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A power study of a laboratory ball mill

Frederick Clearman

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A POWER STUDY OF A LABORATORY BALL MILL.

- By -

Frederick Clearman.

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T H E S I S

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D E G R E E   O F

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Rolla, Missouri,

1 9 3 0.

Approved:

Will H. Coghill, Supervising Engineer,
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United States Bureau of Mines.

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A POWER STUDY OF A LABORATORY BALL MILL.

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PREFACE.

The Mississippi Valley Experiment Station of the United States Bureau of Mines, in cooperation with the School of Mines and Metallurgy of the University of Missouri, Rolla, Missouri, is carrying on a general laboratory investigation of ball milling. This thesis is a description of part of that work, and a record of the results.

ACKNOWLEDGMENTS.

INTRODUCTION.

Ball milling practice in the ore dressing industry is largely empirical. Although many investigators have worked on various of its phases, the present operating methods are mostly a matter of cut-and-try, with the result that the industry is not guided by its underlying principles. Consequently, practice varies extensively with regard to nearly all conditions of operation. Even in neighboring concentrators such factors as speed, ball charge, and ore load differ in similar ball mills.

Since fine grinding is continually becoming of more importance, and often accounts for thirty per cent of the milling cost, it is very necessary that a study be made of ball milling, both in the laboratory and in the field. In view of this need the Mississippi Valley Experiment Station of the United States Bureau of Mines, in cooperation with the Missouri School of Mines and Metallurgy, Rolla, Missouri, is conducting an investigation of ball milling. This investigation is confined, to date, to the laboratory, but an attempt is being made to bridge the gap between theory and practice, so that the acquired knowledge may be utilized to improve ball mill operations. Some of the study has been completed and the work reported elsewhere.[1]

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[1] Kidd, R. L., A Study of Ball Milling; a thesis of the Missouri School of Mines & Metallurgy, Rolla, Mo., 1929.

Gow, A. M., Campbell, A. B., and Coghill, Will H., Laboratory Investigation of Ball Milling; Tech. Pub. No. 326 of Amer. Inst. Min. & Met. Engrs., New York, Mar., 1930.

However, before going into the power studies, with which this paper deals, it will be well to review the associated results already reported.

PREVIOUS INVESTIGATION.

To begin with, five mills were used in batch grinding tests, under various grinding conditions. The mills were 18-, 24-, 30-, 36-, and 42-inches in diameter, respectively, but they were all only six inches long. In addition to the grinding tests ball paths were observed in the 36-inch mill by replacing the solid ends with wire screens.

The above-mentioned paper contained the following conclusions:

"1. Observations have been made with a 3-foot squirrel cage mill. A new theory of ball action has been advanced from this study and a new formula of ball paths has been derived.

"2. Laboratory tests with short mills in which slippage was reduced to a minimum have shown that the best grinding results were obtained at lower speeds than those hypothecated by previous theories. A speed of 65 per cent of the critical gave the maximum grinding while a speed of only 50 per cent of the critical gave the most efficient grinding.

"3. By comparing the grinding results of the mills of various diameters, it was found that at the same per cent of the critical speed:

"<u>a</u>. The units of surface per unit weight varied as the 0.6 power of the diameter;

"<u>b</u>. The surface tons, or grinding capacity, varied as the 2.6 power of the diameter;

"<u>c</u>. The horsepower also varied as the 2.6 power of the diameter;

"<u>d</u>. The surface tons per horsepower-hour, or efficiency of grinding, was constant regardless of the diameter; and

"<u>e</u>. The units of surface per unit weight varied approximately as the peripheral speed.

"4. The larger mills showed larger grinding capacity per unit volume, but no increase in grinding efficiency."

The ball path observations referred to above were made under idealized conditions. Because slippage was negligible, the ball charge was lifted at mill-shell speed.

When very small ball charges were used, the balls would not centrifuge at the critical speed,[*] but loads which were above

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[*]The critical speed is that speed of rotation at which balls, moving at mill-shell speed, would adhere to the mill throughout a complete revolution because of centrifugal force.

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35 per cent of the mill volume did not slip. Observations of these heavier charges showed that at slow speeds the charge becomes tilted to its angle of repose and balls tumble down the slope as the mill rotates. This deportment has been called "cascading." Slightly higher speeds cause the balls to rise so fast that the

outer layers are thrown into the air and fall upon the lower por-
tion of the charge. This throwing has been called "cataracting."
The balls which reach the bottom of the slope roll or bounce be-
yond the foot of the slope and form a toe of unconsolidated balls
beyond. Balls which are cataracted the greatest distance fall
upon this toe. Balls cataracted at a higher speed are thrown
beyond this toe but do not drop as far because they hit higher up
on the mill shell. It was found that the most grinding was done
when the outer balls were thrown onto the toe rather than cas-
caded, or cataracted onto the shell.

While the balls are being cascaded, the power increases
with increased speed. Further speed increase, resulting in initial
cataracting, is also accompanied by increased power until a maximum
is reached when the balls fall on the toe. Cataracting at speeds
so high that the balls go beyond the toe and hit the shell consumes
less power than at slower speeds. At the critical speed very lit-
tle power is required, since the outer layer of balls is centri-
fuged. The drop in power right below the centrifuging speed may
be accounted for when one considers that the flat angle of inci-
dence allows the descending balls to help rotate the shell. The
upper and curved line in Figure 1 portrays the power consumption
of this type of ball action. The data are from a 24-inch by 6-
inch squirrel-cage containing 40 per cent mill volume balls.
Visual observation of the balls showed that there was no slippage.
The balls maintained their original places in the mill until they

FIGURE 1.   POWER CONSUMPTION OF A 24-INCH BY 6-INCH BALL MILL AT VARIOUS SPEEDS UNDER SLIPPAGE AND NON-SLIPPAGE CONDITIONS.

were cascaded or cataracted through their regular paths. The speed which consumes maximum power, and above and below which the power is less, marks the dividing line between "high cataracting" and "low cataracting" speeds. (In Figure 1 this speed was 80 per cent of the critical). Power decreases as high cataracting speeds get higher and as low cataracting speeds get lower.

All the foregoing observations were made on a mill which contained balls only. There was no ore nor water present. However, grinding tests indicated that the action within the grinding mill was much the same as in the squirrel cage.

The revealed principles could be given practical significance were it not for one thing—slippage. Slippage means indeterminable ball speed; and until slippage is controlled or determined there is no known relationship between mill speed and ball action. The charge within a mill rotated at the "critical" speed may be centrifuging, cataracting, or cascading, depending on the amount of slippage. Only the mill shell speed is measurable, but the slippage can be roughly estimated. If increased shell speed results in a power increase,the charge is in the low cataracting speed zone or below. If the power decreases, the charge is in the high cataracting speed zone. A change in power consumption at constant shell speed indicates a change in ball speed and consequently a change in slippage.

The straight line in Figure 1 represents the power consumption of a slipping load comparable to that of the non-slipping one. There was so much slipping that the curve showed no break, even above the critical. Slippage power-curves will be considered later, but it may be noted here that in Figure 1, if slippage had been reduced at 70 per cent speed, the power would have increased; whereas, if slippage had been reduced at 90 per cent speed the power would have decreased.

PRESENT INVESTIGATION.

In order to study ball mill behavior under slippage conditions, without going into the tedious routine procedure of grinding tests, a series of power consumption tests have been made with a mill 24 inches in diameter and 24 inches long, shown in Figure 2. The electrical and mechanical set-up was essentially the same as that used in the previous testing.[1] One-and-one-quarter-inch cast

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[1] loc. cit.

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iron balls were employed.

Power studies in a mill containing little or no ore are justified for two reasons:

First, grinding, itself, does not consume power. Ground rock contains no more energy than unground rock,[2] and hence there

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[2] The possibility of surface energy in solids may detract from the absolute veracity of this statement, but whatever increase there might be in the internal energy of a pulverant system is negligible in comparison with the energy transformation which breaking accompanies.

Figure 2.

Photograph of 24-inch by 24-inch Laboratory Ball Mill.

has been no consumption of power. The kinetic energy expended is transferred eventually into heat. When conditions are suitable, fracturing accompanies the energy transformation. Grinding efficiency becomes a matter of adjusting conditions so that the maximum amount of fracturing becomes coincident with the maximum energy transfer. From this, one is lead to infer that maximum energy transfer, or maximum horsepower consumption, is to be desired. In any case, power studies throw light on the possible points of predominant performance.

Secondly, pulp effects the power consumption of a mill only in so far as it changes the viscosity of the medium between the balls, increases or decreases inter-ball and ball-shell friction, changes the mill volume, shifts the center of mass, or adds to the weight of the total charge. Hence power data are probably comparative even though the normal pulp conditions do not prevail.

Only net power, the power expended within the shell, is considered here.

Mill-volume weights were taken as fractional parts of the weight of balls required to fill the mill. The rock used in making up charges was either rejected chert from previous tests or flint gravel. Both were about 95 per cent silica, and are occasionally called "ore" although they were homogeneous. The following series of tests were made:

(1) Power consumption as various charges of dusted balls and non-dusted balls were tumbled at various speeds.

(2) Power consumption at various speeds as ore and water were fed into the mill in small increments.

(3) Power consumption at various speeds as coarse ore was ground to pulverized ore.

(4) Power consumption at various speeds as the pulp density was changed by adding ore or water in small increments.

(1). POWER FOR TUMBLING BALLS.

Upon prolonged tumbling by themselves the cast iron balls became exceedingly smooth, as though covered with graphite. Because the smoothness made a great difference in the power and the amount of slippage, two sets of tests were made, one using balls which were as slippery as possible, and one in which a handful of sand was added to cut the gloss and dust the surfaces. The mill was equipped with one-inch-mesh wire screen ends. It thus made a squirrel-cage, similar to the one used previously, but much longer.

Charges of balls to make mill volumes of 25, 30, 40, 50, and 55 per cent were used, and power readings were taken at shell speeds of from 40 to 100 per cent of the critical. Thus, five tests, one for each mill volume, were made for both conditions of balls. The results are shown in Figures 3, 4, 5, 6, and 7. On each is shown the curve for both the dusted and the non-dusted balls.

Figure 3 (25 per cent mill volume) shows the character-
istic slippage relationship between power and speed. With this
light load of balls the mill shell slips underneath the charge in
a manner analogous to that of a muller on a bucking-board: the
faster the muller is dragged over the board the greater is the
power consumption. It is obvious that the balls slipped on the
shell because the speed went above the critical without a break in
the power curve. That the non-dusted balls slipped more than the
dusted balls is evidenced by the curves, which show that a greater
mill speed was required for the same power consumption. The amount
of sand added was only enough to place a coating on the balls, yet
it increased the power about 12 per cent. In both tests the power
increased directly as the speed. Within experimental limits, the
curves may be extrapolated to the zero of the coordinate system.

Figure 4 (30 per cent mill volume) shows the same type of
action—extreme slippage; the increased load consumed more power,
thereby making the lines steeper. Also, the two lines lie slightly
closer together, indicating that the difference in the amount of
slippage between dusted and non-dusted balls is not as great as
in the lighter loading. The increased load lessened the amount
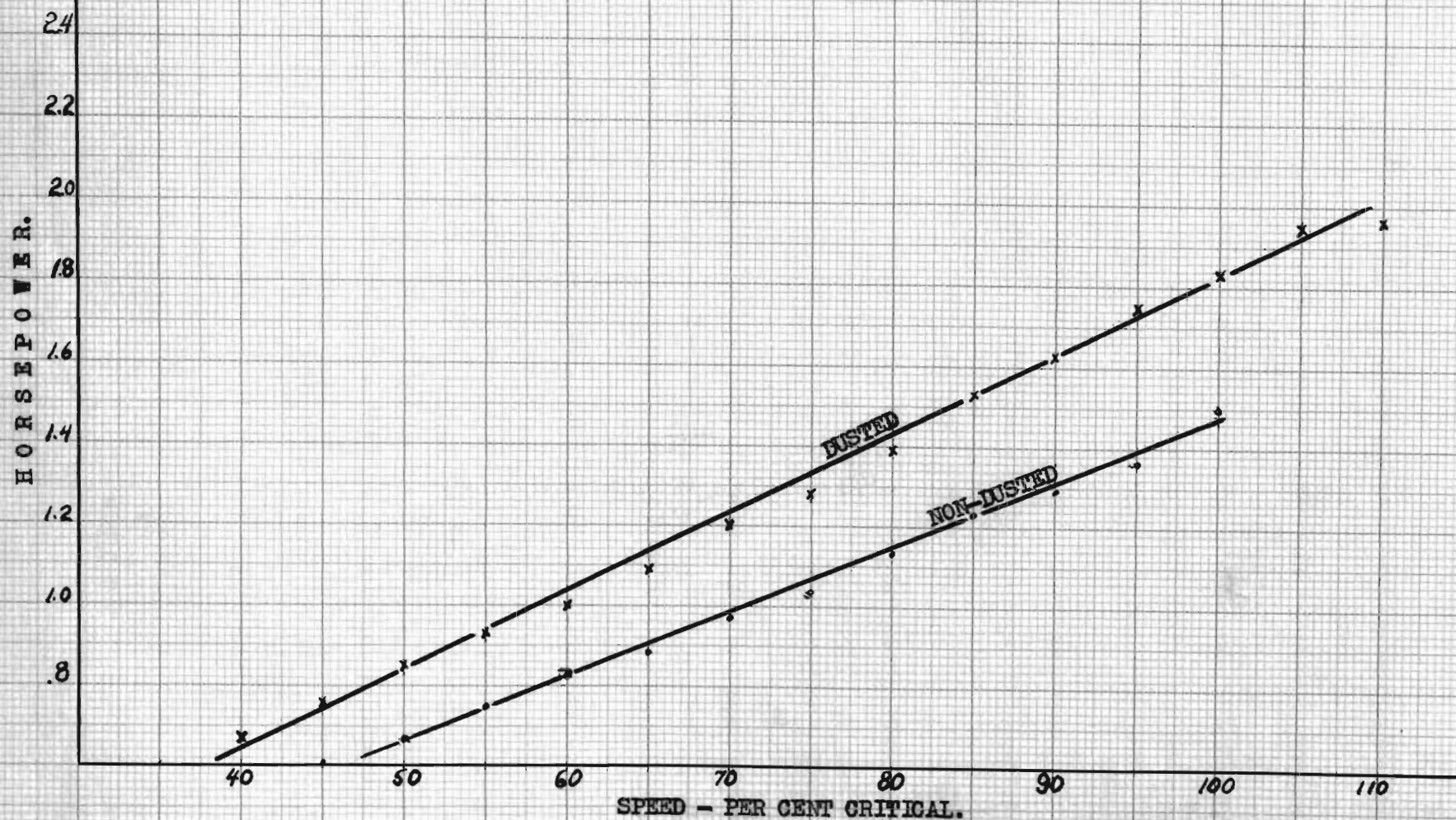of slipping to be combatted by the dusting.

FIGURE 3. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 28 PER CENT FULL OF BALLS, DUSTED AND NON DUSTED, AT VARIOUS SPEEDS.

FIGURE 4. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 30 PER CENT FULL OF BALLS, DUSTED AND NON DUSTED, AT VARIOUS SPEEDS.

Figure 5 (40 per cent mill volume) shows more distinct-
ly this last phenomenon. Here, again, the curves are steeper.
More power is required and there is less power-difference between
the dusted and non-dusted ball charges. Both facts point to a
lessened amount of slipping. However, as yet even with the dusted
balls there is no absolute indicate of slippage being overcome.
At this mill volume, in the earlier work, slippage had been entire-
ly eliminated by using a mill only six inches long. The power
data of the non-dusted balls from this test are divided by four to
give the slippage curve in Figure 1.

Figure 6 (50 per cent mill volume) shows that by filling
the mill half-full the slippage of dusted balls was so much reduc-
ed that, for the first time, the high cataracting speed of the
shell caused a power slump. The curve breaks at about 70 per cent
speed, peaks at 85 per cent, and drops rapidly as the criticial is
approached. Non-dusted balls continue to slip but the slippage is
less than heretofore, as evidenced by the proximity of this curve
to the other and the slight break near the upper end. In all prob-
ability the non-dusted charge could have been centrifuged if the
shell speed had been carried to about 140 per cent of the critical.

Figure 7 (55 per cent mill volume) shows a loading condi-
tion which has practically eliminated slippage among dusted balls,
and has materially reduced it with the smoother ones. At this load-
ing the power for the dusted balls does not reach as high a point
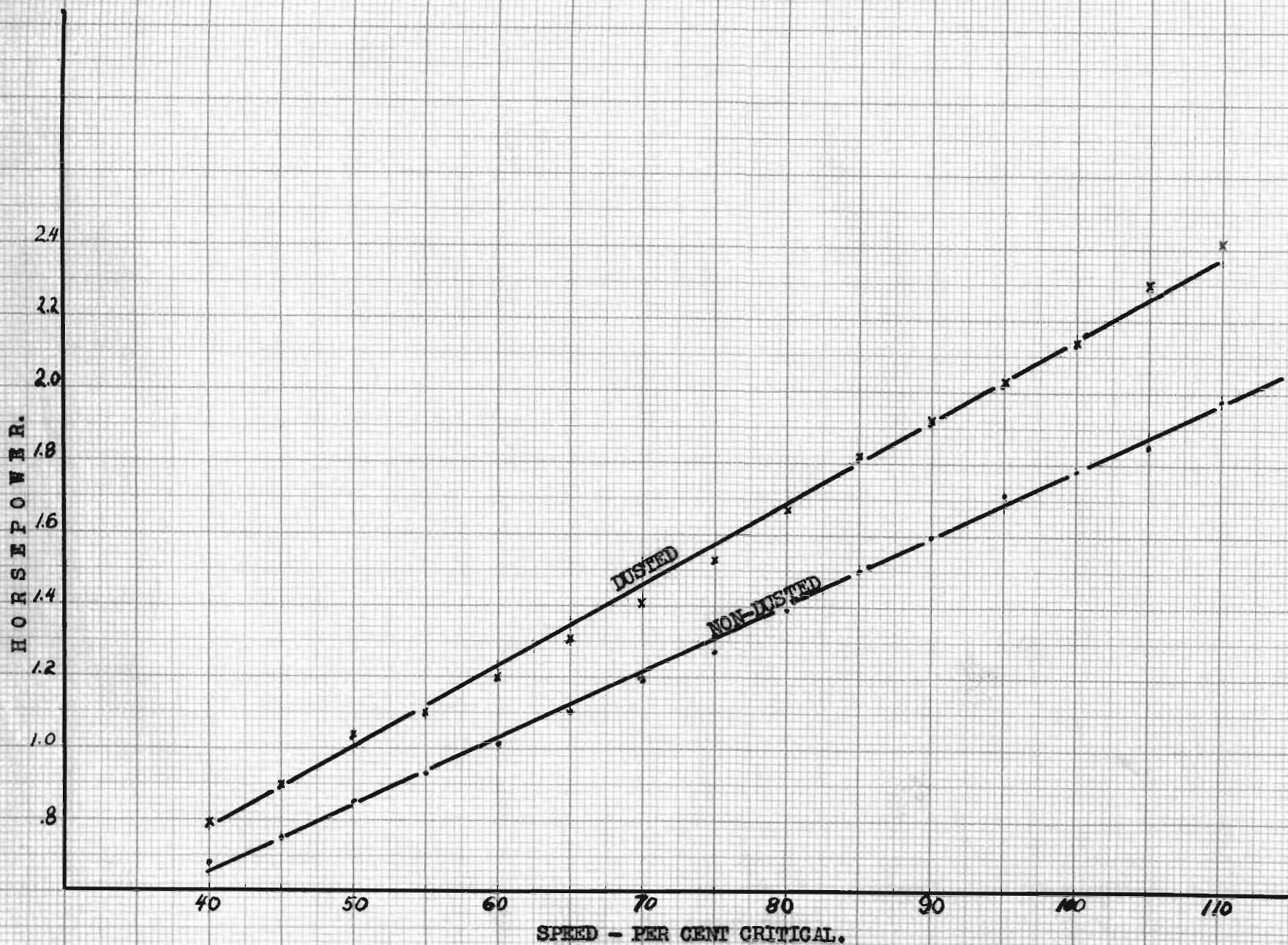as did the one at 50 per cent mill volume. Evidently the overloaded
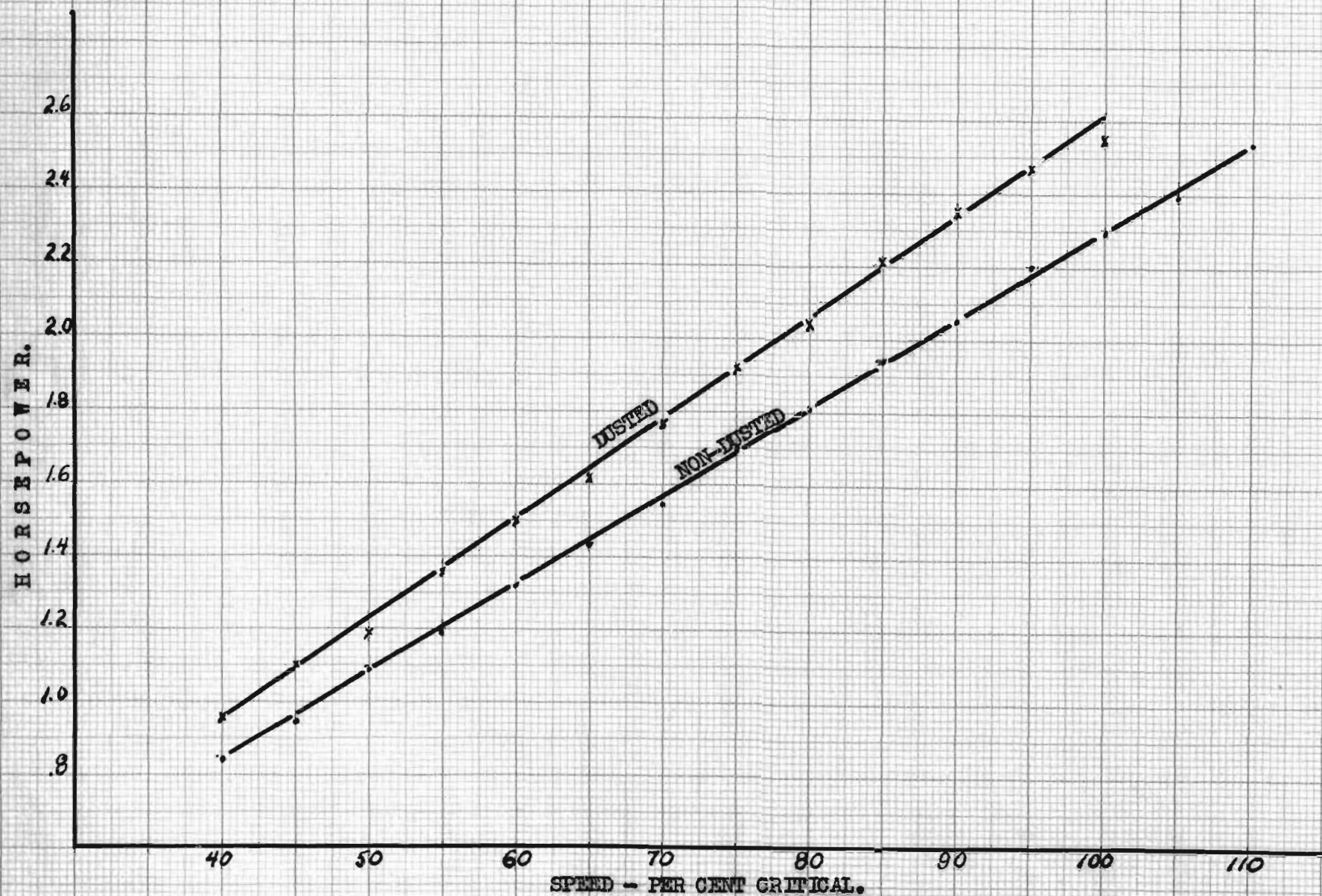
FIGURE 5. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 40 PER CENT FULL OF DUSTED AND NON-
DUSTED BALLS, AT VARIOUS SPEEDS.

FIGURE 6. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 50 PER CENT FULL OF DUSTED AND NON-DUSTED BALLS, AT VARIOUS SPEEDS.

FIGURE 7. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 55 PER CENT FULL OF DUSTED AND NON-DUSTED BALLS, AT VARIOUS SPEEDS.

condition tends to balance the force required to lift the balls.
The greatest difference is in the high speed range. The rapid pow-
er drop with the dusted balls was because of high cataracting.
This was impossible with the undusted balls because when part of
the balls went into the air the remaining volume of balls was so
small that slipping was induced.

To sum up, slippage prevents the forecasting of ball
action at any particular mill speed. In a mill containing only
balls slipping depends chiefly on the amount of balls, although
the smoothness of the balls is also important, particularly when
there is considerable slipping. Thus, dusting the balls seemed
to be more effective with light ball loads. Likewise, dusting at
high speeds made a considerable difference for the reason explain-
ed above. Reducing the slipping, either by increasing the charge
of balls or by overcoming their slipperiness, increased the power
required to rotate the mill at the slowest cascading and up through
the slow cataracting speeds, and reduced it where the ball move-
ment was in the high cataracting speed zone.

If the assumption, stated earlier, is correct, that it
might be advisable to operate a mill at maximum power, it becomes
obvious that slippage grinding at high shell-speed would be best
because of the high power consumption. A power test of this nature,
which is not included here, was made at speeds up to 140 per cent of
the critical. At this high speed the power consumption was 4.2
h.p., almost twice as much as the lightest no-slippage power ob-

tained. The feasibility of using high power through slippage is doubtful, because of the difficulty of maintaining the maximum: The peak of the no-slippage power curve may be reached by speeding up a slow mill, or retarding a fast one. However, in the case of slippage, should the mill centrifuge at a very high speed, it would be necessary to slow down below the critical to break the centrifuging ring, and then accelerate to high speed to regain maximum power consumption; the maximum cannot be reached again once its speed has been exceeded without a complete repetition of the cycle.

(2). POWER CONSUMPTION UPON GRADUAL ADDITION OF ORE.

To determine the effect upon power consumption of various amounts of ore load, or quantity of pulp in a mill, tests were made during which pulp was gradually added to the ball charge. For these tests one end of the mill was fitted with a trunnion through which the batches of pulp were added while the mill was in operation.

The "ore" was chert rejects from previous grinding tests, approximately 80 per cent minus 6 mesh and plus 65 mesh, with six per cent through 200 mesh. The specific gravity of the ore was about 2.6. All charges were weighed out, but the pulp density was calculated by volume, using the above value; all pulp densities are in terms of per cent solids by volume. The mill was started with only the ball charge. Power readings were taken. Then ten pounds of ore and the necessary water was added, and again power readings

were taken. This alternate charging and power-reading was continued until the rotating mill overflowed through the feed trunnion. Since more than an hour was required to run one of these tests the charge was ground very fine towards the end.

Two series of tests were made: (1) with ball volumes of 32, 42, 48, and 53 per cent, all with a density of 43.5 per cent; and (2) with a ball volume of 42 per cent and densities of 53 and 61 per cent. The results are shown in Figures 8 to 13, inclusive.

(a). Various Ball Volumes and Constant Pulp Density.

Referring to Figure 8, a relatively light ball charge, 32 per cent mill volume, and a pulp density of 43.5 per cent by volume gave regular power curves at the various speeds. In each case the power increased as pulp was added until a total of 30 to 35 pounds of ore had been charged. Thereafter, further additions decreased the power until, at the overflowing load, less power was required to rotate the mill than originally. The overflowing load was 120 pounds at slow speed although higher speeds increased the capacity for pulp. The fact that the curves are uniformly spaced indicates slippage, for the power is directly proportional to speed at high speeds. The maximum-power loading of 30 to 35 pounds of ore as pulp is approximately the amount required to fill the interstices between the balls when at rest, and one-fourth the amount to fill the running mill. The maximum power rise was about 20 per cent of the original. Further reference to the curves in Figure 8

gives unmistakable evidence that the mill filled with 120 pounds of finely ground ore required less power than when it contained only ten pounds of fresh charge. When the same type of test was made with the mill 42 per cent full of balls, the same general behavior is noted, as in Figure 9. Speed curves up to the critical are evenly spaced, indicating slippage. All power curves are higher, as would be expected with an increase of ball charge, from 32 to 42 per cent. There is a peak in the power curves between 45 and 60 pounds of ore. This amount is more pulp than before, but like the former, it closely corresponds to the intersticial space in the balls when they are at rest. Faster speeds required more ore for maximum power, as shown by the sloping line A-B in Figure 9. This probably correlates with the increasing amount of interstices at high speed. The maximum power was required when the mill contained about one—third of its capacity for pulp.

Figure 10 shows that a different situation existed when the ball charge was increased to 48 per cent mill volume. The various speed curves are not evenly spaced as they were formerly. At the high speeds the addition of a few pounds of ore caused a power drop, and a large addition of ore restored the mill to a high power consumption. The most plausible explanation is that a small amount of ore keyed the balls and prevented their slipping; but further additions, combined with the reduction in size of the particles after much grinding, lubricated the mass so as to allow slippage again. Since the speed was in the high cataracting zone,

FIGURE 8. POWER CONSUMPTION OF A 24-INCH BALL MILL, 32 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS ORE AND WATER WERE ADDED GRADUALLY. PULP DENSITY, 43.5 PER CENT SOLIDS BY VOLUME.

FIGURE 9. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT VARIOUS

SPEEDS, AS ORE AND WATER WERE ADDED GRADUALLY. PULP DENSITY, 43.5 PER CENT SOLIDS BY VOLUME.

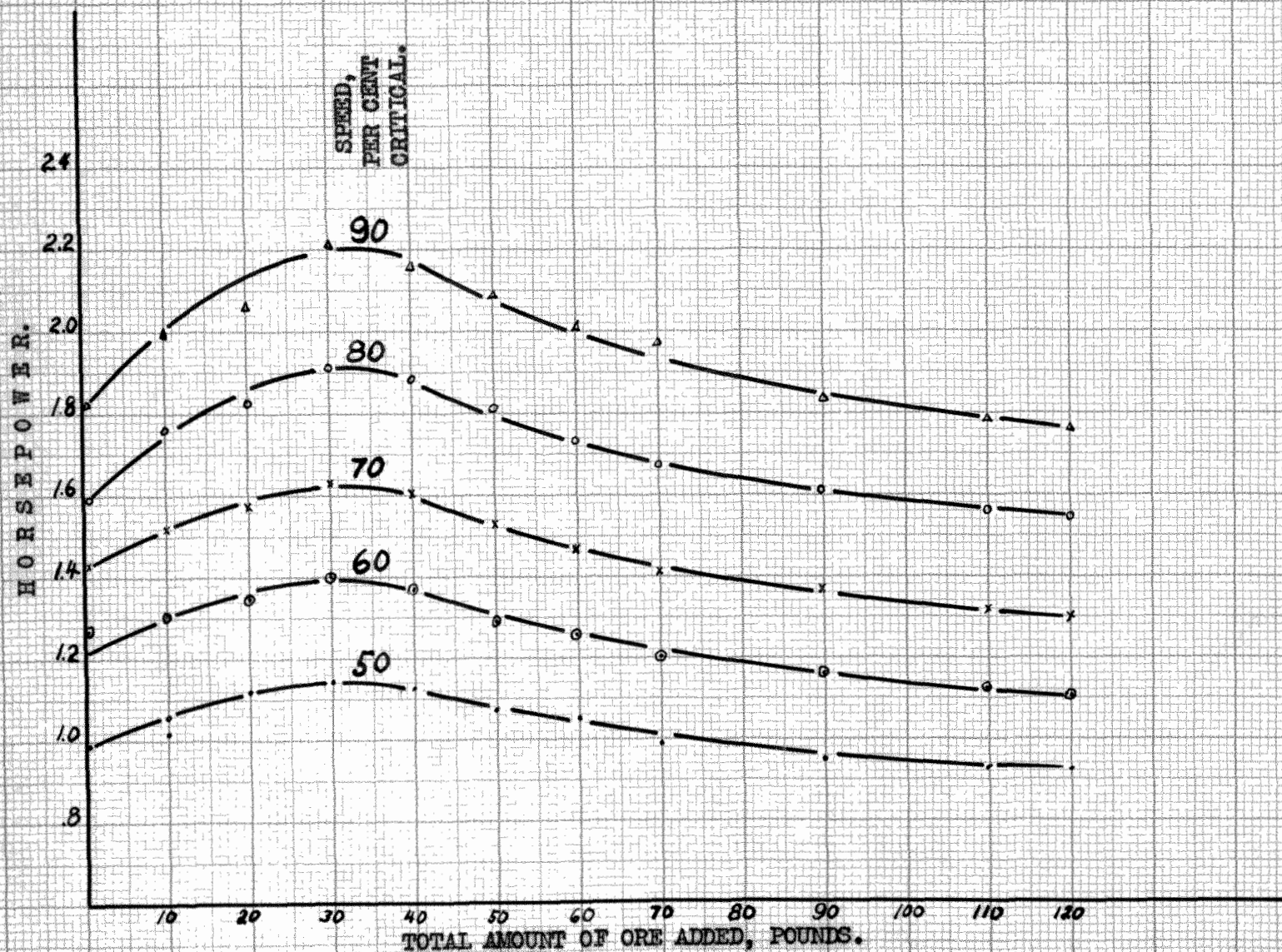FIGURE 10. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 48 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS ORE AND WATER WERE ADDED GRADUALLY. PULP DENSITY, 43.5 PER CENT SOLIDS BY VOLUME.
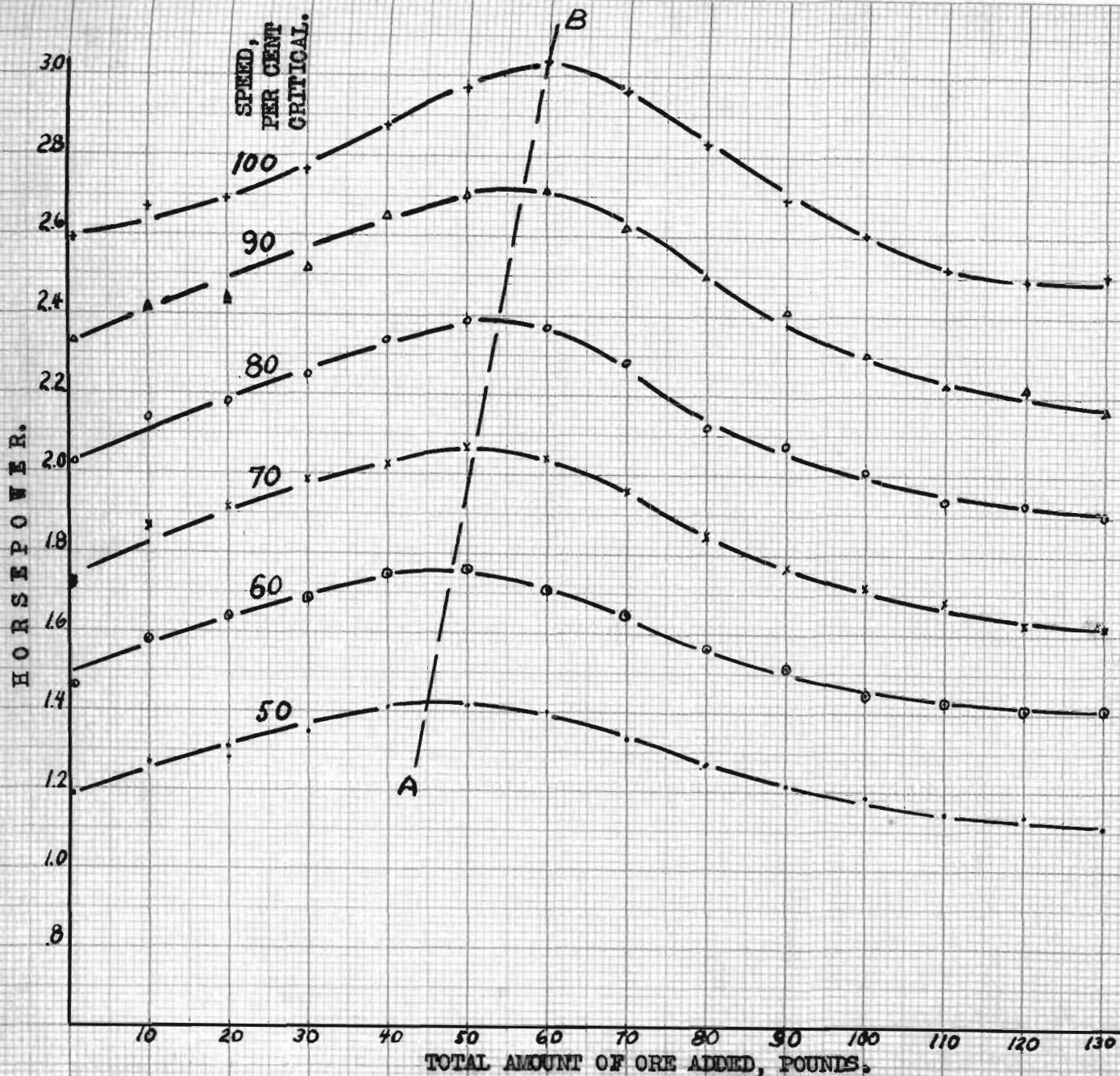
decreased slippage meant decreased power, and vice versa. At the lower speeds, the maximum power is consumed when the mill contains about 50 pounds of ore—about half full. The difficulty of anticipating the power required to grind is exemplified by these curves.

Figure 11 is similar to Figure 10. The mill volume was increased to 53 per cent balls, and the behavior markedly resembled that of the slightly lighter load. The striking difference is in the generally low power consumption at the critical. The difference between this curve and the 100 per cent curve in Figure 10 is caused by an increase of only five per cent ball volume. In other words, slippage was reduced by the volume of balls as well as by the pulp. If it had been entirely eliminated the power for 90 per cent speed would have been less than that for 80 per cent throughout the entire test.

To summarize the tests shown in Figures 8, 9, 10, and 11, upon gradual additions of pulp when the mill was run slowly (in the slow cataracting zone, or below,—60 to 80 per cent speed), the power consumption increased up to a certain point, and then decreased. The load of ore and water which consumed maximum power varied slightly with the ball charge; the amounts were larger with the heavier ball charges. At the higher cataracting speeds (90 and 100 per cent of the critical) the power consumption showed that the action within the mill is dependent upon slippage.

FIGURE 11. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 53 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS ORE AND WATER WERE ADDED GRADUALLY. PULP DENSITY, 43.5 PER CENT SOLIDS BY VOLUME.
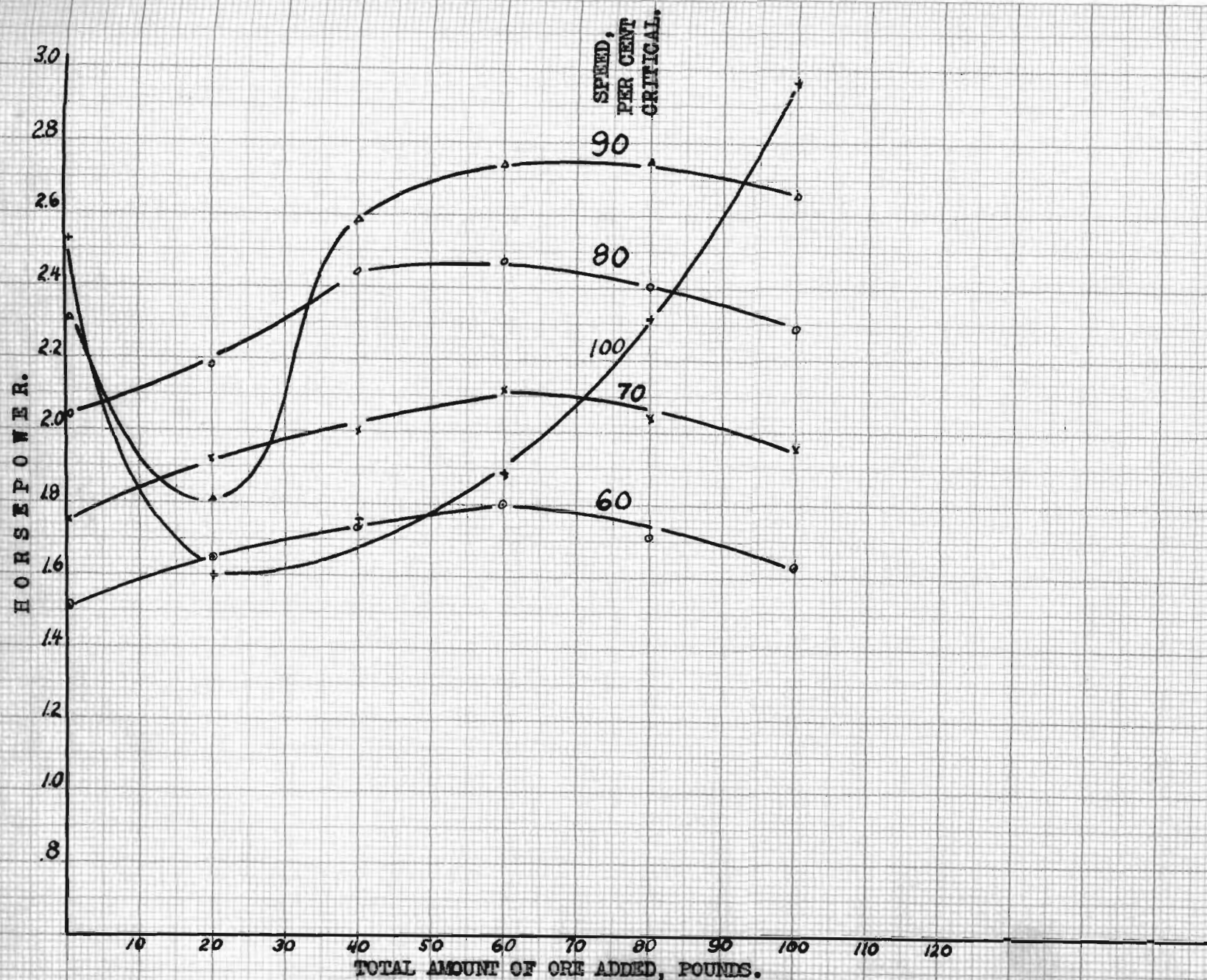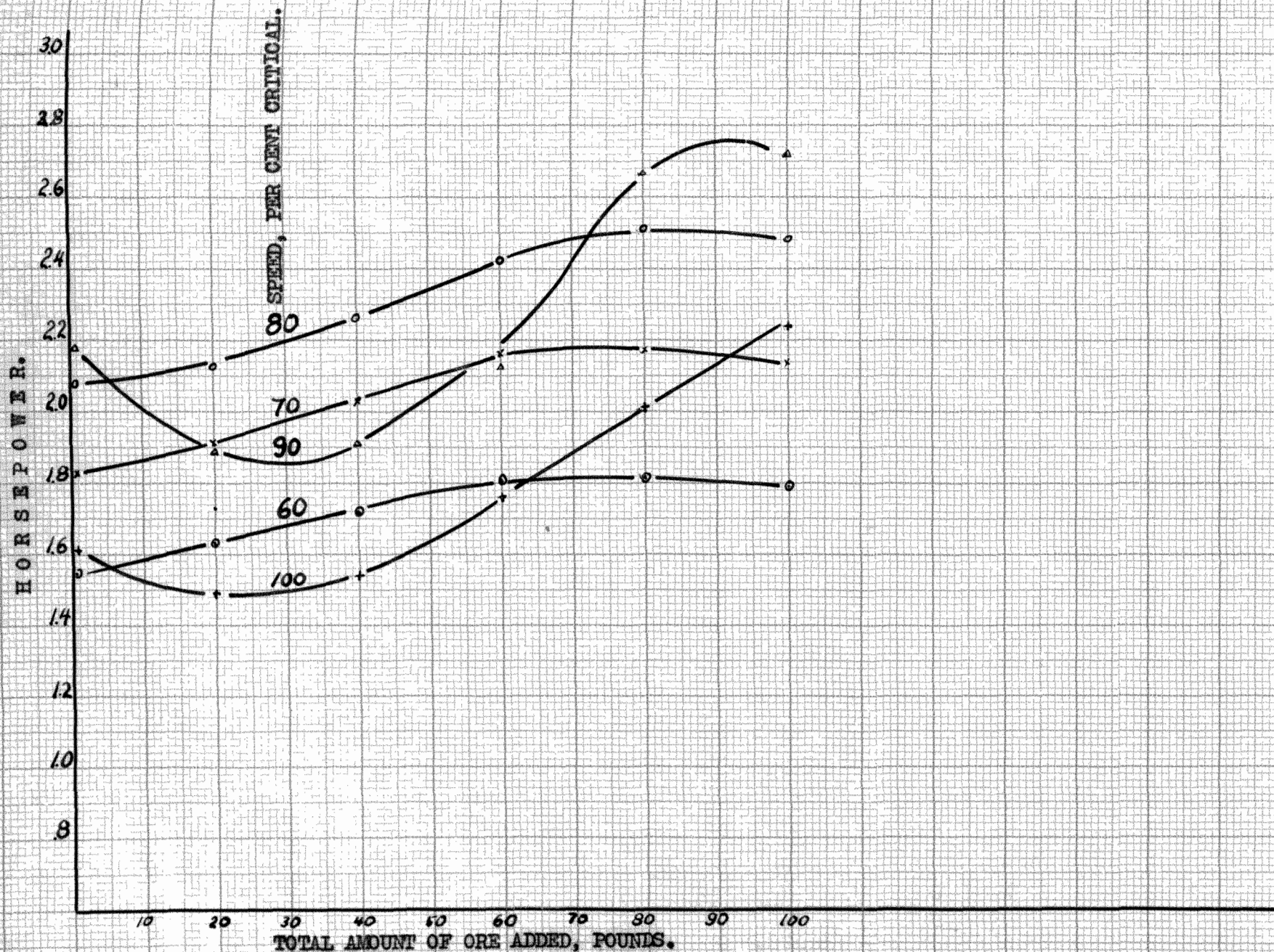
With the heavy ball charges (48 and 53 per cent mill volumes) the slippage seemed to depend chiefly on the amount of pulp. The addition of 20 to 30 pounds of ore was sufficient to reduce the slippage of the heavy ball charges so that the balls nearly centrifuged and consequently used less power than at the lower speeds. This low power at high speed has been discussed above in the tumbling tests.

The power fluctuation, as relatively small amounts of ore were added, suggested that other factors than the amount of pulp and shell speed also influenced ball action; one of these factors is pulp density.

(b). Constant Ball Volume and Various Densities.

With loading conditions the same as in Figure 9, two additional tests were made with thicker pulps to determine the effect on power of pulp density. These were at 53 and 61 per cent solids by volume, and are shown in Figures 12 and 13. Because less water was added, more ore was required to fill the mill to overflowing. Also a larger amount of ore was required to give the maximum power consumption. Otherwise the 53 per cent solids pulp behaved in much the same manner as the 43 per cent one, at speeds up to the critical. At the critical, however, the thicker pulp reduced slippage so that the power dropped when even a small amount of ore was added. More than 70 pounds of ore caused the power to be raised again, presumably by being sufficient and of such a character as to lubricate the balls and cause slipping. The thickest pulp, 61 per cent sol-

FIGURE 12. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS ORE AND WATER WERE ADDED GRADUALLY. PULP DENSITY, 53 PER CENT SOLIDS BY VOLUME.
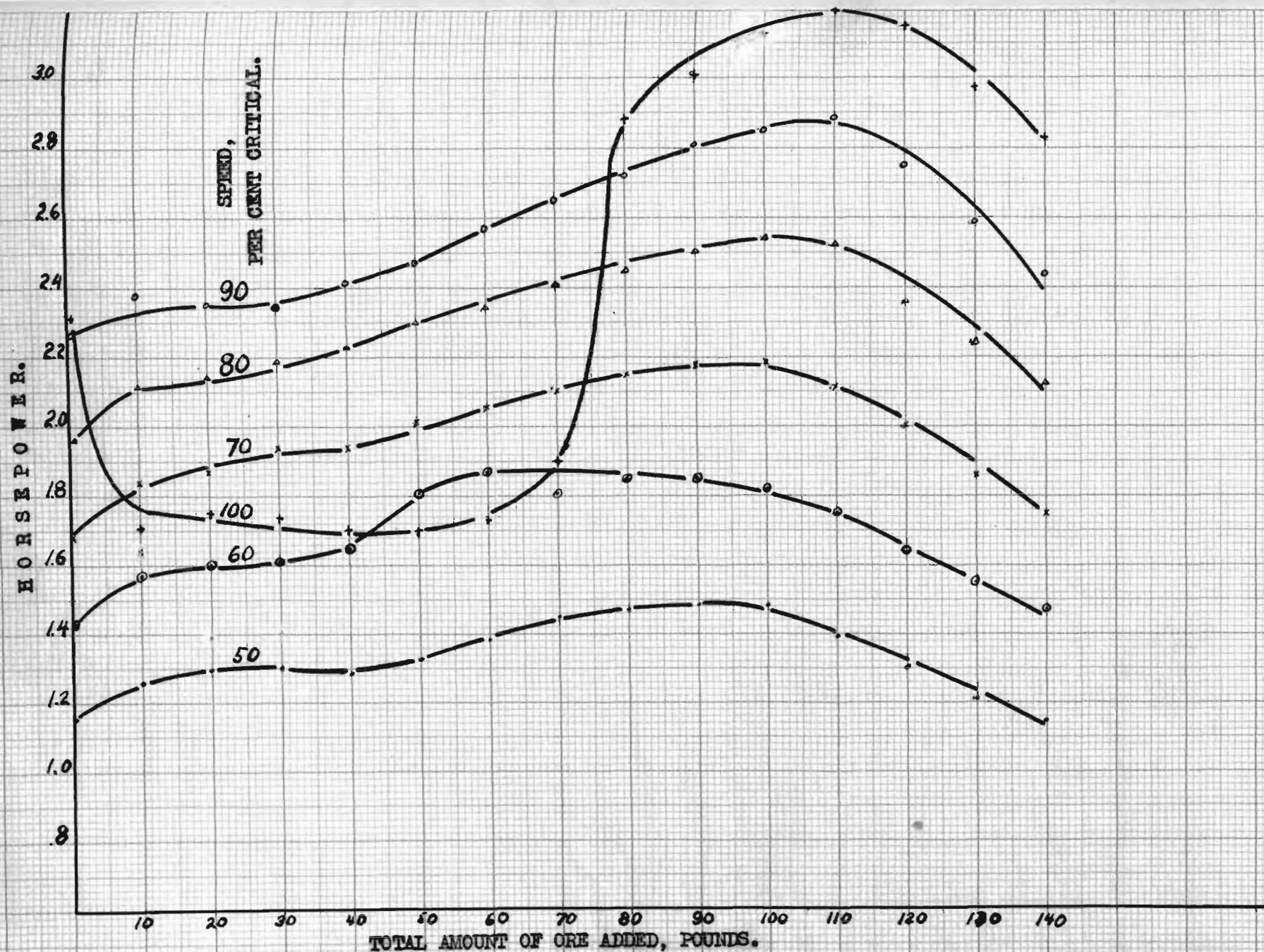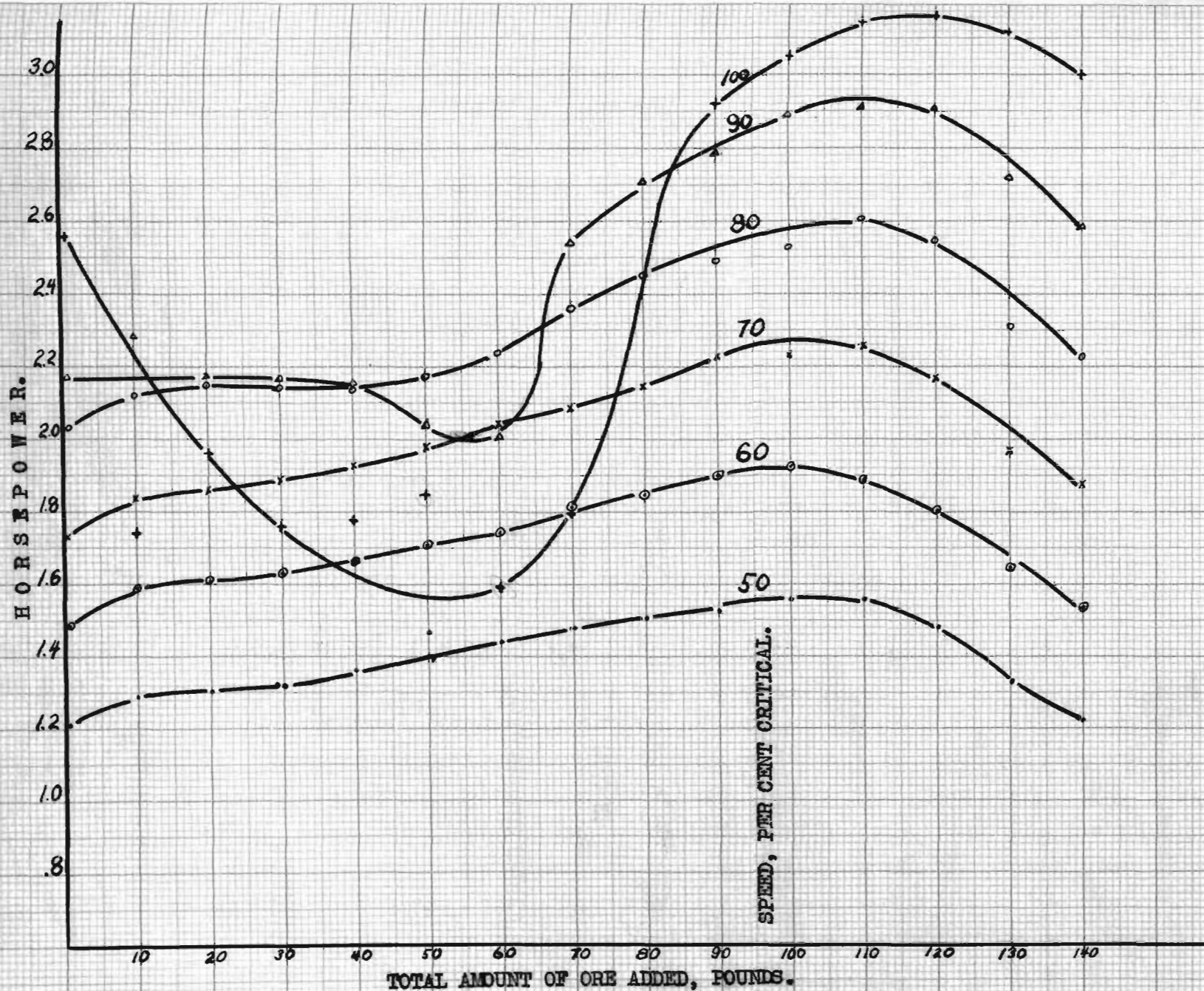
FIGURE 13. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS ORE AND WATER WERE ADDED GRADUALLY. PULP DENSITY, 61 PER CENT SOLIDS BY VOLUME.

ids, showed the same change, but to a greater degree. Even the 90 per cent speed power consumption dropped below the 80 per cent when enough thick pulp had been added. More than this amount of pulp restored the power to its former values, and even to a maximum.

Since the above tests consumed considerable time, grinding reduced most of the ore particles to a fine slime before the tests were completed. The effect of this reduction in grain size was noticed towards the end of some of the runs, and to investigate it further, the third series of tests was made.

(3). POWER VARIATIONS WHILE COARSE ORE WAS GROUND EXTREMELY FINE.

The mill was charged with balls, water, and gravel. Power readings were taken from the start and continued until the repeated readings became more or less constant. The first tests were made with very coarse gravel, 1|2- to 3|16-inch in size. The reduction of this coarse size was slow enough to allow power readings to be taken at several speeds. Later, a finer gravel was used and the mill held at constant speeds while power data were quickly taken. This latter procedure allowed greater accuracy and more readings through the range of greatest power variation. A sizing analysis of partially ground coarse gravel showed that one-and-one-quarter-inch balls were very effective in grinding ore particles which were below 4 mesh in size, but attacked the larger ones more slowly. So, for the finer gravel minus 3|16-inch material was used. All the tests were run with 42 per cent mill volume of 1-1|4-inch balls, 100 pounds of gravel, and water to give the desired pulp density.

A larger ore charge was not used, as it would have caused excess-
ive slopping through the trunnion.

Before reviewing the data, it might be well to consider
the effect that grain-size has on the character of an ore pulp.
It has been noticed that the addition of water makes ball charges
slip in a tumbling mill (one containing only balls), whereas sand
decreased the slipping. A pulp in the mill could, therefore, have
a twofold effect; much of the water in a coarse aggregate would
be free and would tend to increase slippage while the particles
themselves would tend to retard it. Partial grinding would
change the coarse aggregate into a mixed aggregate, having some
coarse, some medium, and many fine particles. The "free" water
would then be used up in wetting the new surfaces and filling
the capillary interstices of the mixed aggregate. The coarse
particles would still retard slippage, and there would be no free
water to help it. Upon still further grinding, the coarse grains
would all become fine, and the pulp would be either a slime or a
mud, depending on the amount of water. A slime would tend to lub-
ricate the balls, thereby aiding slippage. A mud would stick the
balls together, and in extreme cases plaster them to the shell and
to each other. In either case, slippage would not be hindered by
coarse particles. Thus it can be readily seen that the effective
viscosity or bonding power of a pulp may have much to do with the
type of ball action within a mill. Slipping may be increased or
diminished by the size and distribution of grains and the pulp
density.

(a). Tests Using Coarse Gravel.

Figures 14 and 15 show the data from two power tests as coarse gravel was ground to slime. Figure 14 represents a test made at 43.5 per cent solids by volume, and Figure 15 a test at 61 per cent solids by volume. Figure 14 shows that after five to ten minutes of grinding the pulp was of such size and consistency as to be most effective in retarding slipping. This caused the ball charge to approach the mill speed and consume the maximum power. Slippage was sufficient, however, to prevent the 90 per cent speed curve from reaching the high cataracting speed range. Further grinding gradually increased slippage conditions. During the first part of the run it was not possible to get readings at the critical speed of the mill shell.

Figure 15 shows the exaggerated case caused by an excessively thick pulp. The slow speeds of 50 to 80 per cent of the critical behave in much the same manner as they did before, except towards the end of the run, where the upward trend of the curves is misleading on account of the plastic condition of the pulp. At high speeds, irregular readings made power determinations impossible for the first few minutes. After seven minutes the aggregate was of such a size and consistency as to minimize slippage, with the result that the ball speed approaches centrifuging, and powers dropped. Further grinding resulted in a power increase, due, probably, to the reduction of the large particles which keyed together the balls and shell, and heretofore hindered slipping. Still more
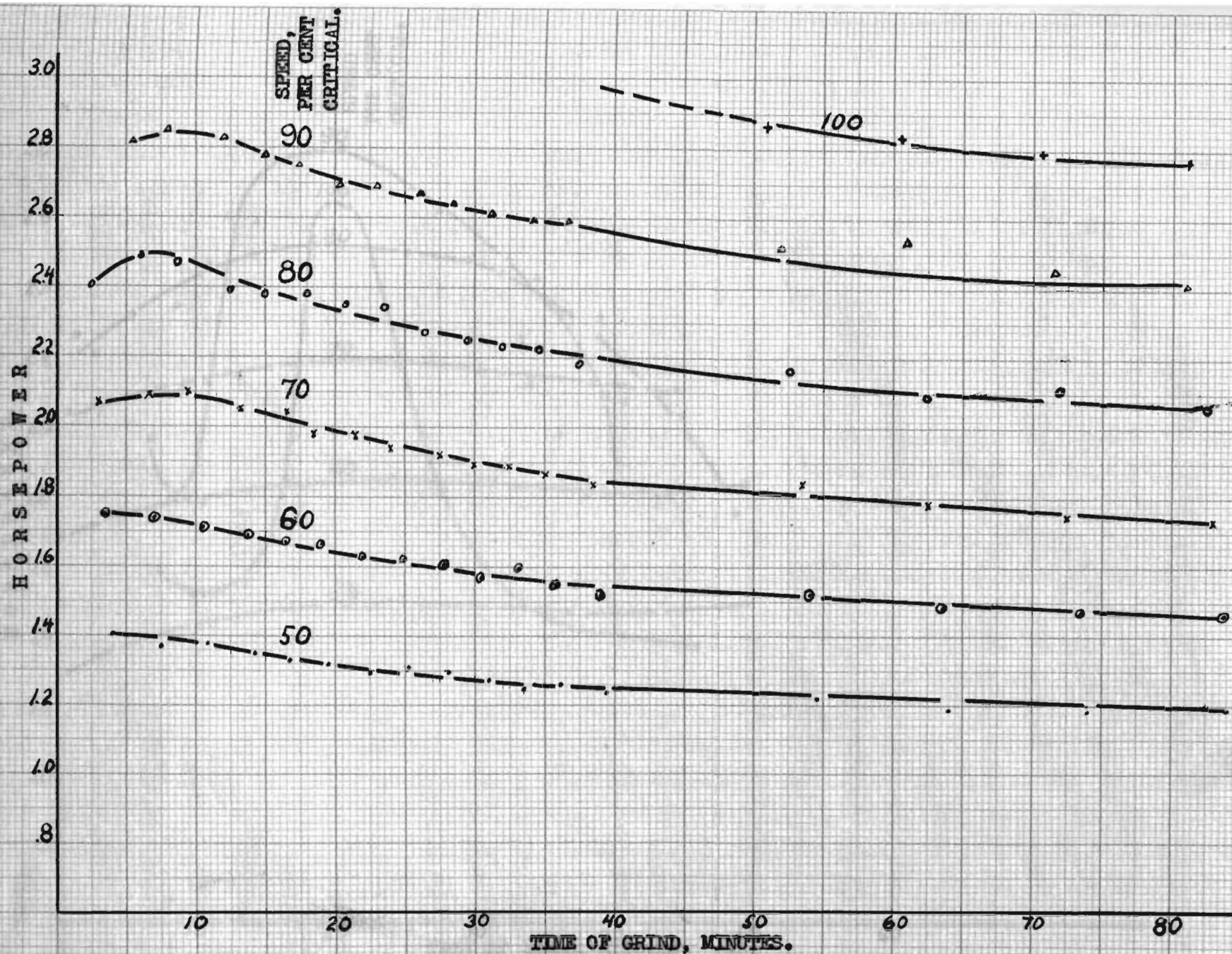
FIGURE 14. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS 100 POUNDS OF COARSE GRAVEL WAS GROUND TO FINES. PULP DENSITY, 43.5 PER CENT SOLIDS BY VOLUME.
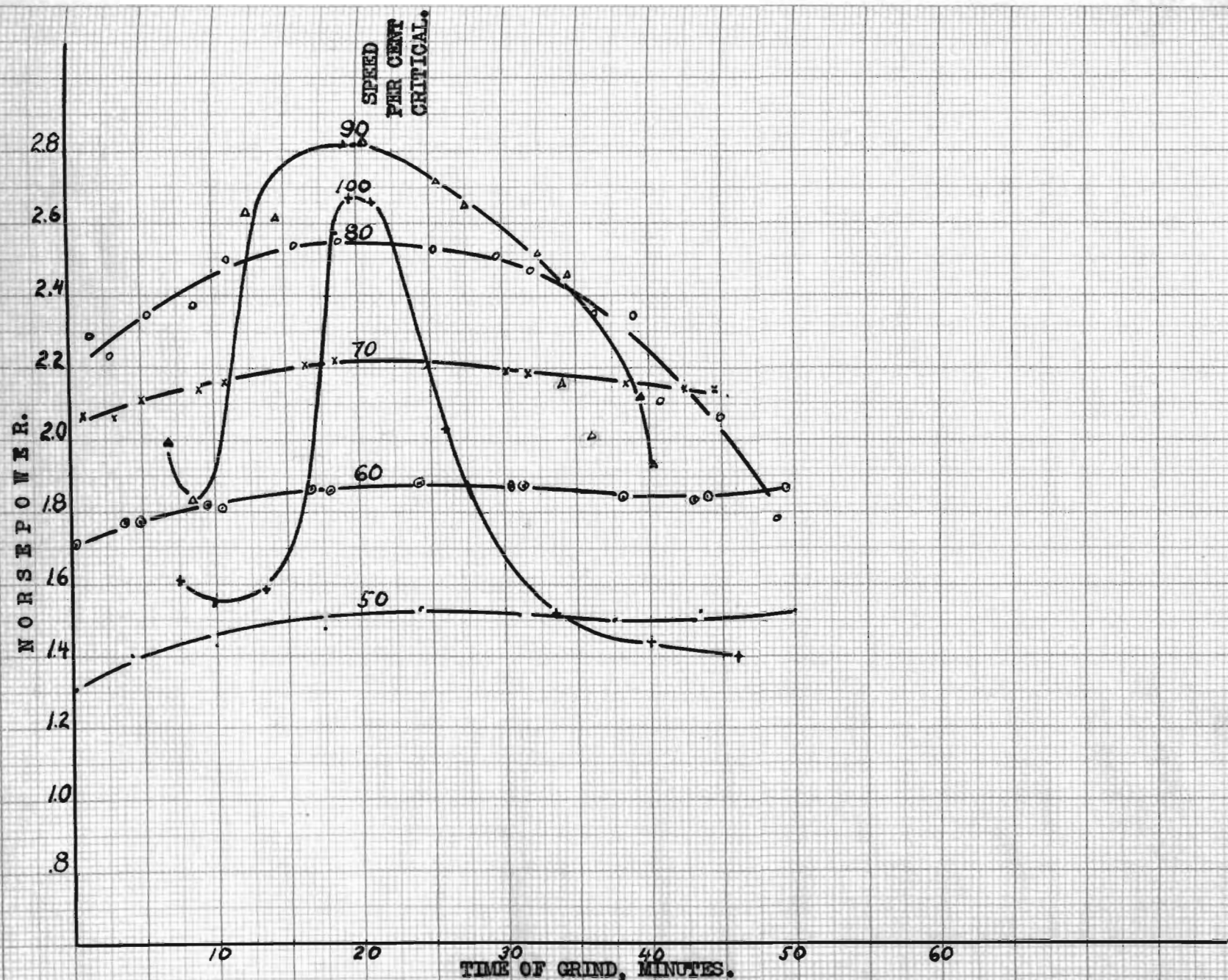
FIGURE 15. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS 100 POUNDS OF COARSE GRAVEL WAS GROUND TO FINES. PULP DENSITY, 61 PER CENT SOLIDS BY VOLUME.

grinding, together with the small amount of water, made the pulp
sticky, again reducing slipping and causing power decreases.
Thus, a pulp density of 61 per cent solids was much too thick to
warrant much further study.

(b). Tests Using Fine Gravel.

Finer gravel was used in making four other tests. This
size, minus 3|16-inch plus 2 millimeter, was closely sized and all
small enough to be ground readily by the 1-1|4-inch balls. Consequent-
ly, the time required for power changes was shortened, and it was
possible to obtain power readings at only one speed during a grind.
Figure 16 shows two such tests, one at 75 per cent and one at 100
per cent of the critical speed. Both are 43 per cent solids. The
75 per cent speed curve drops gradually in power after the first
minute's grind. There, the pulp reached its maximum bonding power,
decreased slipping to a minimum, and caused the maximum power con-
sumption. Thereafter, grinding the pulp reduced its bonding power,
permitted more slipping, with the consequent power decrease shown.

The 100 per cent speed curve, because of the high speed,
showed a different behavior. Grinding did not proceed as fast,
and two minutes elapsed before the pulp reached its maximum bonding
power. Presumably the consistency was the same as after one minute's
grinding at 75 per cent speed. Bonding reduced slipping to such an
extent that the charge nearly centrifuged and power consumption was
low. Further grinding gradually decreased bonding. As slipping in-
creased the power increased until maximum, and then dropped again
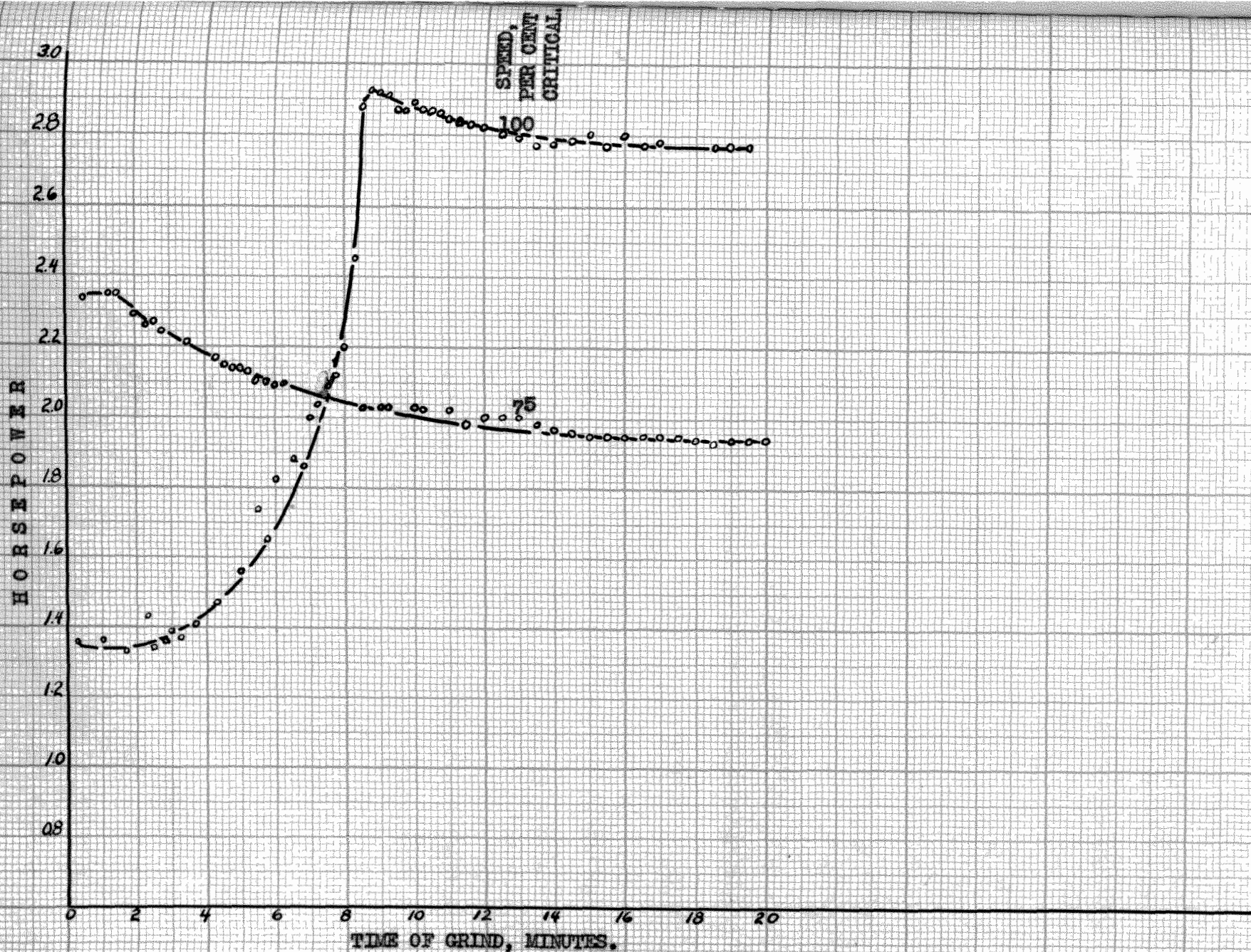slightly.

FIGURE 16. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT 75 AND 100 PER CENT OF THE CRITICAL SPEED AS 100 POUNDS OF COARSE SAND WAS GROUND TO FINE. PULP DENSITY, 43.5 PER CENT SOLIDS BY VOLUME.

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Figure 17 shows two curves, similar to the 100 per cent curve in Figure 16. Both these show the power consumption as 100 pounds of fine gravel was ground to fine sand. The gravel in this case was the same size, minus 3|16-inch plus 2 millimeter, but was not quite as resistant to grinding as that used in the previously-mentioned tests. The difference in the two curves lies in the density of the pulps. The thinner pulp, 43 per cent solids (on the left), went through the bonding changes more rapidly than, but not to as great a degree as, the thicker pulp, 54 per cent solids. In both cases, one to three minutes grinding produced a pulp of high bonding power. The charges nearly centrifuged. Fine grinding reduced the bonding power; the charge slipped and used more power as its actual speed dropped into the low-cataracting speed range. During the tests the power variation was as much as 100 per cent, further illustrating the difficulty of predetermining power.
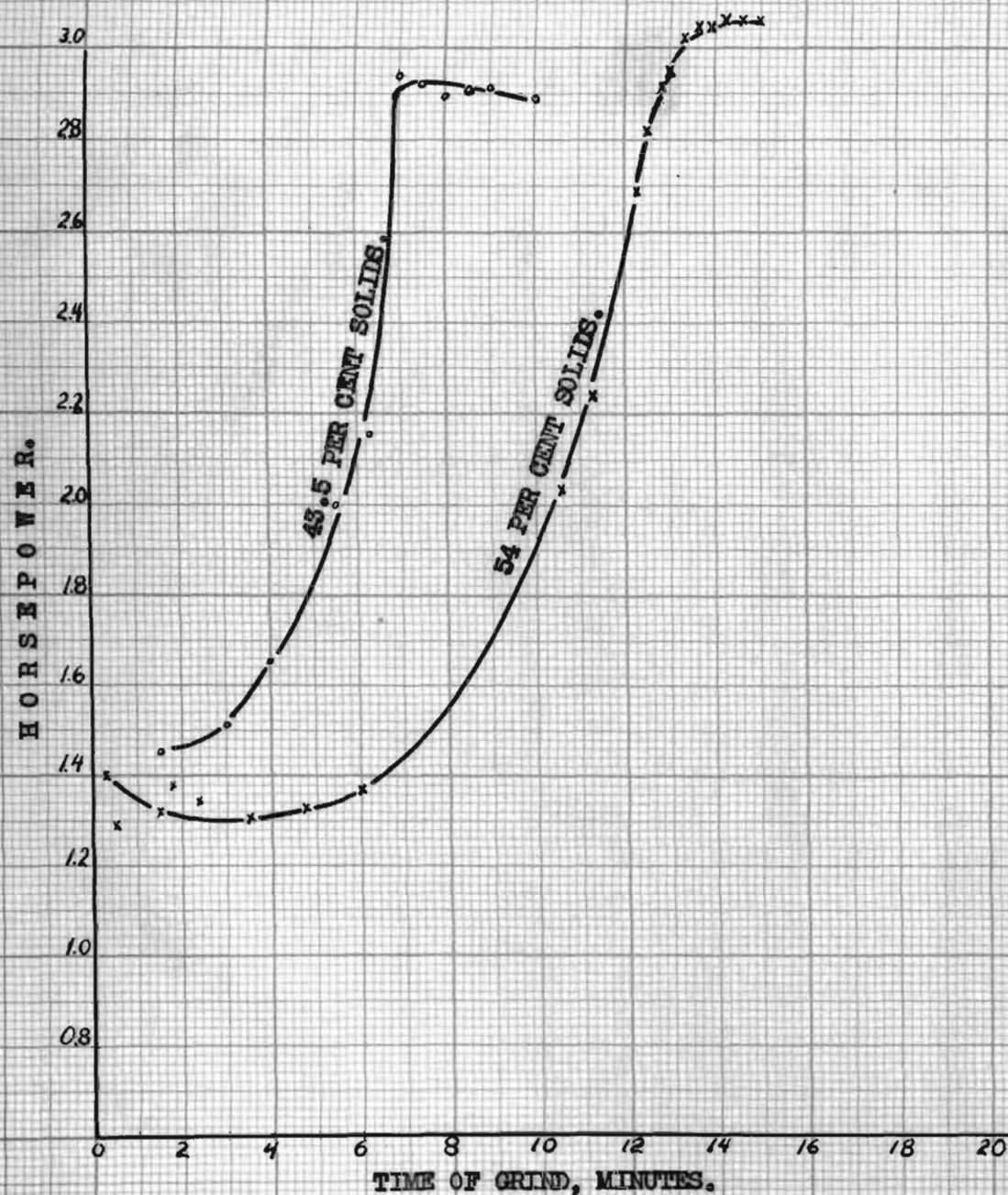
FIGURE 17. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT 100 PER CENT OF THE CRITICAL SPEED, AS 100 POUNDS OF COARSE SAND WAS GROUND TO FINE. PULP DENSITIES OF 43.5 PER CENT AND 54 PER CENT SOLIDS BY VOLUME.

(4). POWER VARIATIONS DURING PULP DENSITY CHANGES.

To determine the effect of pulp density the mill was charged with 42 per cent mill volume balls and 25 pounds of water. As it was rotated at various speeds, 10-pound batches of fine sand were added intermittently, and power readings were taken as the pulp density increased. When the pulp became so thick and plastic that the balls adhered to the shell, even at low speeds, the test was stopped. This point was slightly below 50 per cent solids by volume.

The same kind of test was made, charging the mill with balls and 50 pounds of fine sand, and gradually adding water. The extreme plasticity of the pulp to start with rendered power readings unreliable until a 50 per cent pulp density was reached. Dilutions to give less than 32 per cent density filled the mill to overflowing.

Figures 18 and 19 show the data from these tests. The ore was fine enough so that additional reduction made little difference. The most noticeable feature is that, even with a thick pulp, there was no high-speed cataracting. The evenly spacing of the curves indicates slipping. Evidently coarse aggregates is a requisite to the effective reduction in slippage.

Some tests are recorded with pulp densities as high as 61 per cent solids, but these were run with coarser ore.
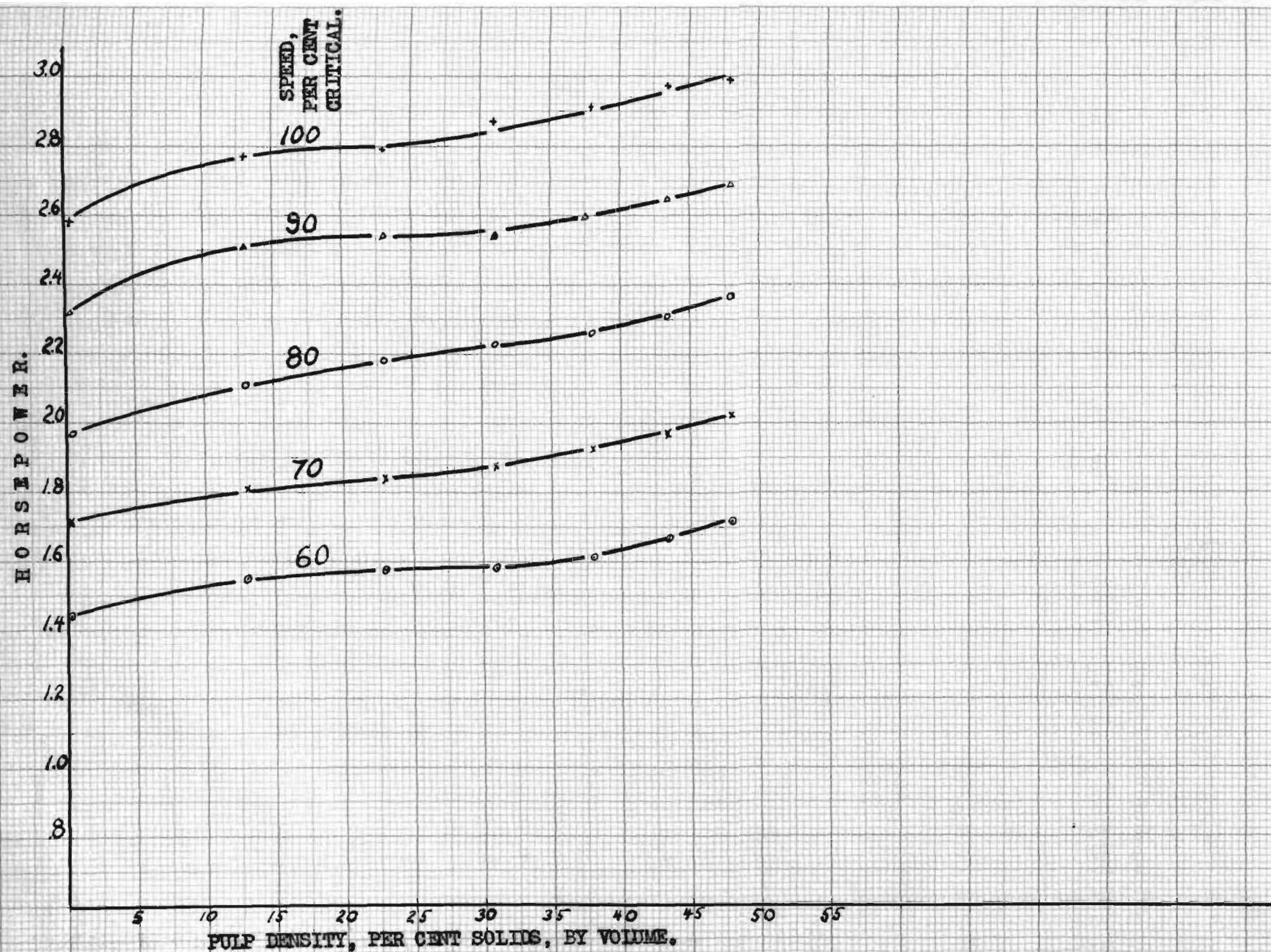
FIGURE 18. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS FINE SAND WAS ADDED TO CHANGE THE PULP DENSITY. 25 POUNDS OF WATER IN MILL.
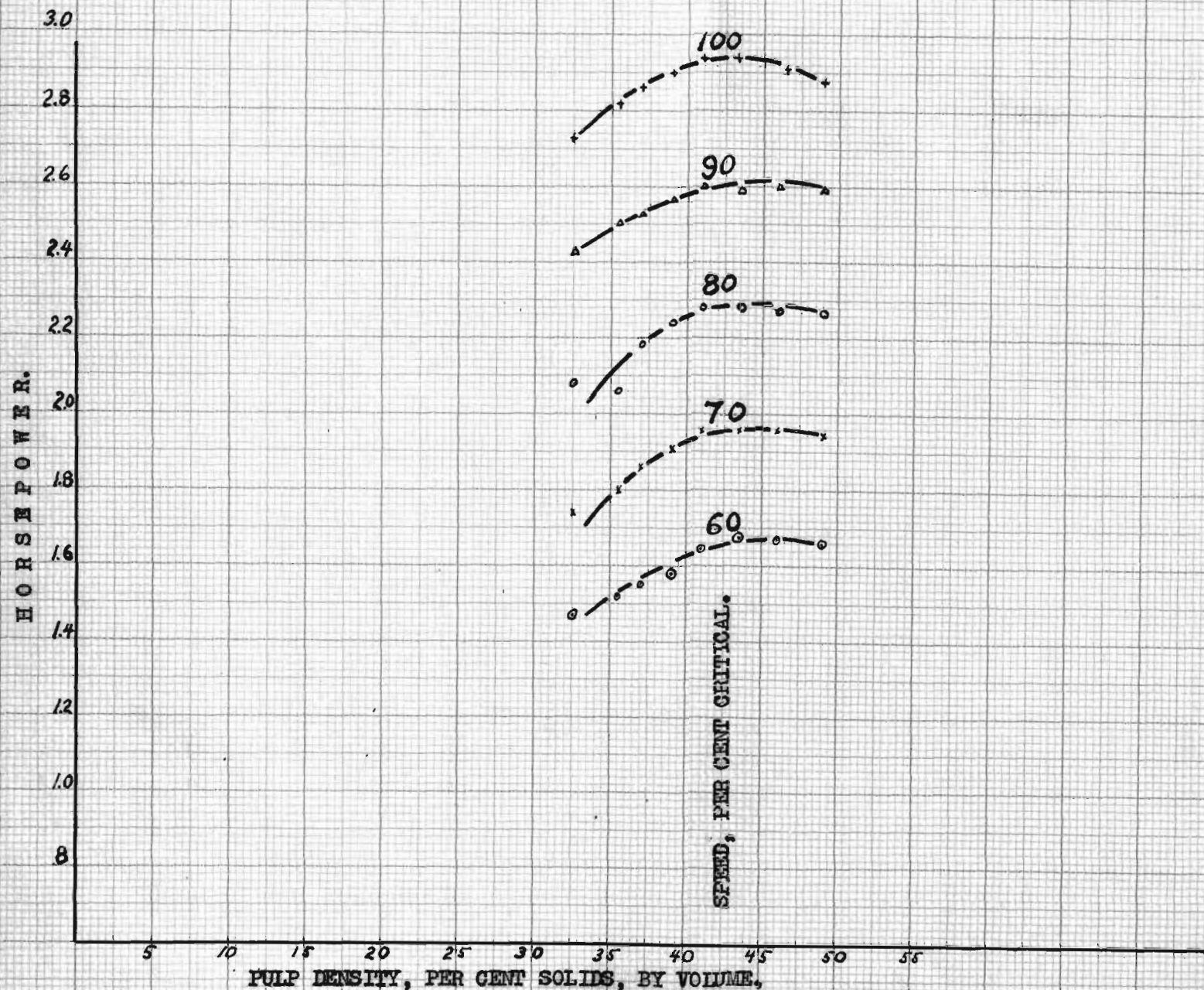
FIGURE 19. POWER CONSUMPTION OF A 24-INCH BY 24-INCH BALL MILL, 42 PER CENT FULL OF BALLS, AT VARIOUS SPEEDS, AS WATER WAS ADDED TO CHANGE THE PULP DENSITY. 50 POUNDS OF FINE SAND IN MILL.

DISCUSSION.

The results of these tests have shown that there are many factors in ball milling which effect the power consumption. If operating conditions are as variable from mill to mill, or from plant to plant, it is of little wonder that manufacturers and operators are so hard-pressed in estimating the power required for their mills. In general, power is overestimated to allow for the "large initial starting torque" (an often misunderstood power requirement, since it is due to fast acceleration), but a little power to spare is never amiss in the light of these power variations.

As a basis for study it is advisable to adopt the no-slippage power-speed relationship shown earlier in Figure 1. When the charge is rotated at mill-shell speed the action may be divided into three types, or speed ranges: (1) the cascading and initial cataracting range, in which the power is directly proportional to the speed; (2) the low speed cataracting range, in which the power increases with, but not in proportion to, speed; and (3) the high speed cataracting range, in which the power drops as centrifuging is approached. Deviation from this power-speed relationship is due to slipping; and slipping depends upon many factors within a mill. If it were not for slipping, ball milling would be a comparatively simple process, since the speed conducive to efficiency in one mill would serve as standard practice; but with slipping, shell speed has little absolute significance in mill

operation. The difficulty of visual observation, in most mills, leaves comparative power observations as practically the only indication of ball action.

Significance of Amperage Variation.

In addition to the horsepower data, which have heretofore served as a guide, the amperage consumption of the compound-wound direct-current driving-motor was used to indicate a power change. As long as the power increased in proportion to the speed, the amperage increased, but when the power increase was no longer proportional to the speed, the amperage decreased. Thus, a peak in the amperage curve was coincident with the break in the power curve; and this peak marked the beginning of the low speed cataracting range. The relationship between the break in the power curve and the peak in the ampere curve is shown in Figure 20. The several pairs of curves are taken from previously described tests. If the grinding efficiency of the low speed cataracting range, which was indicated by early grinding tests, has practical application, the significance of maximum amperage becomes evident.

The series of tests in which the size of grains influenced power justifies the belief that slipping is not the same throughout the length of a mill. Near the feed end there is probably less slipping because of the presence of coarse particles. This might explain the differential wear of ball mill liners, particularly in those mills where the wear is greatest toward the center or discharge end of the mill.
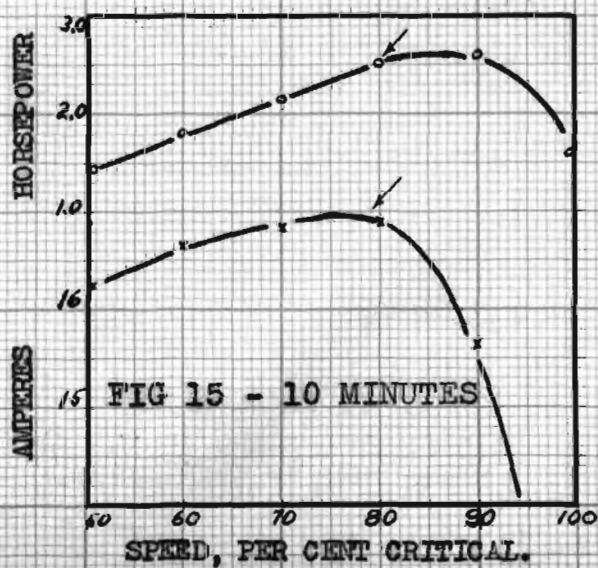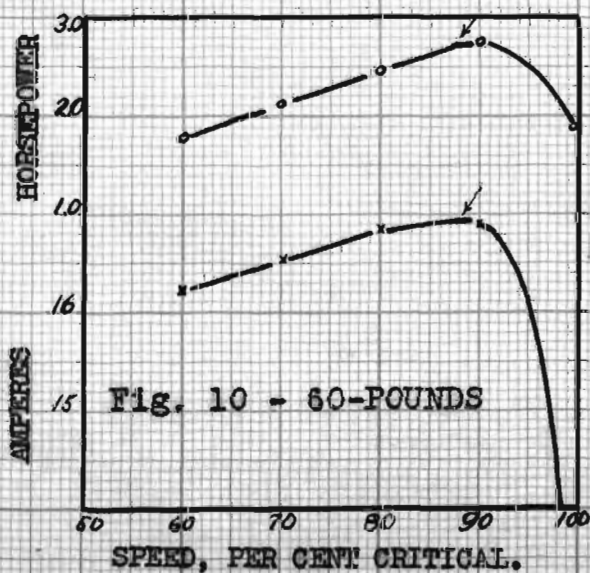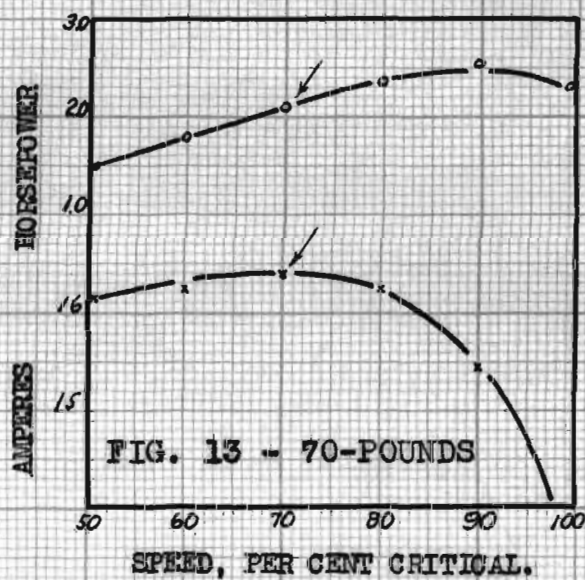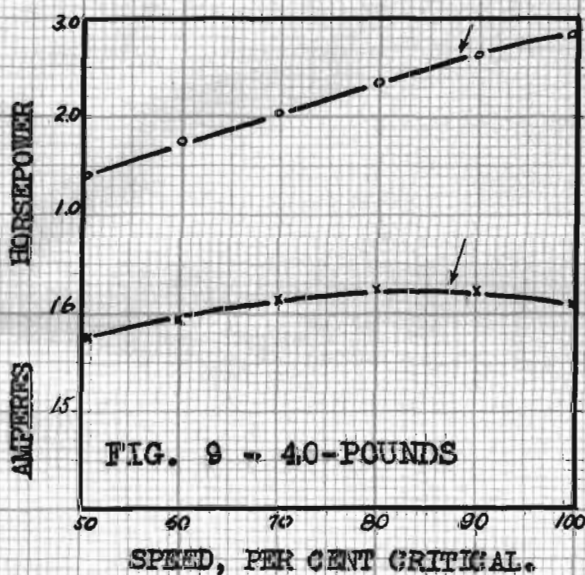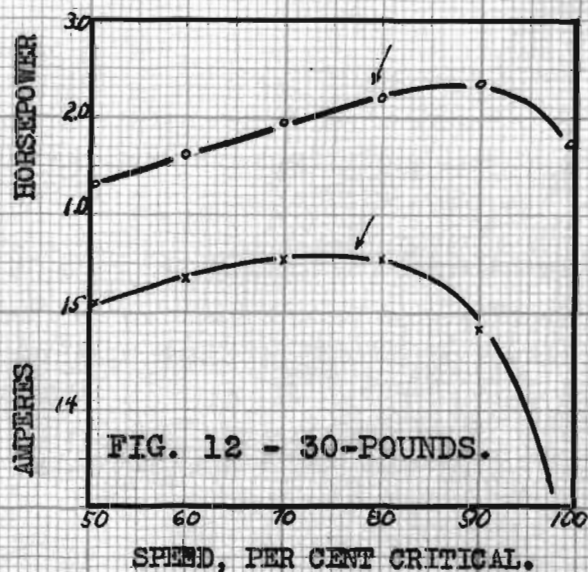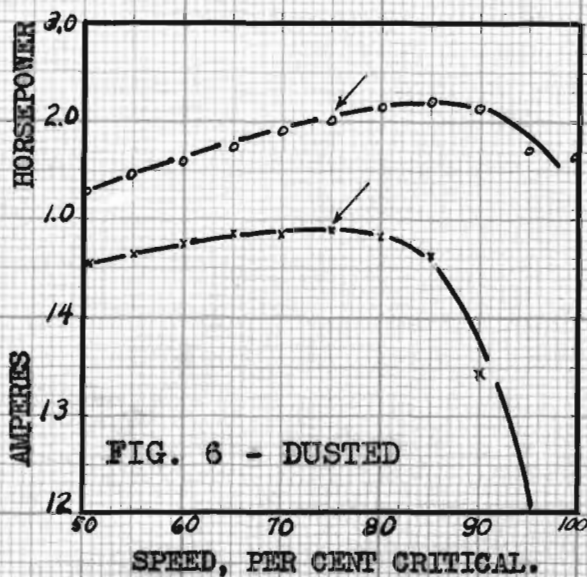
FIGURE 20. GRAPHS SHOWING THE RELATIONSHIP BETWEEN NET HORSEPOWER CONSUMPTION AND ARMATURE AMMETER READINGS IN VARIOUS TESTS.

The idea has been quite generally held that a mill should be operated so that the balls follow the "75 per cent speed parabolic path," or some other theoretical trajectory. From a power standpoint the advisability of such procedure may be questioned. Probably the large power consumption of a slipping charge in a fast rotating mill would be conducive to maximum grinding, since grinding would accompany a great energy transformation. Again, power variations accompanying a change in the condition of the pulp point to a weakness in batch grinding procedure, and might be considered to cast doubt over batch grinding results, unless they are properly coordinated.

Other conclusions might be deduced but such speculation must await a further investigation in the laboratory using closed circuit procedure, and eventually field-testing in operating mills.

SUMMARY.

The ball action in a ball mill is dependent on the speed at which the charge within the mill is rotated. This movement would be equal to the mill-shell speed if it were not for slippage. Generally it is impossible to visually observe the action of the charge during mill operation, but power observations may serve as a basis for the determination. Power studies were made on a 24-inch by 24-inch ball mill, during various kinds of tests, to determine (1) the power consumption as speed, amount of charge, and kind of charge were varied, and (2) some methods of controlling slippage.

Using the no-slippage power-speed relationship as a starting point, it was found that up to a certain speed slippage reduced power, but beyond this point slippage increased power and made possible mill operation at speeds much above the critical with large power consumption.

Control of slippage was affected, at least in part, by several means. Slippage was reduced by (1) increased amount of balls, (2) a critical amount of pulp, (3) a wide range of ore-particle sizes, and (4) a thick pulp. Tests were made as each of these conditions were varied, and the results emphasize the impossibility of fore-telling accurately the power required to run a ball mill, and also show the possibility of using power data as criteria of mill operation.

B I B L I O G R A P H Y.

Davis, E. W., Fine Grinding in Ball Mills; Trans. Amer. Inst. Min.
        & Met. Engrs., Vol. 61, p. 250, 1919.

Gow, A. M., Campbell, A. B., and Coghill, Will H., Laboratory In-
        vestigation of Ball Milling; Tech. Pub. No. 326,
        Amer. Inst. Min. & Met. Engrs., New York, Mar. 1930.

Kidd, R. L., A Study of Ball Milling; a thesis, Missouri School of
        Mines & Metallurgy, Rolla, Mo., 1929.

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