THE ROTARY KILN

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THE ROTARY KILN

A THESIS

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THE ROTARY KILN

In the manufacture of Portland cement, the methods used at the present time are quite crude, but even so, the progress made in many departments has been very rapid; particularly is this true in the Burning Department. In approximately ninety percent of the mills of this country, pulverized coal is used as a fuel, and, with few exceptions, the total burning cost, including the fuel, represents from one-third to one-half of the total cost of manufacture per barrel. Improvements on the present system are being made daily, and experiments on a large scale are being carried on by many of the manufacturers.

It must be remembered that the first rotary kiln was manufactured about 1885, and not until 1895 was the rotary type considered a success. The plants of Ger-

many and England, and also of this country utilized vertical or stationary kilns, which are much more economical in point of fuel consumption, but very costly on account of the hand labor necessary.

In 1885 Mr. Ernest Ransom patented a rotary kiln in England. About a year later Alphonse de Navarro purchased the American rights to this patent, and built the first rotary kiln in this country in a mill, from which the present wonderful Atlas Company was evolved.

The first kiln was 5' in diameter by 40' long. The first fuel tried was wood, but a sufficient temperature for "Clinkering" could not be obtained, and petroleum was utilized. The cost of the petroleum became excessive, and in 1895 (only fourteen years ago) pulverized coal was first tried as a fuel in the Atlas mill.

To the American engineer and finan-

cier is due the wonderful growth of the business, and especially the development of the rotary kiln. It was first used commercially here and developed, before being adopted in Germany and England, where the industry was much older and where it originated. The development of the kiln from its original size of 5'-0" in diameter by 40'-0" long to one 12'-0" in diameter by 200'-0" long indicates a remarkable growth. Whether the limit in size has been reached is a question yet to be determined. Until the last three or four years the 6'-0" by 60'-0" kiln was the standard, and when Mr. Edison installed his 9'-0" by 150'-0" kilns, he was laughed at, but the present manufacturers have him to thank for the biggest single advancement in the history of the industry. The main idea in developing the rotary kiln appears to be, increase in output, decrease in fuel consumption per barrel and decrease in the amount of machinery

operating. In other words--concentration. But it is questionable which is the better proposition - a mill with one large unit producing 2,000 barrels per day, or a mill with four smaller units producing 2,000 barrels per day. Allowing for the ordinary operating difficulties and "shut downs" due to repairs and other ordinary causes, the total output of the one unit mill, we believe, will be considerably less than that of the four unit mill. Whether the saving in fuel consumption of the larger unit mill will make up for this decrease in production, is a question to be considered.

OTHER USES.

The rotary kiln has lately been successfully utilized in burning lime, drying materials of various character, and in driving off the oxides in iron ores. A 7'-0" by 100'-0" kiln is being successfully used in burning lime, and a production of 9# of lime

to 1# of fuel has been secured. The process is continuous, and we believe eventually will be adopted at large. As a direct heat rotary dryer, it is the best in point of production that can be installed, and where a large production is desired with proper installation it is as economical ultimately as the majority of the so-called patent dryers.

The process of reducing iron ore direct to metallic iron by use of the rotary kiln is very interesting, and is now practically past the experimental stage. Crushed ore is passed through a rotary kiln 8'-0" by 120'-0", in which a reducing flame is maintained. The coal saving over the present blast furnace method is approximately 70%. The following is a comparative statement of the fuel consumption per ton of steel:

"Jones Step Process"

1 Kiln for Heat	225#	At Blast Furnace	3000#
1 Kiln for Reduction	400#	At Puddling "	500#
1 Puddling Furnace	500#		
	1125#		3500#

Saving 2375# per ton of steel.

The most important use, however, is in the burning of cement clinker. Following is a general description of the design, installation, operation, etc., of an 8'-0" by 125'-0" kiln, together with some tests on other size kilns.

In the manufacture of Portland cement there are, roughly, three stages:

First --- Preparation of the Raw Materials, which consists of quarrying the Rock and Shale or Clay, crushing and drying, and pulverizing the proper mixture to an average fineness of 90 to 98% through a 100-mesh sieve.

Second -- Burning or Clinkering the mixture to a degree of temperature (about 2600 deg. F.) sufficient for the fusing of the powdered material into small greenish black "clinkers", the size of beans.

Third --- Reducing or Grinding this Clinker to certain required fineness (Generally 95% through 100-mesh sieve).

Plate No. 1 shows a typical installation of an 8'-0" by 125'-0" kiln.

The Raw Mix or "kiln feed" enters the "stack end" of the kiln either by gravity or screw conveyor. The kiln is lined throughout with nine inches of high refractory magnesia brick.

The kiln is set at an incline of 3/8" to 3/4" per foot - which allows the material to travel slowly towards the other end of the kiln, from which it discharges into a conveyor, cooler or elevator.

A mixture of air and gas, oil, or pulverized coal is blown into the discharge end of the kiln by means of compressed air furnished by an air compressor or blower. This mixture of air and combustible is ignited and forms a flame or blast of variable length which, coming in contact with the feed, drives off, first the moisture, then the gases, and finally, "clinkering" takes place at about 2600 deg. F.

The exact temperatures at different points throughout the kiln we have measured in a 7'-0" by 100'-0" kiln operating upon the "wet process", in which the kiln feed contained 50% moisture. The temperatures were taken by means of a LeChetelier Pyrometer, inserting the porcelain tubes through holes previously drilled through the kiln shell and lining.

The kiln revolved very slowly (about one revolution in one to four minutes), and

the temperatures of the gases accurately determined. The temperatures of the material were calculated from this data, as it was very difficult to determine the temperatures of the material without breaking the porcelain tubes. These results were plotted and are shown on Plate No. 3. Samples of the materials were also taken at the same points of temperature observations, analyzed and the results plotted, see Plate No. 4. Plate No. 2 is a curve plotted by W. B. Newberry from analysis of samples taken every four feet throughout the length of a 6'-0" by 60'-0" kiln.

Plate No. 5 is a curve plotted from analysis of samples taken from a 5'-6" by 6'-0" by 160'-0" kiln. This curve shows that the last or "upper" fifty feet were comparatively useless for this diameter since there was no appreciable chemical change in that part of the kiln.

SIZE OF KILNS.

Plate No. 6 is a table of kiln sizes together with outputs, fuel consumptions, etc. It has been observed in practice that the diameter bears a certain relation to the length of the kiln when output and fuel consumption are considered; i. e., a 6'-0" by 60'-0" kiln produces 175 barrels at 150# coal; a 6'-0" by 100'-0" kiln produces 300 barrels at 125# coal, while an 8'-0" by 100'-0" kiln will produce 450 to 500 barrels at 110 to 115# coal.

A typical and popular size just now is 8'-0" to 9'-0" by 125'-0" to 130'-0" long. This relation of diameter to length is expressed as follows:

$$L = 16 \text{ (about) } \times D$$

where L = length of kiln in feet

D = net diameter of kiln in feet

HEAT BALANCE.

The distribution of heat or analyz-

ing the changes, physical and chemical, during the burning of a barrel of cement is as follows - taking for illustration a certain size kiln, actual analyses of raw materials and coal, and from these determining the "mix" or "kiln feed".

DISTRIBUTION OF HEAT PER BARREL.

Size of Kiln 8'-0" by 125'-0" Dry Process

Output of Kiln 600 barrels per day.

25 barrels per hour.

Fuel Consumption 90 lbs. coal per barrel.

Proximate analysis of Coal:

Volatile............38.5

Fixed Carbon........52.75

Ash................. 7.5

Sulphur............. 1.5

BTU's per lb = (14544 x .5275 + 16515 x .385)

+ (354 x .075 - 1635) = 12,421 BTU's

TEMPERATURES.

Air entering Kiln from Blower 70° F.

Air surrounding Kiln, average	70° F.
Raw Mix	60° F.
Clinker discharging from Kiln	1400° F.
Waste Gases to Stack	650° F.
Clinkering Zone	2500° F.
Temperature at which Gases are liberated	1000° F.

Area of Kiln	3141 sq. ft.
Area of Hood	185 sq. ft.

Stack, 6'-6" by 125'-0"

SPECIFIC HEATS

Air	.2375
Waste Gases	.23
Limestone	.166
Shale	.2
Raw Mix	.2

HEATS OF COMBINATION AND DECOMPOSITION.

SO_3	1890 BTU's per lb.	(Decom.)
$CaCO_3$	765 BTU's per lb.	"
CaO	954 BTU's per lb.	(Liber.)
MgO	1488.6 BTU's per lb.	"

ANALYSES.

	Rock	Shale
Loss	43.44	3.
SiO_2	1.54	66.2
Fe_2O_3	.37	5.10
Al_2O_3	.75	18.50
CaO	53.82	3.
MgO	.8	1.5

CALCULATIONS.

Shale $(2.8 \times 66.2 + 18.50 \times 1.1 + 5.10 \times 0.7) - (3 + 1.5 \times 1.4) = 204.18 = n$

Rock $(53.82 + .8 \times 1.4) - (1.54 \times 2.8 + .75 \times 1.1 + .37 \times 0.7) = 49.55 = m$

$\frac{n}{m}$ = parts Rock to 1 part Shale.

$\frac{204.07}{49.55} = 4.12$ parts.

	4.12
Less 10% for safety	.41
	3.71 parts Rock to 1 part Shale.

	Rock		Shale	
Loss	43.34 x 3.71	= 160.79	+ 3.0	= 163.79
SiO_2	1.54 x 3.71	= 5.71	+ 66.2	= 71.91
Fe_2O_3	.37 x 3.71	= 1.37	+ 5.1	= 6.47
Al_2O_3	.75 x 3.71	= 2.78	+ 18.5	= 21.28
CaO	53.82 x 3.71	= 199.67	+ 3.	= 202.67
MgO	.8 x 3.71	= 2.97	+ 1.5	= 4.47
				470.59

		Raw Mix
Loss	163.79 ÷ 470.59	= 34.8
SiO_2	71.91 ÷ 470.59	= 15.27
Fe_2O_3	6.47 ÷ 470.59	= 1.37
Al_2O_3	21.28 ÷ 470.59	= 4.52
CaO	202.67 ÷ 470.59	= 43.07
MgO	4.47 ÷ 470.59	= 0.95
		99.98

100 - 34.8 = 65.2% available for cement.

				Finished Cement
SiO_2	15.27	— .652	=	23.4 %
Fe_2O_3	1.37	— .652	=	2.1 %
Al_2O_3	4.52	— .652	=	6.93%
CaO	43.07	— .652	=	66.0 %
MgO	0.95	— .652	=	1.45%
				99.88%

Cementation Index

$$\frac{(2.8 \times 23.4) + (1.1 \times 6.93) + (.7 \times 2.1)}{66 + (1.4 \times 1.45)} = 1.09$$

Hence no free lime in cement.

HEAT DISTRIBUTION IN KILN PER BARREL.

(1) 77.87% $CaCO_3$ to be dissociated.
.7787 x 600 = 466.5# $CaCO_3$
466.5 x 765 = 357,000 BTU's

(2) 600# dry raw mix to be heated from 60° F. to 1000° (Temp. at which gases are liberated).
600 (1000 - 60) x .2 (sp.ht) = 112,800 BTU's

(3) 380# mix heated from 1000° F. to 2500° F. (Clinkering temperature).
380 (2500 - 1000) x .24 (sp.ht) = 136,800 BTU's

(4) 380# clinker discharged at 1400° F. loses by radiation:-
380 (1400 - 100) x.24 (sp.ht) = 118,500 BTU's

(5) Loss by Radiation.

Kiln Shell

W = total loss in BTU's per sq. ft. per hour

S = Co-efficient of radiation through rough surface steel 2.77

T_1 = Average Temp. Kiln Shell = 450° F.

T_2 = Average Temp. Air = 70° F.

B = Co-efficient of construction = 6

$$W = \frac{125 \times S\ (1.0077\ T_1 - 1.0077\ T_2) - .55\ B\ (T_1 - T_2)}{76.9} =$$

$$\frac{125 \times 2.77\ (1.0077 \times 450 - 1.0077 \times 70) - .55 \times 6\ (450-70)}{76.9} =$$

1738 BTU's radiated per sq.ft. per hour by kiln shell.

3141 x 1738 = 5,549,000 BTU's radiated by kiln shell per hour.

Then $\frac{5,430,000}{25}$ = 218,360 BTU's radiated per barrel by kiln shell.

HOOD

Area = 185 sq. ft.

Average temperature hood = 450° F.

Average temperature air = 70° F.

Difference in temperature = 380° F.

Formula (185 x 380) x.74 = 52,000 BTU's

Now 2.84 = ratio of increase of radiation for difference in temperature of 380°.

Then 2.84 x 52,000 = 147,700 BTU's radiated per hour by hood.

$\frac{147,700}{25}$ = 5910 BTU's radiated per bbl. by hood.

(6) Carried off by CO_2, etc. -temperature escaping to stack 650°.

208.8 (650-70) x 0.24 = 29,080 BTU's

(7) Carried off by waste gases.

Weight air required to burn 1# coal 8# approximately.

Assume 1½ times theoretical air supply

8 x 1.5 = 12# air required to burn 1# coal

12 x 90 = 1080# " " per barrel.

Now (650-70) x 0.23 (sp.ht) = 133.5 BTU's per lb. air.

Then loss per bbl. 1080 x 133.5 = 144,190 BTU's

HEAT DELIVERED TO KILN.

(1) Heat produced by combustion of coal.

(BTU's per lb. coal with theoretical air supply, assuming 1.5 times theoretical air supply) 12,421 BTU's

$8 \times 1.5 = 12\#$ air per lb. coal

$12 - 8 = 4\#$ air excess

$4 \ (650-70) \times .2375$ (sp.ht) $= 550$ BTU's absorbed per lb. coal by excess air.

Then $12,421 - 550 = 11,871$ BTU's per lb. coal available

And $90 \times 11,871 = 1,068,390$ BTU's

(2) Heat received due to cooling of gases (CO_2, etc) from 1000° to 650°.

$.348 \times 600 = 208.8\#$ CO_2, etc.

$208.8 \ (1000-650) \times 0.24$ (sp.ht) $= 17,520$ BTU's

(3) Heat liberated by Chemical Reactions

$.66 \times 380 = 251\#$ CaO per bbl.

Then $251 \times 954 = 239,434$ BTU's

$.0145 \times 380 = 5.51\#$ MgO per bbl.

$5.57 \times 1489 = 8204.39$ BTU's

(4) Heat carried into kiln through Blow Pipe

1080# air required for barrel.

$1080 \times (70-32) \times .2375$ (sp.ht) $= 9750$ BTU's

SUMMARY.

Heat Distribution in Kiln.

		BTU's per bbl.	%
(1)	Dissociation of Carbonates	357,000	26.6
(2)	Heating 600# Dry Raw Mix from 60° F. to 1000° F.	112,800	8.26
(3)	Heating 380# Mix from 1000° to 2500° F.	136,800	10.00
(4)	Loss through radiation from discharged clinker	118,500	8.8
(5)	Radiation by Shell & Hood	224,270	16.8
(6)	Carried off by gases(CO_2,etc)	29,080	2.16
(7)	Carried off by waste gases	144,190	10.70
		1,122,640	83.32
	Received by kiln	1,341,322	
	Difference or unaccounted (Probably Radiation)	218,682	16.45
			99.77

HEAT RECEIVED BY KILN.

		BTU's per bbl.	%
(1)	Combustion of Coal	1,068,390	76.95
(2)	From cooling gases	17,520	1.30
(3)	Liberated by Chemical Reactions	247,662	18.46
(4)	Delivered through air pipe	9,750	.72
	TOTAL	1,341,322	100.13

From the Summary, on preceding page, it will be noticed that only 44% of the heat delivered to the kiln is required theoretically--the balance being lost through radiation, carried off by waste gases, etc.

DESIGN.

In designing a kiln it is necessary to take into consideration the weakening effect of the heat upon the strength of the shell. For this reason it is necessary to so space the riding tires or supports that the outer fibre stresses at points of maximum bending moments will be nearly equal after considering the weakening effect of the heat and the joint efficiencies. Plate No. 7 illustrates the effect of improper spacing of tires. This kiln, while the exact duplicate of the one on Plate No. 9, due to the location of points of support, will carry only one-half of the laod, assuming the same factors of safety.

Were it not for the presence of heat, the design of a kiln would be comparatively simple, as riding tires could be placed as closely as desired. Plate No. 8 illustrates an 8'-0" by 125'-0" kiln on three

supports and the bending moment curve when all three tires are touching carrying rollers and when only two are touching.

In operating a kiln it is very often necessary to stop its rotation a few seconds or minutes for one reason or another:- due to the intense heat, the kiln receives a permanent "set". Assuming the carrying rollers were in proper alingment, there is a portion of the revolution when the kiln is riding upon but two tires. This obviously increases the bending moment and the outer fibre stress way beyond the limits of safety and the inevitable result is shearing of rivets or tearing of plates. Plate No. 9 illustrates an 8'-0" by 125'-0" kiln with tires properly spaced and the outer fibre stress curves plotted. Curve "A" representing stresses in the cold shell; Cruve "B", stresses after considering efficiency of riveted joints; Curve "C", stresses considering weakening

effect of the heat. In this curve, the stresses U'-L", I'-M"', and X'-Q" should be practically equal.

There is a certain law in nature called the Law of Diminishing Returns or "Law of Pivotal Points", and we have endeavored to apply it to the rotary kiln.

Given a certain sized kiln, materials, fuel and other important conditions, there is a certain production in barrels per day, where the fuel consumption is a minimum.

Conditions, materials and other features vary so in different locations that it is extremely difficult to make a definite statement as to this "Law of Pivotal Points" for each size kiln; we have plotted the curve on Plate No. 10, considering an 8'-0" by 125'-0" kiln, operating upon average limestone and shale and the "dry process".

To illustrate:- if this kiln is producing 300 barrels per day, the fuel consump-

tion is 150# per barrel; 400 barrels, fuel used is 125#; and the point of economical fuel consumption is 90# per barrel, at which point the output is 600 bbls. per day. Beyond this production the fuel consumption increases until the kiln is literally "choked".

TYPICAL INSTALLATION OF AN 8' X 125' ROTARY KILN.

DATE: JAN. 13-1909

SCALE: 1/16" = 12"

BY [signature]

SECTION a-a
WING BAFFLE WALL.

BR

Plate No. 1

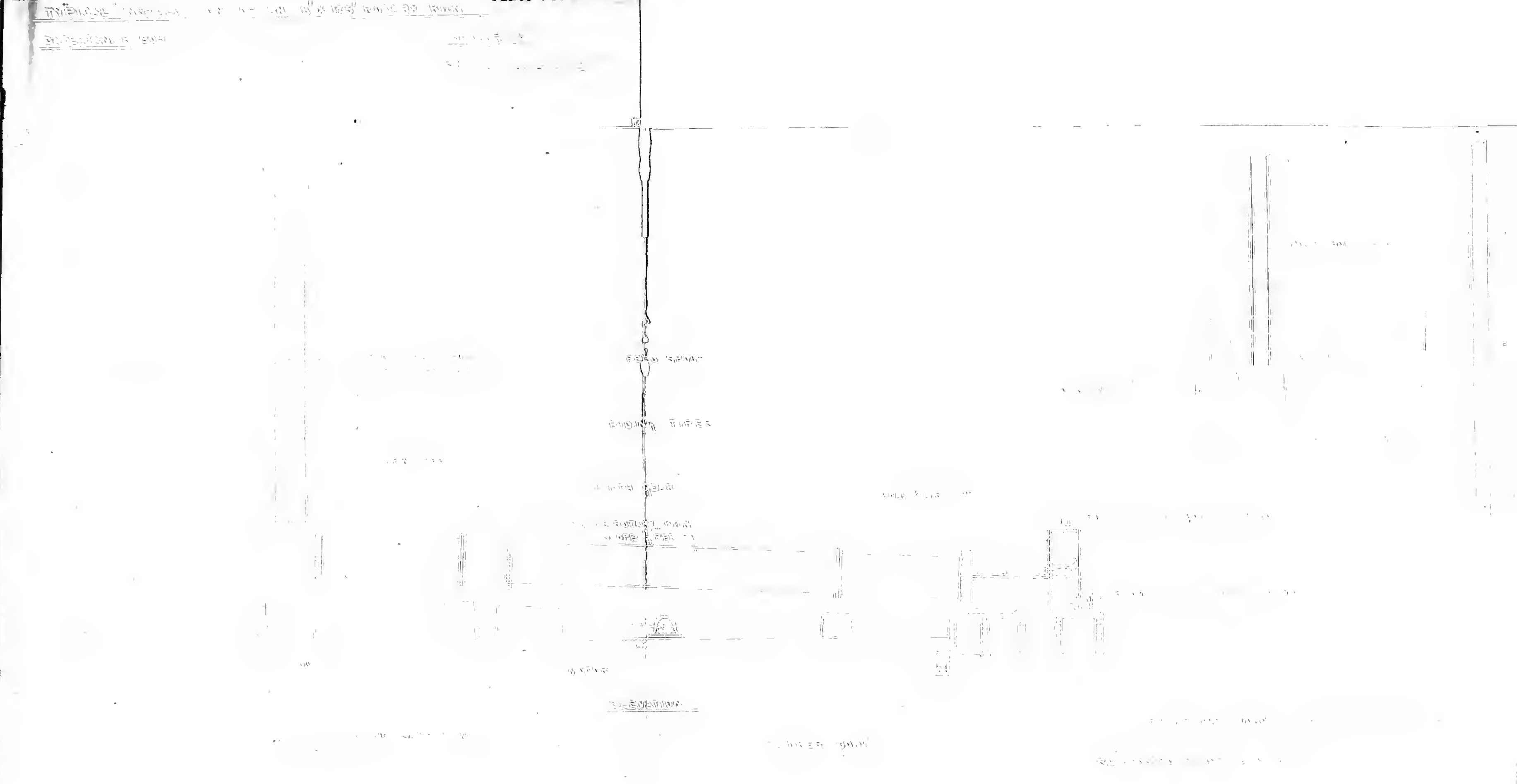


Plate No. 2

TEST ON A 6' X 60' ROTARY KILN.

CURVES PLOTTED FROM ANALYSES OF SAMPLES TAKEN AT INTERVALS OF 4' THRU-OUT LGTH OF KILN.

SCALE:

DATE JAN. 13-190[illegible]

BY: W. E. NEWBERRY

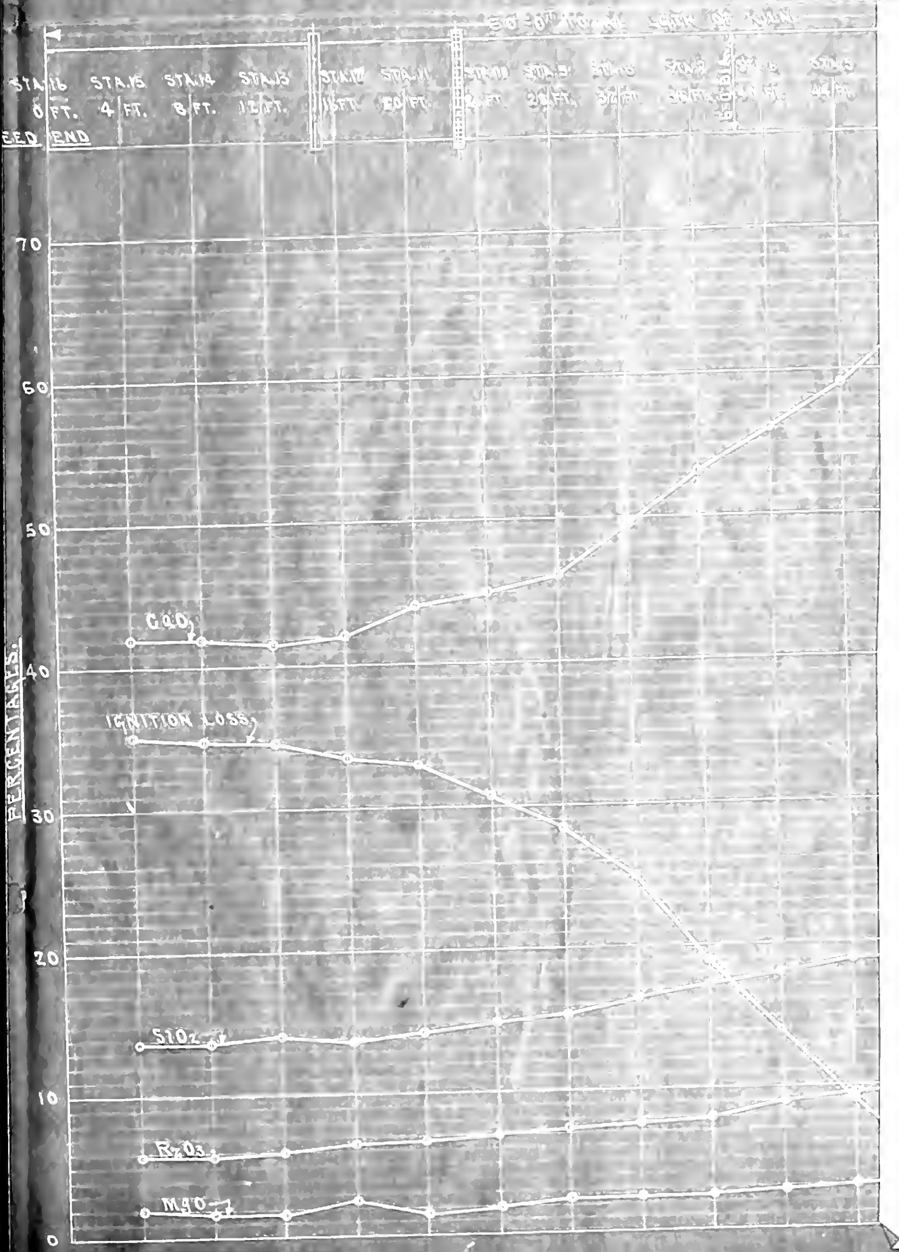


Plate No. 2

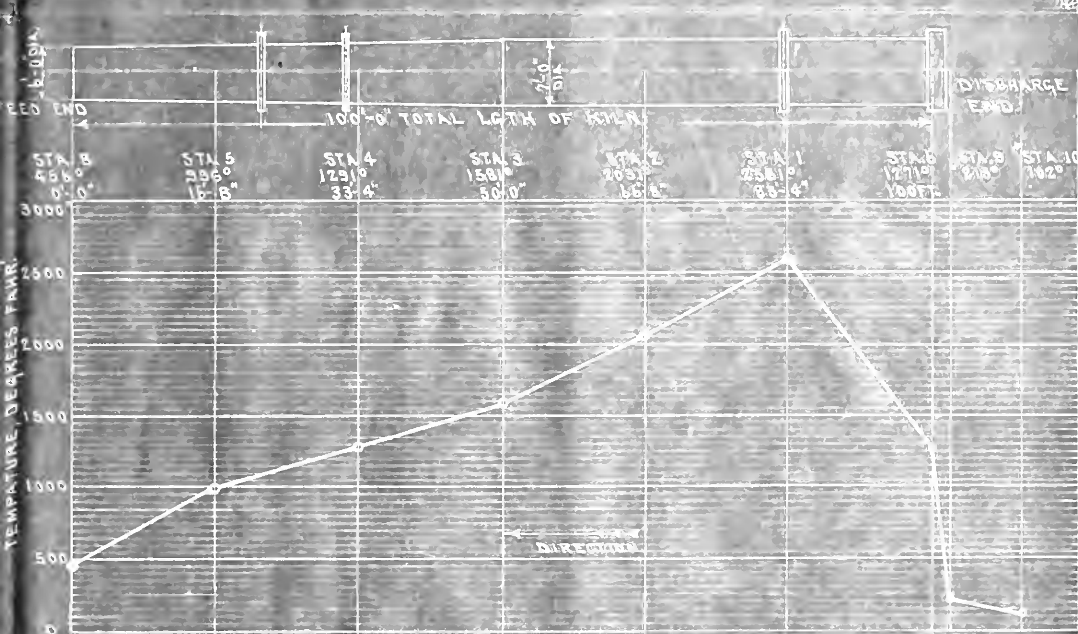
TEST ON A 6 & 7 X 100 ROTARY KILN.

CURVES SHOWING TEMPATURE OF GASES & MATERIAL AT INTERVALS OF 16'-8" THRU-OUT LGTH OF KILN.

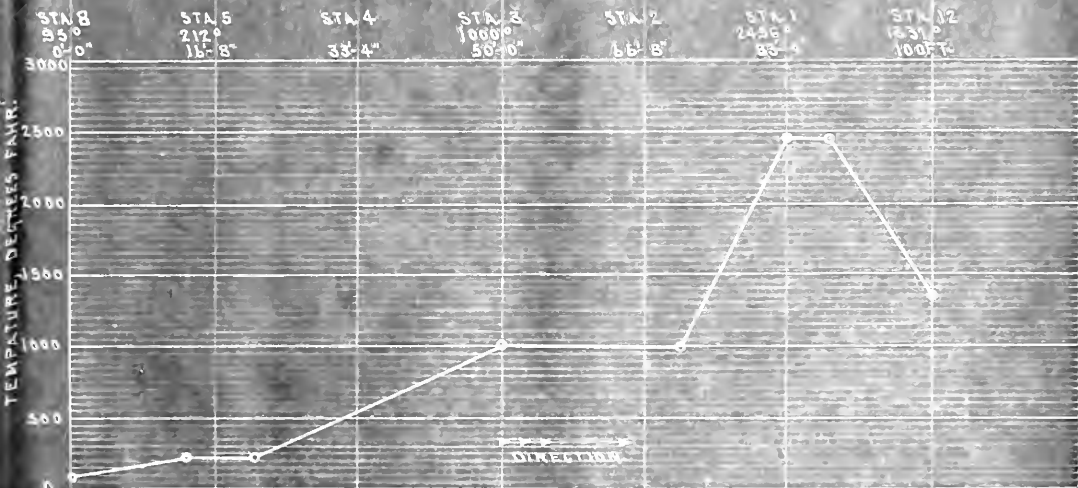
SCALE:-

DATE JAN. 13-1909.

BY [signature]



CURVE-1- MAXIMUM TEMPATURES OF GASES.



CURVE-2- MAXIMUM TEMPATURES OF MATERIALS.
CALCULATED FROM GAS TEMPATURES.
NOTE:- TEMP'S AT STA'S 8, 1, 12 ACTUALLY OBSERVED.

TEST ON A 6' & 7' X 100' ROTARY KILN.

CURVES PLOTTED FROM ANALYSES OF SAMPLES TAKEN AT INTERVALS OF 16'-8" THRU-OUT LGTH OF KILN.

SCALE:

DATE: JAN. 13-1909

BY-

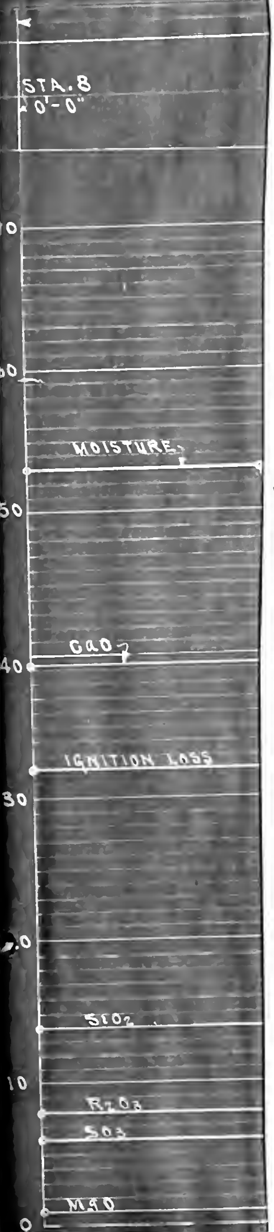
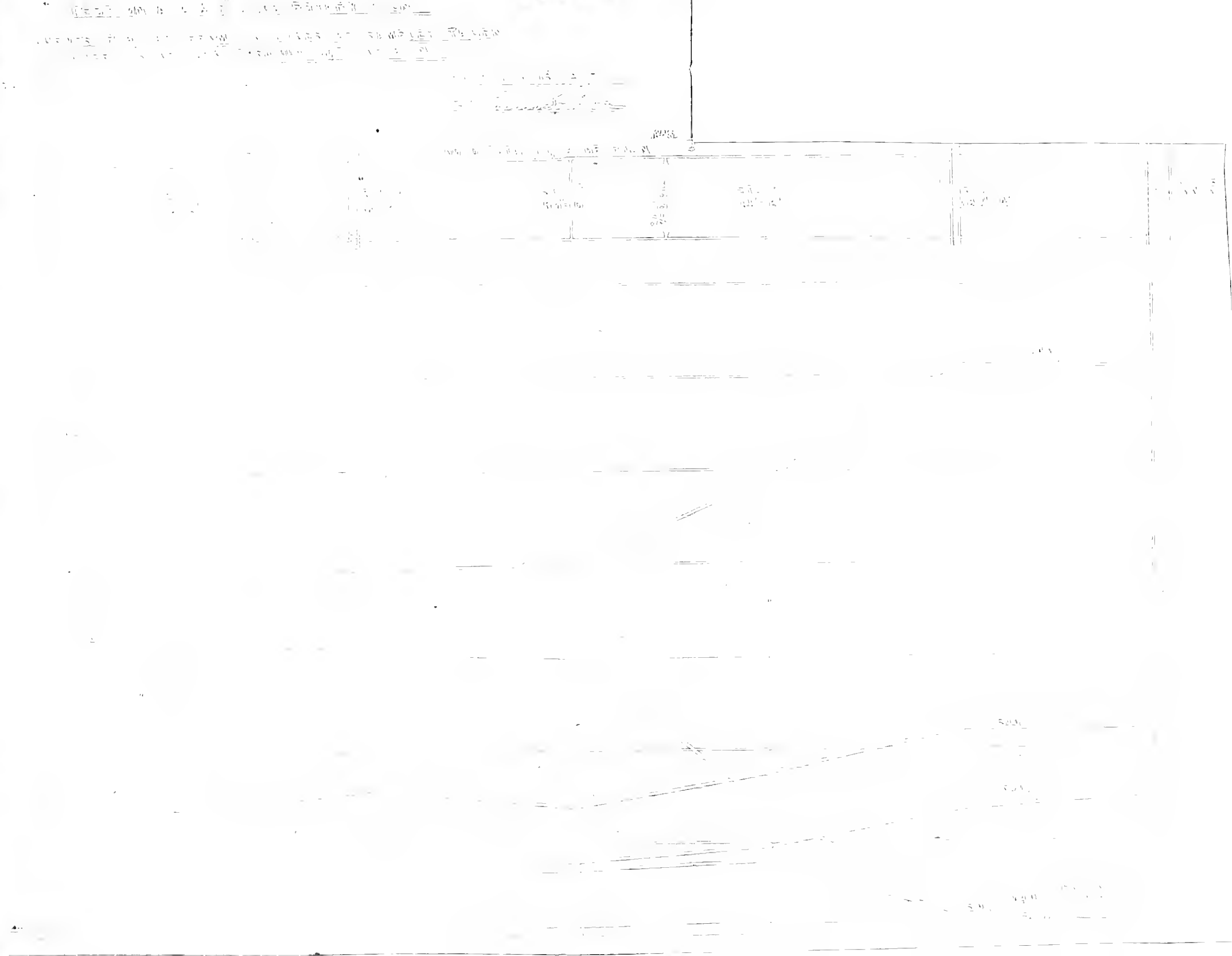


Plate No. 4



TEST ON A 5'-6" & 6'-0" X 160'-0" ROTARY KILN.

CURVES PLOTTED FROM ANALYSES OF SAMPLES TAKEN AT INTERVALS OF 10'-0" THRU-OUT L'GTH OF KILN.

SCALE:

DATE: JAN. 13-1909

BY [signature]

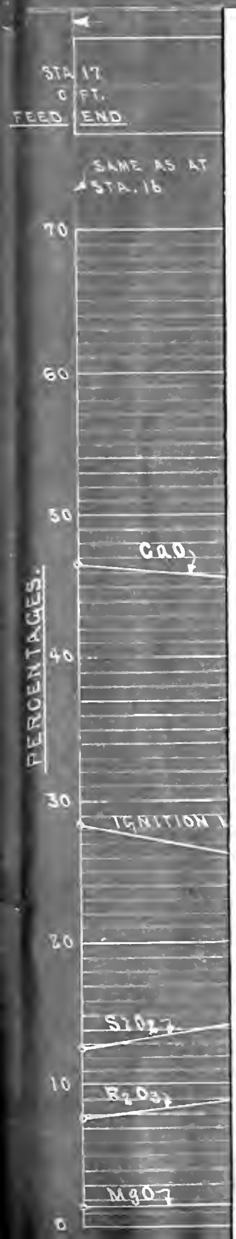


Plate No. 5

[illegible]

SIZE, OUTPUT & FUEL CONSUMPTION OF ROTARY KILNS

SCALE:

DATE [illegible] 1909

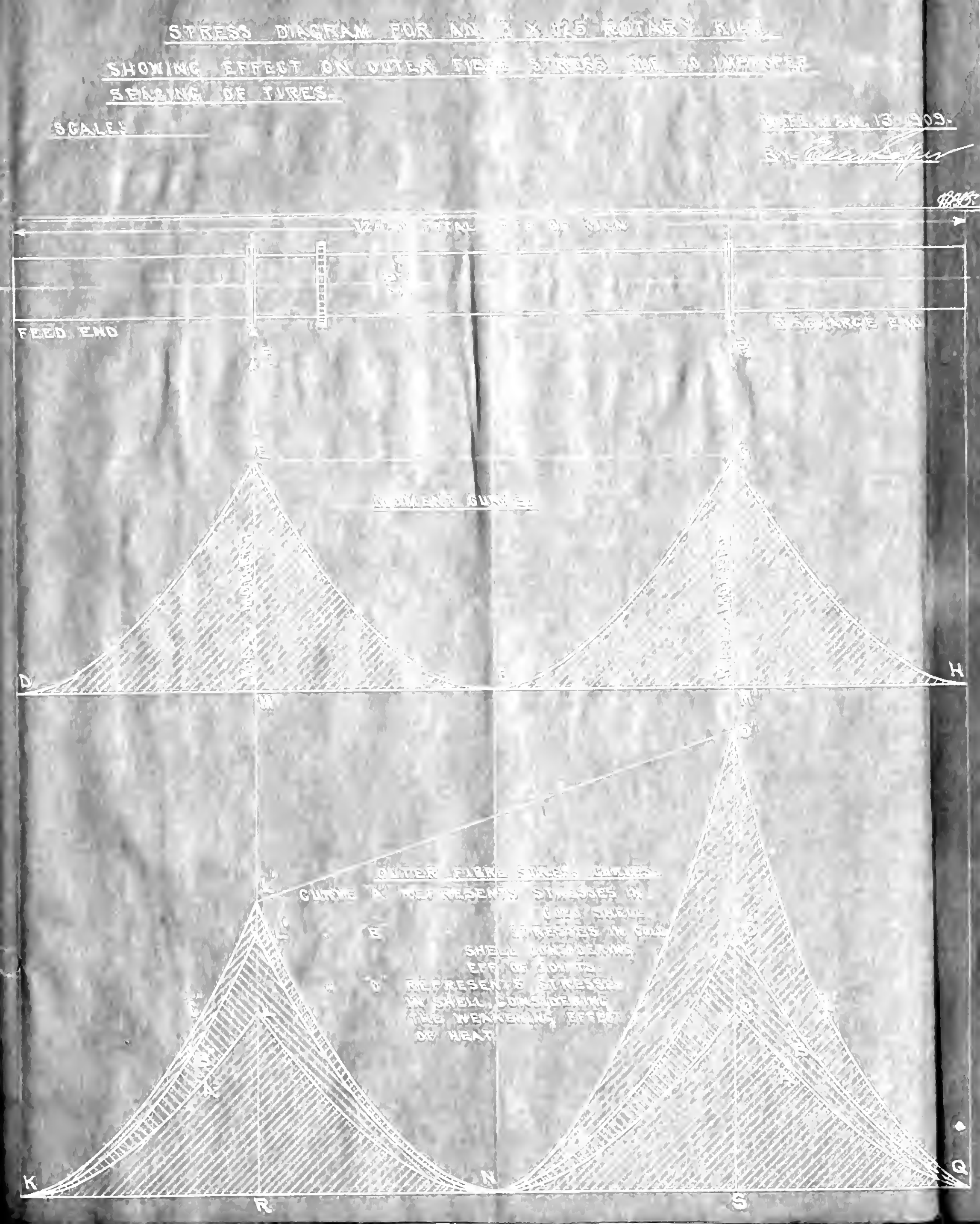
BY [illegible]

DRY PROCESS.

RAW MATERIALS – LIMESTONE & SHALE

TABLE SHOWS AVERAGE OF GOOD PRACTICE

SIZE			OUTPUT BBLS PER DAY	FUEL CONSUMPTION IN LBS COAL PER BBL
LINING	DIAM.	LENGTH		
6"	6'-0"	60'-0"	175	[illegible]
6"	7'-0"	80'-0"	300	[illegible]-135
6"	7'-6"	100'-0"	375	115-135
9"	[illegible]	110'-0"	450	100-[illegible]
9"	8'-0"	125'-0"	[illegible]00	90-100
9"	8'-6"	135'-0"	[illegible]75	85-90
9"	8'-[illegible]	150'-0"	700	80-85
12"	9'-0"	150'-0"	800	75-85
12"	10'-0"	175'-0"	1500	70-80
12"	12'-0"	200'-0"	2000	65-70


STRESS DIAGRAM FOR AN
ROTARY
SHOWING EFFECT ON OUTER
STRESS
SPACING OF TIRES.
SCALE:
13 1909.
BY
FEED END
MOMENT CURVE
D
H
M
OUTER FIBRE STRESS CURVES
CURVE A REPRESENTS STRESSES IN
SHELL
B
STRESSES IN
SHELL CONSIDERING
REPRESENTS STRESSES
IN SHELL, CONSIDERING
THE WEAKENING EFFECT
OF HEAT
K
N
Q
R
S

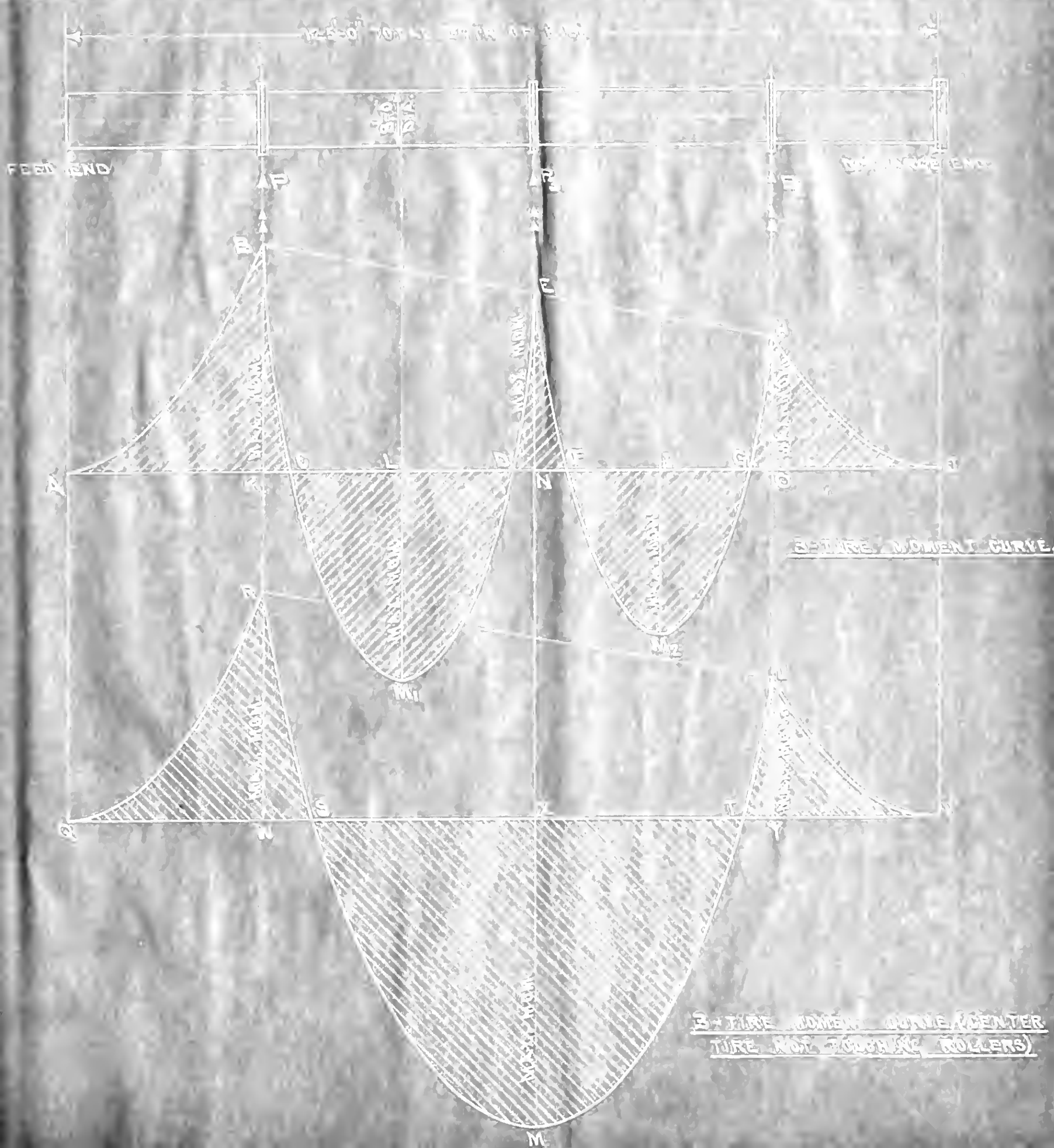
MOMENT DIAGRAMS FOR AN 8' X 125' ROTARY KILN.

SHOWING MOMENTS WHEN KILN IS SUPPORTED ON 3 RIDING TIRES
ALSO WHEN SUPPORTED ON 2 RIDING TIRES.

SCALE.

DATE JAN 15 1909

BY



STRESS DIAGRAMS FOR AN 8'X 125' ROTARY KILN.

SCALE:

DATE: JAN. 13-1909

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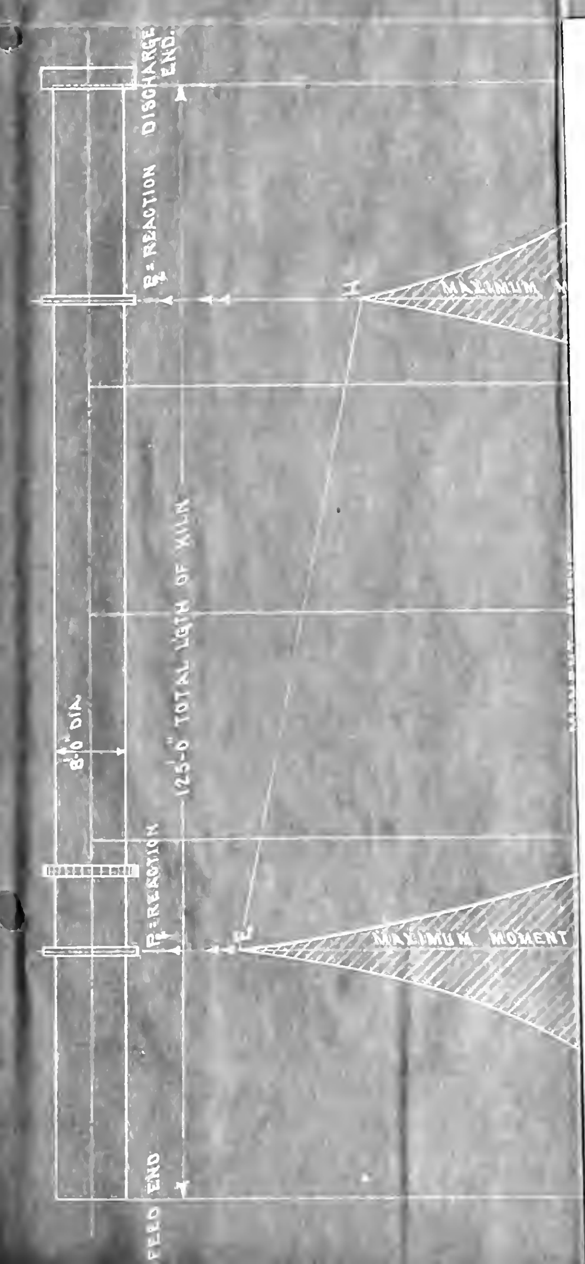
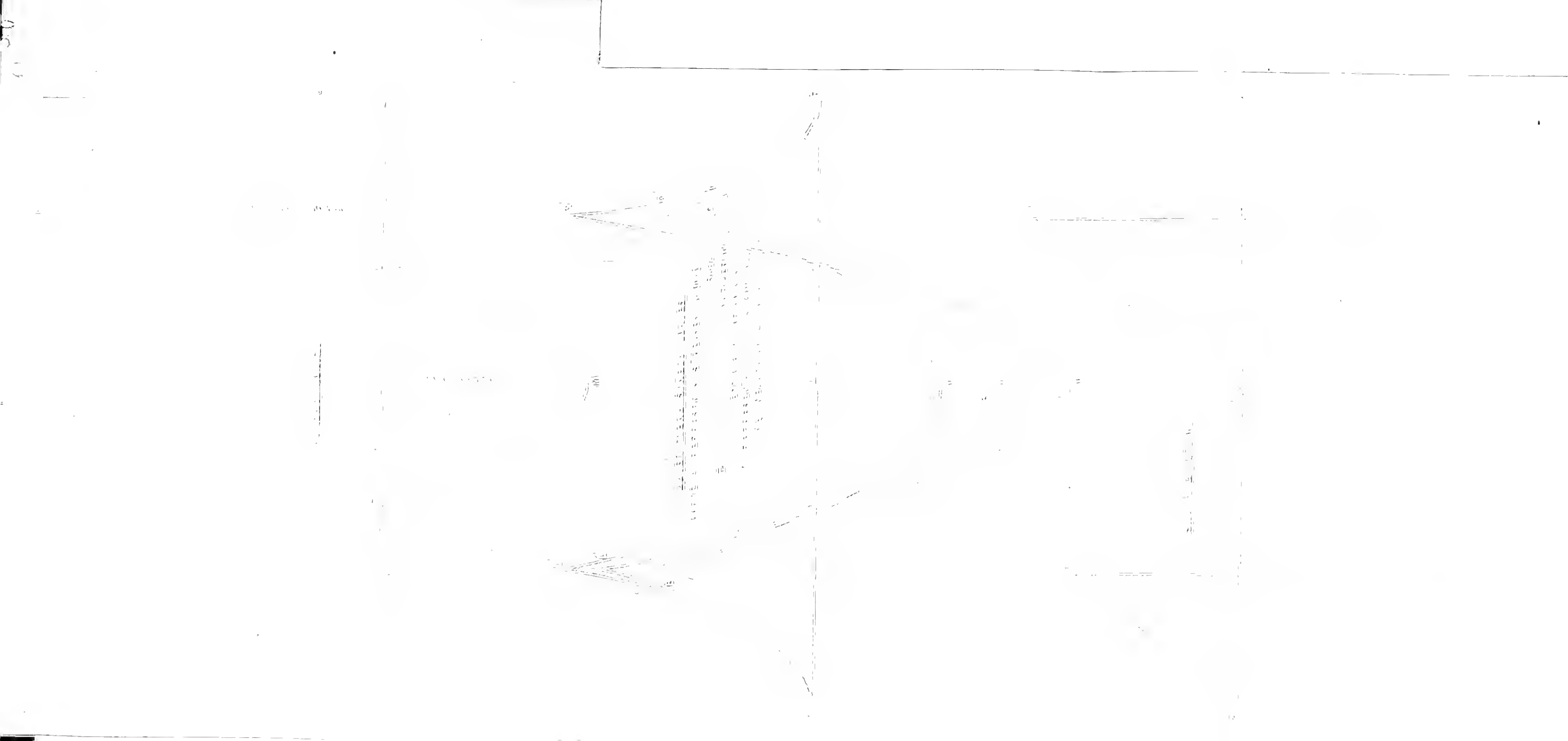


Plate No.9



8' X 125' ROTARY KILN.

CURVE SHOWING FUEL CONSUMPTION PER BBL ILLUSTRATING "LAW OF PIVOTAL POINTS" OR OUTPUT AT POINT OF MOST ECONOMICAL FUEL CONSUMPTION.

SCALE:-

RAW MATERIALS, ROCK & SHALE.

DRY PROCESS.

DATE: JAN.

BY-