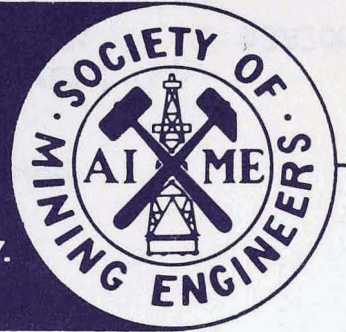


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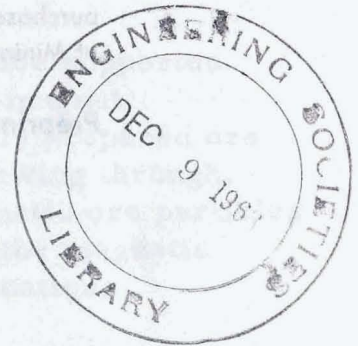
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Norman F. Schulz
Research Associate

Mines Experiment Station
University of Minnesota
Minneapolis, Minnesota



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Norman F. Schulz, Research Associate
Mines Experiment Station, University of Minnesota
Minneapolis, Minnesota

Introduction

The Davis magnetic tube concentrator is a laboratory machine designed to separate a small sample of pulverized magnetic iron ore into magnetic and non-magnetic fractions. It was developed in 1921 by mechanization of a test previously performed manually. (1)(2)(3)(4) No significant changes have been made in the design of the apparatus since that time. The Davis magnetic tube test continues to serve as a practical basis for judging the amenability of an ore to magnetic separation and for controlling magnetic separation plant operations.

The apparatus consists of an inclined cylindrical glass tube supported adjacent to closely spaced pointed poles of a powerful C-magnet. (Figure 1). To conduct a tube test, a sample of a suitably prepared ore is poured into the water-filled tube. With wash water flowing through, the tube is oscillated to gradually reject the weakly magnetic ore particles until the desired degree of separation is attained. Both the magnetic concentrate and the tailings may be recovered for examination.

With natural magnetite ores, usual practice has been to perform a single tube test on a specifically prepared ore sample, continuing the separation until judged "complete" according to the operator's experience. The resulting concentrate grade and iron recovery were used as a basis for controlling plant operations. However, when applied to certain roasted iron ores, this method yields test results which are often more dependent on the experience and judgment of the operator than on the ore itself.

The purpose of this investigation was to evaluate the effects of variables in equipment and procedure on tube test results. This information was then to be used to formulate specifications, preferably within the practical ranges of existing machines, for test procedures capable of yielding precise and meaningful data concerning the magnetic separation of any magnetite ore, regardless of its origin.

A survey of current practice was conducted among laboratories using the Davis tube test. Thousands of tube tests were performed to experimentally evaluate the variables most likely to affect test results. A simple method was then sought for adequately interpreting tube test results.

Summary of Recommended Test Procedure

Davis Magnetic Tube Tester:

- Pole pieces: Conical, 90 degree included angle, on common horizontal axis.
- Pole gap: 3/8 to 3/4 inch.
- Magnetic Field: 4000 gauss or more midway between poles.
- Tube: Cylindrical, glass, 1 inch I. D., 1 1/8 inch O. D. (5% tolerance).
- Tube position: Axis 40 to 50 degrees from horizontal, less than 1/16 inch clearance from pole pieces.
- Tube agitation: Stroke 1 to 3 inches, rotation 60 to 120 degrees.

Test Procedure:

- Ore sample: 10 g.
- Operation: Agitation, 60 to 150 cycles per minute
- Water, 50 to 500 cc per minute
- Time, 3 to 20 minutes
- Number of tests, three or more, at conditions selected to yield data in region of sharpest curvature of MSC or other region of interest.
- Product recovery and examination: Stop machine, drain water from tube to magnet level, remove tube from machine, and rinse contents into a glass beaker. Decant the water from the concentrate with the aid of a hand magnet held at the bottom of the beaker. Dry, weigh, and assay the concentrate.
- Data processing: Calculate iron recoveries from sample and concentrate weights and assays. Plot concentrate grade against iron recovery and connect points by a smooth curve.

Conclusions

It is not feasible to attempt to define a single Davis magnetic tube test which could be applied to all magnetic ores.

The Magnetic Separation Characteristic interprets the results of tube tests in a significant manner. It expresses the actual course of separation rather than merely the achievement of a single arbitrary tube test based on the fallacious assumption of an absolute end-point to the separation. Its general concept is applicable to any separation process.

The magnetic field intensity midway between the magnet poles of a Davis magnetic tube concentrator should be at least 4000 gauss. Machines with lower field intensity can be used for routine test work if suitably calibrated.

Variations in test details are more likely to influence test results for artificial magnetite ores, and especially partially roasted iron ores, than for natural magnetite ores such as taconite.

Magnetic Separation by the Davis Tube

Mechanical separation of a specified mineral component from an ore usually requires comminution to fine sizes for sufficient liberation. Some distinguishing property of the mineral is then exploited to sort the desired mineral particles from the gangue particles.

The magnetic separation of iron ores is based on the fact that magnetite, Fe_3O_4 , is strongly attracted by a magnetic field while the gangue minerals are not. Maghemite, $\gamma\text{-Fe}_2\text{O}_3$, which may occur in certain chemically processed ores, responds similarly to magnetite. The magnetic process is practical only when the loss of iron in the form of relatively non-magnetic hematite, Fe_2O_3 , goethite, $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$, or other iron mineral can be tolerated.

In the Davis magnetic tube concentrator, magnetic attraction holds magnetically susceptible particles in a magnetic field. Forces due to gravity, inertia, and fluid-solid friction tend to remove the less susceptible particles from the field. The probability that a given middling particle

will be rejected from the tube in a given period of time is an inverse function of its magnetite content, with some modification due to particle size and mineral specific gravities. The net result is that ore particles tend to be rejected in their order of increasing magnetite content, while the retained portion or magnetic concentrate increases in grade continuously during the process.

The "Magnetic Separation Characteristic" or "MSC" of a magnetite ore is the correlation between concentrate grade and iron recovery which occurs during a magnetic separation process. It is a function of the structure, composition, and degree of liberation of the ore and of the particular process employed.

The relationships which might occur between grade and iron recovery during magnetic separation are illustrated in Figure 2. The ideal course of magnetic separation of a perfectly liberated magnetite ore would consist of total gangue rejection without loss of magnetite, leaving a pure magnetite concentrate of 72.4 percent iron. The ideal course for an ore sample containing middling particles would consist of rejection of particles in their order of increasing magnetite proportion, as represented by curve I of Figure 2. An experimental separation, being less than 100 percent efficient, might follow the course represented by curve E of Figure 2.

The MSC obtained with the Davis tube represents a highly efficient course of magnetic separation for a specifically prepared ore sample. The overall separation efficiency achieved in a well-designed plant in which mineral liberation is an integral part of the operation should be at least as good as that of the Davis tube.

Magnetic separation in the Davis tube begins at a very high rate which decelerates rapidly in the region of sharpest curvature of the MSC to very low rates beyond. The transition from high to low separation rates occurs quite abruptly for most natural magnetite ores but may be very gradual for some artificial ores as shown in Figures 3 and 4. A given point on the curve for an artificial ore is clearly more difficult to duplicate experimentally. Test results over identical moderate ranges of test specifications were congregated in a much shorter section of the MSC curve for the taconite than for the roasted ore.

Because of the nature of magnetic separation, it is neither practical nor necessary to determine more than the relatively small portion of the MSC curves included within the shaded rectangle of Figure 3.

Data for MSC curves were obtained by processing identical portions of a prepared ore sample to different stages of separation in a Davis tube. Much of the experimental work was concerned with establishing test specifications which would yield an MSC as close to ideality as practicable and with minimum modification of current apparatus or techniques.

Equipment

Although three Davis magnetic tube machines were available (see Table I), this investigation was conducted on DMT-III with only enough work with DMT-I and DMT-II to establish correlations among the three. Magnetic fields were supplied by direct current electromagnets having three-inch diameter cores capped by 90-degree conical pole pieces. The magnetic field intensity of DMT-III was controlled by a rheostat in the field circuit.

Agitation was provided by variable speed motors through a crank and slide mechanism which oscillated the tube both longitudinally and rotationally.

A straight cylindrical glass tube, 1.0 inch I. D. and 1.12 inch O. D., with the lower, outlet end tapered to 0.25 inch I. D. was normally used. Tubes of 0.75 and 1.25 inch I. D. were available for special tests. The conventional side arm for water inlet and enlargement at the upper end were eliminated. A drawn glass tip of about 0.05 inch I. D. was inserted in the rubber tubing on the lower end during operation at low water rates to prevent air bubble intake. The water supply was regulated by a needle valve and flowmeter.

An analytical balance was used to weigh samples to the nearest milligram in a brass scoop designed to transfer the ore sample to the tube. Concentrates were collected in 250 ml glass beakers and a small hand magnet was used to aid the decanting operation.

TABLE I
DAVIS MAGNETIC TUBE MACHINES

<u>Machine</u>	<u>DMT-I Hand-made fixed poles</u>	<u>DMT-II Hand-made adjustable poles</u>	<u>DMT-III Dings Type EDTT fixed poles</u>
Pole gap, inches	0.58	0-1.5	0.56
Magnetic Field*			
Sustained, 110 v	2900	3100	5800
At 1.0 amp.	-	-	3900
Agitation			
Frequencies, cycles per min.	82-97	70-88	50-180
Stroke length, in.	2.0	2.0	2.0
Rotation, degrees	90	120	120

* Magnetic field measured at pole centerline midway
between points, with Bell, Inc., Model 110 Gaussmeter.

Ore Samples

The tube test investigations were conducted on magnetite ores only, including a variety of roasted iron ores and a few magnetic taconites. All were pulverized to approximately normal size distributions with top particle sizes of 44 to 149 microns (325 to 100 mesh) in single stage operations with either a pebble mill or a Davis sample grinder.

The structure and composition of magnetic ores and the techniques employed to liberate the mineral components are not so much basic factors affecting the accuracy of tube test results as they are properties to be studied by means of the tube test. Therefore, the physical properties of an ore sample were considered to be outside influences affecting only the allowable ranges of independent test variables.

Results

Questionnaires concerning details of equipment and procedure for the Davis magnetic tube test were sent to twenty-three laboratories outside the Mines Experiment Station. The contents of the nineteen replies and Station experience are summarized together with the results of this investigation under the following headings.

Magnet Poles

No machines were reported to have other than coaxial 90-degree right circular conical magnet poles. The pole gaps varied only slightly from 0.44 to 0.75 inches, 80 percent being 0.50 to 0.63 inches.

Experimental results with DMT-II showed only minor effects on the MSC due to variation in pole gap from 0 to 1.3 inches and no significant effects over the total reported range.

Magnetic Field

The effective magnetic field strength in a Davis tube, which is approximately proportional to the central field intensity (midway between the magnet poles), must be sufficient to minimize loss of desirable ore. Test results at various field intensities yielded the MSC curves of Figure 5.

Of the 26 machines reported in the survey, 9 had central field intensities of less than 3500 gauss and only 13 had fields of 4000 gauss or more. Test results obtained on different machines can be expected to agree only if the fields are very similar or above 4000 gauss.

Tube Clearance

Tube wall thickness plus clearance between tube and magnet poles constitute the distance separating the pulp column from the poles. In existing machines, this total distance ranged from 0.05 to 0.32 inch, 80 percent being less than 0.20 inch.

Experimentally, increased clearance between tube and poles tended to lower the resulting MSC curve slightly as shown in Figure 6.

Tube Diameter

About 75 percent of the tubes currently in use are 0.94 to 1.06 inch I. D. The largest reported was 1.38 inch and the smallest 0.88 inch.

Variations in tube diameter from 0.75 to 1.25 inch did not affect the separation efficiency of well-roasted or natural magnetite ores. The maximum sample quantity which could be separated efficiently, however, was approximately proportional to the cross sectional area of the tube. The relationship between iron recovery and sample quantity for the three tube sizes is shown in Figure 7 for a well-roasted ore.

Similar data for a partially roasted ore, Figure 8, shows that both the limiting sample quantity and separation efficiency are affected by tube diameter. The rather peculiar behavior of partially roasted ores toward magnetic separation remains as a subject for future study.

Tube Inclination

Davis tube tests are regularly performed with the tube inclined at 40 to 50 degrees by 80 percent of the operators reporting, while the remaining 20 percent prefer to operate at less than 40 degrees from the horizontal. One reported using an angle of 5 degrees during early stages of a test and finishing at 45 degrees. All the machines could be operated conveniently at 45 degrees.

A few tests were performed at inclinations of 25, 53, and 90 degrees from the horizontal. When the results were compared with those obtained for normal operation at 45 degrees, it was concluded that the angle of inclination had no significant influence on the MSC obtained.

Tube Agitation, Magnitude

Most of the 32 machines reported had a stroke of 1.5 to 3.0 inches, the limits being 1 and 3.5 inches. Half were reported to have a tube rotation of about 90 degrees, the limits being 45 and 120 degrees.

The effect of stroke length on test results was not investigated. A few tests were conducted without the rotational component for comparison with the 120-degree rotation of DMT-III. Although the rotation did not influence the resulting MSC, it facilitated movement of the rejected tailing particles down the tube to the outlet.

Tube Agitation, Rate

Many machines were reported to have adjustable oscillation rates of a variety of ranges. Over 80 percent of them are normally operated between 60 and 120 cycles per minute.

Rate of oscillation had no significant effect on most well-roasted or natural magnetite ore separations. Partially roasted ores, however, were much more efficiently separated at the slower oscillation rates as shown by the series of MSC curves of Figure 9.

Water

Most laboratories use whatever tap water is readily available. A few use distilled water, especially when the tailings are to be recovered by evaporation. Occasionally, wetting agents are used. In one instance, sea water is regularly used.

A limited investigation into effects of fluid properties consisted of tests run with acetone and with water at 50°C as compared with normal operation with water at 15 to 20°C. The only effect noted was a retardation of the separation process, probably due to the lower viscosity of the acetone and the hot water.

The addition of a wetting agent to the water supply, 0.1 cc Aersol MA 80 percent per liter, produced no discernible effect on tube test results.

Water Rate

The water flow rate used in tube tests varied widely among operators. About 25 percent specified rates between 100 and 200 cc per minute, 50 percent between 200 and 1000 cc per minute, and the rest higher rates. The highest reported rate was 2300 cc per minute for a machine having a 1.13 inch I. D. tube.

In tests run here on roasted ores, water rates from 10 to 1000 cc per minute had no significant effect on results. The frictional forces acting on magnetic particles held in the tube due to a water rate of 1000 cc per minute are similar to those due to 2-inch oscillations at 25 cycles per minute.

Time

Although some laboratories reported running tube tests until the outlet water is "clear," others specified times of 3 to 20 minutes. The total amount of water used varied from 0.5 to 34 liters per test.

In this investigation, time was found to be a purely extensive variable, having no effect on the MSC of an ore, but being useful in obtaining the necessary spread of data to plot the desired MSC curves.

The degree of separation achieved in the Davis tube for a typical roasted ore was dependent on the total amount of water passed regardless of water rate between 80 and 500 cc per minute.

Sample Quantity

Since there must obviously be a maximum sample quantity which the Davis tube can handle effectively, a program was undertaken to correlate test results with the amount of ore sample treated.

Current practice among laboratories using the test calls for samples of 3 to 20 grams, most commonly 10 to 15 grams, and up to 50 grams on very lean ores.

Experimental results showed that tests on well-roasted or natural magnetite ores of 20 to 40 percent total iron content could be run effectively on any quantity up to about 20 grams without seriously affecting the MSC obtained. (See Figure 7). Some ores yielded consistent results on samples as large as 50 grams.

Some partially roasted ores were most efficiently separated at a sample weight of 15 grams. The iron recovery at a given concentrate grade was lower for both larger and smaller samples. (See Figure 8).

An optimum sample amount applicable to nearly all ores appeared to be about 10 grams for a 1 inch I. D. tube.

Acknowledgements

This investigation was part of a continuing project on magnetic roasting and separation of lean iron ores being conducted as a normal function of the Mines Experiment Station of the University of Minnesota. The author wishes to thank the companies and individuals who furnished requested information about Davis tube equipment and procedures in current use.

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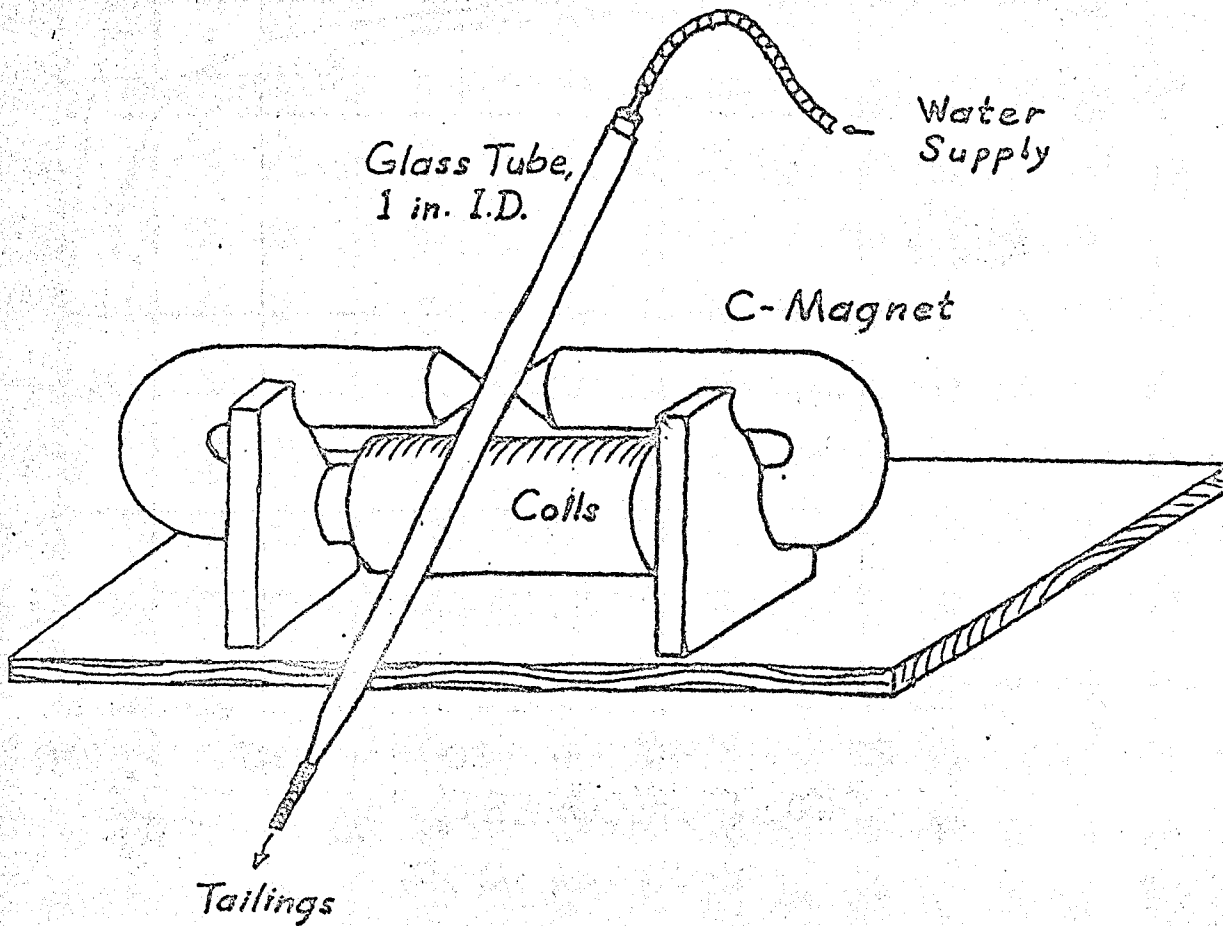


Figure 1. THE DAVIS MAGNETIC TUBE CONCENTRATOR consists essentially of a glass tube and a powerful magnet.

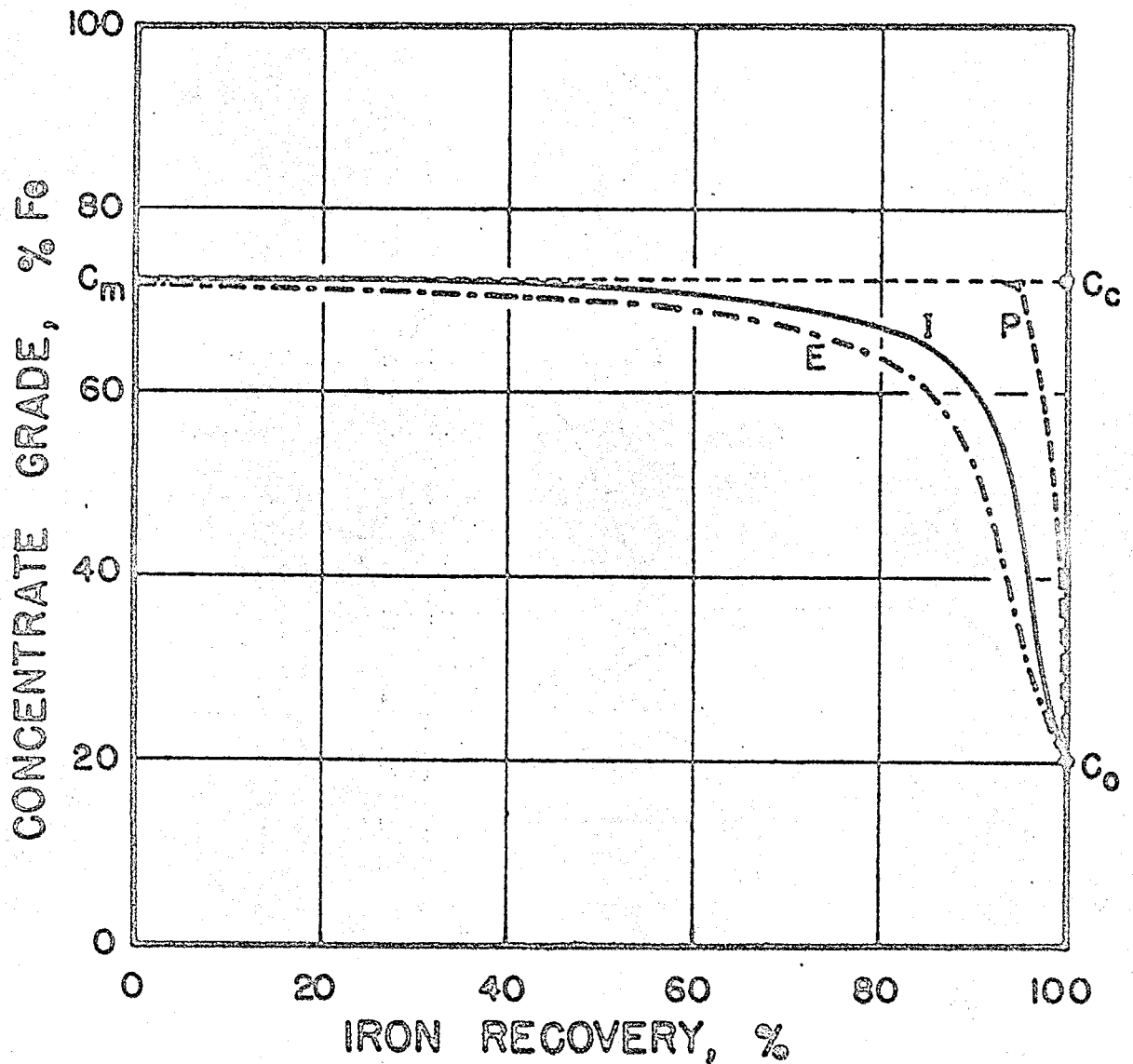


Figure 2. THE MAGNETIC SEPARATION CHARACTERISTIC (MSC) represents the course of magnetic separation of a pulverized ore sample. If the magnetite in an ore is 100% liberated, the ideal course would be the vertical line from C_o , iron content of the head sample, to $C_c = C_m$, iron content of pure magnetite. An experimental separation of such a material might follow curve P. If the ideal separation of an incompletely liberated ore is represented by curve I, an actual separation would yield an MSC such as indicated by curve E.

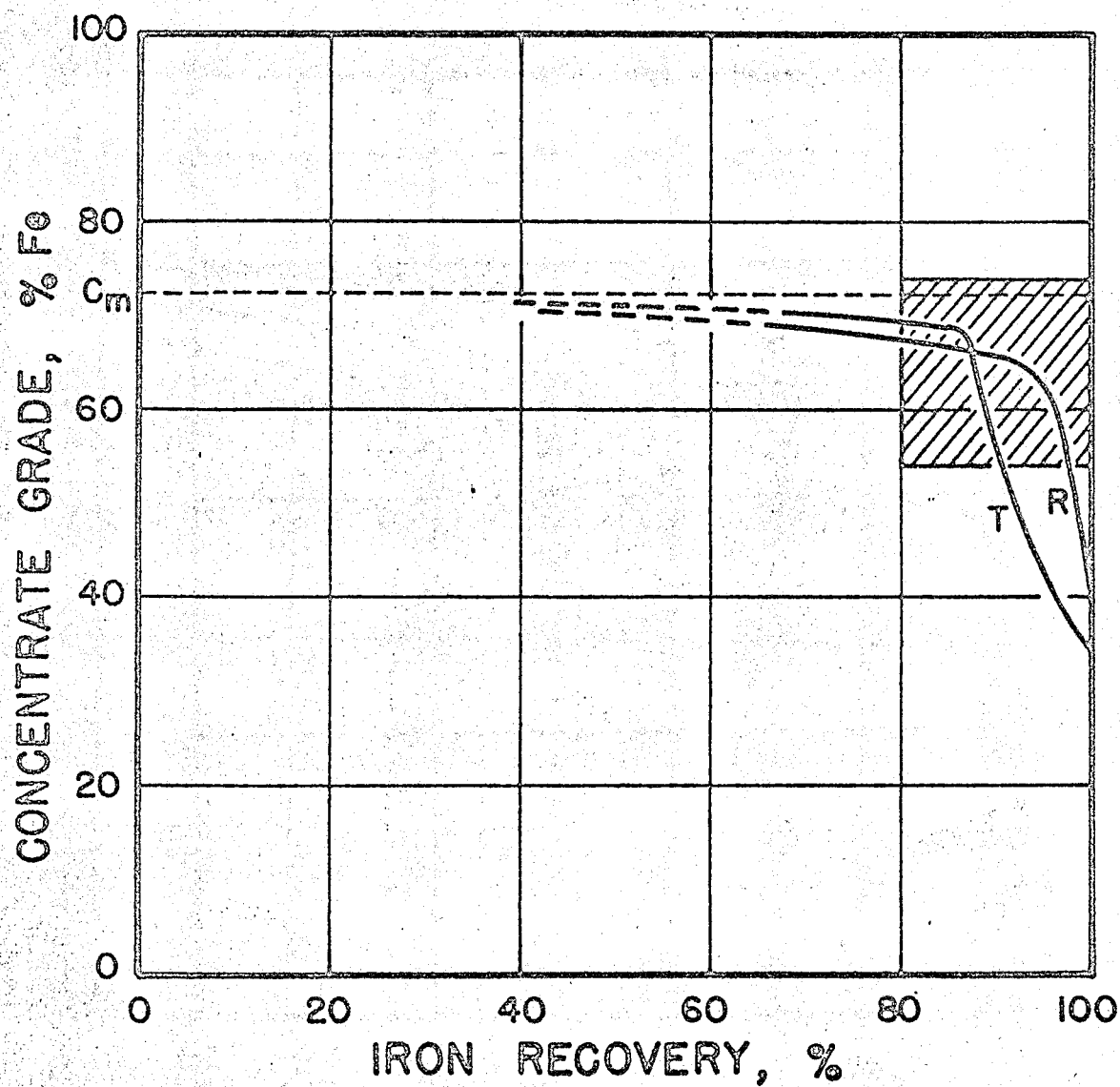


Figure 3. TYPICAL MSC CURVES for taconite, T, and roasted ore, R, illustrate the contrast between them. (C_m is the limiting grade for magnetite, 72.4% Fe).

Taconite, T: 34.2% Fe, $(Fe^{++}/Fe) = 0.41$

Roasted Ore, R: 40.0% Fe, $(Fe^{++}/Fe) = 0.21$

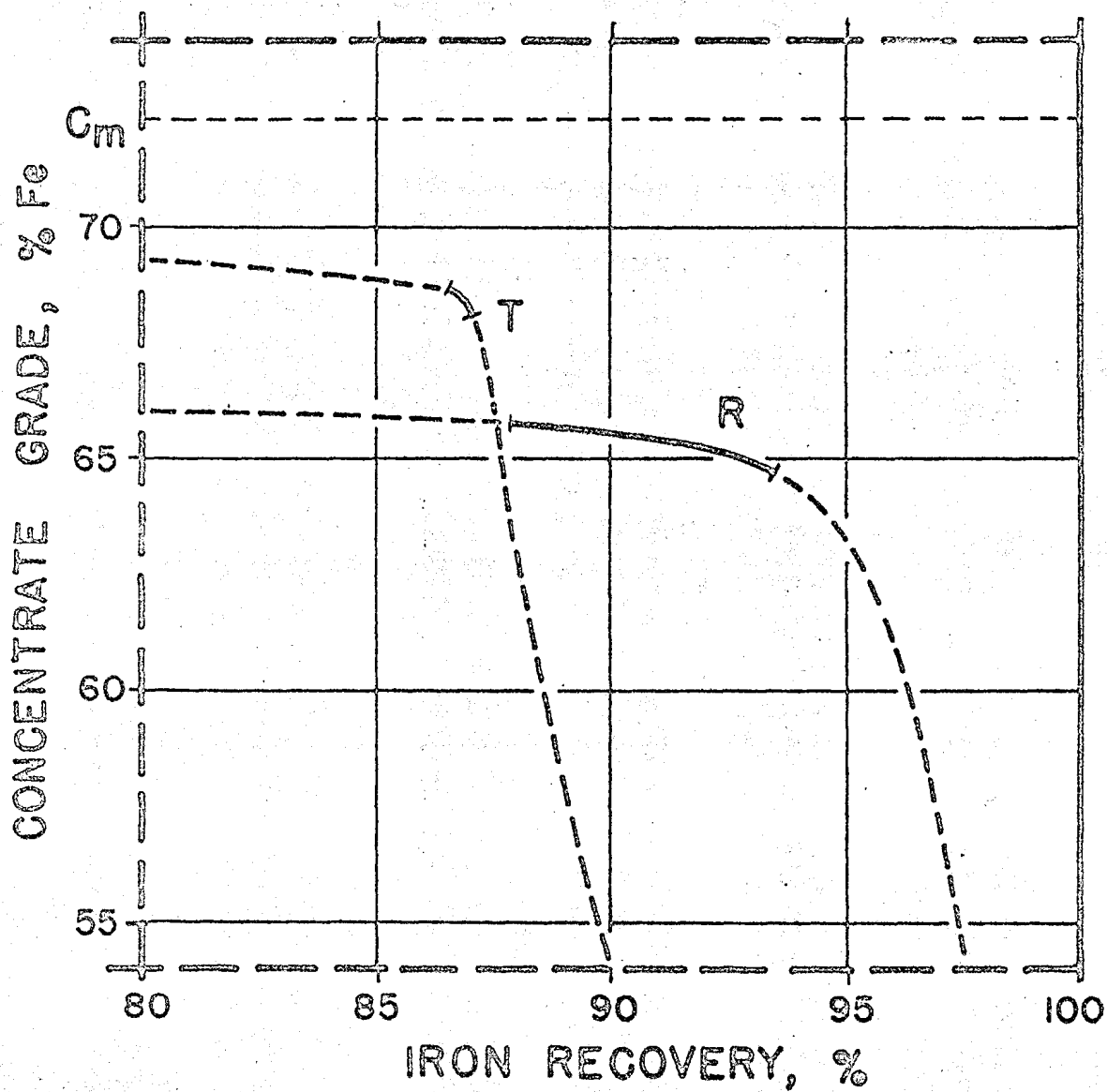


Figure 4. THE USEFUL PORTIONS OF THE MSC CURVES enclosed in the shaded area of Figure 2 are replotted here on an enlarged scale. The solid sections were obtained over identical ranges of tube test conditions.

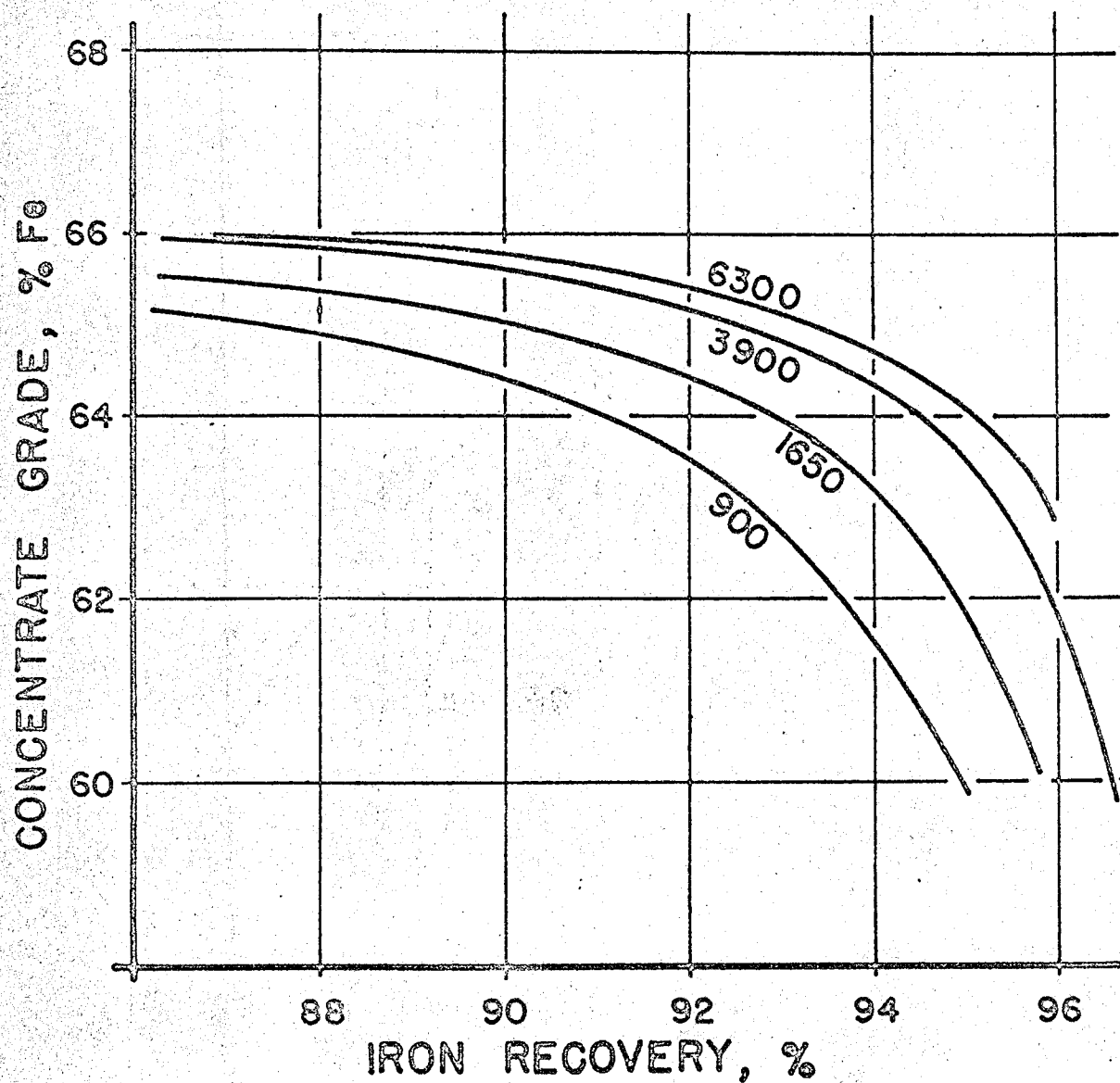


Figure 5. MSC CURVES FOR A ROASTED ORE, 40.0% Fe, $(\text{Fe}^{++}/\text{Fe}) = 0.21$, at central magnetic fields of 900 to 6300 gauss in the Davis tube machine show relatively small gain above 3900 gauss.

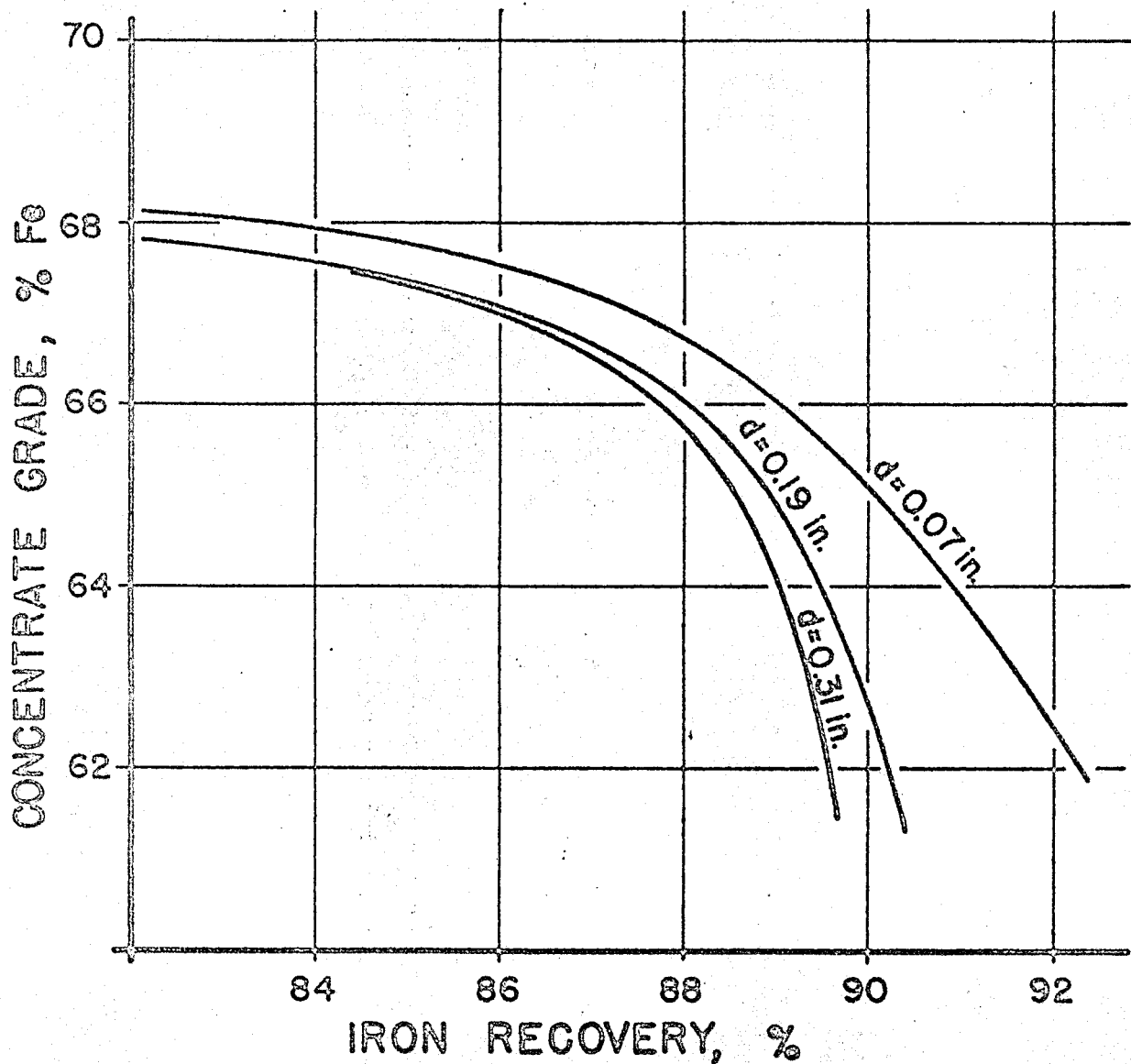


Figure 6. INCREASED TUBE CLEARANCE SHIFTS MSC to lower value. For best operation, the total distance between pulp column and magnet pole faces should be a minimum. Distance, d , equals clearance plus tube wall thickness.
Ore: 35.5% Fe, $(\text{Fe}^{++}/\text{Fe}) = 0.26$.

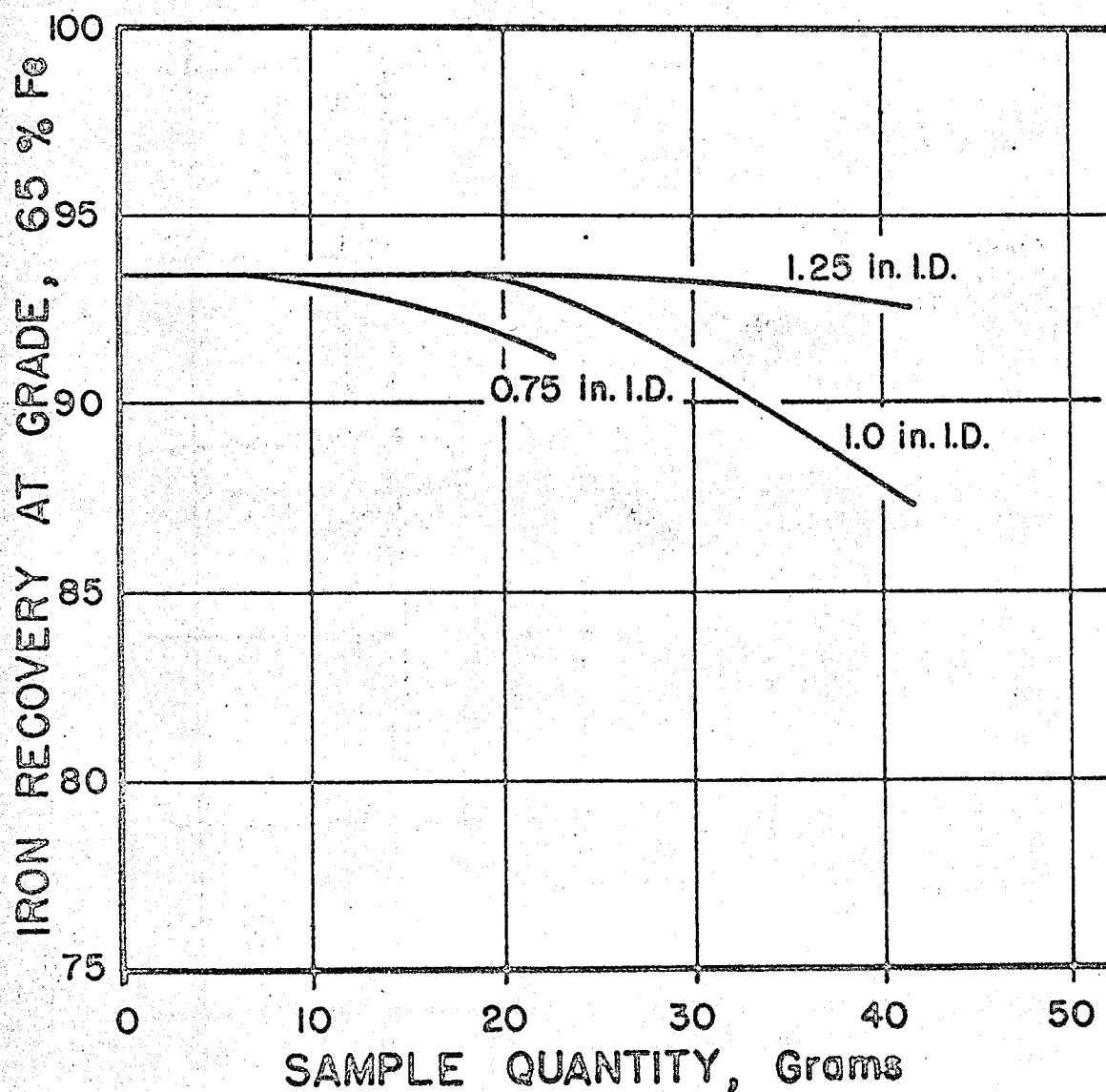


Figure 7. THE EFFECT OF SAMPLE QUANTITY ON IRON RECOVERY was negligible for samples of less than 20 grams of a well-roasted ore in a 1.0 inch I. D. tube. The sample limit was roughly proportional to the square of the tube diameter. Ore: 37.2% Fe, $(\text{Fe}^{++}/\text{Fe}) = 0.29$.

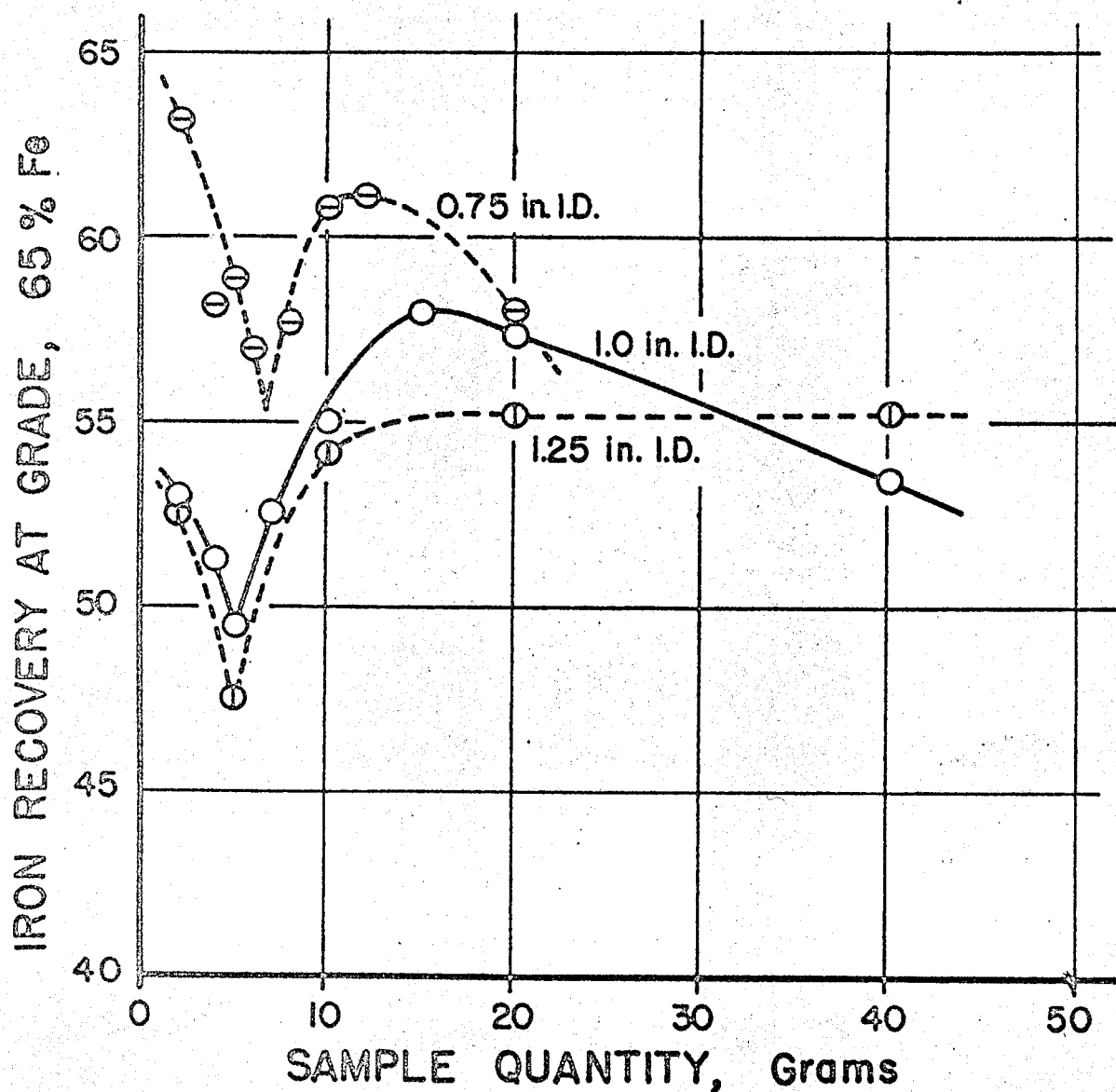


Figure 8. THE IRON RECOVERY FROM A PARTIALLY ROASTED ORE was a complex function of tube diameter and sample quantity. The optimum sample was about 15 grams for this particular ore, 31.1% Fe, $(\text{Fe}^{++}/\text{Fe}) = 0.09$.

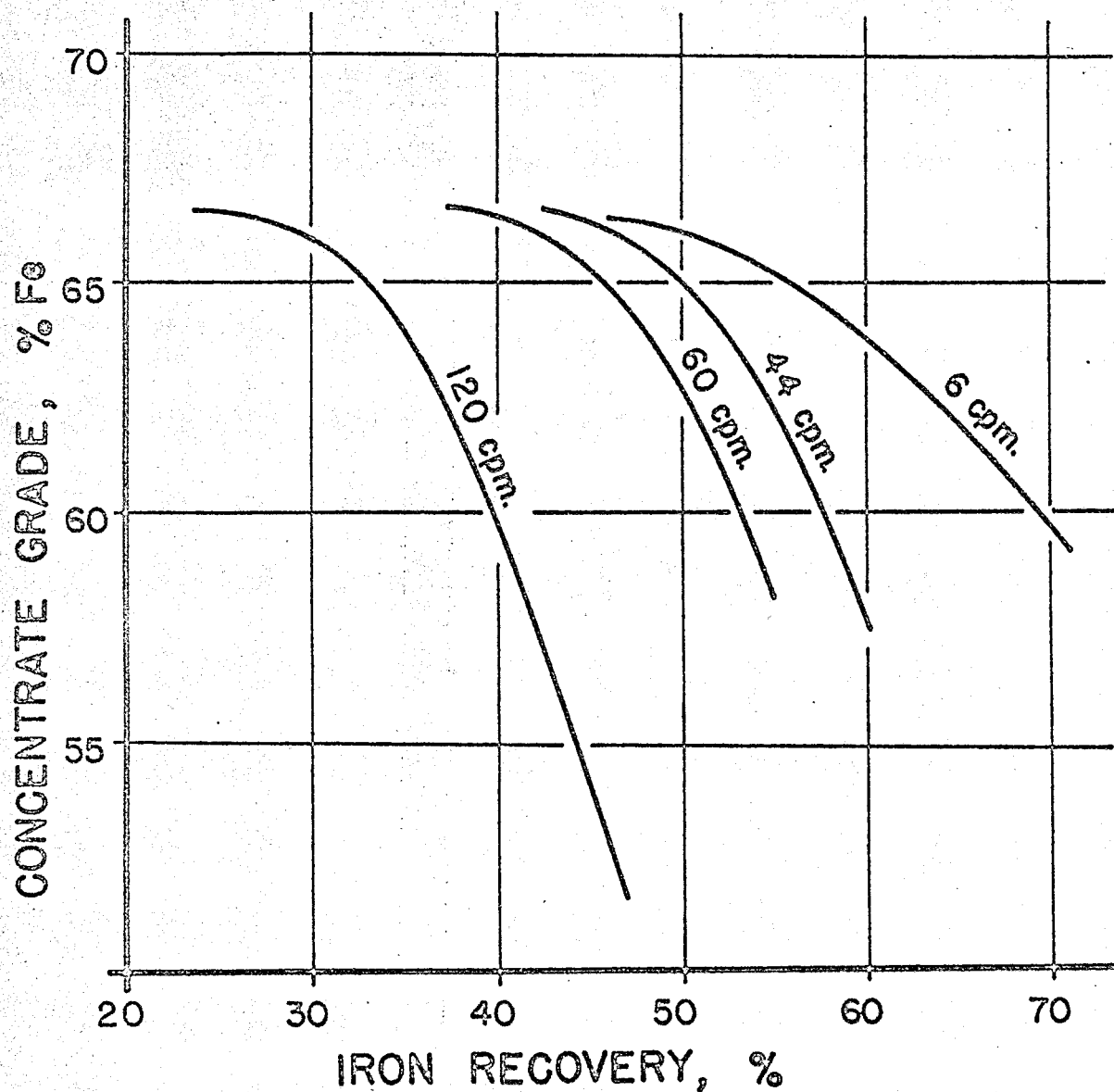


Figure 9. THE MSC DEPENDS ON OSCILLATION RATE in the case of a partially converted iron ore, 36.2% Fe, $(\text{Fe}^{++}/\text{Fe}) = 0.09$. The lowest rate was attained by intermittent operation at the minimum drive speed of 44 cycles per minute.