GRINDING EFFICIENCY

IN

BALL MILLS

A STUDY OF THE FACTORS AFFECTING GRINDING EFFICIENCY IN BALL MILLS.

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May 1933

INDEX

Introduction........................Page 1.

Description of Apparatus............Page 4.

Calibration of Equipment............Page 13.

Investigation of Certain Factors

Affecting Relative Mech. Effic...Page 20.

Discussion of Tests.................Page 32.

Acknowlegements.....................Page 37.

Bibliography........................Page 38.

Plates..............................Page 41.

Tables..............................Page 50.

Photographs.........................Page 58.

INTRODUCTION.

An examination of the literature concerning general crushing practice and ball mill grinding in particular clearly indicates the need for a thorough investigation into all the phases affecting the efficiency of this type of grinding machine.

Today ball mills are used extensively wherever grinding is an adjunct of a mechanical process but it is in the mining and metallurgical industry - in the reduction of ores and minerals-that ball mill grinding has its widest application.

There are many papers, articles and technical publications dealing with the problems of fine grinding and almost as many different and varied conclusions based on the experimental results outlined. The reasons for the wide difference of opinion in these instances are:-

1. The use of laboratory machines for experimental work when the macine so used does not duplicate conditions met with in practice.

2. Unreliable and varied methods of determining the amount of crushing performed.

3. Improper elimination of mechanical sources of error.

4. Reducing experimental results to mathematical formulae which are based on unsound foundations.

(a) On results which at best are only approximations.

(b) On conditions which are ideal but impossible to attain in economic practice.

(c) On the measurement of equally important factors with different degrees of accuracy.

5. Improper co-ordination of results - stressing the effect of a few variables in the product of a combination of numerous related variables.

6. Too hasty and inaccurate interpretation of results.

These few factors outline some of the major causes for the confusion which now exists in the field of fine grinding.

It was felt that a thorough investigation extending over a number of years with particular care paid to details, each factor being stressed in turn, would give considerable data from which accurate conclusions could be drawn to clear away the existing difficulties and point the way to increased efficiency in ball mill grinding. With this in view a grinding plant was installed in the Mining Laboratory during the summer of 1932 and the session 1932-33 was spent in examining, testing and studying the mechanical characteristics of the plant and equipping it with the necessary regulators and control apparatus. Attention was directed principally to the elimination or minimizing of mechanical losses, investigation of each link in the chain from power line to crushed rock and a study of a few factors in the grinding cycle.

The control and grinding equipment consists of:

(1) 220 and 110 volt power lines D.C. current.

(2) A Thompson integrating wattmeter (G.E.Co.) permitting direct reading to within 10 watts and estimating to 5 watts of the power consumption.

(3) A voltmeter and an ammeter for direct sight readings.

(4) A $7\frac{1}{2}$ h.p. English Electric D.C. motor directly connected to a Bell brake with lever arms and a balance for the measurement of applied brake loads. Also connected to a mechanical speed counter.

(5) Line voltage resistances and motor field resistance for control of input voltage and speed of the motor.

(6) Pulley drive on the motor connected by a rubber belt to the main pulley on the ball mill which turns a pinion driving the main gear on the ball mill. The belt has an automatic tightening device - a counterweight and pulley which keepsit in tension.

(7) A Marcy ball mill made by Mine & Smelter Supply Co., Denver, Colorado, with a feed scoop and quick discharge grid. The mill is mounted on trunions.

(8) A Denver classifier.

(9) An endless rubber belt conveyor for the mill feed.

(10) A centrifugal pump.

(11) An automatic pressure grease gun delivering grease to the main mill bearings.

(12) Automatic pulp samplers.

(1) In the mill discharge circuit

(2) In the classifier return "

(3) In the classifier overflow "

(13) Electric revolution counters, counting Feed belt travel. Mill revolutions. Classifier strokes.

(14) Oil container continuously oiling the gear and pinion drive on the mill.

(15) Adjustable water feed valves from constant level tanks.

(16) Additional laboratory accessories necessary in making a crushing investigation

(a) Filters

(b) Calibrated glass graduated beakers

(c) Drying ovens

(d) Bell screening machine with Tyler standard screens.

DESCRIPTION OF APPARATUS.

The power line in the laboratory comes from the University power house and is direct current, usually delivered at 224 to 228 volts depending on the line load which fluctuates widely during the day. In order to be certain of the efficiency and speed of our motor we found it necessary to keep the applied voltage constant during our tests. In order to do this two variable resistances of .036 ohms each were inserted in series in the incoming line. They each have 24 taps. For light loads a further fixed resistance can be plugged in the circuit. With this arrangement it was possible at all times to keep the applied voltage at 220 volts. A sight voltmeter recorded the voltage and the controls were shifted manually.

Power measurement.

With the voltage constant, sight power readings could be obtained with the ammeter. During all tests power consumption was measured with a Thompson integrating D.C. wattmeter. The test needle on the meter was replaced by a larger dial which was graduated and facilitated reading the meter accurately. The wattmeter was examined and tested by the electrical department. It varied less than 1% of the true reading at the end of one hour's use. This correction was not made in any of our calculations as we are principally interested in motor output which we determined accurately.

Motor.

The motor was designed and built by the English Electric Company. It is compound with a continuous rating of 30.6 amps, 220 volts at 625 r.p.m.

The speed is controlled by two variable resistances in series. The smaller resistance has 36 taps and the larger 21 taps, two taps on the larger have about the same effect as the total smaller resistance so that a very fine adjustment of speed is available. The resistances cut the field current from 1.5 to 0.2 amps with a corresponding speed range from 640 to over 2000 r.p.m. at light loads. The motor has a cooling fan attached to its shaft. This permits good cooling of the windings and the temperature of the machine under load becomes and remains constant after a short period.

The Bell Brake.

In order to determine the output of the motor for any input, the armature shaft was permanently connected through a flexible coupling to a Bell brake. The brake consists of the usual brake drum with a steel shaft mounted in ball bearings. The braking load is applied by winding or lapping a canvas belt, which has been soaked in oil, on the drum. One end of the belt is attached to a system of levers, the other passes around a portion of the brake drum, over a roller, which can be shifted to any position about the drum (hence lapping or unlapping the amount of belt on the wheel), and is attached to a lead weight (11 pounds) hanging freely. The roller which controls the belt lap is operated through a worm gear so that very minute changes in load conditions can be made. In using the brake the tare of the belt and weight is obtained and this weight substracted from the weight recorded on the balance. The drum is cooled by a continuous stream of water from a constant level tank which is directed inside the drum, flows to the edges, around the inside of the braking surface and is scooped out by a pipe, adjusted close to the inside periphery of the wheel and run to waste. The advantages of this type of brake over others is its extreme sensitivity and smoothness of applying a load which can be kept constant for long periods.

Speed Reduction Drive.

The motor has a 5¾" paper pulley on the armature shaft. It drives a 4-ply endless rubber belt running on the 24 inch wooden mill pulley. This in turn drives the countershaft and pinion with 15 teeth and the main mill gear with 91 teeth. Both gear and pinion are kept lubricated with oil as the gear dips constantly into an oil reservoir. Both are protected from dirt and grit by a metal cover which also prevents oil from spraying about the laboratory when the mill is operating.

The belt is kept in uniform tension by a counterweighted idler pulley or belt tightener.

Ball mill.

The ball mill is three feet long and averages 24.04" in diameter inside the liners. The liners are of manganese steel - wave type with 6 longitudinal waves. The height of the wave crest above the trough is 1.05". They are made in 6 pieces and are bolted to the mill shell. The feed scoop is of a standard type with a spiral conveyor through the main trunnion. The mill is equipped with a Marcy quick discharge grid. The weight of the mill is carried on the two main trunnions which are mounted in babbit journal bearings kept constantly lubricated by grease from an automatic grease feeder. The total weight of the assembled mill and liners is 3725 lbs. Facilities are arranged so that the mill can be lifted out of the bearings and lowered to the laboratory floor where the end of the mill can be removed for any necessary internal adjustments. The mill is equipped with a small man hole through which the ball load may be put in the mill.

The weight and location of the scoop feeder caused a fluctuation in the amount of power drawn by the mill during its revolution. The scoop was counterbalanced by attaching lead weights to the main gear. The power drawn by the counterbalanced mill was quite steady.

Continuous Grease Feeder.

The grease feeder for the main mill bearings consists of a large cylinder containing a piston, piston rod and the necessary packing. The piston rod is threaded and has a stop catch key which prevents it from rotating when in place. The rod passed through a threaded wheel driven by a worm gear. The worm gear is operated by a speed reducer which in turn is driven by a large pulley connected by a leather belt to a small pulley on the mill countershaft. The overall speed reduction of the feeding arrangement is 2000-1.

The cylinder is filled with grease by pulling back the piston to its extreme position, (removing the key mentioned above in order to do this) attaching a hose from a vacuum pump to a pipe on the side of the cylinder and drawing grease from a container by means of the suction. When the gun is filled, necessary piping is replaced and the mill started. The slowly revolving threaded wheel forces the rod and the piston forward displacing the grease which is forced through piping to the incoming side of the journal bearings. The cylinder when charged is 7" long 4" diameter. Such a charge at about 80% critical speed lasts 60 hours.

Discharge Screen.

The discharge end of the mill is fitted with a circular screen (8 mesh) to take out large pieces of rock from the discharge. These might interfere with the pump if left in the circuit. The screen is washed with a continuous spray of water from a constant level tank. The water has a dual purpose; it keeps the screen open and washes most of the fine particles of crushed rock off the oversize which is discharged by the screen.

Pump.

The mill discharge, mixed with a regulated amount of water is pumped to the classifier by a standard $1\frac{1}{2}$" centrifugal pump.

Classifier.

The classifier is a recent development brought out by the Denver Equipment Co. It consists of a rotating drag in an inclined box. The drag is a half section of a low pitch spiral; and has a reciprocating motion. During the down stroke the spiral is clear of the sand and water but on the up stroke it helps move the sands up the incline. In effect, the operation is a combination of Dorr and Akins principles.

Feeder.

The conveyor feeder consists of an endless rubber belt driven by a friction roller arm which is raised and lowered by a cam operated by a speed reducer and a small motor. The speed of the belt is controlled by adjusting the amount of movement the cam imparts to the lever arm. This is measured by a vernier attached to the arm.

The belt is loaded from a small hopper with a fixed opening. Felt pads under which the belt passes at the edges keep a feed of uniform cross section and prevent losses. The spill-way is directed into the feed reservoir at the feed end of the mill.

Automatic Samplers.

The samplers used to check quantity and quality of pulp in the mill circuit were developed in the McGill laboratory. As originally designed they consisted of a discharge pipe sloping at an angle of 45° which was rotated by a motor through a worm gear drive. In the circular path which the discharge end of the pipe made, a radial cutter was placed. The cutter opening was made 1/50 of the area of the discharge ring and the edges were made radial so that it was natural to expect 1/50 of the total discharge would be caught by the cutter. When the sampler was connected to a steady flow of water which could be varied it was found that the portion of the total water retained by the sampler varied from 1/36 to 1/44 depending on the flow of water.

A study of the elemental equation representing the mathematics of the system verified the fact that the portion should be 1/50 but it also indicated that in the sampler as arranged the time factor (during which the sample was procured) was a function of the flow of water and that this was disturbed due to the relative oscillation of the water in the discharge pipe. It was felt that if the distributor was made narrower and radial the time factor would then be practically independent of rate of flow. A radial distributor was made and the results then varied from 1/41 to 1/44. The variation was traced to a disturbed oscillating condition in the water coming out of the distributor. Two baffles were then inserted in the elbow at the entrance to the distributor and the sampler became quite steady. They did not reach the 1/50 expected but in all probability the difference is due to the thickness of brass about the cutter opening - diverting an extra amount of water through the opening.

Table No. 1 illustrates the results obtained for a given sampler (with water).

Water Supply.

The main water supply comes from a large constant level reservoir and is fed through calibrated valves to the system. The small amount of mill feed water required is regulated from a separate tank and can be controlled very accurately.

Feed Hopper.

The rock is fed to a large hopper from which is drops directly to a small box built over the conveyor belt. There is a clearance between the main hopper and the feed box so that the feed pressure on the belt is more or less independent of the amount of rock in the main hopper.

Recorders.

The motor is directly connected to a speed counter - a worm gear and graduated wheel operating a Crosby recorder. The classifier, mill and conveyor feeder have make and break contacts on them which are incorporated in an electric circuit as outlined.(Plate V). The revolutions or strokes are recorded by magnetic recorders presented to the department. The counters require about 27 volts for steady operation. Four 28 volt lamps were connected in series, three are used to illuminate the recorders and the circuit was tapped off across the fourth making a very satisfactory arrangement.

Feed Cover.

The feed scoop had a tendency to throw the feed about the laboratory at high speeds so it was enclosed with a metal cover.

Calibration of Equipment.

The work actually expended in crushing and which we have to measure accurately in order to understand just what is going on inside the mill is the total work delivered to the system less the mechanical losses which occur in the crushing machinery.

In studying the efficiency of a ball mill a great many of these losses are inherent in the machine and should be directly charged to the efficiency of the mill but I felt that in order to make our work of practical use it would be well to segregate even the inherent losses in our machine in order that they could be compared with similar losses in actual practice. It appears reasonable to suppose that the laboratory ball mill, because of its relatively small size and capacity has a higher ratio of mechanical losses than a standard commercial machine.

Electrical input to the motor was recorded by the wattmeter. The output for different speeds and load conditions was determined with the Bell brake. In obtaining the input and output curves the load was applied with the brake, the motor field resistance being set at a particular tap. After the speed became steady for the given condition the watt meter was read at 10 minute intervals until the electric input reached a constant quantity. Speed did not become steady until the motor temperature became steady. This usually took about 1 hour at medium loads and longer at lighter loads. The procedure was followed for loads from 0 to $7\frac{1}{2}$ b.h.p. and motor speeds from 650 r.p.m. to 1550 r.p.m. at full load and over 2000 r.p.m. at light loads.

The water which cooled the brake during the motor tests was shut off during the mill tests so a correction curve for the work expended on the water was determined.

The energy so used is lost in whirling the water about and in expelling it through the discharge pipe. It is a curious fact that the total loss in this manner is less at high speeds than at intermediate speeds. The power consumed increases slowly to a maximum and then decreases as the speed is increased. See Plate No. II. This is in all probability mainly due to two variable forces which exert their effects on the brake drum.

1. The amount of energy consumed in whirling the water

around at high speed.

2. The impinging of the ring of cooling water inside the drum on the sharp cutting edge of the stationary pipe which removes water from the wheel. The impinging action exerts a retarding action which absorbs a small amount of energy. Possibly it may be explained in part by considering the formula

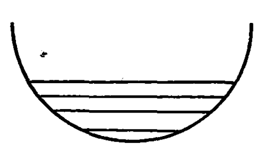
$$Q = VA$$

where Q = quantity of water removed

V = velocity

A = the cross section area of water impinging on the cutting edge of the pipe

Q is absolutely constant. An increase in speed reduces the impinging area as the attached sketch illustrates until at high speeds the area can become very small, hence less power may be absorbed in this manner. This might account for the decrease in power noted in the curve at the higher speeds.



The curve was obtained by connecting the motor to the empty ball mill and running it at different speeds until the input per period became constant and then, with the help of the uncorrected efficiency curves, approximating very closely the water loss. This was then added to the motor output and used in drawing the final curves.

Initially, the motor was equipped with a small external field resistance, so only a small speed variation was possible.

Five complete curves were obtained over this range before the new resistance was purchased. The original plan was to obtain higher mill speed by changing pulleys on the mill and motor but this was rather an awkward arrangement and as it was possible to vary our motor speed much more than we were then able to do, a new resistance controller was installed and seven complete curves obtained over its range. See Plate III.

In using the curves to find the output for a given condition speed and input are the governing factors. Efficiency between any two consecutive curves varies almost directly as the speed - using direct proportion introduces no appreciable error above curve No. 2. Between (1) and (2) however the variation is not a straight line relationship but the five curves mentioned before cover this area. Plate IV shows the relationship as determined by experiment.

The output energy of the motor is used or lost in the following manner;

(1) A mechanical loss due to friction and slip in the belt transmission.

The belt and tightener are standard equipment and the losses are probably small. Slip over the range investigated was negligible. With mill speed varying from 29 r.p.m. to 77 r.p.m. and motor speed from 684 to 1819 the relationship between the two on 24 intermediate readings under different load conditions (1.29 k.w.h. to 4.01 k.w.h.) was constant.

(2) A friction loss in the pinion or countershaft bearings. This amount should be slight as the shaft runs in ball bearings.

(3) Mechanical loss in the pinion gear drive.

The gears used in the ball mill are made of cast iron and were originally very rough. The mechanical loss was undoubtedly high at first. This was reduced a great deal by running in the gears using crushed quartz to smooth off the irregularities. After several hours running the grit was carefully cleaned out and the mill started. Power readings were taken with dry gears and oil was then added and the change in power noted. At the light load (empty mill) the total input dropped 15% when oil was added. It was then decided to keep the gear drive constantly lubricated in order to approach a steady and maximum efficiency. A cover and oil bath for the drive was constructed and added to the mill.

In order to segregate the losses from the motor output to end of the gear chain, the possibility of putting a prony brake directly on the end of the mill and by applying loads which could be ascertained, determine the actual loss, was considered. The success of this idea would depend on the constancy of the main mill bearings. After consultation with Mr. Patten of the Mechanical Engineering Department this idea was abandoned. He pointed out that a brake attached directly to the mill would introduce torque disturbances in out bearing reactions and that the resultant of this variation would probably be greater than the variation in efficiency of our gear for different loads. This difficulty could be eliminated by attaching a brake through a flexible coupling to the mill, but as the necessary equipment was not available the investigation was not attempted. After an examination of the gear Mr. Patten was of the opinion that our gear was quite efficient and that the variation over our loading range would be small.

Main Mill Bearings.

The total weight of the ball mill and load rests directly on two large babbit bearings. These bearings were originally lubricated by grease from grease cups on each side of the bearing, these fed into channels in the bearing surface. In order to try and improve the lubrication,oil sight feeders were inserted on top of the journal box covers and during tests these fed oil continuously to the bearings.

The overall power consumption of the grinding plant still varied considerably even after several hours continuous running and the bearings were suspected to be the principal cause of the variation. The original grease cups were replaced and power readings taken, feeding grease to the bearings by hand. The power consumption dropped immediately and began to approach a steady condition. Professor Bell then devised the automatic grease gun described before and after it was installed power tests could be repeated and steady conditions prevailed.

The mill was then allowed to run continuously for several hours a day for four days and the amount of grease fed to the bearings was cut down to an economical yet safe limit. The mill could then be started, power readings taken at half hour intervals and after two hours running power consumption became steady.

Mill Feed Conveyor.

The rock feeder was calibrated for different feed rates. This variation was obtained by shortening or lengthening the distance through which the cam raised the lever arm and noting the corresponding vernier reading. The result so obtained approximated a straight line relationship between feeding rate and vernier setting, but individual tests rarely gave repetitions of results, so a small wheel with eight contact points and the necessary brushes was attached to the return pulley of the conveyor system and this was tied into our electrical system in series with a counter. This recorded every time the return wheel made 1/8 turn. The relationship between the fractions of a turn and weight of feed rock was found to vary slightly more than 1%, so our recorder served as a check on amount and rate of feed in grinding tests.

INVESTIGATION OF CERTAIN FACTORS AFFECTING R.M. EFFICIENCY.

In most of the published works dealing with grinding, speed of the ball mill is represented as a percentage of the theoretical critical speed. Most of the results shown here are based on absolute mill speeds for convenience in using these results in future investigations. The final results can be expressed in the usual manner which is much better for comparative purposes.

The theoretical critical speed is the speed at which the peripheral speed of the mill will carry the outermost ball layer around the complete circuit.

It is derived from the expression

$$\cos\theta = \frac{4\pi^2 SN^2}{g}$$

where $\cos\theta$ = 1

S = radius of rotation of the ball (radius of the mill less the radius of the ball)

N = Revolution of the mill per second.

g = Acceleration due to gravity.

In our mill using the largest available ball ($1\frac{3}{4}$") the theoretical critical speed is 56.7 r.p.m.

The first phase of the work investigated was the dead load power consumption. When a ball mill is grinding ore only a percentage of the input to the machine is doing useful work. By eliminating the grinding work and otherwise duplicating conditions the loss of power or the amount of power which does not go into grinding action can be ascertained. In investigating the efficiency of a ball mill it is impossible to eliminate some of these losses as they are necessary adjuncts of the process, but at the same time we are not justified in assuming that our ball mill behaves in a manner similar to a standard machine as far as these inherent losses are concerned.

By dead load loss is meant the total amount of power consumed by the mill outside of the mill liners. It includes bearing friction and such mechanical losses. It can be determined by duplicating the weight of the ball charge in the mill as a solid load and determining the power consumption for different speeds.

Recently (Dec. 1932) Gow and Guggenheim have published the results of their investigation of the dead load loss in a commercial ball mill. Their work will be used as a basis of comparison.

Three dead weight load tests were run. The investigation will eventually include an examination of the effect of different weights of grinding media and it was felt that by investigating three conditions, intermediate load losses could be determined by interpolation.

A timber compartment equal to 40% of the mill's volume was built in the centre of the mill. This was packed tightly with the ball charge and securely wedged in place. The mill was then closed and replaced in its bearings. The ends of the mill were sealed and the space not occupied by balls filled with water.

The heavy mill was allowed to run for a few days and then power readings were taken at half hour intervals throughout the individual speed tests. When the mill was set at a new speed two hours were allowed to obtain a normal condition, then readings were commenced and repeated until they became steady. A speed range from 27 to 78 r.p.m. was investigated. Upon completion of this series the water was drained from the mill and another series of tests run at this lighter load. Then the empty mill dead load loss series was determined. As a result three curves were plotted for loads of 0, 1164 and 1764 lbs. added weight. The curves are plotted on a direct speed base. The power readings are net power from the motor. See Plate No. V.

The ball load to be employed in the tests was set at 1200 lbs. By using the above curves I have determined the dead load loss for a 1200 lb. load and have plotted it on the same base as Gow and Guggenheim used. I have also included their curve. See Plate VI. The new curve approximates a straight line as did their results. In order to correctly visualize the difference between the two curves I have taken their figures for 80% critical speed and compared them with our figures for the average of test 1E and 2E which will be described later. The figures are:

	COMMERCIAL	LABORATORY
Motor Input	87 H.P.	6.36 H.P.
" Output	78.3 H.P.	4.58 H.P.
Dead load loss	11.0 H.P.	1.17 H.P.
Speed	80% crit.	80% crit.
Overall Mechanical loss (includ. dead load)	23%	46.5%

If we draw our dead load power consumption curve on a scale which bears the same relation to the commercial mill scale as the motor output of the laboratory plant does to the motor output of the commercial plant they would coincide if the ratio were the same in each case - that is if our mill duplicated commercial conditions. This has been done in curve three on Plate VI. The curve is much steeper showing a greater relative dead load loss.

This can be extended still further if desired. If we are certain that the figures shown by Gow and Guggenheim represent good average commercial conditions then we can use their curve and our new scale to obtain a relative dead load loss in our experiments.

A glance at the figures submitted will show that the overall efficiency of our plant is going to be very low compared with a commercial plant. A good deal of our loss is in our motor. It was not designed for a given set of conditions, rather efficiency was sacrificed for ruggedness, stability and to allow for considerable variation in speed and load conditions.

From our experiments using the motor efficiency and dead load loss curves we can obtain the nett grinding power in any test. Most of the future work will be concentrated on the relation of nett power and grinding. I would like to suggest that a comparative figure for commercial work can be obtained by using our nett power figure, adding in a comparative dead load loss determined from the new scale and the commercial curve and increasing the sum by 10% to allow for a practical motor loss. This resultant figure would then, in my opinion, be applicable to practical work.

Otherwise, future investigators must bear in mind that there are higher inherent losses in our plant than will be met in standard practice and care must be exercised in preparing results in order that they may not distort their findings.

It must also be noticed that the power transmission units - belt, pulleys, gear and pinion will not transmit all amounts of power with the same efficiency. Under different grinding conditions the amount of power lost in this way will vary with the load transmitted so that the actual nett power expended in grinding is probably a lower amount than that obtained using the provided data; however until the absolute efficiency of these items is known the dead load loss will have to be approximated by this method. In addition the bearing loss due to a rotating flywheel and that due to the weight of moving balls is not identical because of the shift in the reaction points on the bearings, however, the results obtained are a fairly close approximation of the nett loss and as such are worthy of inclusion in the calculation of nett efficiency.

Our limited experiments with different lubricants in both the mill bearings and the gear drive seem to point towards a possible source of power loss which could be lowered considerably. The field for such an investigation is one of major importance. In commercial machines, using the figures given by Gow and Guggenheim the loss of power in this manner amounts to 13% in the mill and they are probably striving to maintain the best conditions possible. An elimination of a portion of this loss would result in considerable saving in a machine which commonly requires 200 h.p. to operate it.

Upon completion of the above tests the mill was charged with 1200 lbs. of balls - 300 lbs. each of $1\frac{3}{4}$, $1\frac{1}{2}$, $1\frac{1}{4}$ and 1 inch balls. These ratios were used to approach conditions existing in practice where a gradation in size of the balls is inevitable.

Short speed tests were then made of power consumption, rotating the ball load dry and then with water. The results were obtained by running the mill at different speeds throughout the range and determining the power consumption for each trial. The dead load loss was subtracted from the motor output and the nett power expended inside the liners determined. This was plotted on a speed base. See Plate VII.

After the dry ball tests were completed water was allowed to run through the mill and the procedure repeated with wet ball charge. Another curve was plotted on the same base (Plate VII).

Owing to limited time, the results are only qualitative in that bearing conditions were probably not constant during the trials but the curves show a fair uniformity, power increases to a maximum probably at the actual critical speed, then as speed increases, power decreases until the whole mill and balls move as a single unit when it becomes similar to the solidly loaded mill. These tests should be repeated for the times required to attain uniform bearing conditions.

When the water was added, power consumption increased throughout the entire range of speed. This is due to increased grinding between the balls and bears out the generally accepted belief that wet grinding is more effieient than dry grinding. There is also a slightly heavier load in the wet test as the mill retained 50 lbs. of water with the ball charge and a small amount of power was used to scoop up the water from the feed reservoir.

The rock used in our tests, tinguaite, was a product of a local quarry; a hard tough dyke rock of uniform composition. It is a nepheline-feldspar rock having a tendency to offer considerable resistance to crushing. It was quarried in large lumps and impurities, mostly marble and limestone, were picked out. The large pieces were broken by sledges to about 6 inch cubes and then reduced in a crushing circuit including a small gyratory crusher, rolls and a hummer screen to $\frac{-2}{+40}$ mesh. The rock was bagged and sampled. A screen analysis of the samples was prepared and the average analysis of the feed computed.

A preliminary grinding test was then undertaken. The mill was rotated at 40 r.p.m. which was the speed recommended by the manufacturers for the mill. The feed rate was set at 200 lbs. per hour, water was added to the feed at 86 lbs/hr. equal to 30% and 500 lbs. of water was added to the mill discharge before it was pumped to the classifier. The grinding circuit is outlined in Plate VIII.

The mill, under these conditions, did not grind the rock fed to it. A great deal of uncrushed tinguaite was discharged from the mill as a +8 mesh oversize. It was thought that the ball charge did not have a sufficient number of the larger balls to do the work required of it, and that a smaller feed would give better grinding conditions. As a result the mill was cleaned out and recharged with 1200 lbs. of balls made up of the following sizes.

616 lbs. $1\frac{3}{4}$ inch balls

584 " $1\frac{1}{2}$ inch balls

The maximum available weight of the largest balls was used and balance made up of the next size. Using the figures recently published by A.M.Gow the ball charge amounts to 4 cubic feet or 42.4% of the theoretical mill volume.

The crushed and prepared rock was then re-screened and the +4 mesh removed. This amounted to nearly 50% of the total rock. It was recrushed to $\frac{-4}{+40}$ mesh. The whole amount was then thoroughly mixed by coning and shovelling on the laboratory floor. It was then segregated into 40 and 50 lb. lots. It had been noticed in the preliminary run that the main hopper on the feeder had a slight classifying action in feeding the rock to the second hopper, so it was determined to only feed the rock to the hopper in small amounts.

The oversize which was discharged from the mill screen was covered with a coating of fine slime. The screen also had a tendency to block and allow some slime to run out with its discharge. In order to prevent this loss of ground rock a water wash spray from a constant level tank was directed on the screen. This was calibrated and fixed at 69 lbs. per hour. It effectively kept the screen open and washed slime particles off the oversize.

The mill feeder water valve was replaced by a special water system. A small overflow tank with constant head of water was connected through piping and a small specially constructed valve, to the mill intake. The valve was accurately calibrated so that the amount of water entering the mill could be determined exactly. The valve controlling the water to the mill discharge was also calibrated.

With a few more adjustments the plant was ready for operation. At first it was planned to run a series of tests throughout the speed range, to investigate the effect of speed on grinding efficiency. It was felt that with speed the only variable the results would not establish any definite conclusion in themselves, but that a limited number of tests at different speeds and different feed rates would give some indication of the effect of speed and at the same time indicate characteristics of the plant which should be known before investigating any important factor. The preliminary test showed clearly that a large quantity of rock would be necessary for each test, and as time and supply of rock was limited, only three tests could be carried out.

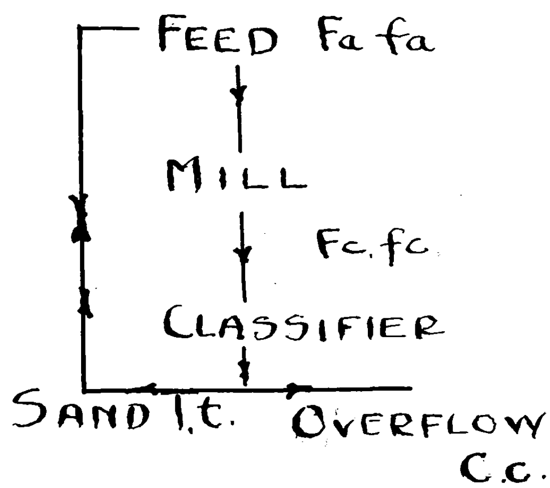
In order to facilitate the calculations, a number of graduated beakers were accurately calibrated and used to catch the samples from the samplers. The net weight and volume of the pulp sample was measured and the specific gravity of the pulp was calculated. The specific gravity of the tinguaite was found to be 2.54 and this value was used throughout our calculations.

The important data obtained in our tests are given in Tables 2, 3, 4, 5 and 6. The procedure followed was similar for all the tests. The mill was started and the feed with the necessary water turned on. After a few hours running samples of the classified overflow (finished product) were taken at intervals until the rate of overflow of finished product approximated the rate of mill feed. Two complete sets of samples were then taken in rotation from the overflow and the other samplers. These were taken to check up the circulating load. At the end of the first test the mill was speeded up and the feed rate with added water changed. The procedure was then repeated.

In order to obtain the mechanical value of the feed and crushed products, samples were screened and the mechanical value of each was calculated. (See Tables 2, 3, 4, 5 and 6). An investigation of the size of particle showed that the reciprocal of the mean diameter of the sizes above 200 mesh was sufficiently accurate (as determined in Tyler standard series) for a surface factor. For the -200 mesh the figure 1400 was used. This was based on the results of an experiment undertaken several years ago determining the size of particles under the microscope. It has since been adjusted using the work of Gross and Zimmerley as a basis for corrections. The figure is probably not accurate but for our purposes it will serve to show the trend in our tests. A great deal of work will have to be directed towards a satisfactory method of determining the surface factor of -200 mesh product before quantitative results can be expected.

The probable correctness of Rittinger's Law is assumed in this investigation. Crushing is measured by the amount of new surface produced in the grinding circuit.

Taggart's Ore Dressing handbook on page 1243 gives the following formula for determining tonnages in a grinding circuit knowing the screen analysis of the various products. It is based on the distribution of a particular screened grade when the circuit is in balance.



$$T = Fc - C = \frac{Fa\ (c-t)}{fc - t} - Fa$$

where

Fa = Feed (tons) fa = %-200 mesh in feed

Fc = Discharge (tons) fc = %-200 mesh

T = Tons sand return t = %-200 mesh

C = Classifier overflow c = %-200 mesh

The formula is based on theoretical calculations and is absolute, providing the circuit is in balance and the screen analyses are correct. It is based here on the distribution of the -200 mesh product as it is usually the most reliable product although where complete balance is maintained it will check for any given screen grade.

DISCUSSION OF TESTS.

Most of the work performed in the Session 1932-33, has been useful in studying ways and means of developing and experimental crushing plant which will supply the large amount of accurate data necessary in order to determine what actually happens in a ball mill under the numerous variable conditions which affect its crushing performance.

A large amount of time was spent in developing the methods and the data which would enable the determination of accurate power measurements.

A very considerable amount of time was spent on the development of a machine which would not only accurately sample the pulp (crushed rock and accompanying water) passing through it, but also give a reliable indication of the poundage (or tonnage) rate of the flow, without in any material wasy upsetting the equilibrium of the system. Prof. Bell felt that such a development was a vital necessity, and while the results obtained in the few tests which it was possible to make are too few in order to accurately determine the degree of perfection attained, there are substantial reasons for thinking that the required solution of a difficult problem has been substantially achieved.

Due to the fact, that in the installation of the mill discharge sampler, it was necessary to rotate the hopper of the machine, through an angle of 90°, and due to the fact that the rotation upset the correct adjustment of the machine, it was believed that the results it would give might be somewhat inaccurate. This seemed to be the case, however, prior to Test 3. Mr. E.McBride managed to replace it with another one in fair adjustment so that the results in Test 3 afford a more reliable indication of the performance to be expected from this feature of the crushing plant.

With accurate screen analyses, as has been shown, it is possible to determine by a formula the tonnages of finished product, return sand and mill discharge. These calculations gave the results in Table 7 and included in this Table are the tonnages measured by the sampler-poundage machines.

It is interesting to notice that in the flow most nearly approaching the viscosity of water, i.e., the classifier overflow, the water factor and the pulp factor are nearly identical and this is fortunate because it is this sampler which tells us when the mill reaches a state of equilibrium.

Going back to the other reliable test - Test 1, and preparing a similar table we get the following results.(Table 8).

It would now appear that the first mill discharge sampler was in reality not as inaccurate as we thought it was, and that by obtaining the correct factors for each machine depending on the viscosity of the pulp passing through it, it will probably be possible to determine the poundage (or tonnage) of material passing through it within an error of only one or two percent. Before reaching a final conclusion in this regard, additional corroborative results should be obtained.

The data tables include corrected figures as established by the screen analysis formula. Tests 1 and 3 are good tests, No. 2 was probably, due to some unknown factor, not in balance. A study of our samples taken over the period of this test showed, afterwards, that the mill built up a circulating load and then began to reduce it steadily, hence our overflow product reached a figure approximating the input and lead us to believe that the mill was in balance when it was still unbalanced.

The analysis of the feed and products in each test is given in the tables with the analysis of the products. Both have their mechanical values and the difference between the two, taking into account the tonnage affected, gives the total work done. This is shown on the basis of a unit ton and then converted to the given tonnage. It will be noticed that the discharge from the mill screen contains a negligible quantity of surface areaand could be neglected.

The tests show a slight decline in the relative mechanical efficiency, that is the ratio between total work done and the power required to do it, as the speed increases. (See Table 6). This figure is based on net power and gross power. In using net power it must be realized that this is not a quantitative figure. If the gear transmission is 90%

efficient the actual nett power would only be 90% of that shown and the R.M.E. would be higher. As the characteristics of the gear are unknown it was though best to leave it in its present form. There are so many variables coming into the tests that the change cannot be placed on speed alone, but the trend shows that at increased speeds there is no gain in relative mechanical efficiency over the range investigated.

Several other interesting points can be derived from the data. It will be noticed that there is a progressive drop in the classifier efficiency. The return sands contain a greater percentage of fine slime as the classifier's tonnage is increased.

The tests show the imperative need of absolute control of the water entering the system and plans are now made to have this item completely calibrated. It is useless to attempt to draw definite conclusions from the tests, but they did did show up points of weakness in the plant which can be remedied for future investigators.

As a result of the work during the session 1932-33 there has been developed a grinding plant with which it will be possible to intelligently investigate the numerous factors which affect grinding efficiency in ball mills. The field for such an investigation is an extremely broad one and a cautious approach to each phase is advisable, however with the facilities now available a good deal of confidence can be placed in the results that they are capable of producing and the ultimate object- a complete practical investigation of this subject- should be successfully attained.

Acknowledgements.

The writer wishes to express his appreciation of the Sir William Dawson Research Fellowship in Mining Engineering which made his participation in the investigation possible.

The keen interest and assistance given unstintingly by Professor J.W. Bell and Professor W.G. McBride is largely responsible for the results achieved.

The assistance and advice of Professor Wallace and Mr. Craig of the Department of Electrical Engineering and Professor Patten of the Department of Mechanical Engineering proved of material assistance.

The writer also wishes to express appreciation of the co-operation of his co-worker, Mr. E.E. Brown who is unable, owing to circumstances over which he has no control, to present his Thesis at this time therefore giving the writer prior use of the joint data.

The ability and help of Mr. Edward McBride, Chief Mechanic and his assistant Mr. Hugh McBride is greatly appreciated.

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II. Relation of Measured Surface of Crushed Quartz to Sieve Sizes. P.27.
III. Relation of Work Input to Surface Produced in Crushing Quartz. P.35.

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PLATES

PLATE I

Sampler No. 2

Table No. I

Rate of Flow of Water, lbs/hr.	Actual Wt. Water, lbs.	Sample Weight lbs.	Factor[5]
540	176.29	4.13	43.7
[6]615	200.23	4.83	42.5
710	265.67	6.24	43.4
815	301.54	7.07	43.7
905	341.85	8.07	43.3
1050	351.02	8.25	43.6

[5] Note;

The sampler factor is the ratio

$$\frac{\text{Total weight of water}}{\text{Weight of sample}} = \frac{W+w}{w}$$

where W. = Weight of water coming out of the sampler

w = Weight of sample

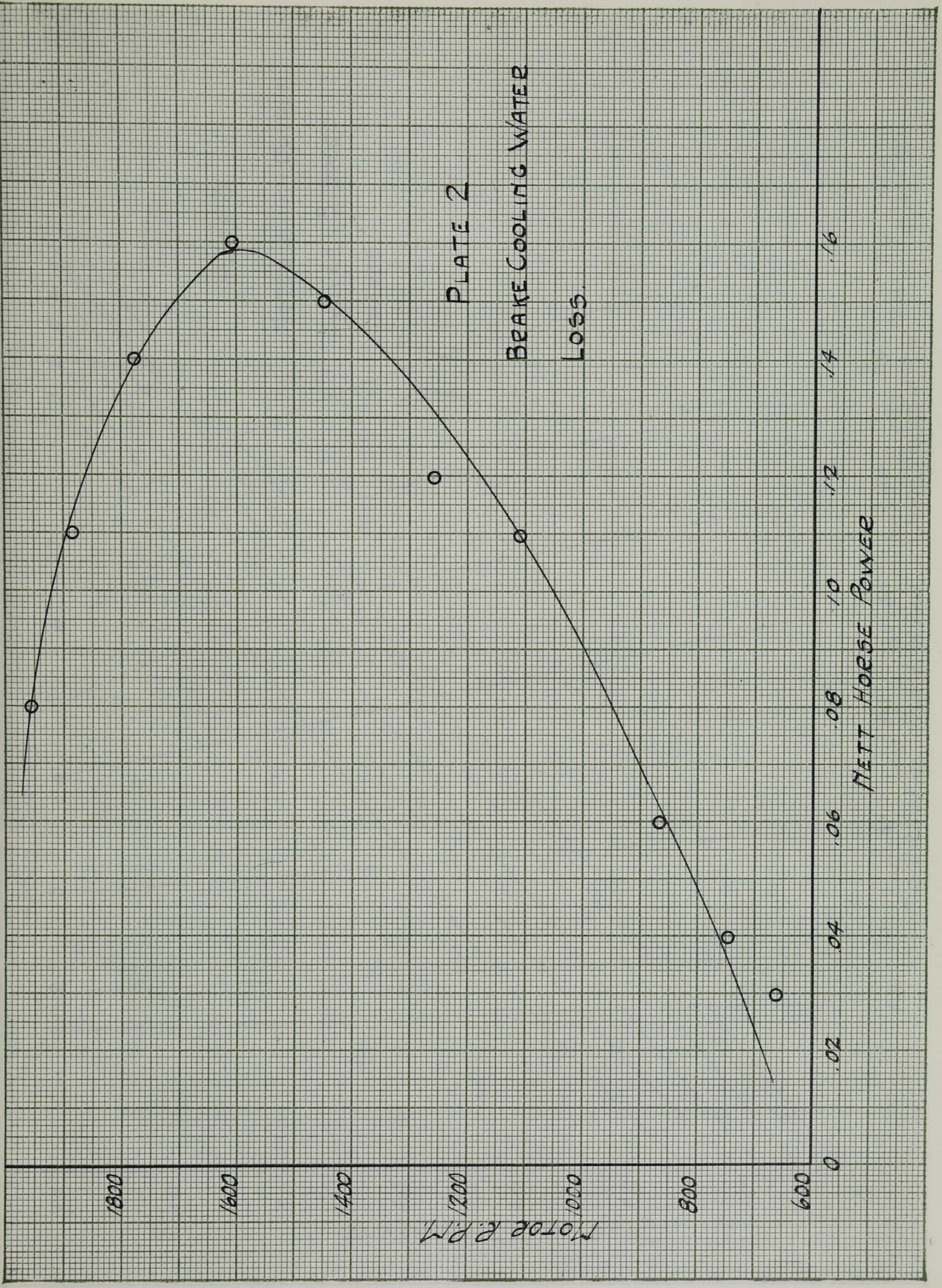


PLATE 2
BRAKE COOLING WATER
LOSS
NETT HORSE POWER
0
.02
.04
.06
.08
.10
.12
.14
.16
MOTOR R.P.M.
600
800
1000
1200
1400
1600
1800

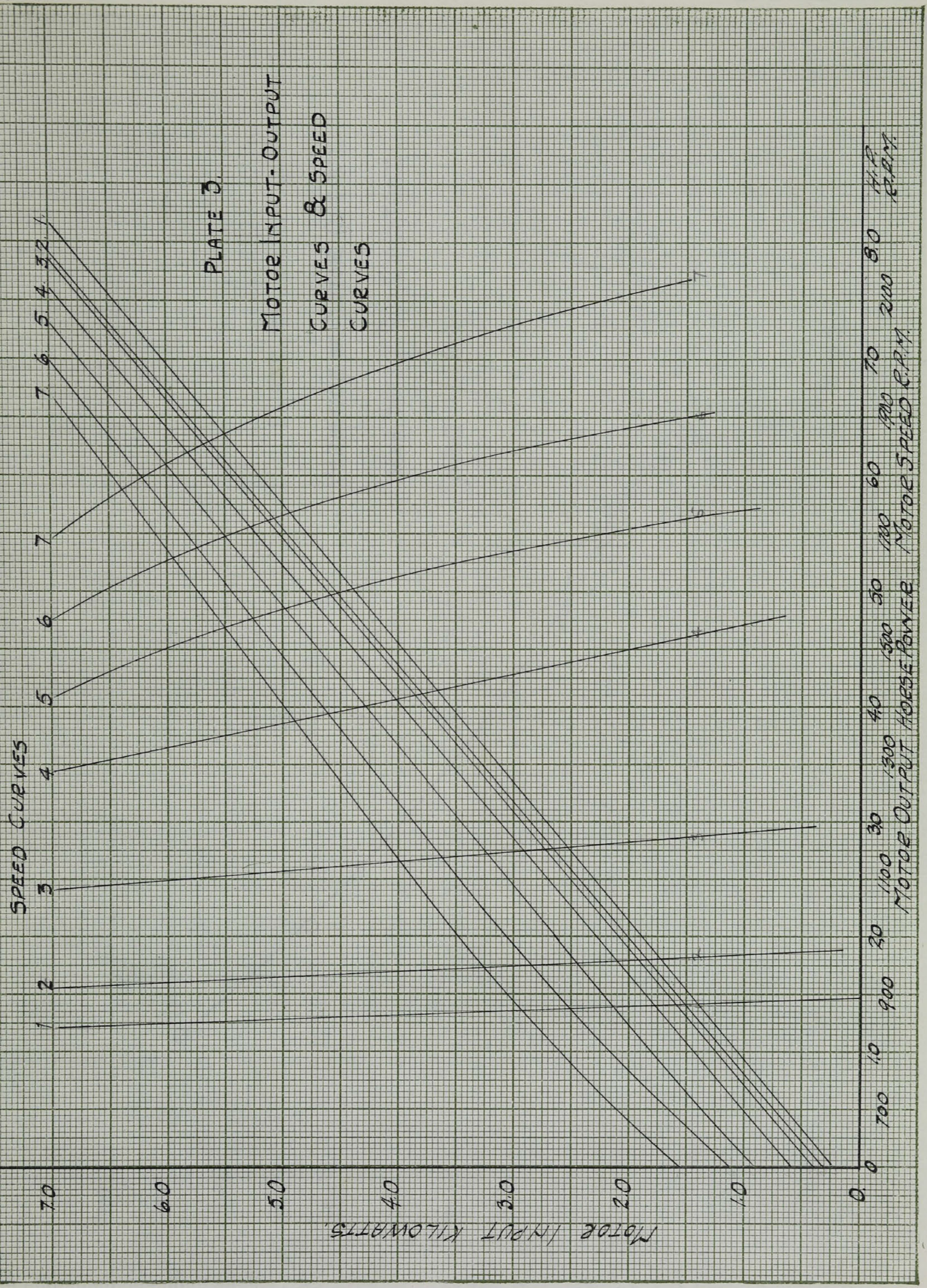


PLATE 3.
MOTOR INPUT-OUTPUT CURVES & SPEED CURVES
SPEED CURVES
MOTOR OUTPUT HORSEPOWER
MOTOR SPEED R.P.M.
H.P.
R.P.M.
MOTOR INPUT KILOWATTS.
0 10 20 30 40 50 60 70 80
700 900 1100 1300 1500 1700 1900 2100
0. 1.0 2.0 3.0 4.0 5.0 6.0 7.0

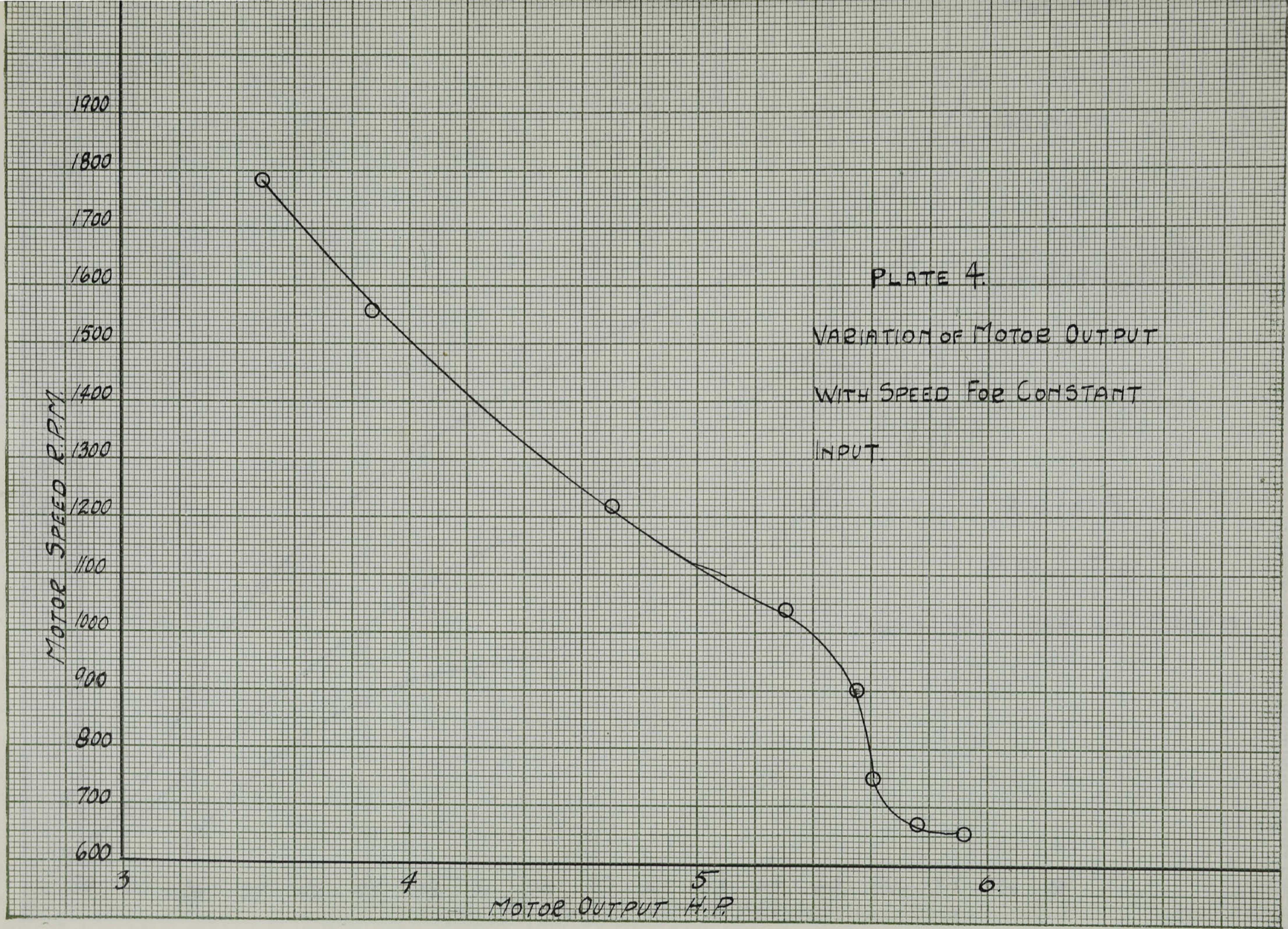


PLATE 4.
VARIATION OF MOTOR OUTPUT
WITH SPEED FOR CONSTANT
INPUT.
MOTOR SPEED R.P.M.
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
3
4
5
6.
MOTOR OUTPUT H.P.

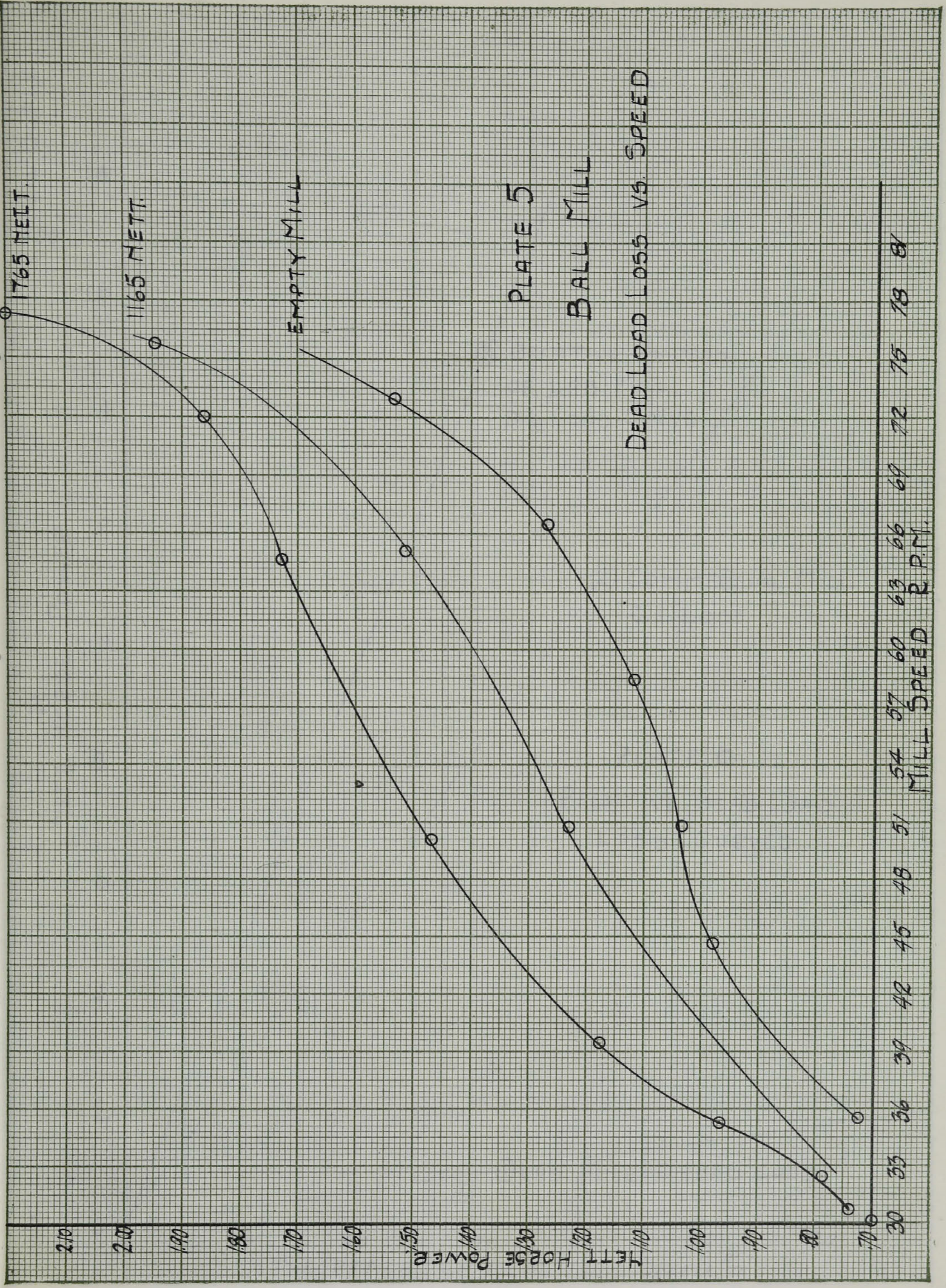
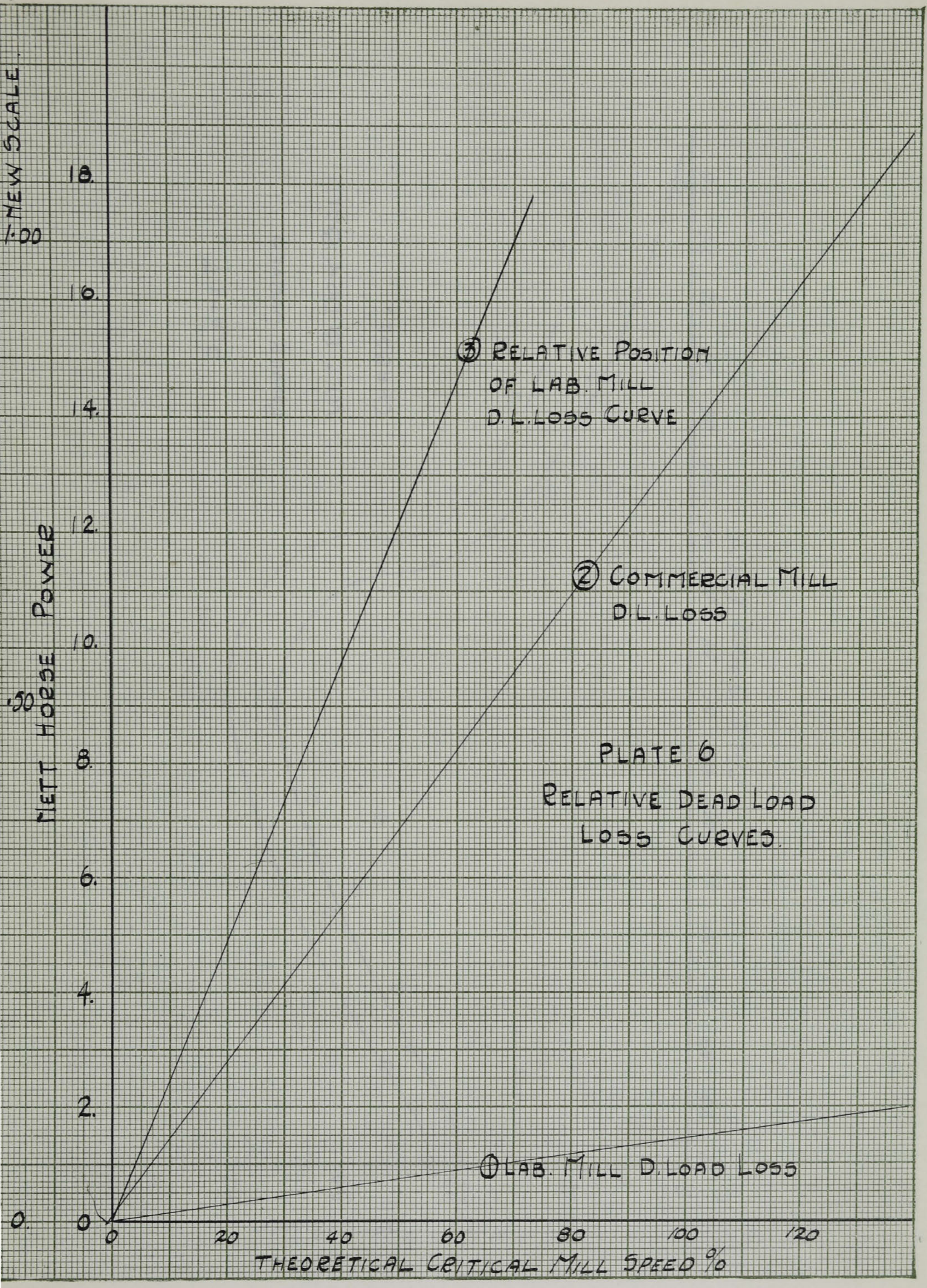


PLATE 5
BALL MILL
DEAD LOAD LOSS VS. SPEED
1765 METT.
1165 METT.
EMPTY MILL
MILL SPEED R.P.M.
30 33 36 39 42 45 48 51 54 57 60 63 66 69 72 75 78 81
METT HORSE POWER
.70 .80 .90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10


NEW SCALE
1·00
·50
0.
NETT HORSE POWER
18.
16.
14.
12.
10.
8.
6.
4.
2.
0
0
20
40
60
80
100
120
THEORETICAL CRITICAL MILL SPEED %
③ RELATIVE POSITION OF LAB. MILL D.L.LOSS CURVE
② COMMERCIAL MILL D.L. LOSS
① LAB. MILL D.LOAD LOSS
PLATE 6
RELATIVE DEAD LOAD LOSS CURVES.

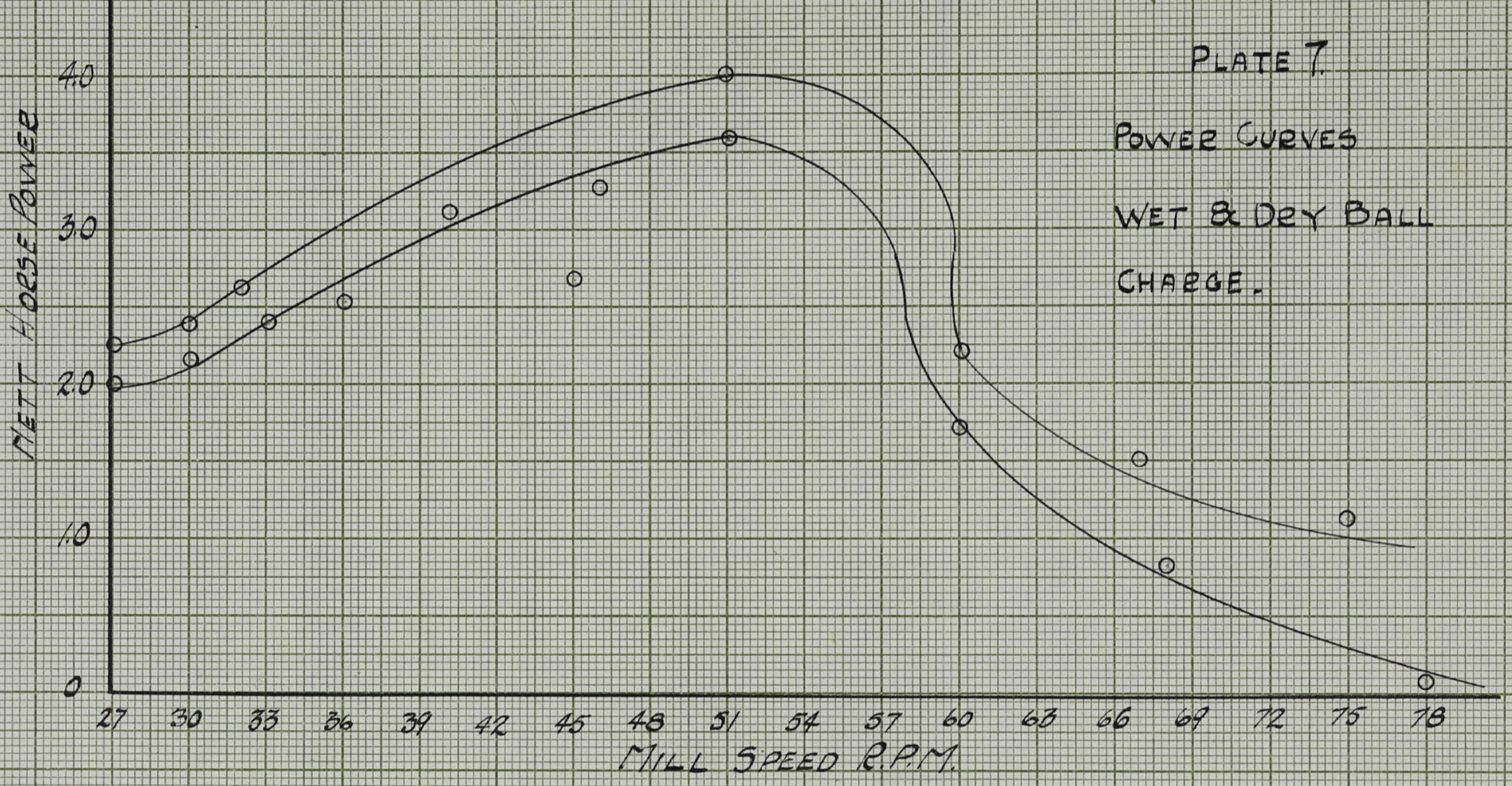
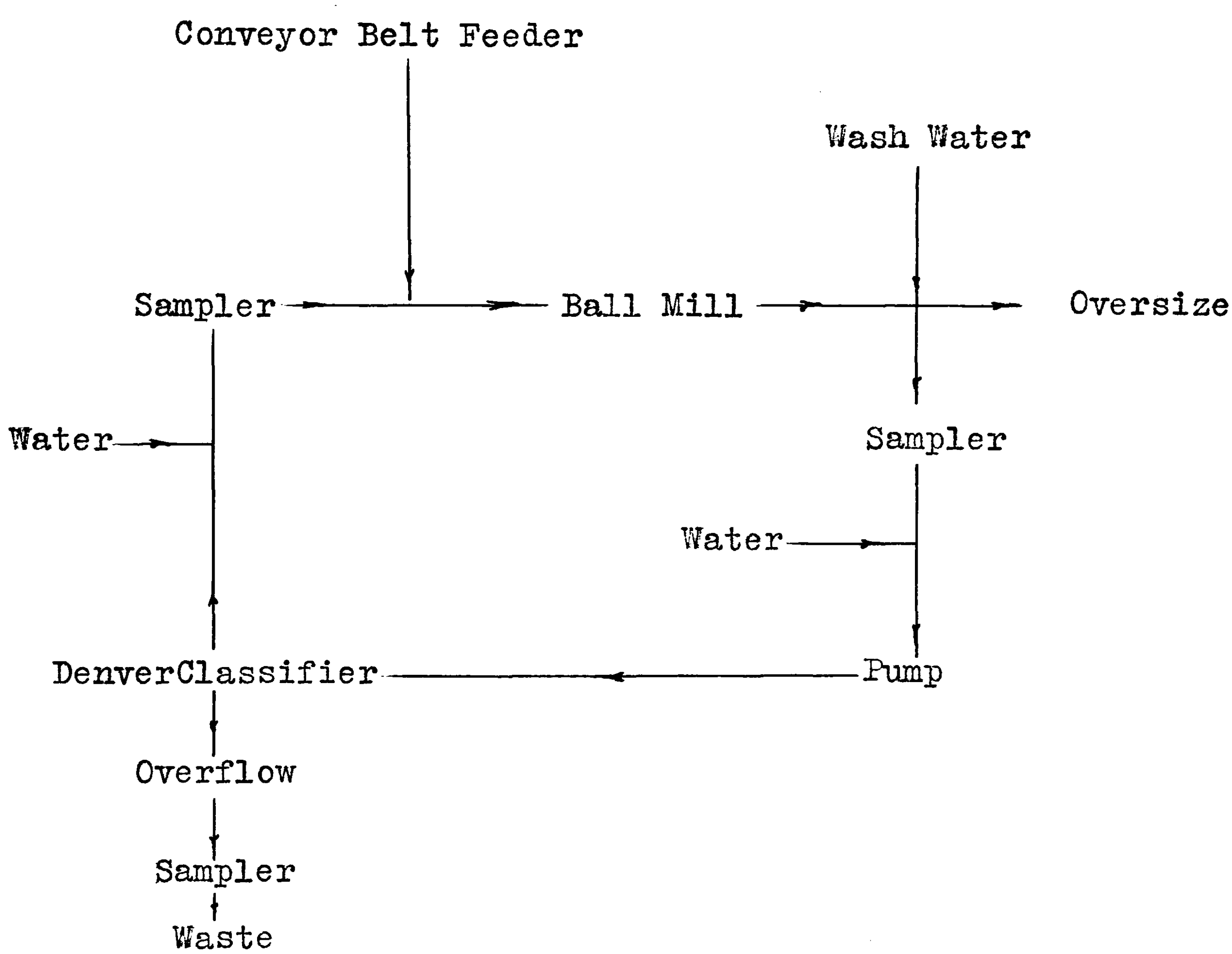


PLATE 7.
POWER CURVES
WET & DRY BALL
CHARGE.
NETT HORSE POWER
0
1.0
2.0
3.0
4.0
27
30
33
36
39
42
45
48
51
54
57
60
63
66
69
72
75
78
MILL SPEED R.P.M.

PLATE VIII



FLOW SHEET OF GRINDING CIRCUIT

TABLES

Note.

Table no. I is shown on Plate no. I.

FEED DATA

Table No. 2

Mesh	Sample No. 1	Sample No. 2	Sample No. 3	Average
	%	%	%	%
(- 3 / (+ 4	4.1	4.7	5.0	4.6
+ 6	28.7	32.7	31.7	31.0
+ 8	18.9	19.0	18.6	18.8
- 8	48.3	43.6	44.7	45.6
	100.0	100.0	100.0	100.0

Screen Analyses and Mechanical Values of -8 Mesh Grade.

Mesh	S. #1 %	S. #3 %	Average %	Surf. Factor	Rel. Surface
(- 8 / (+ 10	35.2	34.9	35.1	0.12	4.2
+ 14	17.6	16.9	17.3	0.20	3.5
+ 20	14.8	15.1	14.9	0.25	3.7
+ 28	11.2	11.3	11.2	0.35	3.9
+ 35	8.0	8.0	8.0	0.50	4.0
+ 48	5.5	6.0	5.7	0.70	4.0
+ 65	4.1	4.2	4.2	1.10	4.6
+100	2.6	2.5	2.5	1.40	3.5
+150	0.6	0.7	0.7	2.00	0.1
+200	0.1	0.1	0.1	2.90	0.3
-200	0.3	0.3	0.3	14.00	4.2
Total	100.0	100.0	100.0	M.V. =	36.0

Mechanical Value of Feed

Mesh	%	Surf. Factor	Rel. Surface
(- 3 / (+ 4	4.6	0.05	0.2
+ 6	31.0	0.06	1.9
+ 8	18.8	0.10	1.9
- 8	45.6	0.36	16.4
	100.0	Mech. Value:	20.4

BALL MILL TEST NO. 1

Table No. 3

Mesh	Classifier Sand % wt.	Mill Disch. % wt.	Class. Overf. % wt.	Surf. Factor	Rel. Surf.
+ 10	0.6	0.3			
14	0.8	0.4			
20	1.2	0.5			
28	1.8	0.8			
35	3.5	1.6			
48	5.8	2.6			
65	11.5	5.2	0.1	1.10	0.1
100	21.7	10.3	1.5	1.40	2.1
150	25.2	16.3	9.0	2.00	18.0
200	5.2	4.7	5.2	2.90	15.1
-200	22.7	57.3	84.2	14.00	1178.0
Total	100.0	100.0	100.0	M.V.=	1213.3

MILL R.P.M.

42

Mill Discharge - Dry Tons per 24 Hours 5.14

Class Sand - Dry Tons per 24 Hours 2.25
Class Overflow " " " " " 2.89
Total... 5.14

Mechanical Value. Finished Product 1213.3
" " Feed 20.4
Work Done per Ton.. 1193

Total Work = Tons per 24 Hours x Work per Ton

= 1193 x 2.89 = 3450

$$R.M.E. = \frac{\text{Total Work}}{\text{H.P./24 hrs}} = \frac{3450}{3.24} = \underline{1065} \text{ per H.P. (Nett) /24 hrs.}$$

$$= \frac{3450}{613} = \underline{563} \text{ per H.P. (Gross) /24 hrs}$$

BALL MILL TEST NO. 2 — Table No. 4

Mesh	Classifier Sand % wt.	Mill Disch. % wt.	Class Overf. % wt.	Surf. Factor	Rel. Surf.
+ 10	0.7	0.2			
14	1.2	0.5			
20	1.6	0.9			
28	2.5	1.4			
35	4.6	2.9			
48	6.8	4.4			
65	12.7	7.6	0.4	1.10	0.4
100	21.4	12.6	3.0	1.40	4.2
150	22.4	15.7	10.7	2.00	21.4
200	4.5	4.6	5.1	2.90	14.8
-200	21.6	49.2	80.8	14.00	1131.0
Total	100.0	100.0	100.0	M.V.=	1171.8

MILL R.P.M.

48

Mill Discharge - Dry Tons per 24 Hours 6.79

Classifier Sand - Dry Tons per 24 Hours 3.62
Classifier Overflow " " " " " 3.17
Total... 6.79

Mechanical Value. Finished Product 1171.8
" " Feed 20.4
Work Done per Ton... 1151.4

Total Work = 1151 x 3.17 = 3650

R. M. E. = $\frac{3650}{365}$ = 1000 per H.P. (Nett)

= $\frac{3650}{669}$ = 546 per H.P. (Gross)

BALL MILL TEST NO. 3

Table No. 5

Mesh	Classifier Sand % wt.	Mill Disch. % wt.	Class. Overf. % wt.	Surf. Factor	Rel. Surf.
+ 10	0.4	0.4			
14	1.2	0.6			
20	1.9	1.1			
28	3.0	1.7			
35	5.3	3.1			
48	8.9	5.6			
65	15.9	9.7	0.8	1.10	0.9
100	22.5	15.0	4.1	1.40	5.7
150	18.8	16.5	13.1	2.00	26.2
200	3.7	4.2	5.0	2.90	14.5
-200	18.4	42.1	77.0	14.00	1076.0
Total	100.0	100.0	100.0		1123.3

MILL R.P.M.

52.6

Mill Discharge - Dry Tons per 24 Hours 8.78

Classifier Sand - Dry Tons per 24 Hours 5.22
" Overflow " " " 24 " 3.56

Total... 8.78

Mechanical Value. Finished Product 1123.3
" " Feed 20.4

Work Done per Ton... 1103.

Total Work = 1103 x 3.56 = 3930

$$\text{R. M. E.} = \frac{3930}{3.82} = 1030 \text{ per H.P. (Net)}$$

$$= \frac{3930}{7.05} = 560 \text{ per H.P. (Gross)}$$

SUMMARY TESTS 1 - 2 - 3 Table No. 6

Test No.	% Moisture in Mill Pulp	Tons Mill Discharge per 24 Hrs.	Tons Finished Product	Crushing Work Done per Nett Horse Power	Speed % Critical
1	28.6	5.14	2.89	1065	75.0
2*	29.8	6.79	3.17	1000	84.8
3	30.2	8.78	3.56	1030	93.2

* There are substantial reasons for concluding that the mill did not reach a balance in Test No. 2, although the data probably approximate the truth. This test should be repeated.

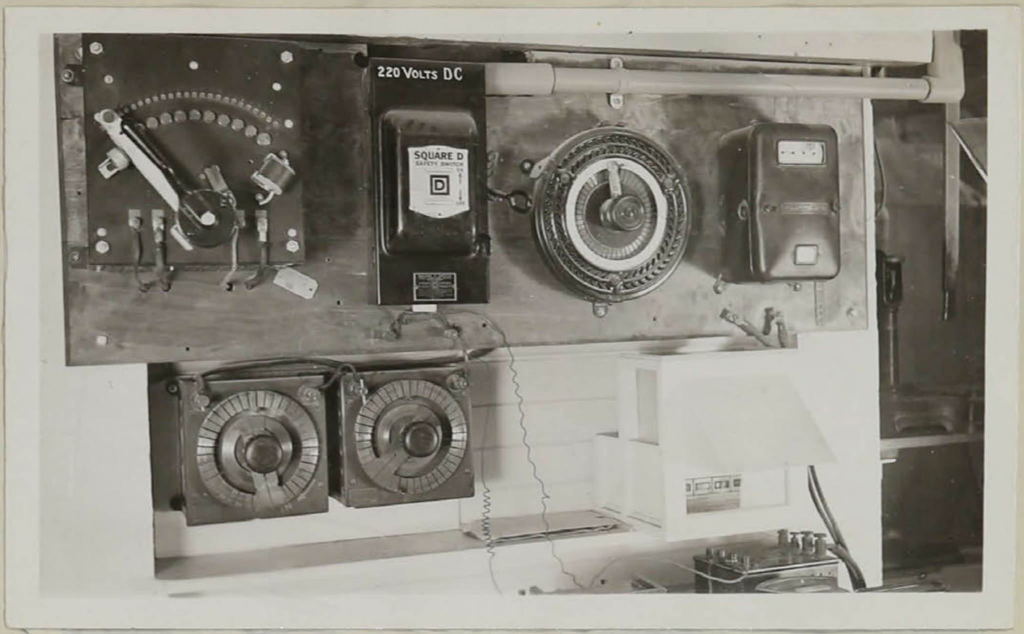
Grinding Tests 1-2-3. Table No.7

Product	Calc. poundage Dry lbs. / hr,	Sample poundage. Factor=43 Dry lbs./hr.	Recalc. factor.
Mill Disch.	732	673	46.7
Return Sand	435	412	45.4
Class Overflow	297	294	43.5
Total	732	706	-

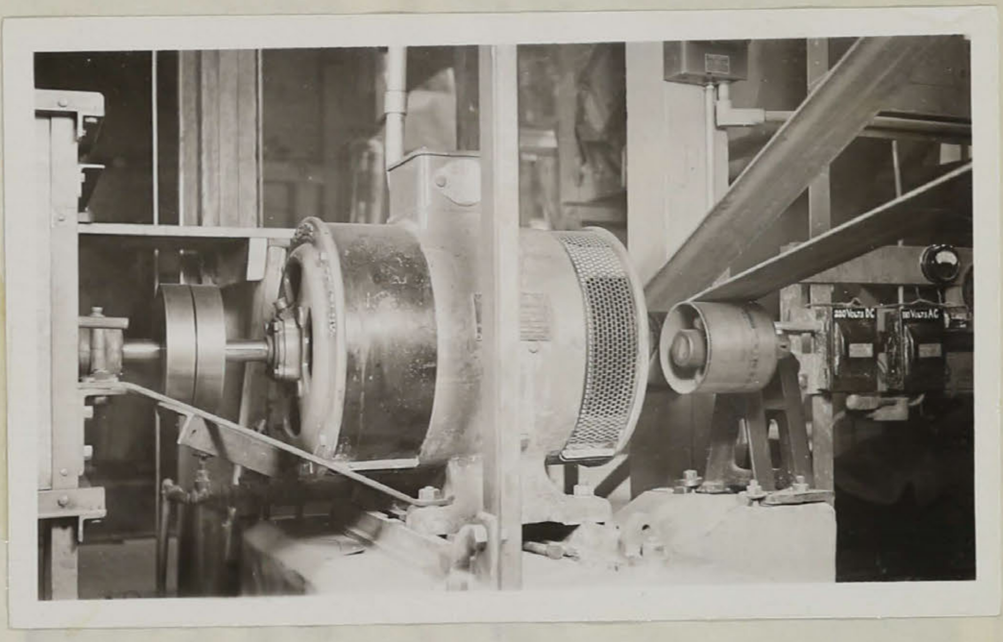
Table No. 8

Product	Calc. poundage Dry lbs./hr.	Sample poundage, Factor%43. Dry lbs./hr.	Sampler Poundage. Recalc. results.
Mill Discharge	428	400	433
Return Sand	187	176	186
Class Overflow	241	239	241
Total	428	415	427

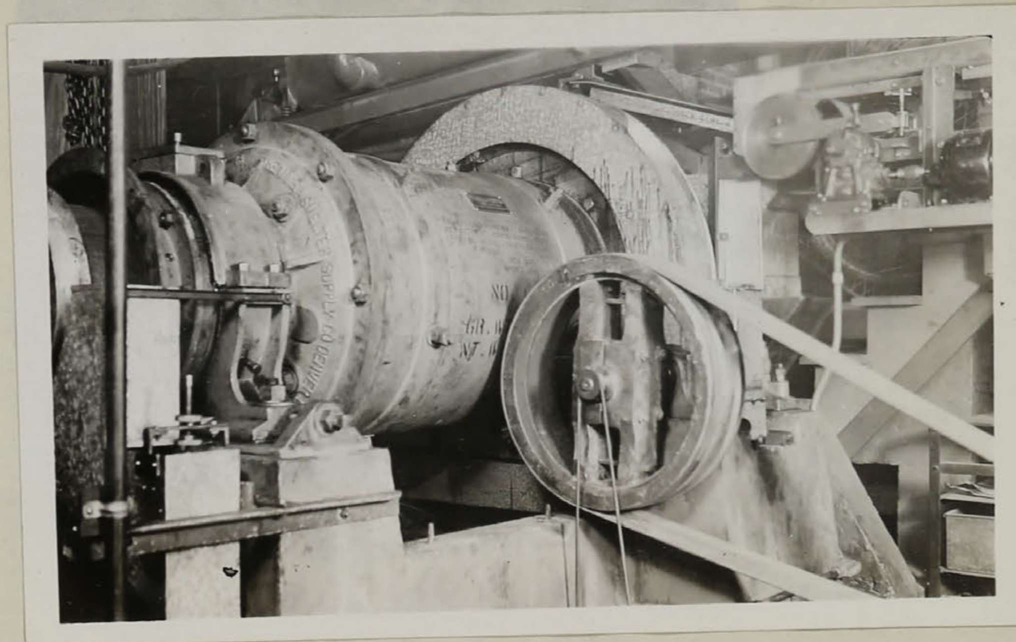
PHOTOGRAPHS OF EQUIPMENT.



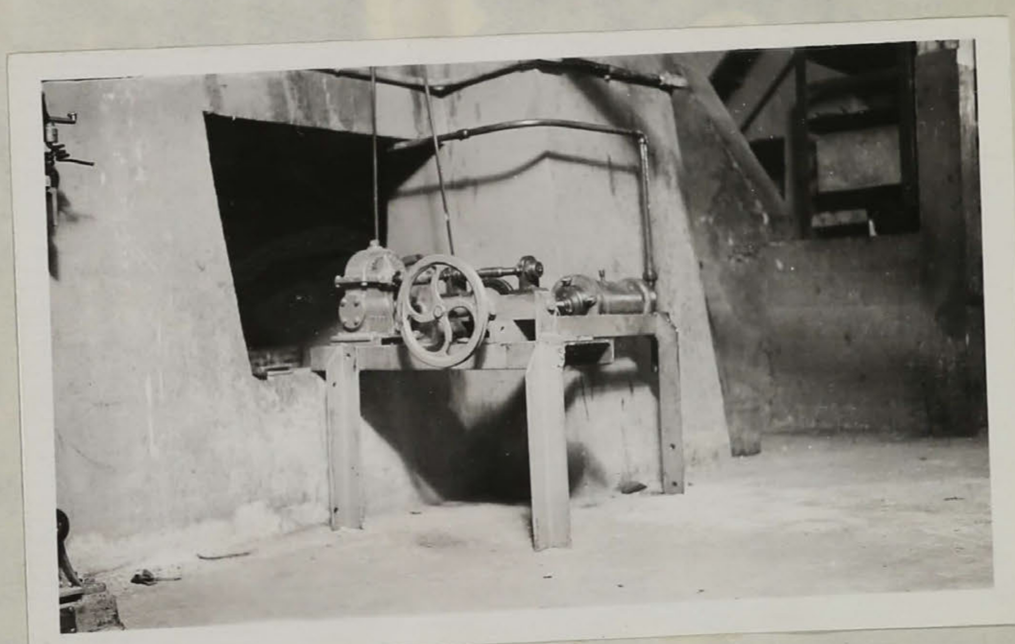
Control panel showing Speed Control, Resistances, Wattmeter, Recorders and Main Switch.



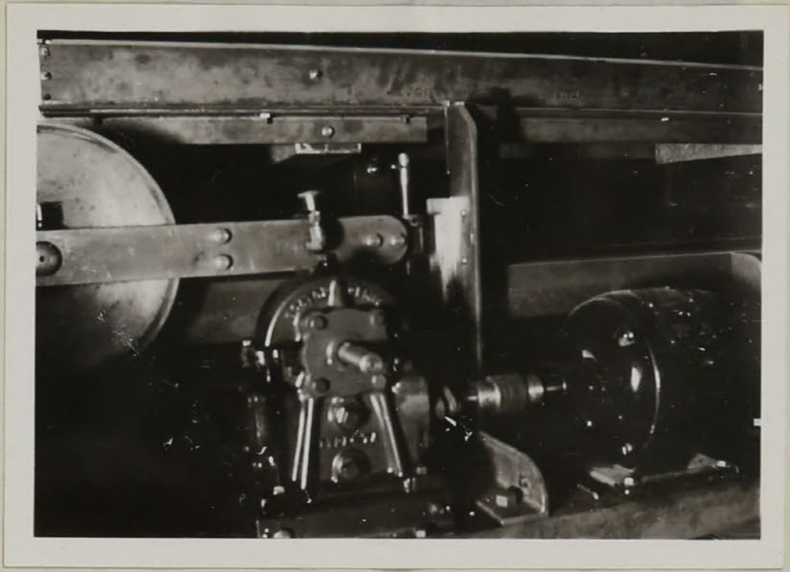
Mill Motor showing Coupling to Bell Brake and Belt Tightener.



Ball Mill - Side View.

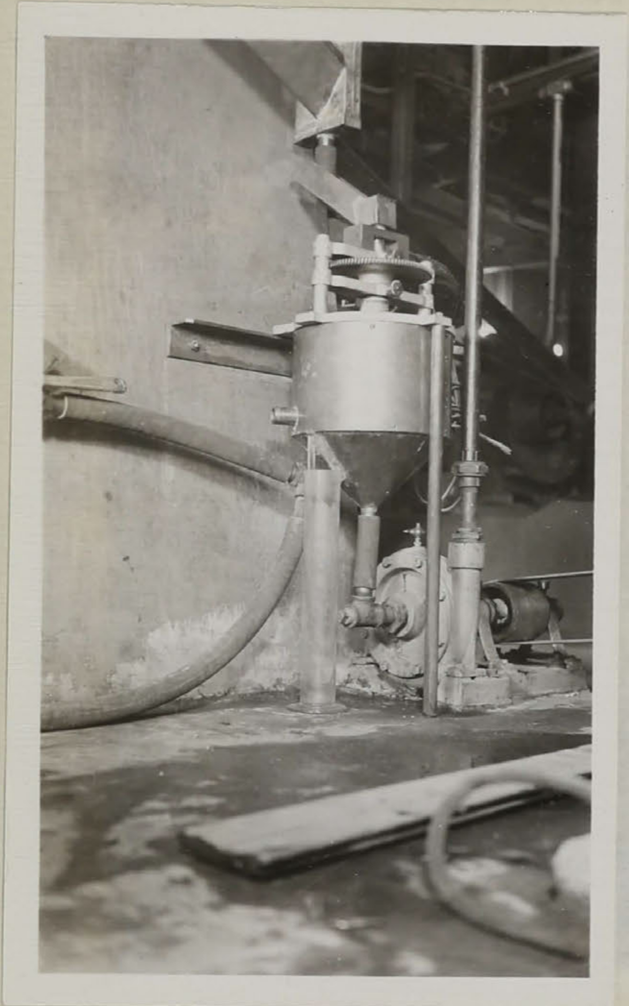


Automatic Grease Feeder.

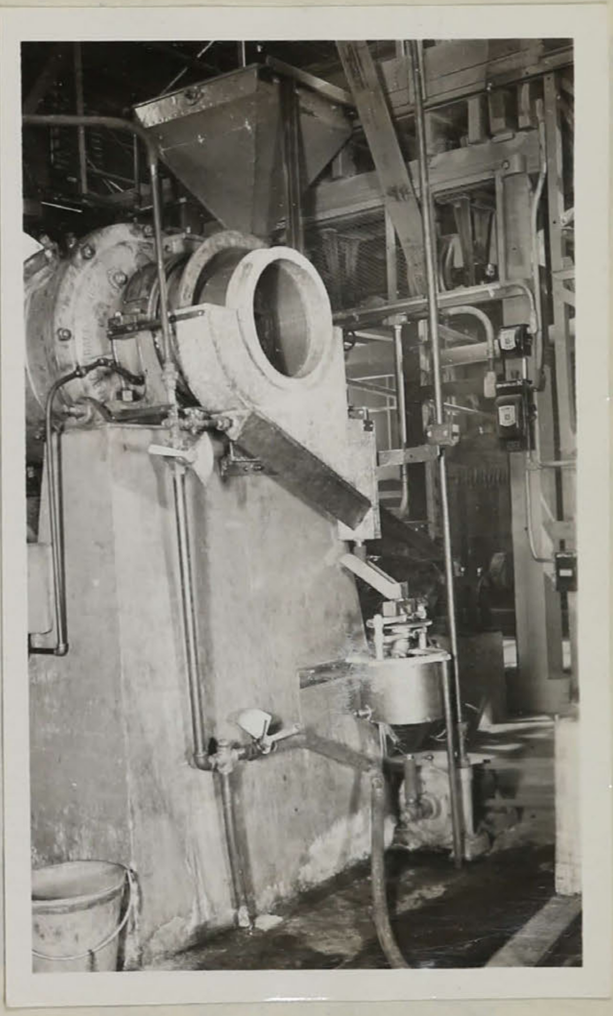


Conveyor Belt Drive with

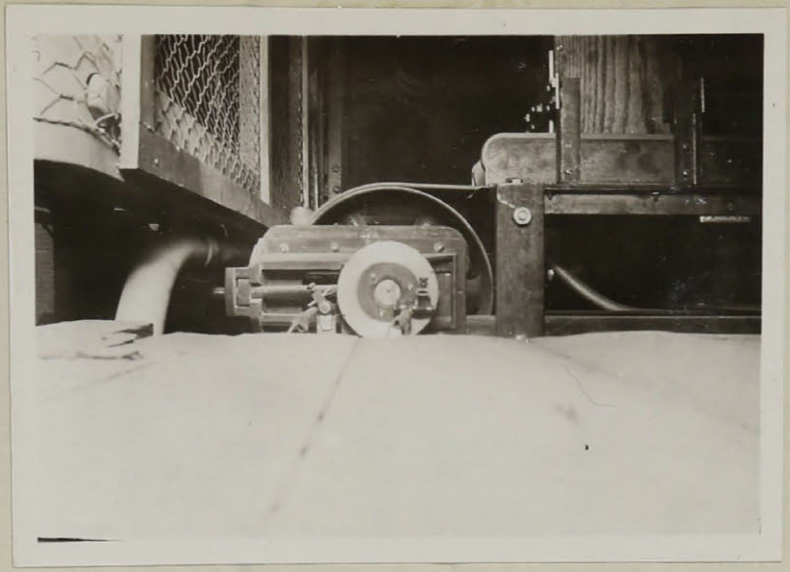
Vernier Control.



Automatic Sampler.

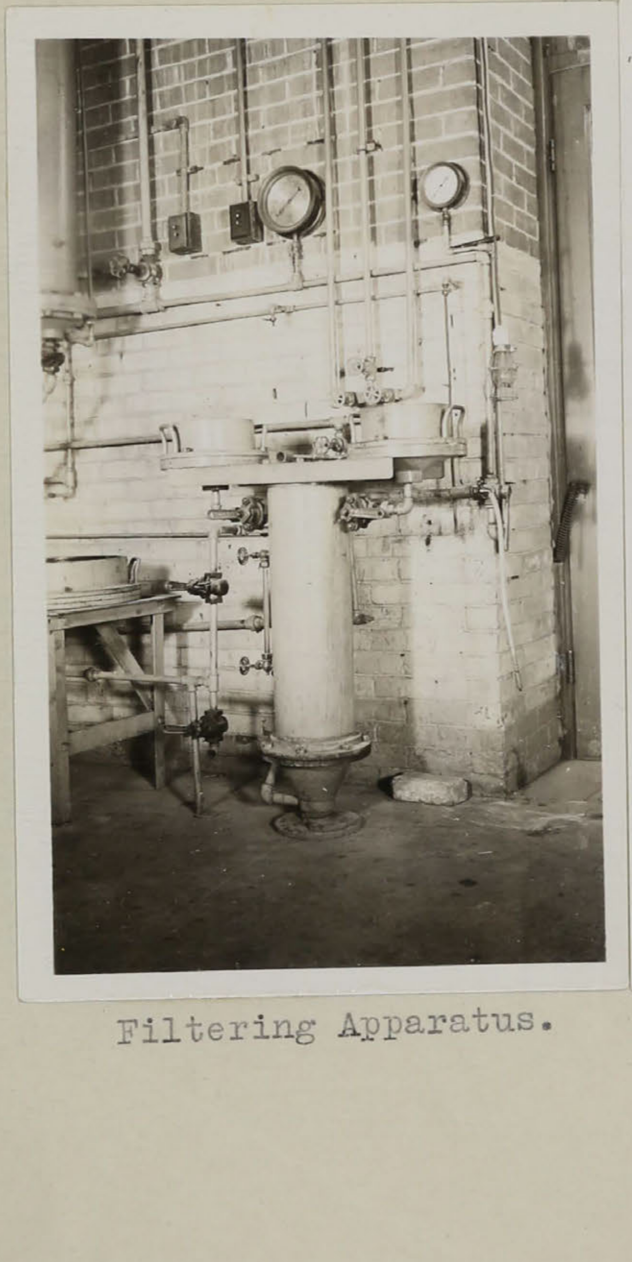


Discharge End of Mill.

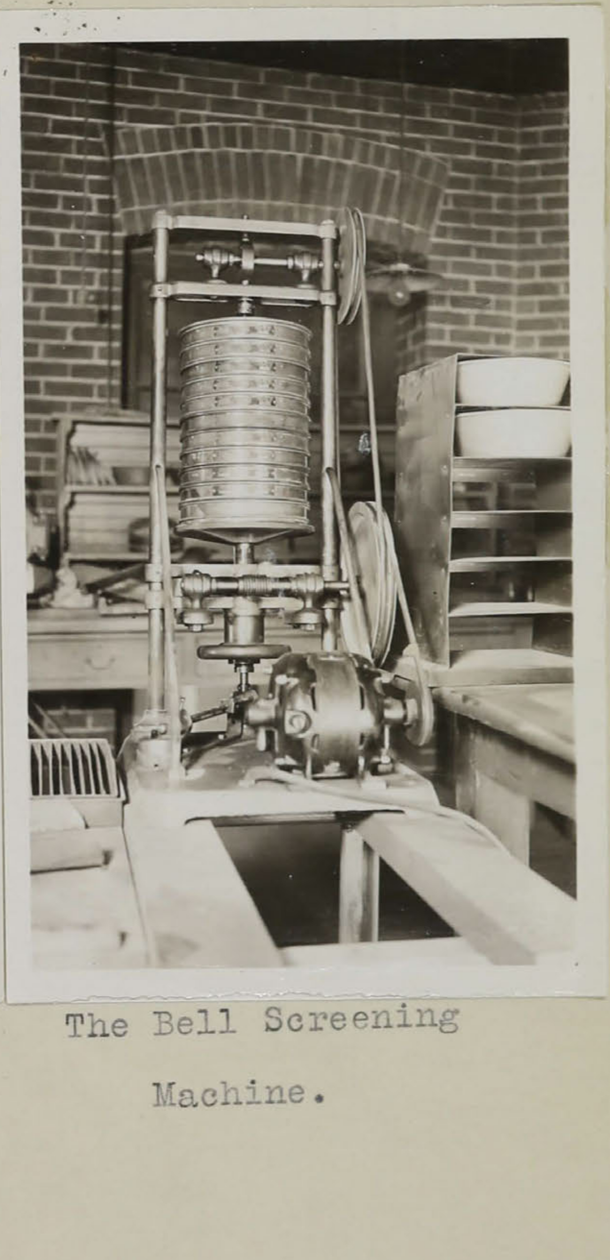


Contactr Wheel on Belt

Conveyor.



Filtering Apparatus.



The Bell Screening

Machine.