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PILOT PLANT INVESTIGATIONS ON AUTOGENOUS GRINDING

by

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MINERAL DRESSING AND PROCESS METALLURGY DIVISION

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SUMMARY OF RESULTS

The Hardinge Cascade Mill was used to grind ore from Faraday Uranium Mines, taking primary crusher discharge and reducing it to minus 8 mesh, except for one fine grinding test, 7-W. The mill was operated both dry and wet.

In both the dry and the wet grinding tests, an increase in the feed rate at a constant mill speed resulted in greater power input to the mill. However, two dry grinding tests (1 and 4-A) deviated from this trend, possibly because they did not last long enough to establish equilibrium conditions.

From the dry grinding tests 2, 3 and 4-C, using peripheral discharge, work indices, based on net power consumptions, of 11.21, 10.27 and 9.31 were obtained respectively, while wet grinding tests 1-W and 2-W, also using peripheral discharge, yielded work indices of 9.68 and 11.54 Thus, with peripheral discharge, dry and wet grinding were about equally efficient.

Wet grinding test 6-W, using medium level grate discharge, was an exploratory test to determine what effect an increase in speed would have on the overloading tendency of the mill. It was at the end of this test that it was found that the finely ground material had become packed along the periphery of the mill. This packing of ground material appeared to be the chief cause of overloading. The net work index was 9.68.

Wet grinding test 7-W, also using medium level grate discharge, was a fine-grinding test. The reduction ratio obtained was 522.7 with high circulating loads. This resulted in high power consumption, but due to high reduction ratio, the net work index was 8.41.

In wet grinding test 8-W medium level grate discharge was also used. The overall net power consumption was 3.71 kwh/ton and the work index, 9.00.

Wet grinding test 9-W, using low level grate discharge resulted in the lowest net power consumption of 3.01 kwh/ton and the lowest net work index of 6.88. In other words, the mechanical efficiency of the mill was at its highest, though as in previous wet grinding tests packing of the fine-ground material took place along the periphery of the mill.

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(59 pages, 23 tables, 9 figures)

INTRODUCTION

In January 1958, at the request of two large Canadian companies, for specific grinding tests on their products, a Hardinge 6 ft x 2 ft Cascade mill, which is an autogenous grinding unit, was installed in the Mineral Dressing laboratories of the Mines Branch at Ottawa.

Upon completion of these tests, it was decided to take advantage of the availability of the mill to carry out a series of basic tests in order to establish, if possible, the characteristics of autogenous grinding. From June 26 to October 21, 1958, dry and wet grinding tests were made, for the following purposes:

(a) to determine and compare the net power required to produce a -8 mesh product at various speed and feed rates;

(b) to determine the effect of mill speed on the grinding rate and on the net power consumption;

(c) to compare the results of wet and dry grinding tests under the same conditions of feed and speed rates; and,

as a corollary to (a), (b) and (c),

(d) to determine the feasibility of replacing secondary crushers and rod mills by an autogenous grinding unit, in order to produce a -8 mesh feed for ball mills.

For these tests the Mines Branch obtained 102 tons of ore from Faraday Uranium Mines Limited, since this mine uses secondary crushers and rod mills for the preparation of their ball mill feed. Later, an additional 51 tons was obtained by the Hardinge Company from the same mine, making a total of 153 tons of ore treated.

DEFINITION OF SYMBOLS

In this investigation the same terms and symbols will be employed as were used by F. C. Bond in the development of his Third Theory of Comminution[1], namely:

F = 80% passing size in the feed expressed in microns.

P = 80% passing size of the product expressed in microns.

R_r = reduction ratio = F/P.

W = work required, in Kwh per short ton, to reduce a material from F to P.

W_i = work index. It is the amount of work required, Kwh/ton, to reduce a material from infinite size to 80% passing 100 microns.

W_t = total work or energy input in Kwh per ton required in order to reduce a feed of infinite size to a definite product size.

These terms are related by the following formulae, which are given by the Third Theory of Comminution.

$$W_t = W \frac{(\sqrt{F})}{(\sqrt{F} - \sqrt{P})} \quad \ldots\ldots\ldots\ldots (1)$$

$$W_i = W \frac{(\sqrt{F})}{(\sqrt{F} - \sqrt{P})} \sqrt{\frac{P}{100}} \quad \ldots\ldots\ldots\ldots (2)$$

TEST METHODS AND APPARATUS

A. Dry Grinding Tests

During the dry grinding tests, the peripheral discharge arrangement was used. This arrangement consisted of four peripheral slotted openings through which the ground material could be discharged as the mill rotated. The flowsheet used for the dry grinding tests is shown in Figure 1.

Test 1-W was started with the mill containing an initial load of pebbles that had been left over from previous preliminary tests. This initial load occupied a volume of about one-third the inner volume of the mill, but was not weighed. In subsequent dry grinding tests the material left in the mill at the end of each test provided an initial pebble load as grinding media for the next test.

The feed was weighed out in tubs, in amounts depending on the desired feed rate, and each tubful of ore was fed to the mill by shovel over a 2 min period. The mill discharge was conveyed to a No. 18 Sweco screen fitted with a 4-mesh scalping sieve over an 8-mesh sieve. To reduce the amount of dust product in the material transported by the conveyor, a No. 6 Clarage fan was used to collect the dust. Both the dust product and the screen undersize were weighed.

During each test, samples of the screen undersize, of the screen oversize, and of the dust products were taken for screen analyses and for determinations of the rate of flow. A sample of the feed was obtained by taking every tenth tub of new feed during the tests and using these tubs to make a composite sample for screen analysis.

Specific gravity determinations which had been made on the ore gave an average value of 2.68.

The following pieces of equipment were used for the dry grinding tests:

(a) A 6 ft x 2 ft Hardinge Cascade mill with four peripheral openings, each containing thirty-two 3/8 in. x 7 in. slots.

The mill was equipped with bronze bushed bearings which were lubricated by drip-type oilers. A 25 hp English electric motor, connected to the mill by means of a chain drive and a Winsmith H-51 speed reducer having a ratio of 21.5 to 1, comprised the main drive for the mill. Two 9.5 in. x 11.5 in. pitch diameter vari-speed sheaves were used to vary the mill speed from 18.75 to 28.15 rpm (the critical speed of the mill was calculated to be 32.19 rpm, using the inside diameter of the mill as 5 ft 8 in.).

(b) A Sweco No. 18 screen with a 4-mesh scalping sieve over an 8-mesh sieve.

(c) A kilowatt-hour meter to measure the total power input to the mill.

(d) A 12 in. Link belt conveyor.

(e) A Link belt bucket elevator having a rated capacity of 14 tons per hour.

(f) A No. 6 Clarage fan, rated at 400 cfm and driven by a 2 hp motor. This was used to reduce the amount of fines present in the mill discharge.

B. Wet Grinding Tests

The mill discharge arrangements that were used for these tests were as follows: (i) peripheral discharge only; (ii) half-grate discharge, giving a moderately high pulp level; and (iii) full-grate discharge, giving a low pulp level discharge within the mill.

The flowsheets used for these tests are shown in Figures 2 to 4. Figure 2 is the flowsheet used for tests 1-W to 3-W, while for tests 4-W to 6-W, the flowsheet shown in Figure 3 was used. A slightly modified flowsheet, shown in Figure 4, was used for the fine-grinding test 7-W. In tests 8-W and 9-W, the flowsheet used was quite similar to that for tests 4-W to 6-W.

During the wet grinding tests 1-W to 3-W, the feed was added in the same manner as in the dry grinding tests. Also, the initial pebble load in the mill was made up of material left over from previous tests. In tests 6-W to 9-W only, a nominal 1200 lb, dry weight, of pebbles was added to the mill prior to the test. This pebble load acted as grinding media for the new feed. The weight was taken for material balance calculations.

The mill discharge was then fed by gravity to a Denver 9 in. double-screw classifier, which was used to convey the sands to a Denver 6 in. single-screw classifier, that, in turn, conveyed the sands to the bucket elevator. The overflow from the first classifier was pumped to the bucket elevator by means of a Denver sand pump. There was no overflow from the second classifier. From the elevator the material was then discharged to a No. 18 Sweco 8-mesh screen. The screen oversize was returned to the mill, while the undersize was fed by gravity to a Dorr 12 in. single rake classifier. The classifier sands were collected in tubs, weighed wet, and finally discarded, while the overflow was discarded directly.

Water was added to the mill at a controlled rate by means of a flowrator. The amount of water added to the mill was based on an estimated 3% moisture in the feed to the mill and an estimated 76% solids in the mill discharge.

During each test, samples were collected for 30 sec or 1 min intervals. These samples were used for determining rates of flow and for screen analyses.

An almost similar procedure was used for wet grinding tests 4-W, 5-W and 6-W. Test 7-W was a fine-grinding test and will be discussed separately.

The sampling procedure used for these wet grinding tests was as follows:

i) Classifier overflow: for rate and pulp density, every 15 min; for screen analysis, every 10 min.

ii) Classifier sands: for pulp density, every 30 min.

iii) Screen oversize, with the exception of tests 4-W to 6-W: every 30 min.

iv) As a check on the pulp density of the classifier sands, grab samples were taken every 30 min during the test period. These were weighed wet, dried, and reweighed in order to obtain the moisture content.

In tests 4-W to 6-W, the mill discharge was fed by gravity directly to the bucket elevator, and subsequently to a $1\frac{1}{2}$ ft x 4 ft double-deck Dillon vibrating screen. The undersize was fed to the rake classifier, from which the sands were collected, weighed, and then discarded. The classifier overflow was then fed by gravity to a Denver 12 in. rotary classifier, the sands from which were collected and weighed, and the overflow was then thickened in a Type 50 Allen cone and also weighed for material balance purposes.

The Denver rotary classifier was used as it provided a much steadier overflow rate for sampling purposes than did the rake classifier.

On account of their inaccessibility, neither the screen undersize nor the screen oversize could be sampled for screen analysis, pulp density, or rate of flow. Because the rate of flow of the spiral classifier sands was quite low, grab samples of the sands were taken over a period of time during the tests in order to obtain pulp densities.

Samples of the feed were taken every 20 min, to obtain a composite sample for a screen analysis. Grab samples were also taken for determination of moisture content.

The equipment used for the wet grinding tests is listed below;

a) A 6 ft x 2 ft Hardinge Cascade mill having

i) A peripheral discharge arrangement.

This arrangement was previously described under 'Dry Grinding Tests'. In the wet grinding tests during which this arrangement was used, two of the peripheral grates were closed, to provide a greater retention time for the ore in the mill.

ii) A grate discharge arrangement for medium pulp level discharge and low pulp level discharge.

The grate discharge arrangement consists of filler-plate castings with webs and scoops mounted against the discharge head of the mill. The grate liners are mounted on top of these filler-plate castings in such a way that the pulp passing through the grates is scooped upward and then discharges by gravity through the trunnion. There are two rows of grate liners. If both rows of grate liners are used, the pulp level in the mill is kept low.

However, the outer (lower) row of grate liners can be replaced by liner plates to raise the pulp level to medium height. The 3/4 in. slots in the grates are arranged circumferentially.

b) A Denver 9 in. double-screw classifier, used as a conveyor.

c) A Denver 6 in. single-screw classifier, also used as a conveyor.

d) A bucket elevator.

e) A No. 18 Sweco screen, with 4 and 8 mesh sieves.

f) A $1\frac{1}{2}$ ft x 4 ft Dillon double-deck vibrating screen, with 4 and 8 mesh sieves.

g) A Dorr 12 in. single rake classifier.

h) A Denver sand pump.

i) A Type 50 Allen cone. Inside diameter, 4.5 ft; height, 5.0 ft; and volume, 26.5 ft^3.

j) A Denver 12 in. rotary high-weir type classifier.

DESCRIPTION OF TESTS

A. Dry Grinding Tests (With Peripheral Discharge Arrangement)

Six dry grinding tests were performed, using the following conditions:

Test No.	Speed, rpm	Percent Critical Speed	Dry Feed Rate, lb/hr
1	28.15	87.5	4000
2	28.15	87.5	3800
3	22.9	71.2	3400
4A	18.87	58.7	3200
4B	18.87	58.7	3000
4C	18.75	58.75	2800

Test 1

This test lasted for 2.0 hr, during which time the mill speed was 28.15 rpm or 87.5% critical speed, and the feed was added at the rate of 4000 lb/hr.

After about one hour of operation, a sharp drop in the readings taken of the total power input to the mill indicated that the mill was being overloaded. The feed rate to the mill was stopped for several minutes to relieve this overloading tendency.

The screen oversize was sampled once prior to the end of the test, for screen analysis and determination of rate of flow.

Results of test 1 are summarized in Table 1, along with the results of the other dry grinding tests. Screen analyses of the various products are given in Tables 2 to 5. (Note: The tables are placed at the end of this report.)

Test 2

During this test, the mill was operated at the same speed as in the first test, but the feed rate was reduced to 3800 lb/hr. The total length of the test was 3.9 hr, during which samples and power readings were taken as in the previous test.

Test 3

This test was started using a feed rate of 3800 lb/hr and a mill speed of 22.9 rpm or 71.2% critical speed. However, the mill soon became overloaded, and the feed rate was reduced to 3400 lb/hr for the remainder of the test.

Test 4A

This test was operated at lower feed and speed rates than in test No. 3. The initial power readings were considerably less as compared with those of the previous tests. However, the readings soon increased, probably because a constant feed rate was not maintained. A resulting increase in the product suggests that the feed was added at a greater rate than desired, hence the increased power input.

Test 4B

The same mill speed was used as in test 4A, but the feed was reduced to 3000 lb/hr. However, the test lasted only a short time, 1.33 hr, and the results obtained have little significance.

Test 4C

The feed rate for this test was reduced further to 2800 lb/hr, but the speed of the mill was 18.75 rpm, or 58.75% critical speed. The run lasted a total of 3.68 hr, considerably longer than in test 4B.

Of the dry grinding tests, Nos. 2, 3 and 4 can be considered as the most reliable ones, for the following reasons:

(a) The running time was longer.

(b) The mill did not overload.

(c) The power readings remained essentially constant after the test had been underway for a short period of time.

(d) No delays or interruptions occurred during these tests.

Table 6 contains the reduction ratios, the net power consumption, and the 80% passing sizes in the feed and screen undersize products for tests 2, 3 and 4C.

B. Wet Grinding Tests

1. With Peripheral Discharge Arrangement -

These tests were operated under the following conditions:

Test No.	Speed, rpm	% Critical Speed	Dry Feed Rate, lb/hr
Preliminary test	18.75	58.0	-
1-W	28.15	87.5	3800
2-W	22.9	71.2	3400
3-W	28.15	87.5	3400

As a preliminary test the mill was operated at a speed of 18.75 rpm and fed at an initial rate of 2800 lb/hr. Because the mill became overloaded under these conditions, the feed rate was reduced to 2600 and then to 2500 lb/hr, but had to be stopped entirely as the mill continued to overload. No samples were taken for the discharge rates or for screen analyses.

Test 1-W

This test lasted over 6.3 hr, using a speed of 28.15 rpm and a feed rate of 3800 lb/hr. Compared with test 2-W, the mill used less power in test 1-W.

Test 2-W

Test 2-W was done to determine the amount of power that would be consumed at a reduced feed and speed for the mill. The results of this test, which ran for 4.1 hr, indicated a higher power consumption.

Test 2-W produced a finer product in the classifier sands and a coarser one in the screen oversize. The degree of fineness in the classifier overflow was the same in both of tests 1-W and 2-W.

Test 3-W

The results of test 3-W were discarded, because the mill became overloaded and the test was discontinued.

2. With Grate Discharge Arrangement for Medium Pulp Level -

The tests conducted with this arrangement were 4-W to 8-W, inclusive.

These tests were performed because no definite comparisons could be made between the previous wet and dry grinding tests. It was also decided to increase the running time in these tests in order to allow the mill sufficient time to reach equilibrium conditions.

The type of arrangement used allowed a moderately high pulp level discharge and an increased retention time in the mill.

Gross input power readings and samples of the products were taken during all tests. As a check on the readings of the mill input power obtained from the Kwh meter, a KVA test unit was connected to the Cascade mill electrical power circuit, and both sets of readings compared.

The tests were operated under the following conditions:

Test No.	Speed, rpm	% Critical Speed	*Feed Rate, lb/hr	Dry Feed Rate, lb/hr
4-W/5-W	23.0	71.5	3900	3760
6-W	27.7	86.2	3900	3760
7-W	27.7	86.2	765**	737**

*Includes 3.6% moisture

**Sized feed; feed rate was calculated from weighed products.

Test 4-W/5-W

During the first half of the test the mill was rotating in the wrong direction, as the electrical contacts had been reversed when the KVA test unit was connected to the mill circuit.

The first part of the test was called 4-W, and the second half, after the direction of the mill rotation had been corrected, 5-W.

Because the contacts had been accidentally reversed, and because neither test lasted long enough to allow equilibrium conditions to be reached, the results of 4-W and 5-W were discarded.

Test 6-W

This test was performed to determine what effect the increase in speed would have on the overloading tendency in the mill.

Every hour, during the test, the mill was stopped for several seconds and the level of the charge in the mill was checked. When the level became too high, the feed was either reduced or stopped entirely for a short period of time.

After about 4 hr, a decrease in the power input readings, and fluctuations in the mill discharge pulp densities and rates, indicated that the mill had started to overload. Upon completion of the test, inspection of the interior of the mill revealed a layer, 2 to 3 in. thick, of finely ground material that had become packed along the periphery of the mill.

This compacted layer is thought to be the chief cause of overloading. The layer would act as a pad, and a much longer grinding or retention time in the mill would be needed before any material could be discharged. Continued feeding during this time would overload the mill.

Material Balance, Test 6-W

Product	Dry Weight, lb
(1) Material fed to mill (counted), 240 tubs @ 130 lb @ $3\frac{1}{2}$% moisture	30,050
(2) Collected classifier sands, 30,260 lb @ 75.8% solids	22,950
(3) Spiral classifier sands	35
(4) Classifier overflow, average rate 2990 lb/hr @ 9.3% solids for $9\frac{1}{2}$ hr	2,640
(5) Material from cone - 5390 lb @ 58.2% solids	3,134
(6) Total collected product = (2) + (3) + (4) + (5) =	28,759
(7) Mill load at end of test:	
(a) Material removed from mill = 2090 lb dry	
(b) Material packed in mill = 605 lb dry	
Total = 2695 lb dry	
Mill load before test = -1400	
Gain in mill load = 1295 lb dry	
(8) . . Total weight of treated products = (6) + (7) =	30,054 lb

Test 7-W

This test was a fine-grinding test and was performed for the following reasons:

(a) To produce a finished product of about 55% -200 mesh, by autogenous grinding of run-of-mine ore.

(b) To obtain indications of capacity and power requirements.

During this test the mill was operated wet at 86.2% of critical speed, using a feed rate of 765 lb/hr. Also, the mill was inspected for overloading condition as in the previous tests. The flowsheet used for this test is shown in Figure 4. The only changes that were required were rearrangements of the classifiers in order to recirculate the rake classifier sands to the mill.

A screen analysis of the feed was obtained. The feed was then screened and mixed in the same proportion as the screen analysis, in order to keep a constant ratio between the coarse and fine fractions.

Two separate screen analyses of the rake classifier overflow were made during the test. During the first half of the test the classifier became overloaded and the overflow contained some coarse material. The screen analysis of a sample taken of the overflow during the first half of the test is given in Table 17. After normal conditions had been attained in the classifier, another sample of the overflow was taken during the latter half of the test; its screen analysis is given in Table 16. Since the amount of overflow material produced during each half of the test was not known, the two screen analyses could not be combined. An average taken from the screen analyses showed that the overflow consisted of 55.5% -200 mesh material, which was the desired fineness of grind.

During the test, 500 lb of -8 + 2 in. rounded pebbles of Faraday ore were added to mill as grinding media, to help relieve the overloading condition.

Material Balance, Test 7-W

Product		Dry Weight, lb
(1) Material fed to mill, 31 tubs @ 130 lb @ 3½% moisture		3890
Coarse pebbles added during test		500
Total feed		4390 lb
(2) Unfinished rake classifier sands, 1107 lb @ 90% solids (estimated)		996
(3) Classifier overflow:		
(a) Collected overflow = 3920 lb @ 73% solids (estimated)	=	2860
(b) Discarded overflow = 3000 lb/hr @ 8% solids @ 5.75 hr	=	1380
(4) Total collected mill discharge = (2) + (3)	=	5236 lb
(5) Mill Load:		
(a) Material in mill before test = 1200 lb dry		
(b) Material in mill after test = 465 lb dry		
Weight reduction in mill = 735 lb		-735 lb
(6) Net mill discharge = (4) - (5)	=	4501
Feed to mill	=	4390
Excess material	=	111 lb
Discrepancy = 2.53%		
Total finished product collected = total		
Classifier overflow = 2860 + 1380	=	4240 lb
Calculated discharge rate = 4240/5.75	=	737 lb/hr

Test 8-W

This test was conducted similarly to test 6-W except that the feed was sized and the feed rate was reduced to 2960 lb/hr from 3760 lb/hr.

The purpose of the test was to determine whether the mill would still overload when a sized feed was used at a reduced rate.

The same flowsheet was used for tests 8-W and 9-W as had been previously used for tests 4-W to 6-W, except for the following changes:

(a) Only an 8 mesh screen was used before the classifiers, instead of the 4-mesh-over-8-mesh arrangement.

(b) A Denver 12 in. rotary classifier was replaced by an Akins 12 in. spiral classifier.

(c) A Hardinge electric ear with a Weston sound recorder was used to record the sound level of the mill during the last two tests.

(d) The feed was added by hand, as before, except that the rate of feeding was controlled by the observed power readings correlated with the sound level readings. The point at which overloading started within the mill could be detected. Once overloading was thought to be taking place, the feed was either stopped for several minutes, or very coarse (+6 in.) material was added until the load in the mill reached a suitable level.

A graph, shown in Figure 6, was made to show the variation of the rates of flow of the mill discharge and rake classifier sands, and of the power consumed as the test was in progress. Referring to Figure 6, the classifier discharge held quite steadily at about 2900 lb/hr. The gross power input curve indicates that the mill began to overload after about 5 hr of operation, and remained in that state for about 2 hr. Overloading of the mill also took place before the test was stopped after 10.25 hr of operation. Figure 8 is a sound record taken of the mill during the test. The sound level remained constant for the first $4\frac{1}{2}$ hr of the test, then dropped. The accompanying drop in power readings indicated that the mill was overloaded.

Material Balance, Test 8-W

Product	Dry Weight, lb
(1) Mill feed:	
(a) Material fed to mill, 57 buggies @ 550 lb @ 3.2% moisture	30,350
Average dry feed rate to mill, based on 10.25 hr operating time	= 2,960 lb/hr
(2) Mill Products:	
(a) Collected rake classifier sands, 30,896 lb @ 80.4% solids	24,840
(b) Collected spiral classifier sands, 576 lb @ 70.8% solids	480
(c) Classifier overflow collected in cone:	
3297 lb @ 69.2% solids	2,281
746 lb @ 66.3% solids	495
640 lb @ 58.3% solids	373
(d) Discarded overflow (based on timed rate samples and moisture samples): 3680 lb/hr @ 3.6% solids for 10.25 hr	1,360
(3) Total collected product = (a) + (b) + (c) + (d)	= 29,757
Rate of total product discharge = $\frac{29,757}{10.25}$	= 2,900 lb/hr
(4) Mill Load:	
(a) Mill load at end of test = 1840 lb	
(b) Initial charge in mill = 1200 lb	
Gain in load 640 lb @ 90% solids	575
(c) Spillage = 755 lb @ 90% solids (estimated)	680
Total dry collected product = (3) + (4)	= 31,012 lb
Total dry feed to mill	= 30,350
Discrepancy	+ 662 lb

Test 9-W

The same conditions and flowsheet were used for test 9-W as in the previous test, except that the mill was equipped with a full grate discharge arrangement. The latter decreased the retention time of the material in the mill, thereby giving a discharge product coarser than that of test 8-W, as shown in Tables 10 to 20, which contain the screen analyses of the various products for the wet grinding tests.

The test was started with an initial charge of coarse pebbles, weighing 1200 lb. The feed was added at the desired rate, but after about one hour of operation the average power input began to decrease. Figure 7 shows the variation of the power input, rake classifier discharge, and mill discharge during the test. Figure 9, the sound record of the mill for this test, shows that the sound level within the mill began to decrease soon after the test had started. These trends indicated that packing of fine material inside the mill had started and that the mill was being overloaded. In order to prevent this latter condition, the feed was stopped for a period of $\frac{1}{2}$ hr, followed by the addition of coarse (+6 in.) feed. Also, the amount of water added to the mill was increased from 660 lb/hr to 880 lb/hr. Later, about 46 lb of scrap steel was charged to the mill. However, the mill remained in a semi-overloaded state during the last 4 hr of the test. At the end of the 10 hr run, the load in the mill was dumped, and a 6 in. layer of relatively fine material was found to be packed along the shell of the mill.

A summary of the results from this test is given in

Table 9. Screen analyses of the products are given in Tables 10 to 20, and the calculated reduction ratios and net power consumptions are given in Table 21.

Two observations concerning the last two tests (8-W and 9-W) must be noted here. First, the screen analysis of the feed used for the tests showed that the feed was much coarser for tests 8-W and 9-W than that for the previous tests. Also, in the previous tests, the feed consisted of a coarse to medium grained, light-coloured granite pegmatite; pink feldspar was the main mineral, but quartz was also present in appreciable amounts. The ore used for tests 8-W and 9-W contained a greater amount of the dark ferromagnesian minerals, such as chlorite and hornblende. The light coloured pegmatite used prior to tests 8-W and 9-W was more brittle and fractured quite readily, whereas the rock used in tests 8-W and 9-W was much harder to break. The characteristics of these two types of ore would have an effect on their grindability.

Material Balance, Test 9-W

Product	Dry Weight, lb
(1) Mill Feed:	
(a) Material fed to mill, 51 buggies @ 550 lb = 28,050 lb	
(b) +6 in. feed 900 lb	
28,950 lb @ 3.2% moisture	28,000
Average dry feed rate based on 10.0 hr running time	2,800 lb/hr
(2) Mill Products:	
(a) Collected rake classifier sands, 24,697 lb @ 80.8% solids	19,950
(b) Collected spiral classifier sands, 802 lb @ 70.0% solids	562
(c) Solids collected from classifier overflow,	
2809 lb @ 69.2% solids	1,940
1301 lb @ 67.5% solids	880
(d) Discarded overflow (based on timed-rate samples and moisture samples): (8300 lb/hr) (10 hr) (3.1% solids)	2,580
(3) Total collected mill product = (a) + (b) + (c) + (d)	25,912 lb
(4) Mill Load:	
Mill load after test = 3762 lb @ 90% = 3390 lb	
Mill load before test = 1200	
Gain in mill load	2,190 lb
Total (3) + (4)	= 28,102 lb
Feed	28,000
Discrepancy	102 lb
Total dry product discharge rate $= \frac{25,912}{10}$	= 2,591 lb/hr
Actual feed rate $= \frac{28,000 - 2190}{10}$	= 2,581 lb/hr

Method of Calculation of Work Index, Wi for Test 9-W:

80% passing size in feed from screen analysis = 140,000 microns

80% passing size in combined product from screen analysis = 465 microns

$\therefore Rr = F/_P = \frac{140,000}{465} = 301.1$

Net hph/ton total dry product, W = 4.03

Net Kwh/ton total dry product = (0.746)(4.03) = 3.01

$$W_i = W\left(\frac{\sqrt{F}}{\sqrt{F}-\sqrt{P}}\right)\sqrt{\frac{P}{100}} = W\left(\frac{\sqrt{Rr}}{\sqrt{Rr}\ -1}\right)\sqrt{\frac{P}{100}}$$

$$W_i = (3.01)\left(\frac{\sqrt{301.1}}{\sqrt{301.1}\ -1}\right)\sqrt{\frac{465}{100}}$$

$$W_i = 6.88 \text{ Kwh/ton}$$

DISCUSSION

Comparisons

Of the wet and dry grinding tests performed in the Cascade mill when equipped with a peripheral discharge arrangement, the following comparisons can be made: Tests 2 (dry) and 1-W (wet), at 28.15 rpm and a 3800 lb/hr feed rate; and Tests 3 (dry) and 2-W (wet), at 22.9 rpm and a 3400 lb/hr feed rate.

Test 2 (Dry) vs Test 1-W (Wet) -

The wet grinding test had the following advantages:

a) A finer 80% passing size in the screen undersize and a higher reduction ratio of 126.4 as against 105.9 for test 2.

b) A smaller circulating load than the dry grinding test. However, the amount of -8 mesh material present in each test was about the same.

c) Test 1-W consumed slightly less power than did test 2.

Screen analysis of the products showed that test 2 produced coarser screen undersize, coarser dust and coarser oversize products.

Test 3 (Dry) vs Test 2-W (Wet) -

Test 2-W had the following advantages:

a) It had a finer 80% passing size in the screen undersize, and a larger reduction ratio, than test 3.

b) The circulating load returned to the mill, as well as the percent of -8 mesh product present in the returned product, was less than for test 3.

c) Test 2-W produced finer classifier sands and overflow products, but a coarser screen oversize material.

However, the dry grinding test consumed less power -- 4.35 net hph/ton of total dry product discharge as compared with 5.34 for test 2-W.

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Separate comparisons of the two dry grinding tests and of the two wet grinding tests were also made, with the following results:

Test 2 (Dry) vs Test 3 (Dry) -

Test 3 consumed less power, had the higher reduction ratio, and had a smaller amount of -8 mesh product in the circulating load.

Test 1-W (Wet) vs Test 2-W (Wet) -

In test 1-W, the mill was operated at greater rates of feed and speed than in 2-W. It produced as fine a screen undersize product, and had the same reduction ratio, but consumed less power per ton than did 2-W. However, the actual amount of -8 mesh material returned to the mill in the circulating load was nearly seven times that returned in test 2-W.

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Since all the tests mentioned above were run for relatively short periods of time, no conclusions can be made as to which test was the most efficient. The results obtained can only be used for comparison.

Test 7-W required the least gross input of power, but since the product discharge rate was so low, the calculated net power required was 8.13 hph/ton of total dry product --- the highest value of all tests.

Test 9-W was the only wet grinding test in which the mill was equipped with a full grate discharge arrangement. This test, when the mill was operated at 86.2% critical speed and fed at 2581 lb/hr, gave the best results as compared with the other tests. It also consumed the least power, and, with the exception of test 7-W, had the highest reduction ratio. The moderate circulating load produced in this test contained the smallest amount of -8 mesh material.

Overloading in Mill

Mill overloading was a problem experienced in all of the wet grinding tests and, to a minor extent, in the dry grinding tests. However, it was not until the mill had been emptied of its charge after test 6-W, that the "packing" was discovered. As was mentioned before, this packed material would decrease the grinding capacity of the mill, hence the feed rate had to be reduced.

Power input readings were taken during the tests, in order to determine when overloading was taking place. In tests 6-W to 9-W, attempts had been made to alleviate overloading by reducing the feed rate and adding coarse pebbles to the mill. In test 9-W, 46 lb of scrap steel was added but no improvement resulted.

The effect of packing within the mill has been quite easily explained, but the exact cause of the packing is not definitely known. To determine this cause, an adequate understanding of the mechanism of grinding that is taking place in the mill is essential. Also, such factors as the speed of the mill, the pulp density of the charge, and the characteristics of the ore, should all be considered.

The following is an attempt to explain the cause of packing in the mill.

The three main mechanisms of grinding in the Cascade mill are considered to be: (a) impact from cascading pebbles and boulders, (b) attrition of sliding pebbles, and (c) crushing action.

The main factors involved in the first mechanism would be (i) weight or size of the boulders, (ii) height of fall, and (iii) velocity of the boulder as governed by the speed of the mill and the relative position of the boulder in the mill--i.e. whether near the centre of the mill or near the inside periphery. The two factors of weight and velocity govern the momentum.

The second mechanism, attrition of sliding pebbles, occurs during operation. The pebbles that are at the periphery of the mill are carried upwards with the revolving motion. Some tumble back to break by impact, while others slide back and undergo attrition. This attrition probably yields very fine material. Any fine material produced by colliding fragments would probably find its way through the spaces between the coarse fragments and collect on the inside periphery of the mill.

The third mechanism, crushing action, would occur when very large fragments act upon the smaller fragments. Centrifugal force governed by the weight of the heavier fragments would split the small fragments into finer sizes.

Which of the three above-mentioned mechanisms is the major one probably depends on the size range or distribution of the charge in the mill. Impact is probably more pronounced in the coarser sizes, while attrition and crushing processes take effect as the material becomes finer.

Summing up, packing would be caused by the fine material travelling through the voids. The amount of this packing would be affected to a certain extent by the speed of the mill and by the pulp densities within the mill.

EVALUATION OF RESULTS

To evaluate the results obtained in grinding tests with the Cascade mill, the work index, W_i, as defined by "The Third Theory of Comminution", is used.

Tables 6 and 21 give the work indices, based on net power consumptions for the complete duration of the tests. Thus, for calculations of the work indices, average tonnages per hour are used as obtained during the full period of test, as well as power consumptions per ton. In this way, the work indices reflect the true picture of the mill performance as affected by stoppages, feed fluctuations, and packing of the ground ore inside the periphery of the mill.

When these work index figures are studied, even considering that the mill performance was often hindered by packing of the ore inside the periphery, they appear to be quite reasonable, although it must be emphasized here that they are work indices based on net power consumptions. What the actual gross power consumptions for commercially sized mills are going to be, the writers are unable to say, since the pilot-size mill used in the tests is much less efficient than a large mill. In a letter dated February 12, 1959, to one of the writers of this report, Mr. Harlowe Hardinge, president of Hardinge Company Incorporated, stated that a rule-of-thumb factor to use would be on the order of increasing the net horsepower to gross power at the mill countershaft by a certain percentage. Mr. Hardinge states:

"For a 12' mill, requiring between 150 and 250 hp, this would be somewhat on the order of 11% to 12%; while for an 18' mill, consuming 600 hp, 9% to 10%; and for a 22' mill, consuming 1200 to 1500 hp, 8%.

These factors are roughly those that we use in our evaluations for our standard interpolations of ball and rod mills, and we see no reason why there should be any basic difference in a Cascade mill, as the same general factors as to varying loadings, running speeds, gear ratios, etc., apply."

Since the power consumptions appear to be satisfactory, since they reflect the overall conditions of the tests, it might be stated here that autogenous grinding is a promising tool in milling. However, no definite conclusions should be drawn till the performance of the Cascade mill is compared with the combined performances of the secondary crusher and the rod mill.

In an article on "Autogenous Grinding", Harlowe Hardinge[2] states:

"The test unit should be of adequate size to handle the coarse feed. Tests must be carried on sufficiently long, and with enough material, to reach the stabilized condition which results after all the rough edges are worn off the feed and the grinding rates of different ranges are established. A short test usually indicates capacity rates that are too optimistic."

Thus, it can be seen that it will require a lot of research and pilot testing on individual ores before the applications and the economic possibilities of autogenous grinding are fully evaluated.

ACKNOWLEDGMENT

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REFERENCES

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2. Hardinge, Harlowe, "Autogenous Grinding". Mining Congress Journal, Vol. 44, No. 10 (1958), pp. 56-62.

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(Tables 1 to 23 and Figures 1)
(to 9 follow, on pages 31 to 57)

LED:RSK:(PES)DV

TABLE 1

Summary of Dry Grinding Tests on Faraday Uranium Ore

	Test 1	Test 2	Test 3	Test 4-A	Test 4-B	Test 4-C
Speed, rpm	28.15	28.15	22.90	18.87	18.87	18.75
% critical speed	87.5	87.5	71.2	58.7	58.7	58.75
Length of run, hr	2.0	3.88	4.83	2.59	1.34	3.68
Feed rate, lb/hr	4000	3800	3400	3200	3000	2800
Average -8 mesh product, lb/hr	3359	3600	3190	2823	2420	2440
Total dust collected, lb	850	912	694	399	260	586
Average dust rate, lb/hr	425	234	150	154	194	160
Average dust rate, lb/hr, from timed samples	338	187	188	174	182	167
Total products, lb/hr	3784	3834	3340	2977	2614	2600
Average gross hp	16.20	18.52	14.80	12.41	13.29	12.11
Efficiency, *%	76	76	79	78	78	78
Net gross hp	12.30	14.08	11.69	9.68	10.35	9.45
No load hp	8.26	8.26	6.81	6.06	6.06	6.06
Efficiency, *%	65	65	65	59	59	59
Net no load hp	5.37	5.37	4.43	3.58	3.58	3.58
Net hp	6.93	8.71	7.26	6.10	6.77	5.87
Net hph/ton	3.66	4.54	4.35	4.10	5.18	4.52
Screen oversize rate, lb/hr	4800	3600	2580	1080	900	1140

*These are mechanical efficiencies of the drive to the mill. They were obtained from prony brake tests performed on the same type and size of mill at the Hardinge Company's York, Pennsylvania laboratory.

TABLE 2

Screen Analysis of -8 Mesh Products Obtained from Dry Grinding Tests

Mesh	Test 1		Test 2		Test 3		Test 4-A		Test 4-B		Test 4-C	
	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing
+ 10	7.5	92.5	8.08	91.92	5.88	94.12	3.5	96.5	2.9	97.1	3.26	96.74
+ 14	16.0	84.0	17.08	82.92	13.40	86.60	9.5	90.5	8.4	91.6	9.30	90.70
+ 20	23.6	76.4	25.24	74.76	21.20	78.80	15.5	84.5	14.1	85.9	15.88	84.12
+ 28	33.4	66.6	34.92	65.08	31.48	68.52	24.8	75.2	23.1	76.9	25.16	74.84
+ 35	43.3	56.7	44.32	55.68	41.84	58.16	34.9	65.1	33.1	66.9	35.04	64.96
+ 48	54.0	46.0	54.04	45.96	52.72	47.28	46.2	53.8	44.6	55.4	46.20	53.80
+ 65	65.3	34.7	64.60	35.40	64.00	36.00	58.2	41.8	57.0	43.0	58.24	41.76
+100	70.9	29.1	73.76	26.24	73.68	26.32	69.2	30.8	70.3	29.7	68.96	31.04
+150	84.0	16.0	80.92	19.08	81.20	18.80	77.7	22.3	79.1	20.9	77.44	22.56
+200	90.0	10.0	86.88	13.12	87.44	12.56	84.6	15.4	86.7	13.3	84.52	15.48
+325	95.4	4.6	92.40	7.60	93.00	7.00	91.2	8.8	93.8	6.2	91.92	8.08
-325 Total	100.0	--	100.00	--	100.00	--	100.0	--	100.0	--	100.00	--

TABLE 3

Screen Analysis of Dust Samples from Dry Grind Tests

+ 48	0.2	99.8	0.2	99.8	0.1	99.9	0.3	99.7	0.4	99.6	0.4	99.6
+ 65	0.5	99.5	0.9	99.1	0.6	99.4	1.0	99.0	1.1	98.9	1.2	98.8
+100	1.5	98.5	3.1	96.9	2.4	97.6	3.2	96.8	3.1	96.9	3.7	96.3
+150	4.7	95.3	7.0	93.0	5.9	94.1	7.2	92.8	7.1	92.9	8.3	91.7
+200	10.6	89.4	13.0	87.0	11.6	88.4	13.2	86.8	12.7	87.3	15.1	84.9
+325	22.4	77.6	24.2	75.8	22.2	77.8	26.2	73.8	24.9	75.1	28.6	71.4
-325	100.0	--	100.0	--	100.0	--	100.0	--	100.0	--	100.0	--

TABLE 4

Screen Analysis of Screen Oversize Products from Dry Grinding Tests

Mesh	Test 1		Test 2		Test 3		Test 4-A		Test 4-B		Test 4-C	
	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing	Cumulative Weight, % Retained	% Passing
+ 3/8 in.			1.8	98.2	3.4	96.6	3.0	97.0	3.4	96.6	3.8	96.2
+ 3 mesh			14.0	86.0	22.4	77.6	20.2	79.8	20.5	79.5	22.4	77.6
+ 4			37.8	62.2	43.6	56.4	39.8	60.2	41.7	58.3	42.0	58.0
+ 6			59.8	40.2	67.2	32.8	61.6	38.4	64.2	35.8	65.5	34.5
+ 8			83.8	16.2	86.3	13.7	80.1	19.9	82.6	17.4	84.5	15.5
+10			96.6	3.4	95.6	4.4	94.6	5.4	96.8	3.2	98.3	1.7
-10			100.0	—	100.0	—	100.0	—	100.0	—	100.0	—

TABLE 5

Screen Analysis of Combined -8 Mesh and Dust Products

+ 10	6.7	93.3	7.6	92.4	5.6	94.4	3.3	96.7	2.7	97.3	3.1	96.9
+ 14	14.2	85.8	16.1	83.9	12.8	87.2	9.0	91.0	7.8	92.2	8.8	91.2
+ 20	20.9	79.1	23.8	76.2	20.2	79.8	14.7	85.3	13.1	86.9	15.0	85.0
+ 28	29.6	70.4	32.9	67.1	30.0	70.0	23.5	76.5	21.4	78.6	23.7	76.3
+ 35	38.4	61.6	41.7	58.3	40.0	60.0	33.1	66.9	30.7	69.3	33.0	67.0
+ 48	47.9	52.1	50.8	49.2	50.4	49.6	43.8	56.2	41.4	58.6	43.5	56.5
+ 65	58.0	42.0	60.8	39.2	61.2	38.8	55.2	44.8	52.9	47.1	54.8	45.2
+100	67.5	32.5	69.5	30.5	70.5	29.5	65.7	34.3	65.4	34.6	65.0	35.0
+150	75.1	24.9	76.5	23.5	77.8	22.2	74.0	26.0	73.8	26.2	73.2	26.8
+200	81.1	18.9	82.4	17.6	84.0	16.0	80.9	19.1	81.2	18.8	80.3	19.7
+325	87.2	12.8	88.2	11.8	89.8	10.2	87.8	12.2	88.7	11.3	88.1	11.9
-325	100.0	—	100.0	—	100.0	—	100.0	—	100.0	—	100.0	—

TABLE 6

Calculated Work Requirements from Screen Analyses of Tests 2, 3 and 4-C

Data	Test 2	Test 3	Test 4-C
80% passing size in feed, F	90,000 μ	90,000 μ	90,000 μ
80% passing size in product, P	850 μ	820 μ	640 μ
Reduction ratio, R_r	105.9	109.8	140.6
W, net hph/ton	4.54	4.35	4.52
W, Kwh/ton	3.39	3.24	3.37
W_i, Kwh/ton	11.21	10.27	9.31
% critical speed	87.5	71.2	58.75

TABLE 7

Screen Analysis of Feed for Tests 1-4C and 1-W, 2-W

Size, in.	Weight % Retained	Cumulative Weight % Retained	% Passing
+ 4	13.0	13.0	87.0
+ 2	18.2	31.2	68.8
+ 1	11.6	42.8	57.2
+ ½	9.6	52.4	47.6
+ ¼	9.5	61.9	38.1
- ¼	38.1	100.0	—
Total	100.0	—	—

TABLE 8

Summary of Initial Wet Grinding Tests on Faraday Uranium Ore

Test Run No.	Preliminary Run	1-W	2-W
Speed, rpm	18.75	28.15	22.9
% critical speed	58.0	87.5	71.2
Length of run, hr	4.45	6.34	4.10
Feed rate, lb/hr	2800) 2600) 2500)	3800	3400
Average overflow rate, lb/hr pulp	2280	3985	4470
Average % solids in overflow	15.9	8.8	8.8
Dry overflow rate, lb/hr	362	350	393
Classifier sands, lb/hr	2100	3743	3230
Average % solids from moisture samples	76.7	79.6	77.6
Average % solids from pulp density samples	78.9	80.4	78.4
Net average % solids	77.8	80.0	78.0
Dry sands, lb/hr	1635	3000	2520
Total dry products, lb/hr	1997	3350	2913
Average gross hp	13.01	17.13	15.24
Efficiency, *%	78.0	75	80.0
Net gross hp	10.16	12.87	12.20
No load hp	6.06	8.26	6.81
Efficiency, *%	59	65	65
Net no load hp	3.58	5.37	4.43
Net hp	6.58	7.50	7.77
Net hph/ton	6.59	4.47	5.34
Screen oversize rate, lb/hr	--	2740	840

*Based on York Laboratory prony brake test.

TABLE 9

Summary of Results Obtained from Grinding Tests 4-W to 9-W on Faraday Uranium Ore

Test	4-W	5-W	6-W	7-W	8-W	9-W
Mill speed, rpm	23	23	27.7	27.7	27.7	27.7
% critical speed	71.5	71.5	86.2	86.2	86.2	86.2
Intended feed rate, lb/hr dry	3760	3760	3760	850	3180	3180
Average rake sands collected, lb/hr dry	2310	2530	2420	C.L. 4400	2425	1995
Average spiral sands collected, lb/hr dry	—	—	—	—	40	56
Average classifier overflow, dry lb/hr	508	497	608	738	460	540
Increase or decrease in mill load, average dry lb/hr				decrease + 128	incr. - 123	incr. - 219
Total dry product, lb/hr	2818	3027	3028	738	2925	2591
Actual average dry feed rate,lb/hr	3760	3760	3170	737	2960	2581
Duration of test, hr	1.284	2.0	9.5	5.75	10.25	10.00
Average screen undersize lb/hr dry	3500	3500	3625	6820	3390	3510
Average screen oversize lb/hr dry	—	—	636	179	1480	1450
Average mill discharge lb/hr dry	3510	3510	3625	8210	4200	4180
Total power consumption,Kwh			135.9	52.4	135.7	113.1
Average gross input per hr (KW)	17.27	12.50	14.3	9.13	13.23	11.31
Average hourly gross input hp	23.10	16.75	19.15	12.22	17.73	15.15
Efficiency, *%	65	71	72	68.5	71.4	70.1
Average net gross hp (1)	15.00	11.90	13.80	8.38	12.65	10.60
No load hp (input)	8.25	6.81	8.40	8.40	8.40	8.40
Efficiency, %	51	56	64	64	64	64
Net no load hp (2)	4.2	3.81	5.38	5.38	5.38	5.38
Average net power hp (1)-(2)	10.8	8.09	8.42	3.00	7.27	5.22
Net hph/ton dry product	7.67	5.34	5.56	8.13	4.97	4.03

C.L. = circulating load.

*The efficiency curve of the kwh meter was used and the drive-chain efficiency of 98% included.

TABLE 10

Screen Analyses of Products Obtained from Wet Grinding Test No. 1-W

Mesh	RAKE CLASSIFIER SANDS Av. Cum. Wt. % Retained	RAKE CLASSIFIER SANDS Average % Passing	RAKE CLASSIFIER OVERFLOW Av. Cum. Wt. % Retained	RAKE CLASSIFIER OVERFLOW Average % Passing	COMBINED CLASSIFIER SANDS AND OVERFLOW Wt. % Retained	COMBINED Cumulative Wt. % Retained	COMBINED % Passing	SCREEN OVERSIZE SIZE	SCREEN OVERSIZE Av. Cum. Wt. % Retained	SCREEN OVERSIZE % Passing
+ 10	5.66	94.34			5.1	5.1	94.9	+ 3/8 in.	0.75	99.25
+ 14	12.74	87.26			6.3	11.4	88.6	+ 3 mesh	9.85	90.15
+ 20	19.95	80.05			6.5	17.9	82.1	+ 4	26.75	73.25
+ 28	28.23	71.77			7.4	25.3	74.7	+ 6	52.35	47.65
+ 35	36.76	63.24			7.6	32.9	67.1	+ 8	80.30	19.70
+ 48	46.84	53.16	0.15	99.85	9.0	41.9	58.1	- 8	100.00	--
+ 65	59.57	40.43	0.35	99.65	11.4	53.3	46.7			
+100	71.01	28.99	0.75	99.25	10.3	63.6	36.4			
+150	81.01	18.99	1.50	98.50	9.0	72.6	27.4			
+200	88.96	11.04	3.95	96.05	7.4	80.0	20.0			
+325	95.17	4.83	15.85	84.15	6.8	86.8	13.2			
-325	100.00	--	100.00	--	13.2	100.0	--			
					100.0	--	--			

TABLE 11

Screen Analyses of Products Obtained from Wet Grinding Test 2-W

Mesh	RAKE CLASSIFIER SANDS			RAKE CLASSIFIER OVERFLOW			COMBINED CLASSIFIER SANDS AND OVERFLOW		
	Wt. % Retained	Cum. Wt. % Retained	% Passing	Wt. % Retained	Cum. Wt. % Retained	% Passing	Wt. % Retained	Cum. Wt. % Retained	% Passing
+ 10	3.60	3.60	96.40				3.1	3.1	96.9
+ 14	4.68	8.28	91.72				4.0	7.1	92.9
+ 20	5.52	13.80	86.20				4.7	11.8	88.2
+ 28	7.40	21.20	78.80				6.4	18.2	81.8
+ 35	8.68	29.88	70.12				7.4	25.6	74.4
+ 48	11.00	40.88	59.12	trace			9.4	35.0	65.0
+ 65	14.52	55.40	44.60	0.1	0.1	99.9	12.5	47.5	52.5
+100	12.88	68.28	31.72	0.2	0.3	99.7	11.1	58.6	41.4
+150	11.20	79.48	20.52	0.6	0.9	99.1	9.7	68.3	31.7
+200	8.72	88.20	11.80	2.5	3.4	96.6	7.8	76.1	23.9
+325	6.80	95.00	5.00	12.6	16.0	84.0	7.6	83.7	16.3
-325	5.00	100.00	—	84.0	100.0	—	16.3	100.0	—
							100.0	—	—

SCREEN OVERSIZE			
SIZE	Wt. % Retained	Cum. Wt. % Retained	% Passing
+ 3/8 in.	4.7	4.7	95.3
+ 3 mesh	17.7	22.4	77.6
+ 4	22.3	44.7	55.3
+ 6	25.4	70.1	29.9
+ 8	20.4	90.5	9.5
- 8	9.5	100.0	—
Total	100.0	—	—

TABLE 12

Screen Analysis of Mill Feed - Tests 4-W to 9-W

Mesh	TEST 6 - 7-W		TEST 8 - 9-W	
	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing
+ 6 in.	8.6	91.4	25.0	75.0
+ 4	14.9	85.1	--	--
+ 2	30.8	69.2	40.0	60.0
+ 1	44.6	55.4	52.1	47.9
+ ½	54.8	45.2	60.9	39.1
+ 3/8	59.2	40.8	64.7	35.3
+ ¼	--	--	--	--
+ 3 mesh	65.8	34.2	70.4	29.6
+ 4	68.9	31.1	73.1	26.9
+ 6	72.6	27.4	76.3	23.7
+ 8	75.3	24.7	78.6	21.4
+ 10	76.9	23.1	100.0	--
+ 14	80.2	19.8		
+ 20	82.6	17.4		
+ 28	85.3	14.7		
+ 35	87.3	12.7		
+ 48	89.8	10.2		
+ 65	91.8	8.2		
+100	93.6	6.4		
+150	94.9	5.1		
+200	95.9	4.1		
+325	96.9	3.1		
-325	100.0	--		

TABLE 13

Screen Analysis of Screen Undersize Product

Mesh	Test 7-W		Test 8-W		Test 9-W	
	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing
+ 8	3.6	96.4	--	--	0.07	99.93
+ 10	5.55	94.45	1.33	98.67	2.23	97.77
+ 14	8.35	91.65	4.33	95.67	5.46	94.54
+ 20	12.95	87.05	9.43	90.57	9.56	90.44
+ 28	22.20	77.80	18.32	81.68	15.96	84.04
+ 35	34.20	65.80	28.08	71.92	23.33	76.67
+ 48	47.20	52.80	38.44	61.56	31.96	68.04
+ 65	63.25	36.75	49.87	50.13	42.76	57.24
+100	76.95	23.05	59.87	40.13	53.26	46.74
+150	86.00	14.00	68.07	31.93	62.36	37.64
+200	91.10	8.90	74.90	25.10	70.33	29.67
+325	94.55	5.45	82.00	18.00	78.93	21.07
-325	100.00	--	100.00	--	100.00	--

TABLE 14

Screen Analysis of Rake Classifier Sands

Mesh	Test 6-W		Test 7-W		Test 8-W		Test 9-W	
	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing
+ 8	--	--	4.3	95.7	--	--	--	--
+ 10	1.9	98.1	6.5	93.5	2.00	98.00	4.23	95.77
+ 14	4.9	95.1	10.0	90.0	5.90	94.10	10.56	89.44
+ 20	10.05	89.95	16.1	83.9	12.66	87.34	18.29	81.71
+ 28	18.80	81.20	27.5	72.5	23.30	76.70	28.69	71.31
+ 35	27.85	72.15	41.5	58.5	35.30	64.70	39.56	60.44
+ 48	40.95	59.05	56.3	43.7	48.20	51.80	51.26	48.74
+ 65	54.45	45.55	72.9	27.1	62.54	37.46	64.96	35.04
+100	67.60	32.40	84.7	15.3	73.62	26.38	76.76	23.24
+150	78.20	21.80	92.1	7.9	82.38	17.62	85.90	14.10
+200	85.95	14.05	95.7	4.3	89.22	10.78	92.30	7.70
+325	92.20	7.80	97.9	2.1	94.52	5.48	96.97	3.30
-325	100.00	--	100.0	--	100.00	--	100.00	--

TABLE 15

Screen Analysis of Spiral Classifier Sands

Mesh	Test 6-W		Test 7-W		Test 8-W		Test 9-W	
	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing
+ 35	0.3	99.7			0.4	99.6	0.6	99.4
+ 48	0.7	99.3			0.8	99.2	1.2	98.8
+ 65	4.6	95.4			1.8	98.2	2.4	97.6
+100	31.8	68.2			6.9	93.1	8.3	91.7
+150	61.1	38.9			24.1	75.9	28.5	71.5
+200	74.3	25.7			54.4	45.6	59.1	40.9
+325	83.1	16.9			83.1	16.9	87.5	12.5
-325	100.0	---			100.0	---	100.0	---

TABLE 16

Screen Analysis of Spiral Classifier Overflow

+ 48	0.1	99.9	0.3	99.7	0.3	99.7	0.7	99.3
+ 65	0.2	99.8	2.1	97.9	0.7	99.3	1.4	98.6
+100	0.6	99.4	10.4	89.6	1.3	98.7	2.5	97.5
+150	2.5	97.5	25.2	74.8	2.3	97.7	4.5	95.5
+200	7.65	92.35	40.6	59.4	5.3	94.7	9.8	90.2
+325	23.80	76.20	56.8	43.2	17.5	82.5	24.8	75.2
-325	100.00	---	100.0	---	100.0	---	100.0	---

TABLE 17

Screen Analysis of Spiral Classifier Overflow - Sample Taken During First Half of Test 7-W

Mesh	Cum. Wt. % Retained	% Passing
+ 3	0.3	99.7
+ 4	0.6	99.4
+ 6	1.1	98.9
+ 8	1.5	98.5
+ 10	2.2	97.8
+ 14	3.0	97.0
+ 20	4.2	95.8
+ 28	6.7	93.3
+ 35	9.2	90.8
+ 48	12.7	87.3
+ 65	17.0	83.0
+100	24.9	75.1
+150	36.1	63.9
+200	48.4	51.6
+325	61.6	38.4
-325	100.0	--

TABLE 18

Screen Analysis of Screen Oversize

Mesh	Test 6-W Cum. Wt. % Retained	Test 6-W % Passing	Test 7-W Cum. Wt. % Retained	Test 7-W % Passing	Test 8-W Cum. Wt. % Retained	Test 8-W % Passing	Test 9-W Cum. Wt. % Retained	Test 9-W % Passing
+ 1 in.	3.65	96.35			--	--	4.5	95.5
+ 7/8	6.37	93.63			0.5	99.5	8.9	91.1
+ 3/4	9.18	90.82			2.7	97.3	17.2	82.8
+ 5/8	14.58	85.42	1.3	98.7	6.8	93.2	28.1	71.9
+ 1/2	21.90	78.10	4.3	95.7	10.8	89.2	39.6	60.4
+ 3/8	35.90	64.10	18.0	82.0	20.4	79.6	56.1	43.9
+ 3 mesh	53.27	46.73	36.2	63.8	34.0	66.0	71.0	29.0
+ 4	65.77	34.23	37.4	62.6	45.2	54.8	79.7	20.3
+ 6	79.70	20.30	38.5	61.5	60.2	39.8	89.4	10.6
+ 8	89.99	10.01	39.1	60.9	74.4	25.6	96.2	3.8
+ 10	96.14	3.86	40.7	59.3	88.8	11.2	99.8	0.2
- 10	100.00	--	100.0	--	100.0	--	100.0	--

TABLE 19

Screen Analysis of Combined Products (Rake Classifier Sands (Spiral Classifier Sands (Classifier Overflow

Mesh	Test 6-W		Test 7-W		Test 8-W		Test 9-W	
	Cum. Wt. % Retained	% Passing	Cum. Wt. % Retained	% Passing	Cum. Wt % Retained	% Passing	Cum. Wt. % Retained	% Passing
+ 10	1.52	98.48	2.2	97.8	1.70	98.30	3.26	96.74
+ 14	4.01	95.99	3.0	97.0	4.90	95.10	8.14	91.86
+ 20	8.11	91.89	4.2	95.8	10.50	89.50	14.09	85.91
+ 28	15.09	84.91	6.7	93.3	19.30	80.70	22.10	77.90
+ 35	22.30	77.70	9.2	90.8	29.31	70.69	30.47	69.53
+ 48	32.76	67.24	12.7	87.3	40.07	59.93	39.64	60.36
+ 65	43.55	56.45	17.0	83.0	52.04	47.96	50.35	49.65
+100	54.16	45.84	24.9	75.1	61.40	38.60	59.80	40.20
+150	63.05	36.95	36.1	63.9	69.10	30.90	67.70	32.30
+200	70.29	29.71	48.4	51.6	75.59	24.41	74.40	25.60
+325	78.52	21.48	61.6	38.4	82.31	17.69	81.75	18.25
-325	100.00	---	100.0	---	100.00	---	100.00	---

TABLE 20

Screen Analysis of Cascade Mill Discharge

Mesh	Test 6-W Cum. Wt. % Retained	Test 6-W % Passing	Test 7-W Cum. Wt. % Retained	Test 7-W % Passing	Test 8-W Cum. Wt. % Retained	Test 8-W % Passing	Test 9-W Cum. Wt. % Retained	Test 9-W % Passing
+ 1 in.	2.9	97.1			1.14	98.86	4.8	95.2
+ 7/8	---	---			---	---	11.3	88.7
+ 3/4	---	---			2.32	97.68	14.9	85.1
+ 5/8	3.9	96.1			2.93	97.07	23.1	76.9
+ 1/2	5.3	94.7			3.42	96.58	30.0	70.0
+ 3/8	7.5	92.5	0.7	99.3	5.76	94.24	38.0	62.0
+ 3 mesh	11.0	89.0	2.1	97.9	8.38	91.62	45.2	54.8
+ 4	13.7	86.3	2.9	97.1	10.70	89.30	49.1	50.9
+ 6	16.3	83.7	4.1	95.9	12.90	87.10	53.1	46.9
+ 8	19.3	80.7	5.2	94.8	15.45	84.55	56.3	43.7
+ 10	21.2	78.8	7.7	92.3	17.15	82.85	59.0	41.0
+ 14	25.2	74.8	9.7	90.3	21.23	78.77	60.6	39.4
+ 20	29.4	70.6	14.7	85.3	25.64	74.36	63.2	36.8
+ 28	36.2	63.8	24.1	75.9	32.62	67.38	66.8	33.2
+ 35	42.3	57.7	36.7	63.3	40.56	59.44	70.5	29.5
+ 48	51.9	48.1	53.1	46.9	49.11	50.89	74.5	25.5
+ 65	60.6	39.4	70.0	30.0	58.57	41.43	79.1	20.9
+100	68.9	31.1	80.7	19.3	66.85	33.15	83.3	16.7
+150	75.3	24.7	87.5	12.5	73.55	26.45	86.8	13.2
+200	80.5	19.5	91.8	8.2	79.12	20.88	89.7	10.3
+325	85.9	14.1	94.7	5.3	85.10	14.90	92.8	7.2
-325	100.0	---	100.0	---	100.00	---	100.0	---

TABLE 21

Calculated Work Requirements from Screen Analyses for Wet Grinding Tests

	Test 1-W	Test 2-W	Test 6-W	Test 7-W	Test 8-W	Test 9-W
80% passing size in feed, F	90,000μ	90,000μ	92,000μ	92,000μ	140,000μ	140,000μ
80% passing size in product, P	700μ	700μ	470μ	176μ	520μ	465μ
Reduction ratio, R_r	126.4	126.4	195.7	522.7	269.2	301.1
W, net hph/ton	4.47	5.34	5.56	8.13	4.97	4.03
W, Kwh/ton	3.34	3.98	4.15	6.06	3.71	3.01
W_i, Kwh/ton	9.68	11.54	9.68	8.41	9.00	6.88
% critical speed	87.5	71.2	86.2	86.2	86.2	86.2

TABLE 22

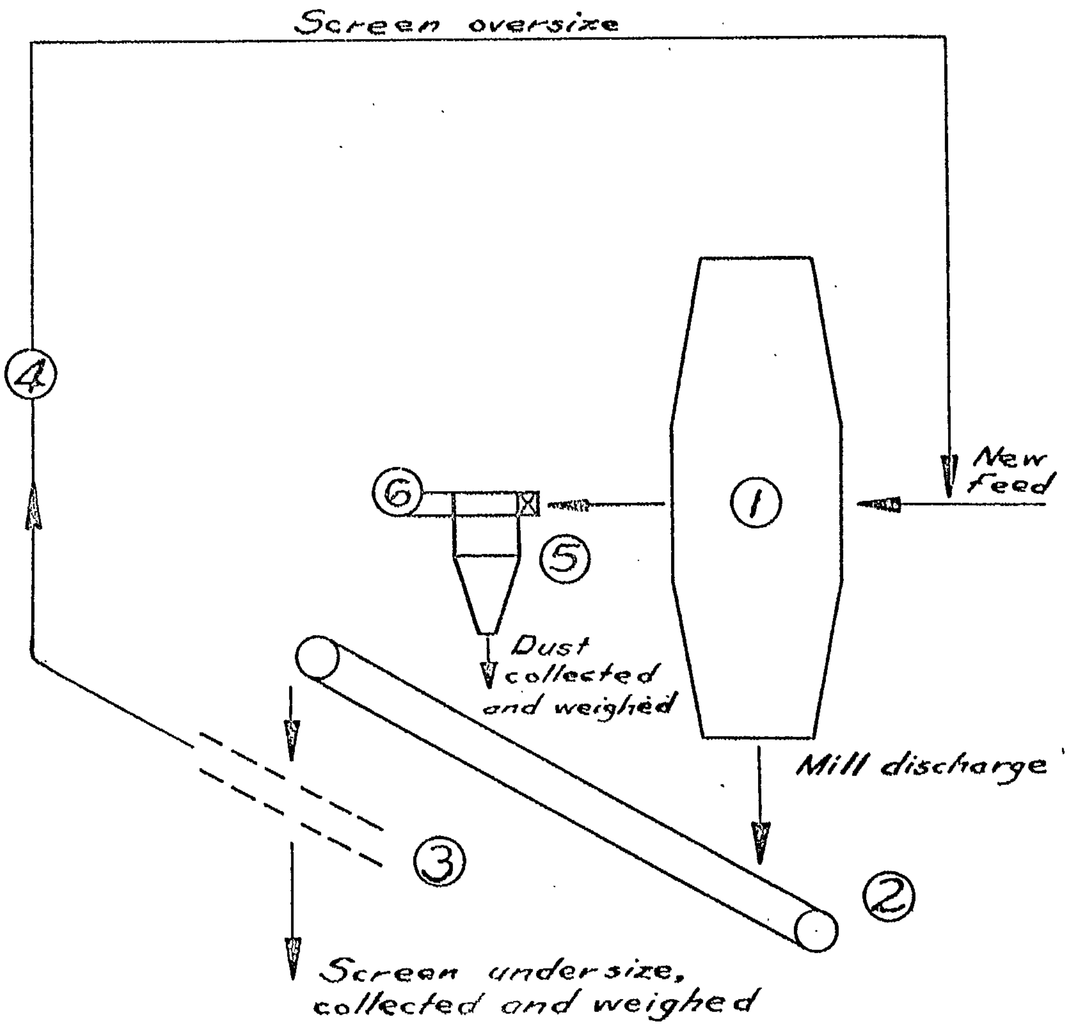
Pulp Densities of Various Products from Wet Grinding Tests
(% Solids)

	Test 1-W	Test 2-W	Test 6-W	Test 7-W	Test 8-W	Test 9-W
Rake classifier sands	80.0	78.0	75.8	78.5	80.4	80.8
Spiral classifier sands	--	--	57.9	--	70.8	70.0
Screen undersize	--	--	--	73.9	42.4	30.0
Screen oversize	--	--	33.7	84.6	88.1	94.5
Classifier overflow	8.8	8.8	9.3	24.5	14.7	8.8
Mill discharge	--	--	72.9	72.8	78.7	67.0

TABLE 23

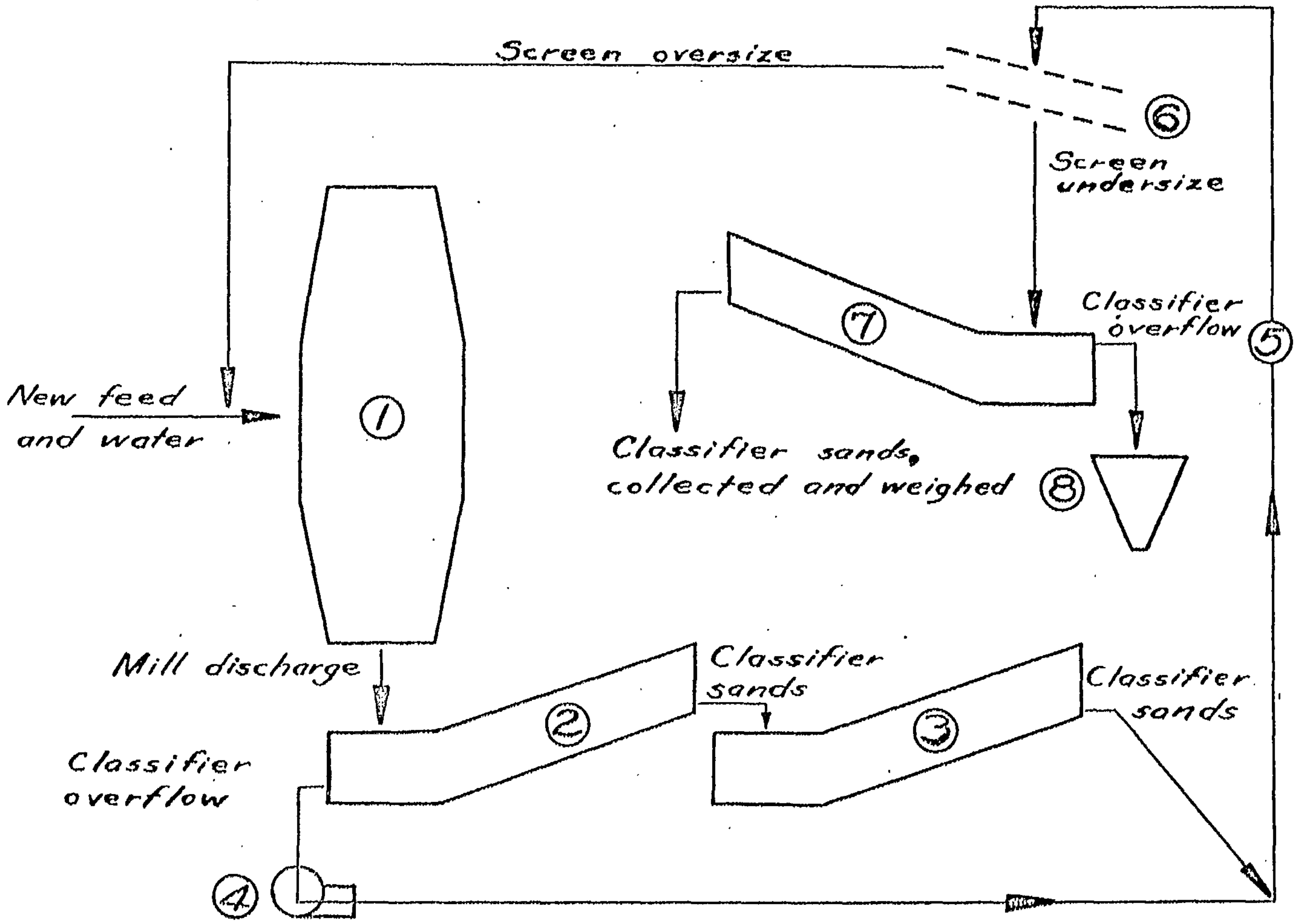
Rates of Discharge of Various Products
(Dry lb/hr)

Rake classifier sands	3000	2520	2420	4400	2425	1995
Spiral classifier sands	--	--	--	--	40	56
Screen undersize	--	--	3625	6820	2630	3510
Screen oversize	2740	840	636	179	1480	1450
Classifier overflow	350	393	608	738	460	540
Mill discharge	--	--	3625	8210	4200	4180



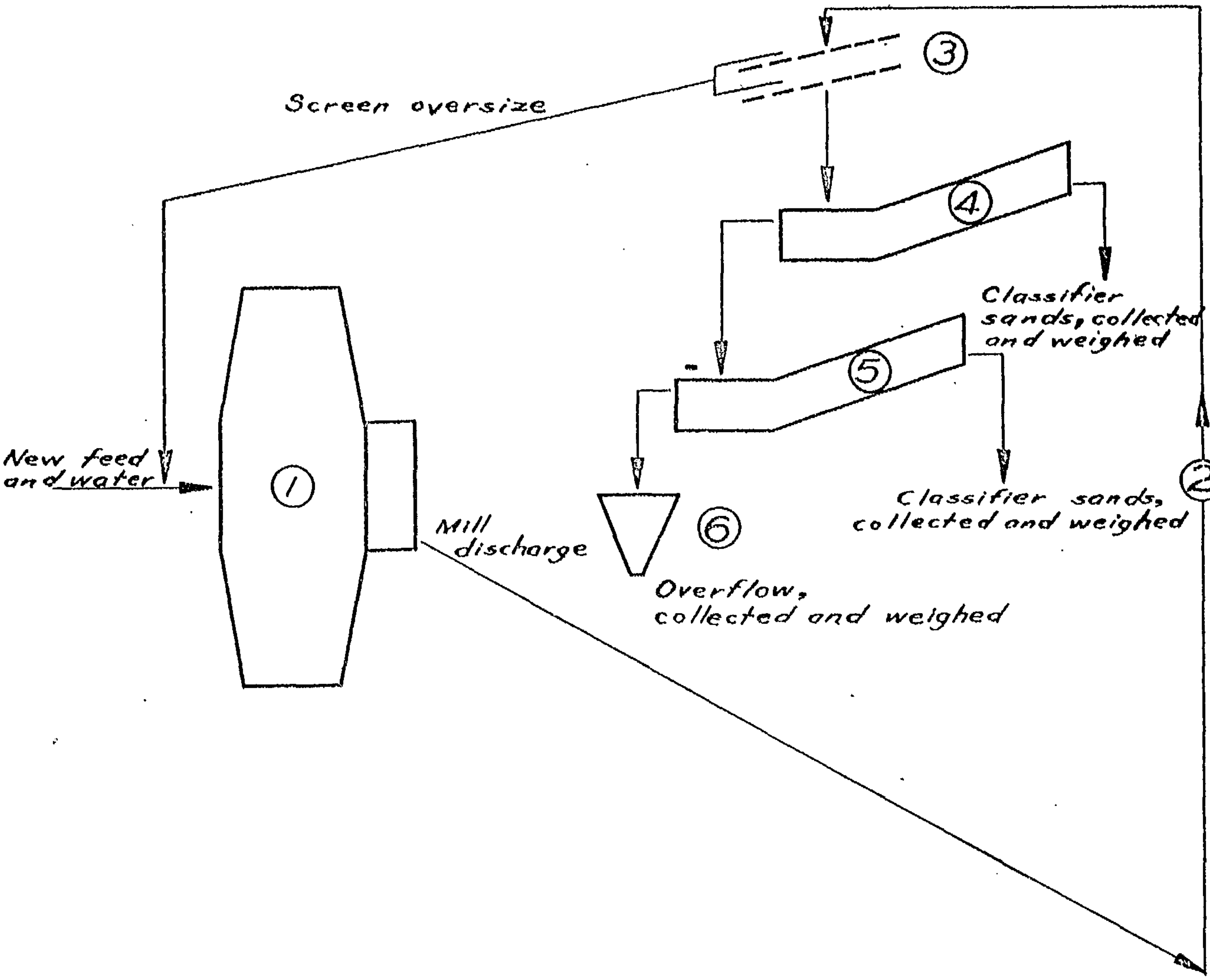
1. 6 ft x 2 ft Hardinge Cascade mill with peripheral discharge - 4 peripheral grates - 32 (3/8 in. x 7 in.) slots per grate
2. 12 in. Link belt conveyor
3. No. 18 Sweco screen - 4 and 8 mesh sieves
4. Link belt elevator
5. 3 ft cyclone dust collector
6. No. 6 Clarage fan - 400 cfm at 4400 rpm

<u>Figure 1.</u> - Flowsheet for dry grind tests.



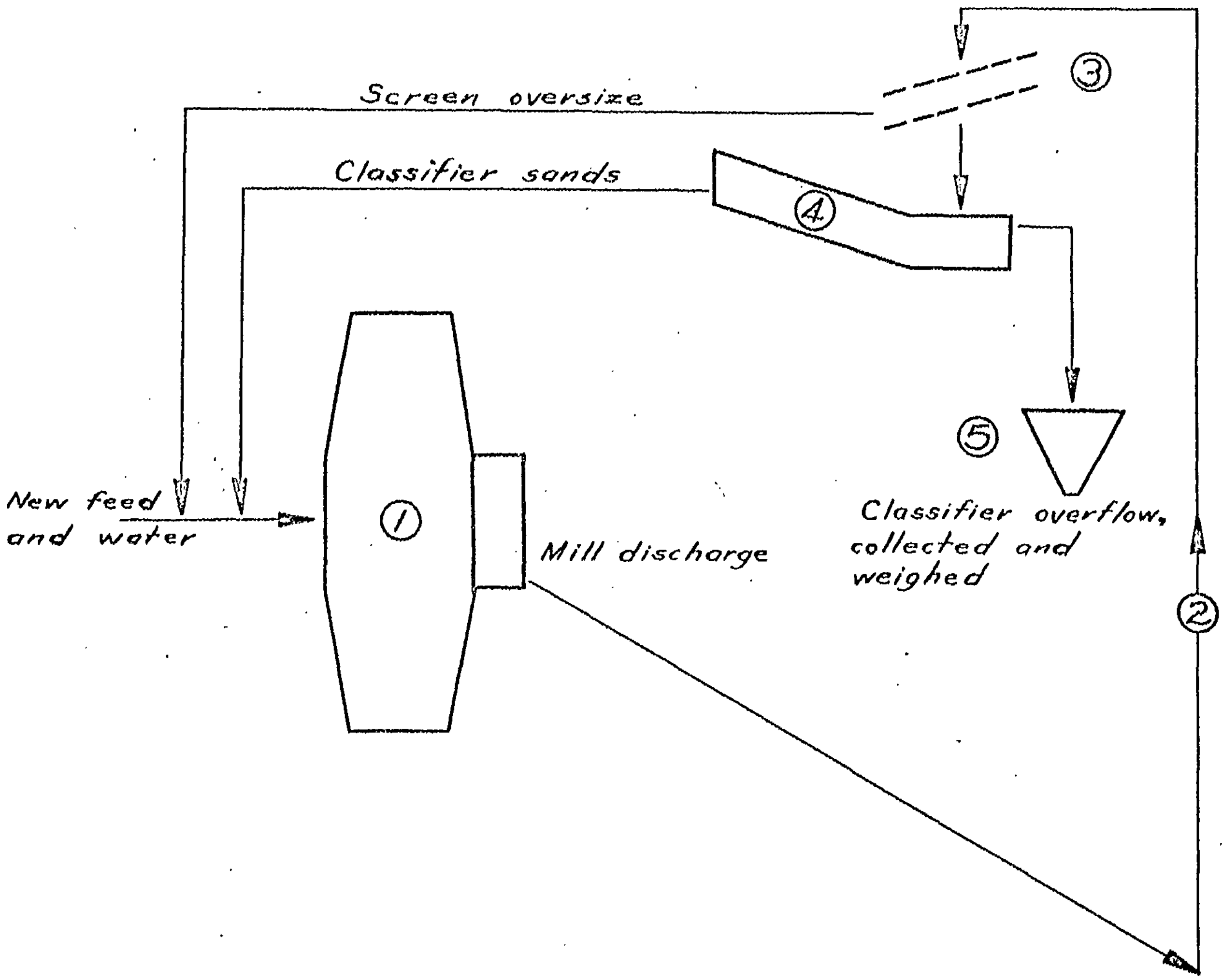
1. 6 ft x 2 ft Hardinge Cascade mill with peripheral discharge - 4 peripheral grates - 32 (3/8 in. x 7 in.) slots per grate
2. Denver 9 in. double-screw classifier used as conveyor
3. Denver 6 in. single-screw classifier used as conveyor
4. Denver sand pump
5. Mines Branch bucket elevator
6. No. 18 Sweco screen - 4 and 8 mesh sieves
7. Dorr 14 in. single rake classifier
8. Type 50 Allen cone - capacity 26½ cu ft

Figure 2. - Flowsheet for wet grind tests 1-W and 2-W.



1. Hardinge Cascade mill equipped with half grate and trunnion overflow discharge
2. Mines Branch bucket elevator
3. No. 18 Sweco screen - 4 and 8 mesh sieves
4. Dorr 14 in. rake classifier
5. Denver 12 in. rotary classifier
6. Type 50 Allen cone

Figure 3. - Flowsheet for wet grind tests 4-W, 5-W and 6-W.



1. Hardinge Cascade mill half grate trunnion overflow discharge
2. Mines Branch elevator
3. $1\frac{1}{2}$ ft x 4 ft Dillon vibrating screen - 4 and 8 mesh sieves
4. Dorr 14 in. rake classifier
5. Type 50 Allen cone

Figure 4. - Flowsheet for fine-grind test 7-W.

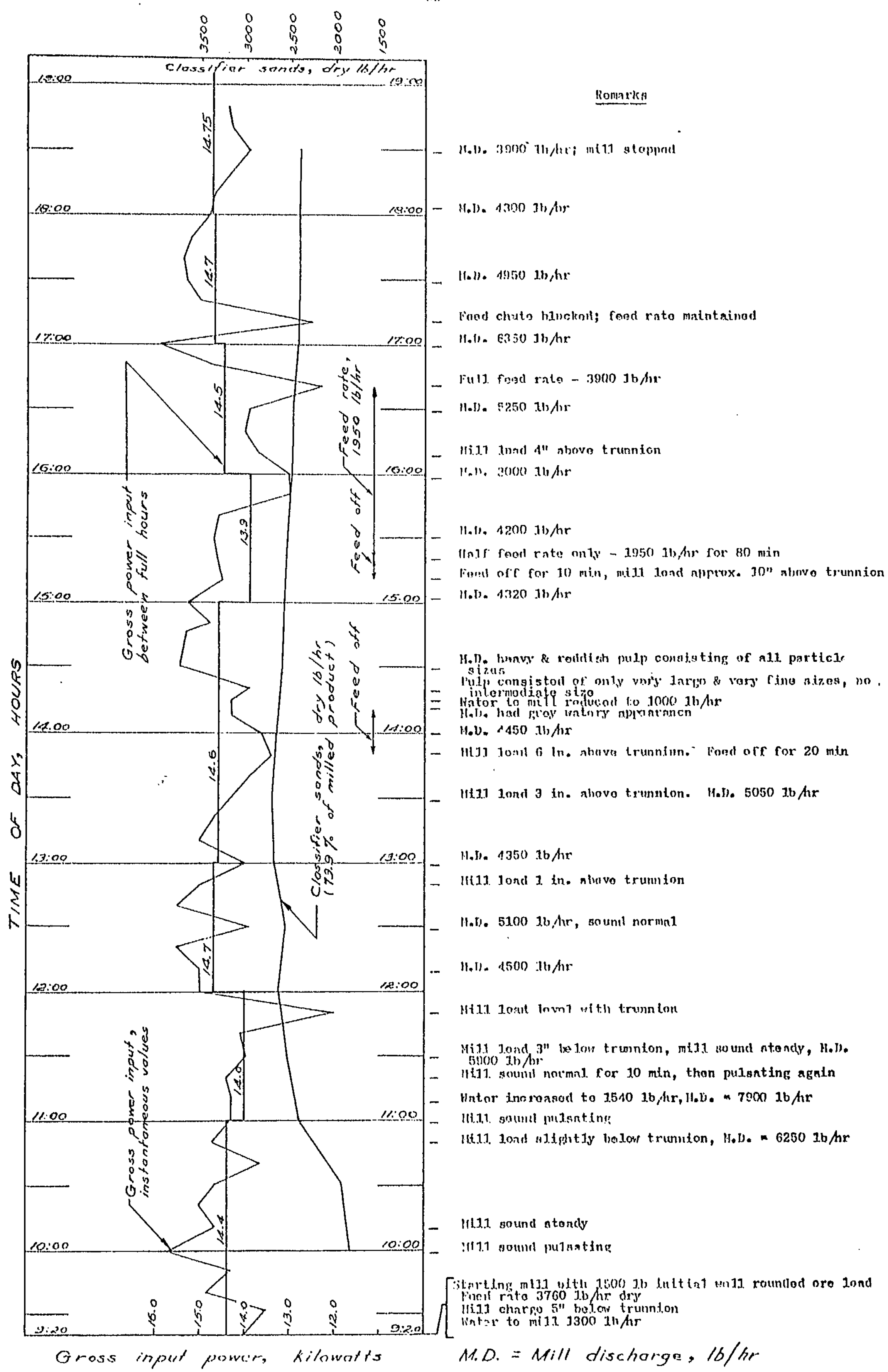


Figure 5. - Graphical Representation of Power Consumption and Classifier Sands Rate of Discharge for Test 6-M.

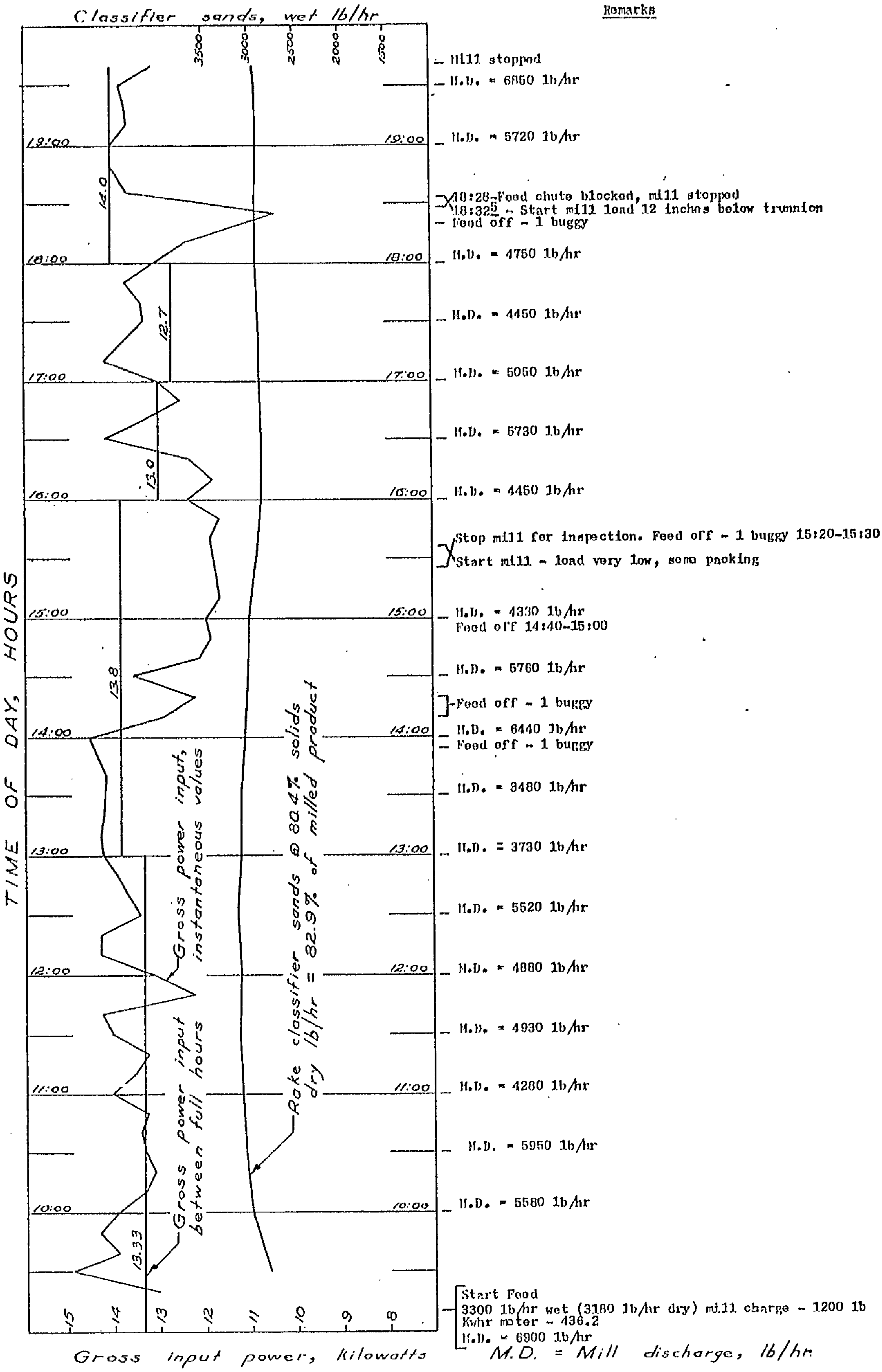


Figure 6. - Power Consumption and Rate of Classifier Sands Discharge for Test 6-W.

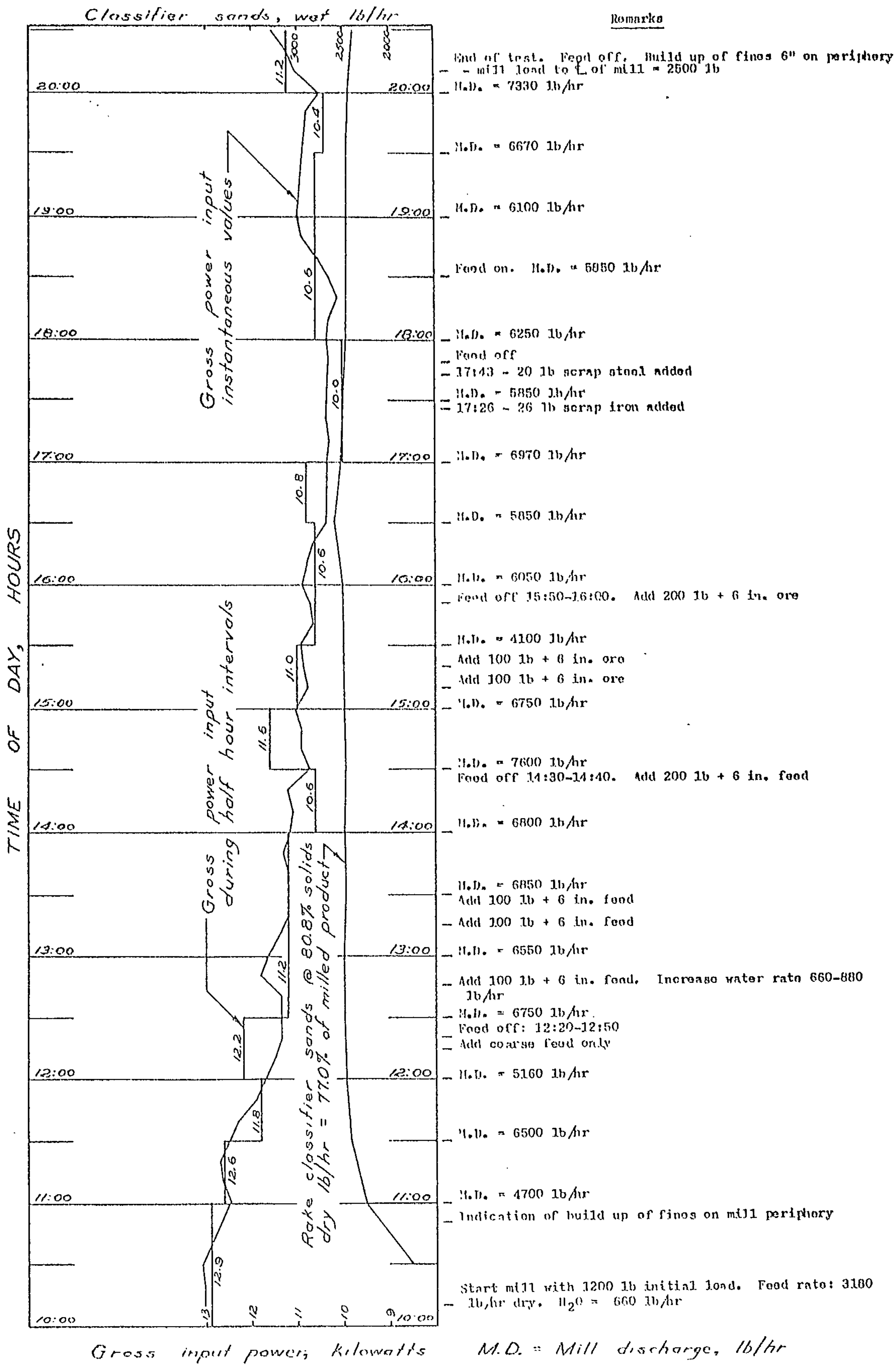


Figure 7. - Power Consumption and Rate of Classifier Sands Discharge for Test 9-W.

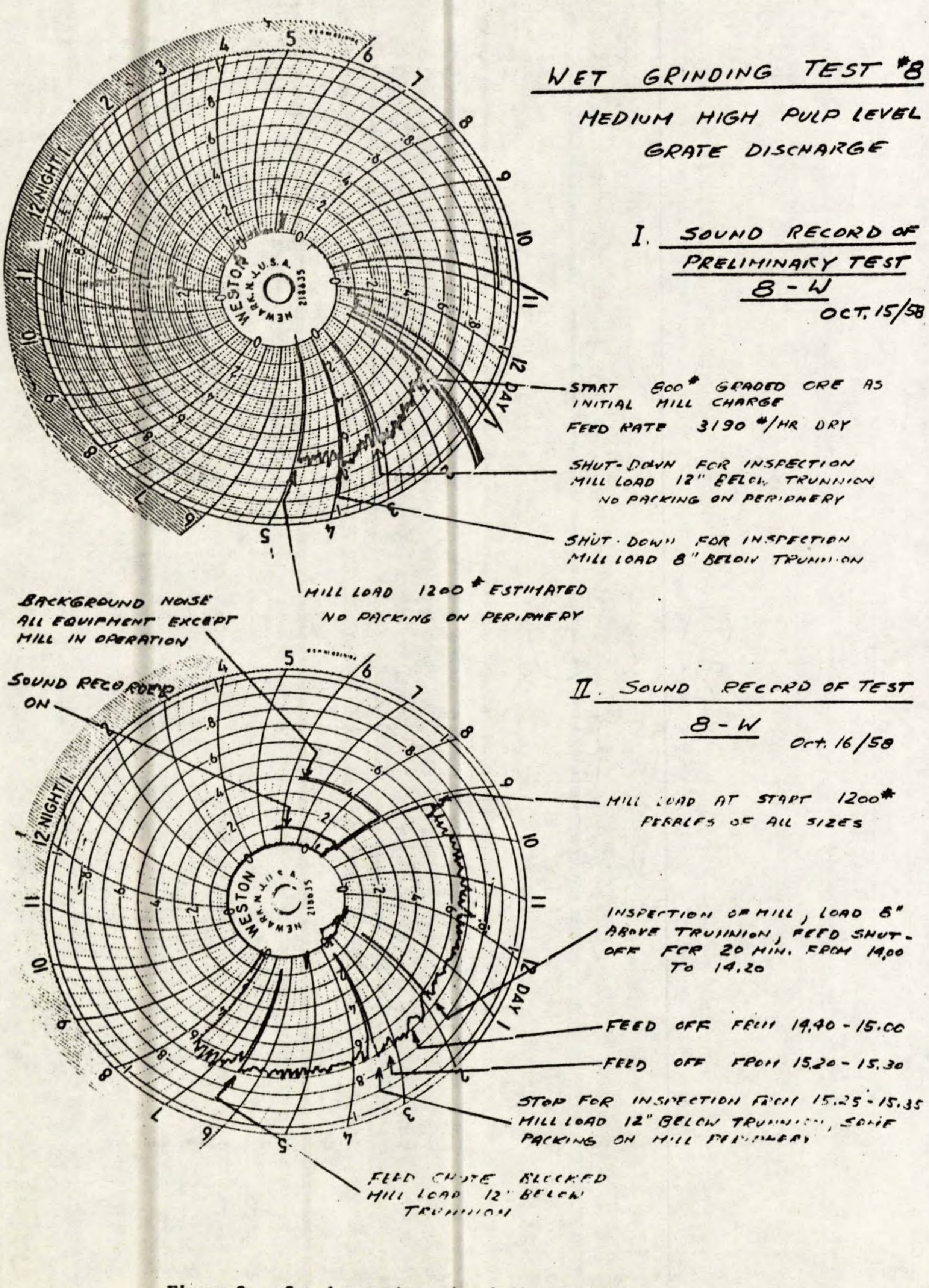


Figure 8. - Sound records, wet grinding test 8-W.

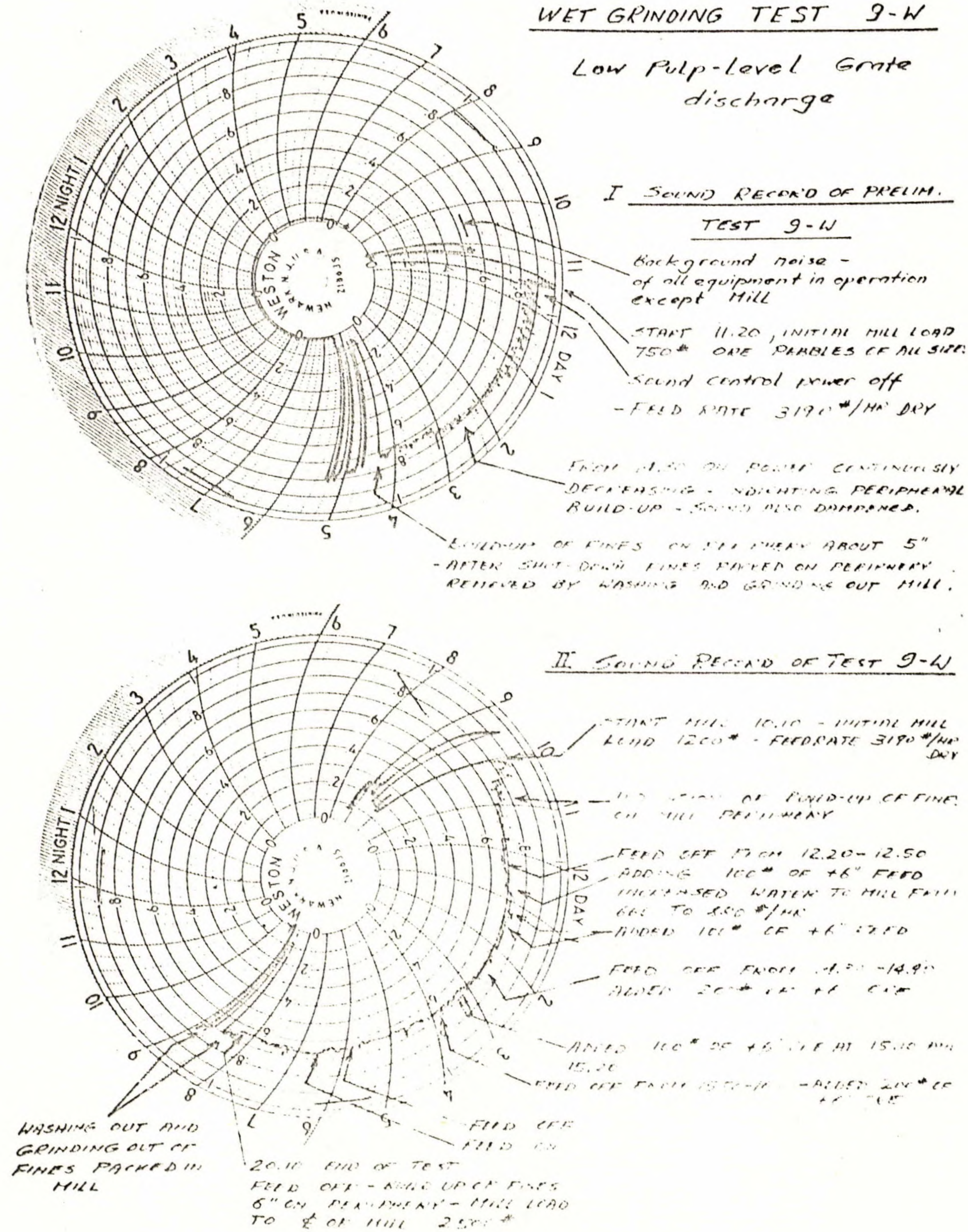


Figure 9. - Sound records, wet grinding test 9-W.