The Magnetic Reflux Classifier

by Lawrence A. Roe

The magnetic reflux classifier, which utilizes the combined effects of magnetic fields and a hindered settling classifier, is a new tool for determining the quantity and quality of middlings in fine-sized magnetite concentrates. Results are given for processing a typical taconite ore, and a sketch of the apparatus is included.

IN examining magnetite ores and beneficiated products it often becomes necessary to make critical studies of the amount of grinding necessary to produce the desired degree of magnetite liberation. In the past this has been accomplished by laboratory heavy-liquid tests, which provide a method for selectively removing middling particles and free magnetite from various-sized fractions. Examination of the various products under the microscope results in fairly accurate determination of the degree of liberation. The method is quite efficient on sizes coarser than 325 mesh. Thus the heavy-liquid method of middling separation was satisfactory until the advent of present day magnetic taconite studies. When magnetite concentrates ranging from 70 to 100 pct —325 mesh are studied it becomes apparent that older methods of determining liberation size are not satisfactory and that there is need for a new method. For example, some of the low-grade magnetite ores of the Wisconsin and Michigan iron ranges require grinding to 100 pct —325 mesh to produce a magnetic concentrate containing less than 12 pct silica. Examination of concentrates from such ores often reveals that many of the middling particles consist of only very minor proportions of iron mineral.

Thus it becomes important to be able to determine the degree of grinding necessary not only for complete liberation, but also for liberation of only 80, 85, or 90 pct of the total iron mineral content. Actually, complete liberation is never attained, but is often used to designate that degree of liberation necessary for production of high-grade concentrates. A rougher concentrate, produced after elimination of a coarse-sized tailing, can usually be subjected to a second grinding stage and concentrated into a higher grade product than could be produced from the same crude ore with one stage of grinding resulting in the same overall size reduction. This fact adds to the importance of being able to determine partial degrees of liberation on any magnetite ore.

Standard laboratory methods such as heavy-liquid separation, microscopic grain counts, Davis tube magnetic separation, magnetic flocculation, classification, flotation, and others often are not applicable, or are prohibitive because of time requirements when large numbers of fine-sized magnetite samples are investigated. The Davis tube magnetic separator is an efficient tool to use in rejecting the non-magnetic mineral particles from an ore sample. The middlings discarded by the tube separator usually are so low in iron content that they can be considered relatively unimportant in liberation studies. This condition is caused by the extremely high flux density used in the Davis tube. This flux density ranges from four to eight times the flux density produced by most of the powerful commercial machines in use today. Thus the problem resolves itself into a search for a method of selectively removing middlings from Davis tube magnetic concentrates which will be both rapid and efficient.

Those methods showing most promise in the development of a process for isolating middlings from extremely fine-sized magnetic concentrates were flotation and magnetic flocculation. The use of flotation to remove middlings from magnetic concentrates is reported in the literature.[1,2] The flotation process is effective in removing middlings from a magnetite concentrate, but physical entrapment of fine-sized free magnetite in the silica-bearing froth is an undesirable feature. The flotation method of removing middlings requires time, effort, and precise control of many variables, and does not meet the required degree of middling isolation.

Magnetic Flocculation

Magnetic flocculation has long been resorted to[3-6] in efforts to upgrade magnetite concentrates. One of the new magnetic taconite plants now under construction on the Mesabi Range includes magnetic flocculation in the flowsheet[4] as an accessory process to remove high-silica middlings and free silica which has been mechanically entrapped in magnetite flocs. The use of magnetic flocculation as a laboratory method of making precise separation of middlings was further investigated, since it offered a rapid, simple method of accomplishing the desired result.

Magnetic flocculation involves the subjection of a magnetic concentrate to a strong magnetic field, passing the concentrate in a highly flocculated condition to a hydroseparator or other classifiers of various types, and removing free silica and middlings as overflow products. In an attempt to utilize simple

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Discussion on this paper, TP 3504B, may be sent (2 copies) to AIME before May 31, 1953. Manuscript, Aug. 4, 1952. Chicago Meeting, September 1952.

magnetic flocculation as a method of removing middlings from a magnetic concentrate, it soon becomes apparent that the method as generally practiced is efficient only in separating those middling particles containing very minor quantities of magnetite. Middling particles containing over 10 to 20 pct by weight of magnetite are strongly attracted to the magnetic flocs and become entrapped in a maze of magnetite particles, all strongly attracted to one another. If the velocity of the upward moving current of water is increased beyond a critical point, the magnetic flocs are torn apart to some extent, and while more middlings are released, a considerable quantity of fine magnetite is released and lost in the overflow product.

The Magnetic-Reflux Classifier

The solution to the problem was found in imposing a controllable magnetic field near the top of a hindered-settling classifier tube. The classifier then became a magnetic-reflux classifier. Fig. 1 is a sketch of one version of the apparatus now in use.

In chemical technology a reflux condenser is defined as "a condenser which continuously returns the condensed vapor to the still." Thus a magnetic-reflux classifier can be defined as a classifier which "continuously recycles or returns magnetically flocculated particles to the upward moving water currents or teeter column."

When a sample of low-grade magnetite concentrate is placed in the classifier tube the middling particles can be removed readily by controlling two variables: intensity of the magnetic field, and velocity of the upward current of water. These variables are the same controlling factors used in most wet magnetic separators, but it must be realized that there is a great difference in the degree of water control in a laboratory hindered-settling classifier tube as compared to water control in any magnetic separator in use today. In some cases it is advantageous to provide additional stirring or dispersing action by use of an AC field which operates intermittently, or a demagnetizing coil near the lower end of the classifier tube.

It has been stated by E. W. Davis of the University of Minnesota Mines Experiment Station that "the tendency for all magnetic particles to remain in the concentrate whether or not they are attached to particles of gangue is characteristic of all direct current magnetic separators when concentrating finely crushed ore. While this tendency can be counteracted to some extent by the use of agitation, with no direct current magnetic machine now in use is it possible to fraction accurately a sample of finely crushed magnetic taconite into products of different iron assay such as can be done by gravity methods using tables, for example."[7] Eketorp also reports on the inefficiency of present DC separation on fine-sized ores.[8]

It is well known that when a classifier is operated to emphasize the differences in specific gravity of the minerals being processed, hindered-settling conditions are preferred. In such cases the classifier not only sizes the materials involved, but concentrates the heavier minerals by a sorting process. This is not true when free-settling conditions are used. Classifier tubes used in laboratory experiments had an ID of 1.80 in. and the constriction plates had holes varying from 0.036 to 0.054 in. in diam. Use of an accurately calibrated manometer on the hydraulic water line assured precise water control to

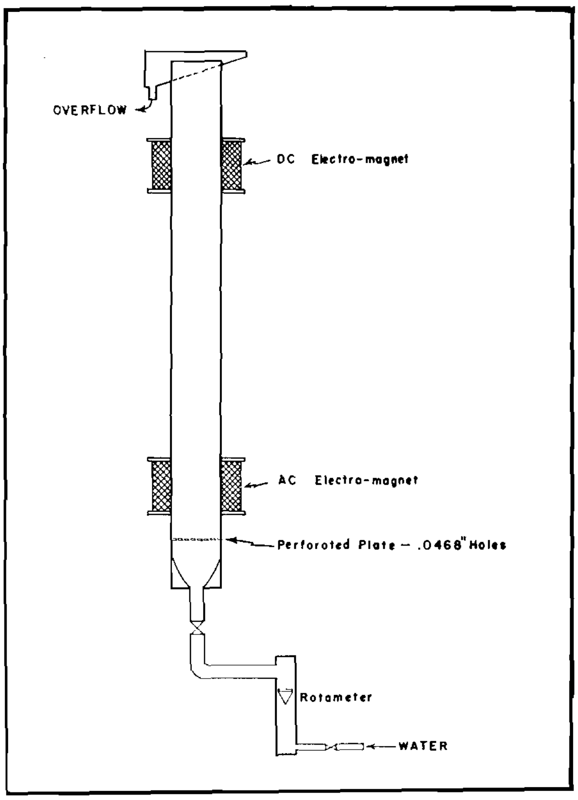

Fig. 1—Sketch of magnetic-reflux classifier for batch tests.

the classifier. High-powered photographers' spotlights were used in studying teeter column conditions in the classifier tube.

The magnetic field imposed on the classifier was provided by a 110-v DC electromagnet. The field of the electromagnet could be varied to produce flux densities from 5 gauss to 300 gauss at the internal surface of the tube wall. This field intensity is very low as compared to the range of 4200 to 14,000 gauss in the Davis tube separator.

Operating Procedures

The use of hindered-settling conditions plus precise magnetic flocculation control results in a laboratory tool capable of separating numerous fractions of magnetite middlings from magnetite concentrates. A typical operational procedure for batch tests with one type of magnetic-reflux classifier used in early tests was:

1—With hydraulic water set at 1700 cu cm per min and field magnet set at high intensity, a 50 to 100-g sample is introduced; all the sample is poured into the tube before the water level reaches the magnetic field level of the tube.

2—Period *a* begins, during which high-silica, low-iron middlings are removed as overflow product.

3—At end of period *a* the magnetic field is adjusted to medium intensity; hydraulic water remains at same flow.

4—Period *b* begins, during which middlings containing nearly equal percentages of silica and magnetite are removed as overflow product.

5—At the end of period *b*, the magnetic field is adjusted to low intensity; hydraulic water remains at same flow.

6—Period c begins, during which high-iron, low-silica middlings are removed as overflow product.

7—At end of period c, the final magnetite concentrates are withdrawn as classifier underflow.

It is evident that different ores and various degrees of grinding for the same ore may require different magnetic field strengths and different hydraulic water flows, but the proper settings are usually quickly arrived at by preliminary runs.

Test Results

Fig. 2 illustrates the appearance of the flocculated magnetite in the magnetic-reflux classifier tube during each of the three periods described under operating procedures.

The magnetite concentrate being tested was from an ore which had been ground through 100 mesh. Table I gives the chemical analysis of the classifier products.

Table I. Chemical Analysis of Classifier Products —100-Mesh Feed

		Analysis, Pct		Dist., Pct	
Product	Wt, Pct	Fe	SiO_2	Fe	SiO_2
Feed	100.0	54.83	22.86	100.0	100.0
Overflow, period *a*	6.5	20.13	62.00	2.4	19.9
Overflow, period *b*	5.1	29.61	51.38	2.8	13.0
Overflow, period *c*	7.5	43.18	33.04	5.9	12.2
Underflow	80.9	60.29	13.74	88.9	54.9

Table II. Chemical Analysis of Classifier Products, —200-Mesh Feed

		Analysis, Pct		Dist., Pct	
Product	Wt, Pct	Fe	SiO_2	Fe	SiO_2
Feed	100.0	57.98	16.23	100.0	100.0
Overflow, period *a*	5.9	24.86	55.78	2.5	20.3
Overflow, period *b*	6.8	37.24	40.12	4.4	16.8
Overflow, period *c*	4.9	51.02	24.40	4.3	7.4
Underflow	82.4	62.48	10.94	88.8	55.5

From these results it is evident that 88.9 pct of the iron was recovered as concentrate, while 45.1 pct of the silica was rejected in three distinct middling fractions. Photomicrographs of these middling fractions are shown above the photographs of the classifier tube in Fig. 2. The magnetite contents of the three middling fractions were 28, 41, and 60 pct respectively. The degree of flocculation of the respective overflow products gives visual indication of the quantity of magnetite present in each product. Photomicrograph (d) of Fig. 2 shows the highly flocculated classifier underflow product which contained 83 pct by weight of magnetite.

The results listed in Table I show that when a —100 mesh grind was used it was possible to produce a final magnetite concentrate containing 60.29 pct iron and 13.74 pct silica. Present day taconite studies are, in many cases, aimed at producing iron concentrates containing not over 12 pct silica. Another test was made on the ore previously tested, but using a —200 mesh grind. Table II lists these results.

Again, 88.8 pct of the iron was recovered as concentrate and 44.5 pct of the silica was rejected in three distinct middling fractions. However, the concentrate grade was raised to an acceptable figure: 62.48 pct iron and 10.94 pct silica.

For comparison, Table III lists the results of standard Davis tube tests, 1.80 amp, on —100, —200, and —325 mesh ore samples and the results of a Davis tube test at low amperage on —200 mesh ore. The ore was the same material used, after a magnetic concentration step, in the magnetic-reflux classifier tests.

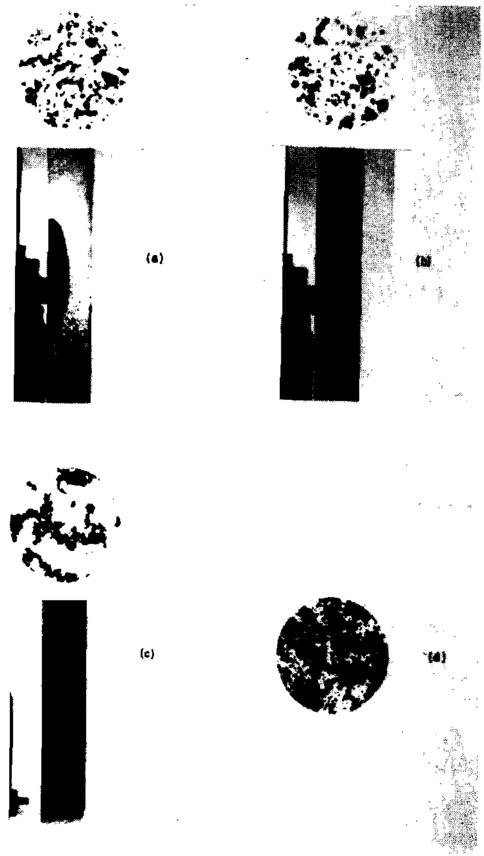

Fig. 2—Appearance of classifier tube during each of the three operating periods *a*, *b*, and *c*. Photomicrographs above the tube show degree of flocculation of the overflow product for each period and the underflow product, *d*. In this particular test the magnetic field was applied to only one side of the tube. Good results were obtained, but capacity was low.

Thus it can be seen that Davis tube tests on extremely fine-grained magnetite ores at either high or low current intensity are not satisfactory for use in liberation studies which have as their objective the rapid determination of an optimum commercial grind. Conventional tube tests show that a —325 mesh grind is necessary to produce a concentrate containing less than 12 pct silica, but no information is obtained regarding the middlings which would be produced in a commercial operation. It was previously shown, by using the magnetic-reflux classifier, that a —200 mesh grind would result in an acceptable concentrate. Also, the three middling fractions in the rougher magnetic concentrate would contain 24.86, 37.24, and 51.02 pct iron respectively.

Table III. Davis Tube Tests

			Analysis, Pct		Dist., Pct	
Product	Mesh	Davis Tube Amperage	Fe	SiO_2	Fe as Magnetite	SiO_2
Feed	—	—	35.82	43.22	95.0	100.0
Magnetic Concentrate	—100	1.80	54.83	22.86	99.0	30.7
Magnetic Concentrate	—200	1.80	57.98	16.23	98.0	22.2
Magnetic Concentrate	—325	1.80	62.89	11.16	98.0	14.4
Magnetic Concentrate	—200	0.20	62.78	11.06	47.9	6.6

The last two fractions, representing 11.7 pct of the weight and 8.7 pct of the iron in the rougher concentrate, would in all probability be reground and recirculated with new feed to the plant. When —200 mesh ore was processed at low amperage in the

Davis tube, an acceptable concentrate resulted, but less than 50 pct of the magnetite reported in the concentrate. When the non-magnetic fraction is reprocessed at successively higher amperages, a series of middling products can be obtained, but the sensitivity of the separation is far too low to enable the segregation of precisely graded middling fractions, and it is difficult to extrapolate how much of the low-silica, high-iron middlings can be added to the 0.20 ampere-concentrate and still not exceed the 12 pct silica figure. At this point it would be well to mention that the Davis tube is a useful tool for studying liberation characteristics of coarse-grained magnetite ores. For the purposes of this paper, coarse-grained ores are those which require grinding not finer than 65 mesh to liberate most of the magnetite. In such ores the extremely fine-sized middling particles are relatively unimportant and thus need not be isolated for study in most cases.

The magnetic-reflux classifier is the subject of a patent application. Interest in the selective separation of middlings from magnetic taconites is running high, and new types of magnetic separators involving principles exemplified by the magnetic reflux classifier may materialize in the future.

Acknowledgment

The original work on the magnetic-reflux classifier was done by the author at the Ore Research Laboratories of Jones & Laughlin Steel Corp., and this work has been continued at the Metallurgical Laboratories of Bjorksten Research Laboratories, Inc., Madison, Wis. Thanks are due both of these corporations for their interest in the problems of magnetic taconite beneficiation.

References

[1] D. W. Scott, A. C. Richardson, and N. Arbiter: Amine Flotation of Gangue from Magnetite Concentrates. *Trans.* AIME (1946) **169**, pp. 466-475.

[2] F. D. DeVaney: Froth Flotation of Silicious Gangue from an Alkaline Magnetic Iron Ore Pulp with an Amine. U. S. Patent 2,450,720 (Oct. 5, 1948).

[3] J. J. Craig: Magnetic Concentration on the Mesabi Makes Progress. *Engineering and Mining Journal* (Jan. 1938) **139**, pp. 48-52.

[4] H. K. Martin: Proposed Flowsheet for Taconite Concentration at Babbitt. AIME Blast Furnace, Coke Oven and Raw Materials Committee Proceedings (1948) **7**, pp. 68-82.

[5] R. W. Braund: Method of Treating Low-Grade Iron Ores. U. S. Patent 2,468,586 (April 26, 1949).

[6] Paul Zinner and Clyde L. Holmberg: Investigation of the Iron-Bearing Formation of the Western Gogebic Range, Iron County, Wis. U. S. Bureau of Mines *R.I.* 4155 (December 1947).

[7] E. W. Davis: Mesabi Taconite—A Study of Concentrating Characteristics. U. of Minn. Mines Experiment Station, Information Circular 4 (March 1944).

[8] Sven Eketorp: Three-Phase A.C. Can Improve Fine-Size Magnetic Separation. *Engineering and Mining Journal* (Oct. 1951) **152**, pp. 82-83, 118.

Work Indexes Tabulated

by Fred C. Bond

SIX years have passed since the last grindability table was published.[1] In that time the list has been increased with many new tests, and the development of the new Third Theory of Comminution[2] has made possible the reduction of all results to a consistent work index value.

In this tabulation all grindability and crushability test results are given in terms of the work index, with formulas for reversion to the older units if desired. The average values for 57 different classes of materials are listed in Table I. The total number of work index values listed is 1211, and the overall average work index is 14.42.

The complete tabulation, with each test listed alphabetically both under material type and under company name, can be obtained by writing to the Allis-Chalmers Manufacturing Co., Processing Machinery Department, Milwaukee 1, Wisconsin.

The work index Wi is the calculated total work input in kilowatt-hours per short ton required to reduce from theoretically infinite particle size to 80 pct passing 100 microns, or to approximately 67 pct passing 200 mesh.

The work inputs required per ton for the same size reduction of different materials are directly proportional to their work indexes, and according to the Third Theory the work input per ton is inversely proportional to the square root of the diameter of the product particles.

Where W represents the work input in kilowatt hours per ton, where F is the feed size, or diameter in microns of the square hole which 80 pct of the feed passes, P the product size, or microns which 80 pct of the product passes, and Rr the reduction ratio F/P, the work index Wi is found from

$$Wi = W\left(\frac{\sqrt{Rr}}{\sqrt{Rr}-1}\right)\sqrt{\frac{P}{100}} \quad [1]$$

When the work index Wi is known, the work input W required to reduce from any feed size F to any product size P is found from

$$W = Wi\left(\frac{\sqrt{Rr}-1}{\sqrt{Rr}}\right)\sqrt{\frac{100}{P}} \quad [2]$$

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Discussion on this paper, TP 3490B, may be sent (2 copies) to AIME before May 31, 1953. Manuscript, Sept. 4, 1952. Revised Dec. 3, 1952. Los Angeles Meeting, February 1953.