[1] for steel which has -.118 as an exponent. The equation developed for steel is

$$\log R = 43.78 - 8.5 \log S$$
$$\text{or} \qquad S = 140000\, R^{-.118}$$

The average value of the exponent for tests in different steels as recorded by Basquin* is also about -.11.

(16) STRENGTH OF WELDS SUBJECT TO FATIGUE TESTS.

Of the twenty welds made by R. B. Rodgers two broke under the pressure of the cutting tool while the specimens were being turned down to dimensions in the lathe. Three were kept for tensile tests.

Of the fifteen pieces subjected to endurance tests nine broke out of the weld and six broke in the weld. Of the nine pieces that broke out of the weld four breaks may be attributed to poor castings such as blowholes and foreign matter. This leaves five pieces breaking out of the weld against six that broke in the weld showing that as far as the mere breaking is concerned the welds stand up quite favorably

* Reference #8 in Bibliography. [1] See reference # [illegible]

against the original metal. However, when the logarithms of stress and numbers of repetitions are plotted on the sheet showing the relation between these variables for the unwelded metal it will be seen that in strength the balance lies decidedly in favor of the unwelded test pieces. Only one loint lies above the line established by the original aluminum, and one point falls upon the line. All others lie below the line and considerably below points for the original metal that do not lie on the line. Of the breaks that occurred in the weld only one showed a perfect weld, the remaining five showed either a knotty unfused structure as if the oxide film previously spoken of had prevented a flowing together of the metal, or the section at the break was traversed by one or more bark-like crystals also due to imperfect welding.

In the quality of the welds those made by the Davis-Bournonville Company were somewhat superior to the Rodgers' welds. Only one of the six pieces broke at the weld due to an imperfection of the weld. One break that occurred out of the weld may be attributed to a poor casting. Counting the two breaks that occurred while the test pieces were being machined eight of Rodgers' welds broke in the weld against nine out of the weld, of which four may be attributed to poor casting. Of the Davis-Bournonville welds three broke in the weld and three out, of which one may be attributed to poor casting. The ratio of breaks in to breaks out of the weld is then for Rodgers 8/5, for Davis-Bournonville 3/2. However,

it can be said that only one of the latters'were unhomogeneous or contained foreign particles, while of the Rodgers welds (including the two that broke in the lathe) seven showed such defects and only one was perfect. In strength, when subject to repeated stresses,the Davis-Bournonville welds are also below the original metal.

(17) EFFICIENCY OF WELDS IN TENSION.

The same remark concerning the quality of the welds applies to the test pieces subject to tension. Only three Rodgers welds were put to tension tests all of which broke in the weld. Two showed rather a low tensile strength. The breaks indicated poor fusion of the metal by the knotty appearance. The third gave a tensile strength higher than that of the average unwelded rod showing that it is possible to attain good results.

By <u>efficiency</u> as here used is meant the ratio of unit stress at which rupture occurred for the welded rod to the average unit tensile tensile stress for the unwelded metal. The efficiency of the three Rodgers welds averaged 54.4%, and the average efficiency of the Davis-Bourninville welds was 73.4%, ranging for the former from 27 to 101%, for the latter from 50 to 86%. The welds here show the same tandency as in the endurance tests, those made by the Davis-Bournonville Company being more nearly of the same quality, while Rodgers' welds show both higher and lower strengths. Most of the former broke out of the weld but quite close to it indicating that original metal had been weakened at the

weld. Small blowholes, of which there was a considerable number, did not seem to weaken the test pieces materially in tension. The efficiency of the two Davis-Bournonville test pieces that broke in the weld was 80%.

(18) STRENGTH OF UNFINISHED JOINTS.

Several tensile tests were made on welded rods as these were sent from the welders, in order to compare the strength of welds on repair jobs with the unwelded metal. All these test pieces broke out of the weld.

(19) EFFICIENCY OF WELDS UNDER COMPRESSION.

In the compression tests a two to one ratio for the length to the diameter was used. The specimens took on the load rapidly without appreciable deformation until a load of about 14,000 pounds was reached when the cylindrical test piece began to squeeze together bulging out at the center until rupture occurred by shearing as shown in the sketch accompanying log of compression tests. The average stress for rupture was for the unwelded specimens 67,450 lb. per sq. in. and for the welded pieces 61,080 lb. per sq. in. This gives an efficiency of 90%, showing that the weld seems to weaken the metal under compression. It does not affect the strength as much under compression as under tension. There was slight difference in the appearance of the rupture of the welded and unwelded specimens, the former showing some crushing in the zone of the weld while the latter showed only the simple shear.

While the compression pieces gave considerable reduction in length or deformation before rupture, the rods subject to tension showed no elongation measurable by means of direct measurement with a scale.

(20) STATIC LOAD TEST ON ORIGINAL ALUMINUM.

An interesting characteristic of aluminum is shown in the curve in which deflection is plotted against load. These tests were conducted in the White-Souther machine in which the test piece was fixed and held stationary while an increasing load was applied at the end and the deflection noted on a deflectometer connected to the specimen by means of a fine wire. Up to a thirty pound load the deflection varied directly as the load, while for loads greater than that the deflection increased faster than the load indicating that the metal has a varying modulus of elasticity. The stress in the outermost fibre at the section of maximum stress got by the equation $= Mc/I$ was for the 30 lb. load about 10,000 lb.per sq. in. During the compression tests it was noticed that the test piece began to crush at about 14,000 lb. per sq, in. The yield point for aluminum under compression lies apparently around 10,000 lb. per sq. in., the two phenomena, that of crushing or spreading of the metal under compression and the increasing deflection of the cantilever beam being occasioned by the same characteristic of the metal.

As all of the tests for endurance were conducted for loads of 30 lb. or greater it will be seen that the metal was put to a stress apparently greater than the elastic limit.

(21) SUMMARY OF RESULTS.

The cast aluminum tested under tension showed no appreciable elongation, and had a tensile strength of almost 15,000 lb. per sq. in.; under compression it gave a deformation of about 30% before rupture which occurs by shearing at about 67,000 lb. per sq. in. Up to a compression of about 10,000 lb. per sq. in. it has a constant modulus. In endurance or fatigue tests the relation between stresses and repetition of stresses seems to be governed by the law

$$S = 48,000\ R^{-.113}$$

Aluminum can be welded satisfactorily but in no cases tested did the average of the strength of a number of welds equal that of the original unwelded aluminum. In endurance the weld is below the unwelded aluminum in strength, under tension the weld made by an expert welder has an efficiency of about 75%, Under compression the weld made by the same welder will give an efficiency of about 90%.

The personal equation enters into the welding of aluminum more than into the welding of other metals. Attempts to weld aluminum made by a man who welds steel and iron with considerable facility were absolutely unsuccessful, the welds made by a man with several years experience were not quite as strong as those made by an expert of a company dealing welding equipment. Oxidation is not entirely eliminated by the use of fluxes.

TABLE I

LOG OF ENDURANCE TESTS.
on
UNWELDED ALUMINUM.

No.	Diam. in.	Load lb.	Arm in.	M	Rev.	Log rev.	I/c	Stress	Log Stress
Ae	..510	45	4.4	198			.0140	14140	4.151
Aw	.509	45	4.35	196	29300	4.467	.0129	15200	4.182
Be	.515	50	4.15	207	35400	4.549	.0134	15440	4.189
Bw	.512	50	4.00	200	37900	4.578	.0134	14900	4.174
Ce	.505	40	4.30	172	73800	4.868	.0126	13650	4.136
Cw	.502	40	4.25	170	42500	4.628	.0124	13700	4.137
De	.508	35	4.20	147	372900	5.571	.0129	11400	4.057
Dw	.511	35	4.45	155	259500	5.414	.0131	11840	4.074
Ee	.508	30	4.20	126	801400	5.904	.0129	9780	3.990
Ew	.508	30	2.15	64	424700	5.627	.0129	5000	3.699
Fe	.514	50	4.20	210	16600	4.220	.0133	15800	4.199
Fw	.511	50	4.25	212	4700	3.672	.0131	16200	4.210
Ge	.505	45	3.35	151	1400	3.146	.0126	12000	4.079
Gw	.524	45	4.30	193	41300	4.616	.0141	13700	4.136
He	.504	40	4.15	166	22200	4.346	.0126	13200	4.120
Hw	.504	40	4.35	174	65700	4.817	.0126	13800	4.141
Ie	.506	45	3.65	164	33700	4.527	.0127	12900	4.111
Iw	.502	45	4.20	189	33700	4.527	.0124	15200	4.183

DESCRIPTION OF TEST PIECES
for
ENDURANCE TESTS.
(By section is meant the break)

Ae - Very poor section. Large blow hole.
Aw - Section O. K.
Be - Section O. K.
Bw - Section O. K.
Ce - Section O. K.
Cw - Section partly darkened as if by foreign matter in metal.
De - Section O. K.
Dw - Section O. K.
Ee - Section O. K. except for small blow hole on circumference.
Ew - Broke away from section of maximum stress 2" from end.
Fe - Section O. K.
Fw - Section O. K.
Ge - Broke away from section of maximum stress at large blow hole.
Gw - Section O. K.
He - Two small flaws in section.
Hw - Section O. K.
Ie - Section O. K. except for one small blow hole.
Iw - Section O. K.

TABLE II

LOG OF ENDURANCE TESTS
on
WELDED ALUMINUM.*

No.	Diam. in.	Load lb.	Arm in.	M	Rev.	Log rev.	I/c	Stress	Log Stress
Ae	.503	35	4.20	147	5200	3.716	.0125	11740	4.069
Aw	.502	35	4.15	145	305400	5.484	.0124	11700	4.067
Be	.511	40	4.10	164	77900	4.892	.0131	12500	4.096
Bw	.506	40	3.50	140	11700	4.068	.0127	11040	4.043
Ce	.509	45	4.50	203	300	2.477	.0129	15740	4.196
Cw	.507	45	4.40	198	200	2.301	.0128	15480	4.189
De	.506	45	3.70	167	101900	5.007	.0127	13140	4.118
Dw	.505	45	4.30	194	57700	4.761	.0126	15400	4.187
Ee	.509	30	4.20	126	0	------	.0129	9750	3.989
Ew	.508	30	4.20	126	300	2.477	.0128	9840	3.993
Fe	.512	50	3.75	188	100	2.000	.0132	14240	4.153
Fw	.505	50	3.90	195	0	-----	.0128	15220	4.182
Ge	.503	30	4.50	135	70800	4.849	.0125	10800	4.033
Gw	.504	30	4.45	133	85600	4.932	.0126	10550	4.023
He	.512	30	4.50	135	100	2.000	.0132	10220	4.009

DESCRIPTION OF TEST PIECES
for
ENDURANCE TESTS.
(By section is meant the break)

Ae - Broke in weld. Bark-like flaws on edge of section.
Aw - Broke in weld. Section O. K. Slight flaw in edge.
Be - Broke in weld. Section O. K. Slight flaw in edge.
Bw - Broke out of weld. Section porous with minute blow holes.
Ce - Broke out of weld.(stock side) Section crystalline & rough.
Cw - Broke out of weld (stock side) Small particles foreign matter.
De - Broke out os weld (stock side) Section O. K.
Dw - Broke in weld. Section O. K.
Ee - Broke in weld. Poor fusion. Bark-like section.
Ew - Broke in weld. Poor weld. Bad flaw. Bark-like section.
Fe - Broke out of weld. (end side) Flaw. Foreign matter in section.
Fw - Broke out of weld. (end side) Flaw. Quite porous.
Ge - Broke out of weld. (stock side) Section O. K. central flaw.
Gw - Broke out of weld. (stock side) Section O. K.
He - Broke out of weld. (stock side) Poor section.

* Welds made by R. B. Rodgers.

TABLE III

LOG OF ENDURANCE TESTS
on
WELDED ALUMINUM.*

No.	Diam. in.	Load lb.	Arm in.	M	Rev.	Log rev.	I/c	Stress	Log Stress
A	.504	45	3.45	155	23500	4.371	.0126	12300	4.090
B	.498	50	2.80	140	400	2.602	.0121	11560	4.063
C	.502	40	3.35	134	133600	5.126	.0124	10800	4.034
D	.500	35	2.70	94	249500	5.397	.0123	7670	3.885
E	.502	30	3.25	97	84800	4.928	.0124	7860	3.890
F	.500	50	3.40	170	100	2.000	.0123	13800	4.141

DESCRIPTION OF TEST PIECES.

A - Broke in weld. one diametral bark-like flaw.

B - Broke out of weld. Section good. Loose crystals.

C - Broke in weld. Homogeneous section.

D - Broke out of weld. Good section.

E - Broke out of weld. Three small blow holes on circumference.

F - Broke in weld. Solid section with diametral flaw.

* Davis-Bournonville welds.

TABLE IV

TENSION TESTS
ON
UNWELDED ALUMINUM.

No.	Diam. in.	Ultimate Load lb.	Stress	Area sq. in.	Remarks
1	.3537	1350	13780	.0980	Section at break O. K.
2	.3543	1500	15200	.0985	Section at break O. K.
3	.3510	1080	11160	.0965	Bad flaw in break.
4	.3550	1400	14150	.0986	Small flaw in break.
5	.3570	1400	14000	.1000	Small blow holes.
6	.3555	1530	15630	.0986	Section O. K.
7	.3570	1510	15100	.1000	Section O. K.
8	.3550	1230	12530	.0986	Many small blow holes.
9	.3550	1300	13270	.0986	Good break.
10	.3545	1420	14430	.0983	Section O. K.
11	.3540	1810	18380	.0981	Section O. K.

A 2" length should no measureable elongation or reduction in area.

No.	Diam. in.	Ultimate Load lb.	Stress	Area sq. in.	Remarks
a	.565	3750	14930	.251	Tests were made on the ends
b	.555	4260	17960	.237	of the welded test pieces
c	.600	3720	13200	.282	as shown in the sketch below.
d	.567	4120	16330	.252	Sections at break were good
e	.601	3740	13200	.283	for all test pieces.
f	.571	4050	15880	.255	As above no measureable elon-
g	.582	4290	16200	.265	gation was shown.

Average of all breaks that did not show a serious flaw= 15150 pounds per square inch tensile strength.

Tests were made upon the .55 inch section 4 inches long shown in Fig. 21.

TABLE V

TENSION TESTS
on
WELDED ALUMINUM.

No.	Diam. in.	Area sq.in.	Ultimate Load lb.	Stress	Eff. %	Remarks
1	.504	.199	2470	12400	82.0	Broke in weld. Loose crystals.
2	.504	.199	2380	11950	79.0	Broke in weld. Diametral flaw.
3	.504	.199	2220	11130	74.6	Broke out of weld. Small b.h.
4	.500	.196	2560	13070	86.3	Broke out of weld. Small b.h.
5	.547	.235	1760	7500	49.5	Broke out of turned center.
6	.500	.196	2050	10450	69.0	Broke out of weld. Section OK.
			Ave.	11080	73.4	DAVIS-BOURNONVILLE WELDS.

Test piece shown in Fig. 21.

No.	Diam in.	Area sq.in.	Load lb.	Stress	Eff. %	Remarks.
a	.425	.142	760	5350	35.5	Imperfect weld.
b	.408	.132	2000	15250	101.0	Perfect weld.
c	.423	.141	580	4100	27.0	Knotty section.
			Ave.	8230	54.4	RODGERS' WELDS

No.	Ultimate Load lb.	Remarks.
A	1460	Tests made on test pieces as they
B1	5050	came from the welder. All broke
B2	5550	out of weld. Several showed large
C1	4320	blow holes at first break. No
C2	5450	diameters were measured as the tests
D1	2770	were made for relative results only.
D2	2400	
D3	1900	
E	6540	DAVIS-BOURNONVILLE WELDS.

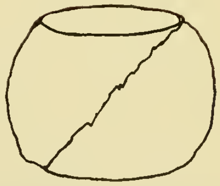
TABLE VI

COMPRESSION TESTS of UNWELDED ALUMINUM.

No.	Diam in.	Area sq.in.	Load lb.	Ultimate Stress	Length int.	Length final	Def. %
1	.750	.442	31000	70500	1.32	0.93	29.5
2	.750	.442	27800	63200	1.32	1.01	23.5
3	.756	.448	30700	68700	1.32	0.95	28.0
4	.751	.443	28880	65300	1.31	0.94	28.8
5	.756	.448	31500	70100	1.42	0.96	32.4
6	.753	.445	28100	63400	1.43	1.02	28.6
7	.750	.442	31500	71600	1.42	0.95	33.1
8	.750	.442	29200	66400	1.46	0.96	34.2
			Ave.	67400		Ave.	29.8

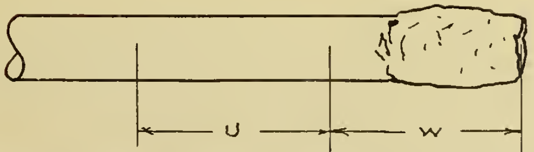
Specimens took load up to about 14000 lb. after which the cylinders flattened out until failure at the loads indicated. Failed by shearing as shown below.

Test piece taken out of 3/4 inch stock of endurance test piece shown in Fig. 19.



Typical failure

No.	Diam. in.	Area sq.in.	Load lb.	Ultimate Stress	Length int.	Length final	Def. %
a	.652	.333	23870	71800	1.21	0.80	33.8
b	.601	.283	15440	54600	1.21	0.86	28.9
c	.646	.327	25000	76500	1.20	0.78	35.0
			Ave.	67600		Ave.	32.6



Stock left over from tension tests of which the results are tabulated in Table V. Section U was used for tests a, b, and c. Section W was used for compression tests on welded aluminum.

TABLE VII

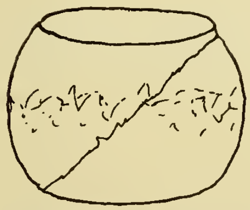
COMPRESSION TESTS
on
WELDED ALUMINUM.

No.	Diam. in.	Area sq.in.	Ultimate Load lb.	Stress	Eff. %	Length int.	Length final	Def. %
1	.652	.333	21040	63200	93.9	1.31	0.87	33.6
2	.650	.332	16600	50000	74.2	1.31	0.93	29.0
3	.640	.322	20000	62200	92.4	1.31	0.86	34.4
4	.631	.312	22500	72200	107.0	1.30	0.86	34.6
5	.652	.333	19220	57800	85.7	1.31	0.94	28.2
			Ave.	61080	90.6		Ave.	32.0

Tests pieces spread similarly to unwelded test pieces.
Failed by crushing as much as by shearing.

DAVIS-BOURNONVILLE WELDS.

Test pieces were turned down to sizes given.



Typical failure

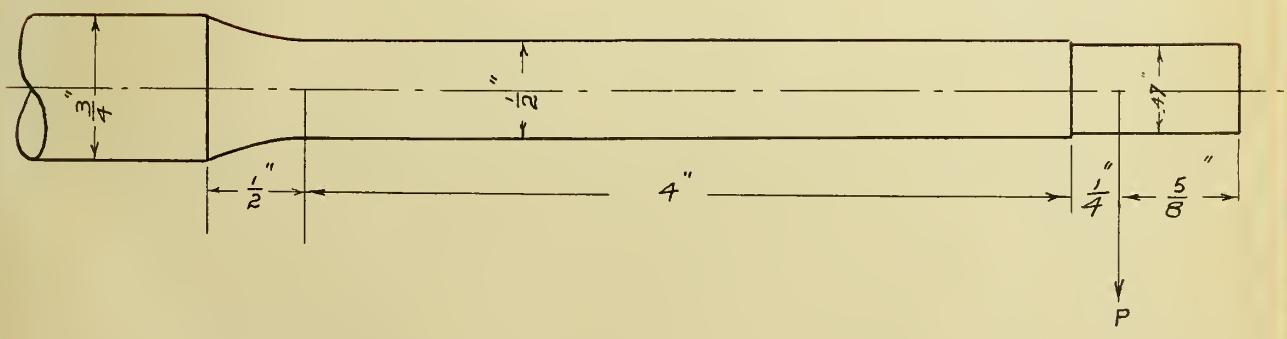
TABLE VIII

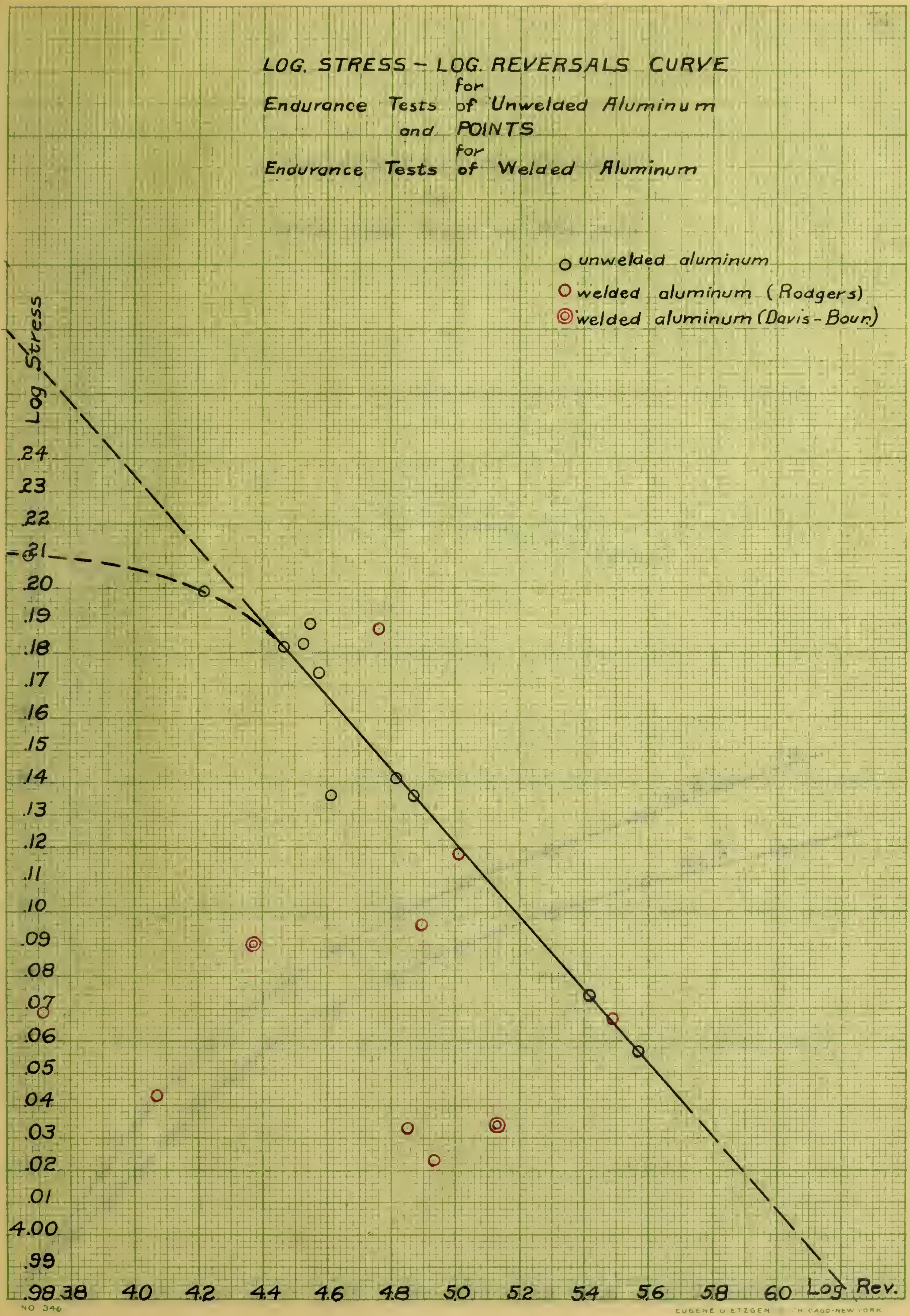
STATIC LOAD TEST
on
UNWELDED ALUMINUM.

#2 P load in lb.	#2 Deflec. in inches.	#3 P load in lb.	#3 Deflec. in inches.
0	.0000	0	.0000
5	.0036	5	.0049
10	.0068	10	.0092
15	.0108	15	.0150
20	.0143	20	.0195
25	.0167	25	.0248
30	.0216	30	.0297
35	.0264	35	.0350
40	.0311	40	.0408
45	.0367	45	.0502
50	.0436	50	.0602
55	.0510	55	.0702
60	.0611	60	.0845
65	.0710	65	.0990
70	.0840	70	.1200
75	.0982	75	.1340
80	.1100	80	.1690
85	.1319	85	.break
90	.break		

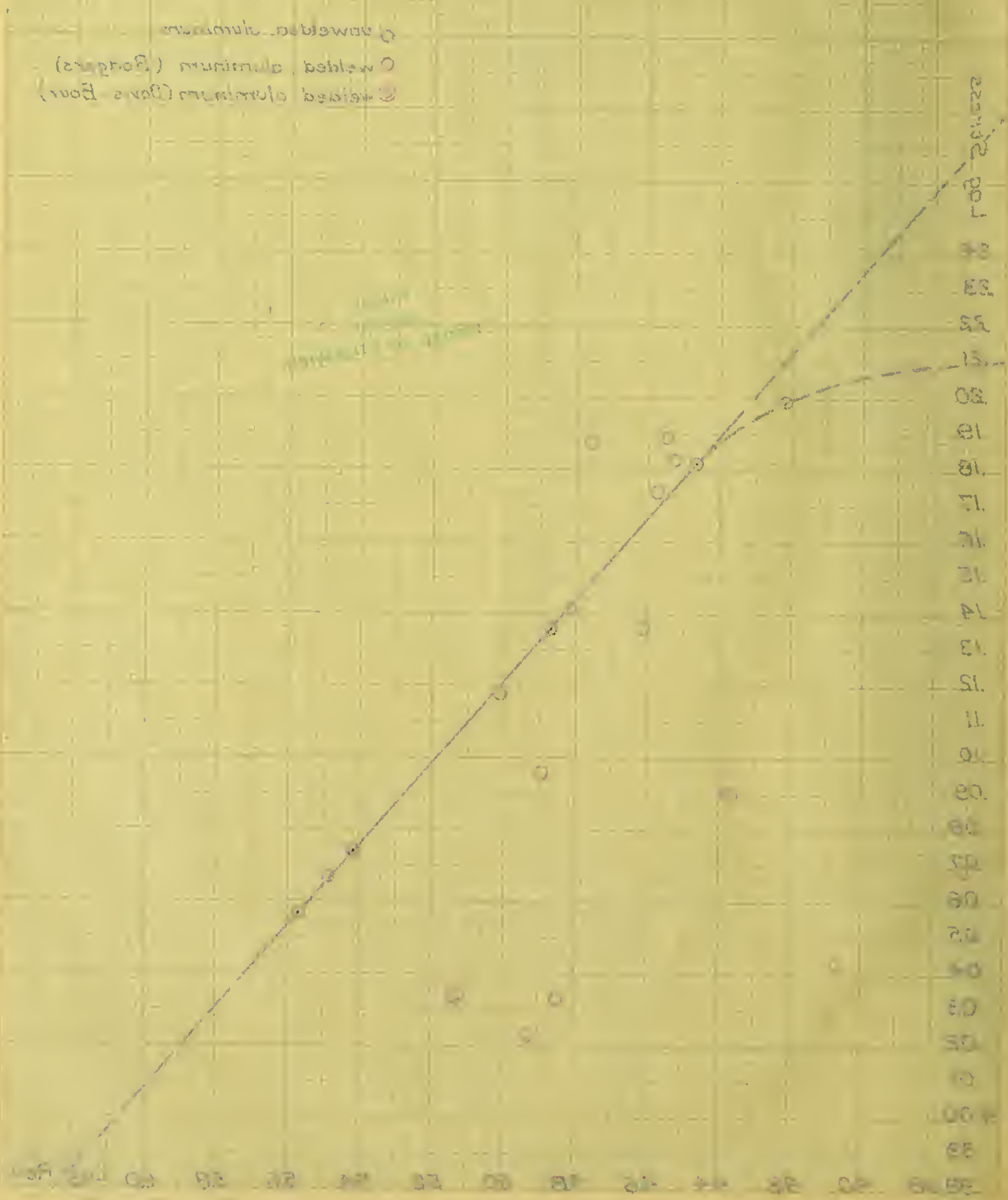
Length 3.9 inches

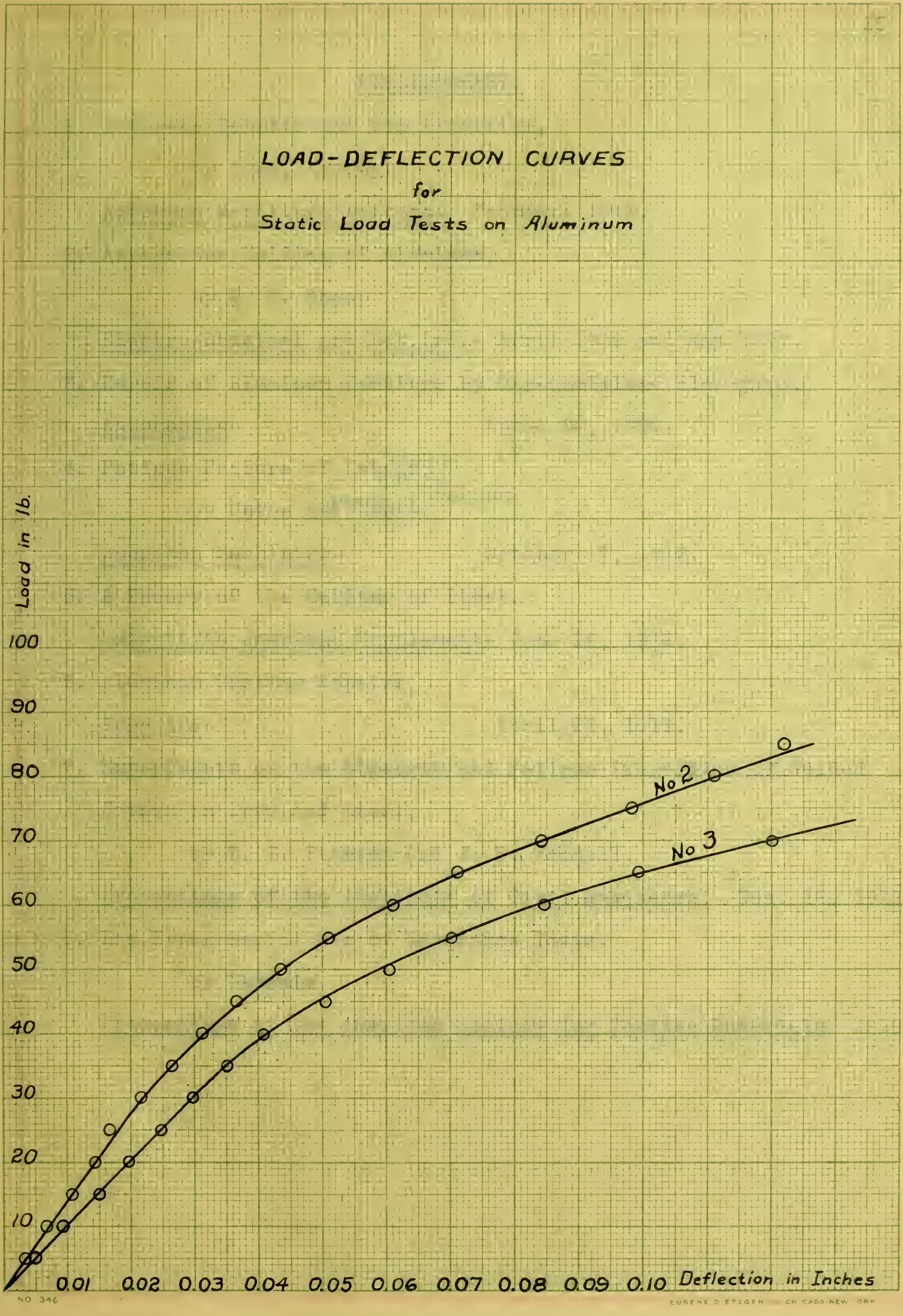
Length 4.15 inches



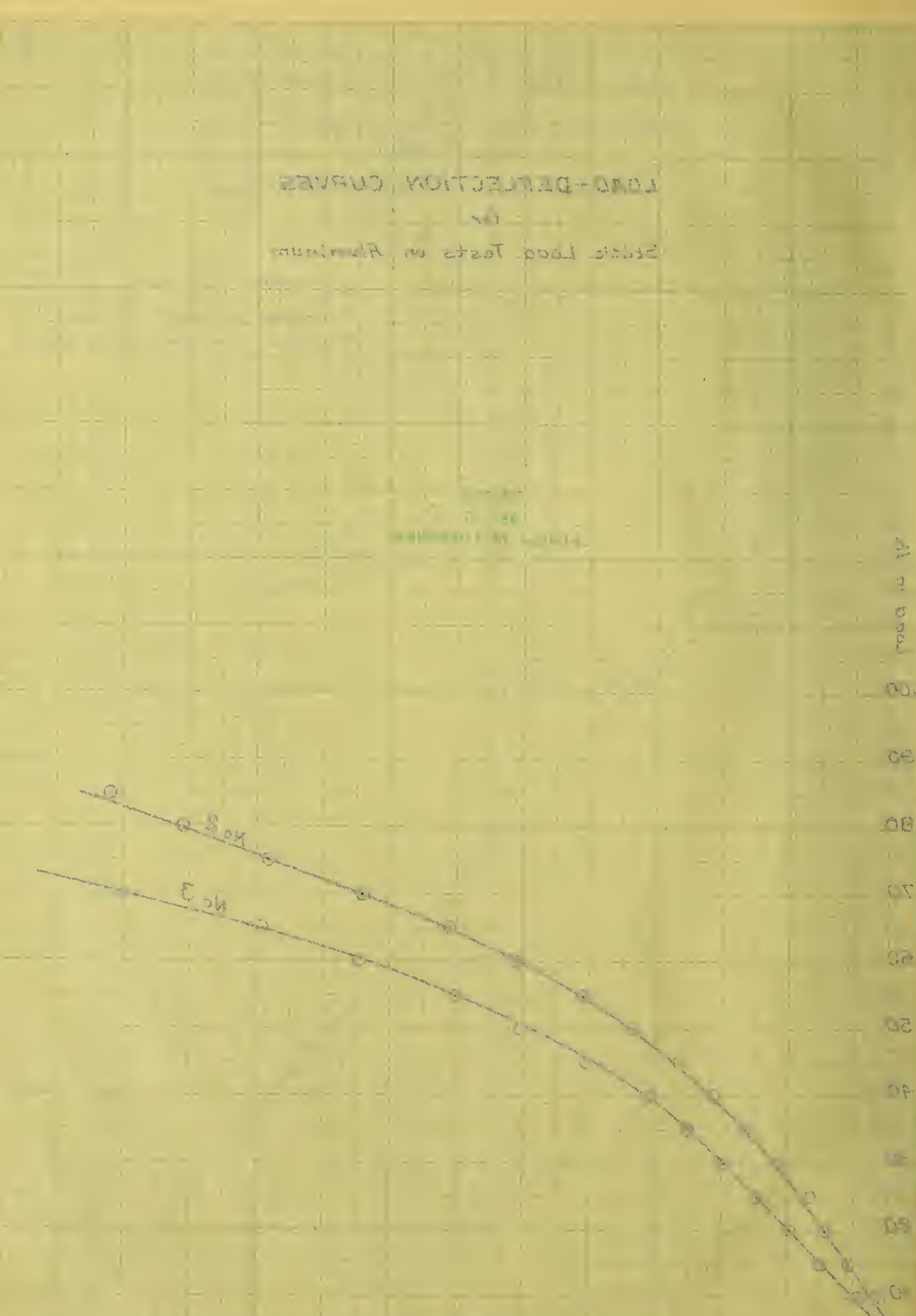

LOG. STRESS – LOG. REVERSALS CURVE
for
Endurance Tests of Unwelded Aluminum
and POINTS
for
Endurance Tests of Welded Aluminum
unwelded aluminum
welded aluminum (Rodgers)
welded aluminum (Davis-Bour.)
Log Stress
.24
.23
.22
.21
.20
.19
.18
.17
.16
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
4.00
.99
.98
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
Log Rev.
NO 346
EUGENE DIETZGEN CO. CHICAGO-NEW YORK

LOG STRESS - LOG REVERSALS CURVE
for
Endurance Tests of Unwelded Aluminum
and
JOINTS
for
Endurance Tests of Welded Aluminum





LOAD-DEFLECTION CURVES
for
Static Load Tests on Aluminum
Load in lb.
100
90
80
70
60
50
40
30
20
10
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
Deflection in Inches
No 2
No 3


LOAD-DEFLECTION CURVES
for
Static Load Tests on Aluminum
No 2
No 3
10
20
40
50
60
70
80
90
100

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