Bulletin 278

DEPARTMENT OF COMMERCE
HERBERT HOOVER, SECRETARY
BUREAU OF MINES
SCOTT TURNER, DIRECTOR

MAGNETIC CONCENTRATION OF IRON ORES OF ALABAMA

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PRICE 20 CENTS
Sold only by the Superintendent of Documents, Government Printing Office
Washington, D. C.

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON
1927

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MAGNETIC CONCENTRATION OF IRON ORES OF ALABAMA

MAGNETIC CONCENTRATION OF HIGH-SILICA RED ORES

By OSCAR LEE, B. W. GANDRUD, and F. D. DE VANEY

INTRODUCTION

The Birmingham district of Alabama, which ranks as one of the important iron and steel centers of the United States, is generally considered to include the iron and coal mines tributary to the blast furnaces of Birmingham but not the mines that supply the furnaces of the Florence-Sheffield, the Attalla-Gadsden, and the Anniston-Talladega districts. The Birmingham district holds large deposits of red hematite, coal, and flux and extends from Springville on the northeast to below Vance on the southwest. Although this belt is about 75 miles long, only a relatively small part is now productive. Most of the mining is confined to a section about 10 miles long between Birmingham and Bessemer, within which lie the so-called merchantable ores. Although the reserves of these ores are extensive and will supply the demand for many years, the larger part of the ferruginous material is low grade and has no value to operators at present; but this low-grade ore will become a valuable source of iron in the future, and the time is rapidly approaching when methods of utilization will have to be developed to justify production in certain localities.

The problem of developing a process that would make the high-silica red hematites of the Birmingham district available for use in blast furnaces was studied at the Southern experiment station of the Bureau of Mines, Tuscaloosa, Ala., in anticipation of future need for concentration. The work was begun in July, 1923, and ores from a number of points within the Birmingham district have since been studied. A method of magnetic concentration has been investigated which, it is believed, will successfully remove a large part of the gangue and incur only a small loss of iron.

ACKNOWLEDGMENTS

The writers deeply appreciate the valuable suggestions and cooperation of the several mining companies of the Birmingham district. Acknowledgments are also due W. R. Crane, superintendent, and W. H. Coghill, metallurgist, Bureau of Mines, for their assistance and encouragement; to H. D. Pallister, director, Alabama School of Mines; and to E. W. Davis, superintendent, Minnesota State Mine Experiment Station, for many suggestions during the early part of the investigation.

Thanks are also due S. P. Kinney, supervising ferrous metallurgist; R. E. Head, microscopist; and H. E. Messmore, junior chemist; all of the Bureau of Mines, for many helpful data.

HISTORY OF CONCENTRATION OF RED ORES

Attempts to concentrate the red hematites of the Birmingham district were made earlier than 1895. Artificial magnetization of the iron minerals, followed by magnetic separation, was one of the first methods tried. The results, which were not particularly promising, were reported by W. B. Phillips.[1]

Between 1895 and 1897 many experiments were made with red ores in Wetherill magnetic separators. Numerous tests were completed during this period, and information regarding them appears in Iron Making in Alabama, second edition, 1898, by W. B. Phillips. While the tests were under way representatives of the Wetherill Separating Co. assisted Phillips in the testing plant, which was provided by the Tennessee Coal, Iron & Railroad Co. at the Little Bell furnace, Bessemer. Soft red ore was crushed to 15 mesh and fed to Wetherill magnetic machines, run under 8 amperes and 100 volts. The experiments were conducted on a large scale in machines of full working size. The work lasted several months, and many varieties of ore were tested. Results of these experiments led to the conclusion that a 50 per cent iron concentrate could be produced with an extraction totaling as high as 85 per cent of the iron of the soft (leached) red ore.

Shipments of iron ore from the Mesabi range, Minnesota, began in 1892; for the year 1901 they exceeded 13,000,000 tons. From about 1900 until a few years ago all active experimental work on Alabama red ores ceased because the output of high-grade Minnesota ores was so large. About 10 years ago the Birmingham Ore & Mining Co. built two small concentrators at the Helen Bess mine, but the plants burned down after short periods of operation. Attempts were made to concentrate the ore by jigging and tabling, with little success.

At various times individuals have reported new methods of concentration, but as far as can be determined no satisfactory process has been established.

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[1] W. B. Phillips, "Notes on magnetization and concentration of iron ores": Trans. Am. Inst. Min. Eng., vol. 25, 1895.

OCCURRENCE OF ORES

Red Mountain, in which the red hematite ores and ferruginous sandstone occur, extends northeast and southwest through Springville, Birmingham, and Bessemer, and for a short way beyond. The ores are in the Clinton formation, of the Silurian age. This formation is 200 to 300 feet thick and consists mainly of sandstone and shale.[2]

Although there are four iron ore beds and several beds of ferruginous sandstone between the ore beds, only two are now being mined. The ore beds from the top down are known as the Ida, the Hickory Nut, the Big Seam, and the Irondale. Crane[3] says:

> The beds of ferruginous sandstone between the Hickory Nut bed and Big Seam and above the Ida bed are thick and in certain places have a surprisingly high iron content; if it were possible to mine and utilize this sandstone as well as ore from the four beds mentioned, the materials available for iron making in the district would be greatly augmented.

In connection with his studies of Red Mountain, Crane reports the extent and average thicknesses of the several beds to be as follows: Ida, 2 feet 9 inches; Hickory Nut, 2 feet 6 inches; Big Seam, 18 feet, divided by a thin band of shale into the upper and lower benches, averaging 10 and 8 feet in thickness, respectively; and Irondale, 4 feet (average).

CHARACTER OF ORES

Two types of red ore are found in the district—oölitic and fossiliferous. The oölitic ore is composed of rounded grains of silica ranging from one-eighth inch down to a minute size, around which layers of iron oxide, calcium carbonate, and clay have been deposited. Very often these constituents also bond the grains. The fossiliferous ore consists of fossil remains of marine life around which layers of iron oxide and clay have been deposited. The entire mass is held together by a bond of the same character.

Percolating waters have leached the ore to a maximum distance of about 500 feet from the outcrop. The leached ores are generally referred to as "soft" or "semihard," and the unleached ore is termed "hard." Leaching has removed much of the lime, thereby increasing the percentage of iron and of insoluble matter. This removal of lime often has made the ores highly siliceous, and they are not at present merchantable.

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[2] Burchard, E. F., and Butts, Charles, Iron Ores, Fuels, and Fluxes of the Birmingham district, Ala.: U. S. Geol. Survey Bull. 400, 1910, 204 pp.

[3] Crane, W. R., Red Iron Ores and Ferruginous Sandstones of the Clinton Formation in the Birmingham district, Alabama; Tech. Paper 377, Bureau of Mines. 1926, p. 4.

PHYSICAL PROPERTIES AND GRADE OF ORES

Crane[4] says that the average true specific gravity of the ores is 3.61, the average apparent specific gravity 3.48, and the average porosity 3.48. Analysis of the samples from which the above figures were determined showed that the specific gravity varies directly with the iron and the porosity with the silica and alumina.

Samples of ore for the investigation were taken at eight points on Red Mountain, from the Ruffner mine northeast of the city of Birmingham to a point over 20 miles southwest. At three of the eight points three or more samples were taken, representing different beds. Chemical analyses of these samples show marked differences in composition; for example, the iron content ranges from 16.7 to 40.9 per cent. Some samples represent leached and others unleached ores. The very low-grade ores are in reality ferruginous sandstones. Virtually all of the grades of red hematite found in Red Mountain are included in Table 1, which shows analyses of the various samples. The composite samples included in the table were made up in direct proportion to the thickness of the ore beds from which the samples were taken.

TABLE 1.—*Partial analyses of red hematite ores*

Source	Type of ore	Iron	Insoluble	Lime	Phosphorus
		Per cent	*Per cent*	*Per cent*	*Per cent*
Milner Heights:					
Ida bed	Leached	40.9	39.4	0.0	0.32
Irondale bed	do	38.8	15.2	12.2	.23
Hickory Nut bed	do	37.5	42.5	.0	.02
Big Seam, upper bench	do	36.4	39.4	2.6	.33
Big Seam, lower bench	do	27.5	50.6	1.7	.19
Sandstone	do	16.7	73.4	.0	.01
Composite sample	do	30.8	48.9	2.5	.13
Ruffner mine:					
Big Seam	do	31.9	33.6	8.0	.21
Ida bed	do	27.9	42.8	7.5	.17
Irondale bed	Unleached	40.0	22.1	8.5	.39
Composite sample	Mixture	32.9	33.0	8.0	.24
Redding mine:					
Big Seam, upper bench	Unleached	37.4	13.9	14.3	.38
Big Seam, lower bench (upper portion)	do	38.5	23.6	8.0	.39
Big Seam, lower bench (lower portion)	do	24.5	38.7	8.3	.22
Composite sample	do	34.2	23.5	10.8	.34
Valley View mine: Big Seam	do	35.9	28.0	6.1	.33
Walkers Gap: Big Seam	do	33.8	26.0	10.4	.32
Spaulding mine: Big Seam	do	33.2	23.1	13.1	.36
Hammond mine: Irondale bed	do	37.0	13.4	13.3	.43
Raimund mine: Big Seam	do	32.6	13.2	17.2	.23

PRELIMINARY TESTS

METHODS USED

The preceding discussion of the character of the ores could have been expanded much more, but the investigation brought out a great

[4] Crane, W. R., Red Iron Ores and Ferruginous Sandstones of the Clinton Formation in the Birmingham district, Alabama; Tech. Paper 377, Bureau of Mines, 1926, p. 12.

deal, and it was thought best to discuss some points in connection with the data gathered from the testing.

A systematic series of tests of each of the ores was made to allow the results of parallel tests of different grades of ores to be compared. Each sample was crushed to one-fourth inch, and a screen analysis was made with a standard set of Tyler screens down to 100 mesh. Each of the screen sizes was observed under the microscope, and it was thus possible to determine the approximate size at which the iron mineral and the gangue might be liberated.

A study of five samples of red ore by the float-and-sink method was made under the direction of W. H. Coghill, metallurgist, Bureau of Mines, at the ore-dressing laboratory, Rolla, Mo. In testing the ore by this method a wet screen analysis was made of the ore crushed to minus 14 mesh. Each of the screen sizes down to minus 325 mesh was tested in heavy solutions having specific gravities of 2.90, 3.34, 3.70, and 4.20. The part of the ore heavier than the solutions sank, while the lighter part floated. This systematic series of tests made it possible to determine the sizes at which the best concentrating results could be expected. Later in the report it will be shown that the work indicated the necessity of grinding to minus 65 mesh and finer.

Because concentrating finely crushed ores by gravity was difficult, a magnetic log-washer method was regarded as best suited to the red ores. The latter are, however, hematites, and therefore not appreciably magnetic; for efficient magnetic concentration they must be converted to the magnetic form (magnetite) by artificial magnetization. For this reason roasting tests of different samples of ore were made under varying conditions of time, temperature, and size of ore. The preliminary roasting tests were performed on a laboratory scale in a small roasting drum. (See fig. 1.) The apparatus consists of a small hollow cylinder of special high-temperature resisting alloy supported on hollow shafts and inclosed in an asbestos box to prevent the loss of too much heat. About 250 grams of ore is placed in the cylinder. One hollow shaft is connected with a gas tube through which the reducing gas flows to the drum. Into the other shaft is inserted a thermocouple, which allows measurement of the temperature inside the drum with a pyrometer. While revolving slowly the drum is heated externally by a blast burner. At the end of the roasting period the ore is partly cooled in the drum and plunged into water to prevent reoxidation. The roasted ore is dried and prepared for further testing in the magnetic tube.

Figure 2 shows the Davis magnetic tube, a laboratory testing-machine used in making magnetic assays of the ore and in determining the amount of grinding necessary for good separation of iron mineral from gangue; it consists of a strong **C**-shaped electromagnet between the poles of which is suspended a mechanically operated glass tube. The tube moves up and down between the poles of the magnet and at the same time rotates through a small angle.

In making tube tests a known weight of ore is placed in the tube, which is full of water. The top of the tube is closed and water is allowed to flow into it near the top and out through the bottom. The tube is then placed in an inclined position and set in motion, and the agitation thus produced causes the ore to move downward. The magnetic particles are held over the points of the magnet while the nonmagnetic material is washed out by the water. After about 15 minutes the water below the magnet becomes clear. The magnetic concentrate is then removed, dried, and weighed. The tailing, which is collected at the discharge end, is also dried and weighed. The tube tests were made with ore crushed to different sizes, with different amounts of ore, with different magnetic strengths, and with samples of ore crushed by dry-disk and pebble-mill methods.

PHYSICAL CHARACTERISTICS OF ORES

All the high-silica red ores had similar characteristics, in that they were hard and composed of rounded grains of silica, around which layers of iron oxide and kaolin had been deposited. Virtually no pure hematite can be recovered from such ore by mechanical means; the kaolin was deposited with the hematite, and the two are therefore very closely associated.

SCREEN ANALYSES

A screen analysis of each of the ores under investigation was made to determine whether or not minerals were segregated in any size or group of sizes of ore, but none of the ores showed any such segregation. The ore was crushed to one-fourth inch, and the screen analyses were made with a standard set of Tyler screens, including the 4, 8, 10, 14, 20, 28, 35, 48, 65, and 100 mesh sizes. Observation under the microscope readily showed that the sizes coarser than 65 mesh contained a large proportion of combined mineral grains. Even the minus 65-mesh size held a large amount of material in which the mineral and gangue both were present. The minus 100 mesh was ordinarily quite clean, although many grains of ore were visible in which the iron mineral had adhering pieces of silica and lime.

Table 2 gives screen analyses of three typical high-silica red ores; they represent the general character of the ores very well. The similarity of the coarsest screen size (4 mesh) to the original ore is decided and can only mean that this size has the same properties as the original ore. From this size down to the plus 20 mesh the iron

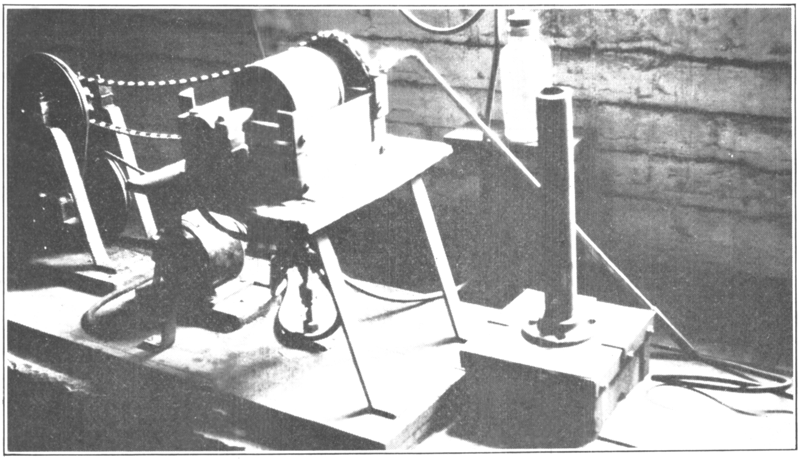

FIGURE 1.—Small roasting drum

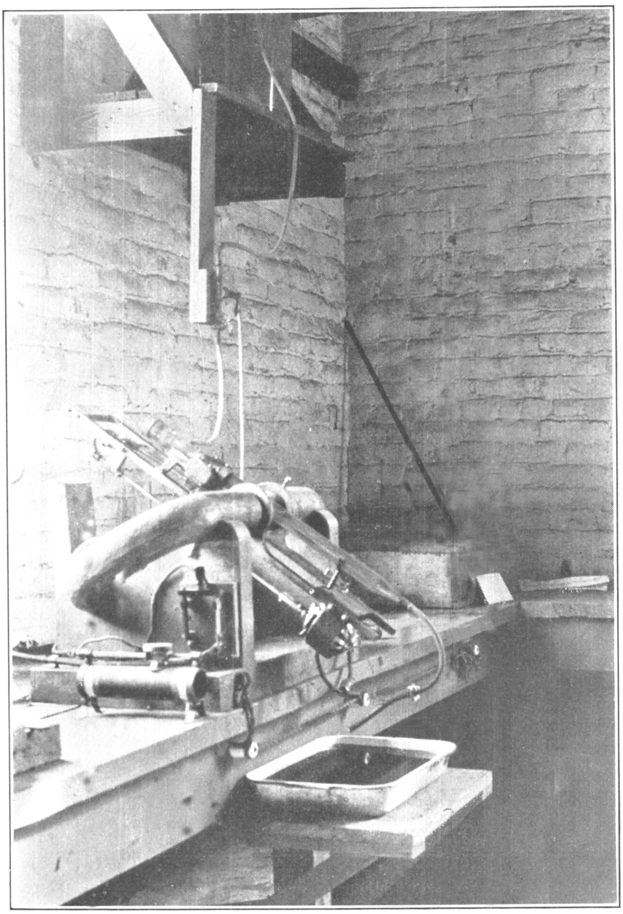

FIGURE 2.—Davis magnetic tube

content drops off and insolubles increase correspondingly. From the minus 20-mesh size down through the remainder of the screen scale the grade of the products shows gradual improvement, the minus 100-mesh size containing more than 40 per cent of iron. The segregation of iron mineral in the finer sizes is not enough, however, to be of value in a concentrating process.

TABLE 2.—*Screen analyses of three typical high-silica red hematites and composition of the various sizes*

[Values in per cent]

Screen size, mesh	Weight			Iron			Insoluble			Lime			Phosphorus		
	Ore 1	Ore 2	Ore 3	Ore 1	Ore 2	Ore 3	Ore 1	Ore 2	Ore 3	Ore 1	Ore 2	Ore 3	Ore 1	Ore 2	Ore 3
Minus 4 plus 8	26.92	29.40	16.62	32.2	34.9	32.1	32.2	22.5	19.5	9.1	11.9	15.5	0.25	0.36	0.43
Minus 8 plus 10	9.27	10.43	8.02	29.8	31.6	31.8	35.7	26.5	22.0	8.5	11.3	13.7	.22	.36	.42
Minus 10 plus 14	7.47	8.78	11.94	27.6	29.3	30.0	40.1	31.7	28.1	8.7	11.0	12.4	.24	.34	.35
Minus 14 plus 20	6.85	8.17	9.48	27.4	29.1	30.8	40.4	33.1	28.0	8.5	11.0	12.3	.23	.33	.34
Minus 20 plus 28	6.72	7.57	12.87	29.1	31.1	32.4	38.3	29.8	26.9	8.4	10.6	10.0	.27	.32	.30
Minus 28 plus 35	9.18	9.14	16.34	30.9	34.5	33.6	36.9	23.6	24.8	8.2	10.6	9.8	.25	.32	.29
Minus 35 plus 48	8.43	7.61	6.75	33.5	35.5	34.0	32.2	20.4	21.1	6.8	11.9	13.5	.26	.33	.31
Minus 48 plus 65	6.17	4.35	3.93	33.5	36.0	34.6	35.2	18.3	17.5	7.1	12.6	15.3	.21	.34	.33
Minus 65 plus 100	7.72	4.80	5.82	32.4	37.9	37.8	34.8	19.0	15.9	7.6	11.3	11.9	.27	.31	.31
Minus 100	11.27	9.75	8.23	42.2	40.6	40.6	18.2	14.7	15.0	7.7	10.9	11.1	.29	.31	.33
Original ore	100.00	100.00	100.00	32.9	34.2	33.2	33.0	23.5	23.1	8.0	10.8	13.1	.24	.34	.36

NOTE.—Ore 1 is from the Ruffner mine, ore 2 from the Redding mine, and ore 3 from the Spaulding mine.

MAGNETIC ROASTING

Because very fine grinding is necessary for clean liberation of mineral from gangue, gravity concentration is not a suitable method of beneficiating the red iron ores. Magnetic concentration is an acceptable method if the iron mineral is in the magnetic form. As the red ores are in the form of hematite, they must be converted into magnetite by roasting in a reducing atmosphere. The method employed has already been discussed.

Many roasting tests demonstrated that time and the size of the ore are important factors influencing the roasting efficiency. Table 3 is offered as an illustration of the effect of roasting the ore at various temperatures. The magnetic-tube separator was used for testing the magnetic properties of the roasted ore and showed clearly the degree of roasting. The reader will observe that only a small amount of the iron was reduced to the magnetic form at 300° C., but that each succeeding increase in temperature yielded a higher recovery of iron in the magnetic tube. These facts proved that complete reduction was approximated only at a temperature of 500° C. and higher.

Several important and interesting facts were obtained through these tests. The higher-grade concentrates are produced from ore roasted at low temperatures, because at a low temperature only the iron mineral on the surface of the oölites is reduced to magnetite, and, as this is the cleanest mineral in the ore, the magnetic-tube concentrate is correspondingly high in iron. The percentage of iron recovered, however, is very low, preventing the use of low-temperature roasting in practice. The tendency is for the percentage of iron in the magnetic concentrate to decrease as the temperature increases, giving a corresponding increase in the content of insoluble matter and of lime.

Obviously, a temperature of 500 to 550° C. is required for proper concentration of the ore. A high recovery of iron is necessary for success and can be obtained only at the temperatures mentioned.

TABLE 3.—*Effect of temperature upon magnetic roasting*

	Magnetic roasting temperatures, °C.					
	300	350	400	450	500	550
Roasted ore:						
Iron ... per cent	36.5	36.5	36.5	36.5	37.0	37.0
Insoluble ... do	27.1	27.1	27.3	27.2	28.3	28.5
Lime ... do	7.4	7.4	7.5	7.5	7.3	7.1
Tube concentrate:						
Weight ... do	4.18	22.89	37.65	55.28	66.26	67.33
Iron ... do	61.7	58.4	56.7	56.4	53.7	53.3
Insoluble ... do	6.9	8.1	9.4	10.1	13.8	13.3
Lime ... do	.7	1.7	2.6	2.6	3.5	3.4
Tube tailing:						
Iron ... do	35.4	30.0	24.3	11.9	4.8	3.4
Insoluble ... do	28.0	32.7	38.1	48.3	56.8	59.8
Lime ... do	7.7	9.1	10.5	13.6	14.8	14.7
Ratio of concentration	23.9:1	4.4:1	2.66:1	1.81:1	1.51:1	1.48:1
Iron recovered ... per cent	7.06	36.62	58.49	85.42	95.57	97.03
Insoluble rejected ... do	99.00	93.04	87.01	79.41	67.71	68.50
Lime rejected ... do	99.70	94.82	87.29	81.09	68.40	67.64

In roasting practice the question of the size of ore is important. Too large a proportion of fine material causes loss in dust, which is very easily prevented if coarse ore can be handled in the furnace. Tests made to determine the effect of the size of ore upon the efficiency of the reducing roast showed that the ore roasted as well at 4 mesh as at 35. Consequently, there is no occasion for crushing finer than 4 mesh; in fact, the ore will roast very well at ½ inch.

Table 4 includes a series of tests made with six sizes, from 4 down to 35 mesh. The uniformity of the results is surprising, with a slight advantage in favor of roasting at the coarsest size. Table 5 shows the results of roasting an ore at minus ½-inch and minus ¼-inch sizes at different temperatures. These results demonstrate the practicability of roasting at ½-inch size. The efficiency column refers to the percentage of iron recovered from the roasted ore by the magnetic-tube separator. The tube tests were made with ore crushed to 100 mesh.

TABLE 4.—*Effect of size of ore on magnetic roasting*

	Size of ore mesh					
	−4	−8	−10	−14	−28	−35
Roasted ore:						
Iron____per cent__	37.0	37.0	37.0	37.0	37.0	37.1
Insoluble____do____	28.3	28.6	28.0	28.3	27.9	27.9
Lime____do____	7.3	7.6	7.8	7.4	7.6	7.8
Tube concentrate:						
Weight____do____	65.84	66.67	64.79	64.78	64.22	68.63
Iron____do____	53.7	53.2	53.9	53.2	53.6	51.5
Insoluble____do____	13.8	14.5	11.9	12.3	11.8	14.1
Lime____do____	3.5	3.7	3.9	3.5	3.5	3.8
Tube tailing:						
Iron____do____	4.8	4.6	5.9	7.2	7.2	5.6
Insoluble____do____	56.2	56.7	57.6	57.7	56.8	58.1
Lime____do____	14.6	15.4	15.0	14.6	14.1	16.5
Ratio of concentration____	1.52:1	1.50:1	1.54:1	1.54:1	1.56:1	1.46:1
Iron recovered____per cent__	95.56	95.86	94.38	93.14	93.03	95.27
Insoluble rejected____do____	67.83	66.07	72.43	71.81	72.84	65.33
Lime rejected____do____	68.32	67.53	67.71	69.48	69.49	66.36

NOTE.—The ore was roasted at 500° C. for 30 minutes. The magnetic-tube tests were made with roasted ore crushed to minus 100 mesh.

TABLE 5.—*Effect of temperature and time on roasting of coarse ore*

Temperature, °C.	Time, minutes	Efficiencies		Iron in concentrate, per cent	
		−½ inch	−¼ inch	−½ inch	−¼ inch
350____	15	32.7	28.0	58.2	61.2
350____	30	32.1	26.7	61.0	60.5
400____	15	88.6	91.8	57.3	56.2
400____	30	91.8	92.2	57.1	56.3
500____	15	95.3	95.9	55.3	55.5
550____	15	95.4	96.1	53.7	55.5
550____	60	95.7	____	55.4	____

The data in the above table indicate that under similar conditions the ½ and ¼ inch sizes show very little difference in the quality of the roasting; hence it is logical that the ore for roasting be crushed to only ½ inch, thereby reducing the cost of crushing.

MAGNETIC-TUBE CONCENTRATION

When roasting, followed by magnetic concentration, was first considered as a method for concentrating red ores, the production of a very high grade of concentrate was expected. A magnetic tube is an excellent magnetic testing machine, and maximum efficiency can be obtained by using it. When the results of the early tests fell below expectations, many tests were made under different conditions, with the idea of establishing the limitations of the ore; thus it was found that grinding to 100 mesh was essential for all of the ores if a concentrate containing over 50 per cent of iron was desired. The results verified the opinions formed from observing the ores under the microscope.

TESTS OF HIGH-SILICA ORES

Tables 6 and 7 contain data from a series of tests of two high-silica ores, one containing a fairly high percentage of lime and the other only a small amount. Table 6 shows that very little improvement can be expected by concentration of relatively coarse sizes. The grade of the concentrate improves remarkably when the ore is crushed to 100 mesh, and from this size down to minus 300 mesh the quality of the concentrate produced improves steadily, though to only a slight degree. This improvement in grade is accompanied by a small decrease in the percentage of iron recovered, and it is doubtful whether grinding the ore all through 300 mesh would be warranted by the small increase in the iron content of the concentrate, especially when some loss of iron is entailed by doing so.

The percentages of insoluble and lime rejected in the tailing by concentration are virtually the same for each of the three finer sizes of screens. The loss of the lime is to be regretted, but since the behavior of the lime during magnetic concentration is the same as that of the other gangue material, there is no way of preventing the loss. Another section of this report shows that the lime can be recovered from the tailing by flotation. With some ores this innovation will make possible the production of a self-fluxing concentrate.

TABLE 6.—*Effect of size of ore on magnetic concentration of limy high-silica red ore*

	Size of ore fed to magnetic tube (mesh)					
	−20	−28	−48	−100	−200	−300
Tube feed:						
Iron ... per cent	34.0	34.0	34.0	34.0	34.0	34.0
Insoluble ... do	26.6	26.6	26.6	26.6	26.6	26.6
Lime ... do	10.9	10.9	10.9	10.9	10.9	10.9
Tube concentrate:						
Weight ... do	89.16	84.71	76.36	60.80	59.34	57.67
Iron ... do	37.5	39.2	42.9	52.7	53.8	55.0
Insoluble ... do	25.7	24.2	20.8	13.3	11.7	10.1
Lime ... do	8.9	8.3	7.4	4.8	4.3	3.8
Tube tailing:						
Iron ... do	5.2	5.2	5.2	5.0	5.1	5.2
Insoluble ... do	34.1	39.8	45.3	47.2	48.4	49.1
Lime ... do	27.7	25.5	22.2	20.5	20.4	20.5
Ratio of concentration	1.12:1	1.18:1	1.31:1	1.64:1	1.69:1	1.73:1
Iron recovered ... per cent	98.34	97.67	96.35	94.24	93.90	93.29
Insoluble rejected ... do	13.91	22.93	40.22	69.54	74.05	78.18
Lime rejected ... do	27.52	35.78	48.16	70.64	76.14	79.81

NOTE.—Ore was crushed to 4 mesh and roasted at 550° C. for 30 minutes.

The ore used for the tests covered by Table 7 contains a large amount of ferruginous sandstone and is not only higher in insoluble and lower in iron than the ore of Table 6 but also contains much less lime. Although the general trend of results parallels those for Table 6, there are some differences. chiefly in the grade of the concentrate produced and in the percentage of iron extracted. The concentrate, for example, contains much more iron and less lime than that produced from the more limy ore, but a somewhat higher percentage of iron is extracted from the limy ore. The ratio of concentration is naturally higher for the lower-grade ore because a larger quantity of gangue material is rejected in the tailing.

The ore represented by Table 7 yields the best results after crushing to 100 mesh or finer. Although the minus 48 and 65 mesh sizes concentrate into a product containing more than 50 per cent of iron, the insoluble content is above 18 per cent, which is rather high.

Except for minor variations, the figures presented in the two tables may be accepted as representative of a large group of high-silica red ores, and they show conclusively that fine grinding is necessary in concentrating the ores.

TABLE 7.—*Effect of size of ore on magnetic concentration of leached high-silica red ore*

	Size of ore fed to magnetic tube (mesh)					
	−28	−48	−65	−100	−200	−300
Tube feed:						
Iron ... per cent	30.8	30.8	30.8	30.8	30.8	30.8
Insoluble ... do	48.6	48.6	48.6	48.6	48.6	48.6
Lime ... do	2.1	2.1	2.1	2.1	2.1	2.1
Tube concentrate:						
Weight ... do	63.55	56.80	52.91	49.63	48.01	47.93
Iron ... do	45.6	50.8	54.3	57.8	59.6	59.7
Insoluble ... do	31.0	22.6	18.2	14.2	12.3	12.2
Lime ... do	1.2	.8	.7	.6	.5	.5
Tube tailing:						
Iron ... do	5.0	4.5	4.4	4.2	4.2	4.2
Insoluble ... do	79.3	81.0	82.6	82.6	82.2	82.2
Lime ... do	3.7	3.7	3.7	3.6	3.6	3.6
Ratio of concentration	1.57 : 1	1.76 : 1	1.89 : 1	2.01 : 1	2.08 : 1	2.09 : 1
Iron recovered ... per cent	94.09	93.68	93.28	93.14	92.90	92.90
Insoluble rejected ... do	59.46	73.66	80.04	85.60	87.86	88.07
Lime rejected ... do	63.80	78.56	82.84	85.70	88.54	88.55

NOTE.—Ore was crushed to 4 mesh and roasted at 550° C. for 30 minutes.

EFFECT OF SIZE OF SAMPLES

All magnetic-tube tests were made with 15-gram samples, and because the concentrates produced were not as high in iron as had been expected it was thought possible that too large a sample was being used in the tube; if this were true, free gangue would be locked between particles of magnetic iron. Tests were made to determine the effect of smaller samples on the work of the magnetic tube. Table 8 includes the results of a series of tests with one ore and shows very well that there is only a slight difference in the grade of the products produced from the three sizes of samples which had been crushed to minus 300 mesh.

The 5-gram sample yielded the best concentrate, although there was a difference of only 1.2 per cent of iron between the highest and lowest grades made from the three sizes. The recovery of iron, however, was the reverse of this; in yielding a richer concentrate the smallest sample lost about 1½ per cent of the iron. For all practical purposes the results of magnetic-tube tests of 15-gram samples are satisfactory, and as larger amounts of the products of the tube can be obtained for chemical assay by using 15 grams it was thought best to adopt the 15-gram sample for all standard tests.

TABLE 8.—*Effect of size of ore samples on work of magnetic tube*

	Weight of sample, grams		
	5	10	15
Tube feed:			
Iron ... per cent	34.0	34.0	34.0
Insoluble ... do	26.6	26.6	26.6
Tube concentrate:			
Weight ... do	55.86	57.11	57.83
Iron ... do	56.2	55.4	55.0
Insoluble ... do	9.8	9.9	10.1
Tube tailing:			
Iron ... do	5.9	5.5	5.2
Insoluble ... do	47.8	48.8	49.2
Ratio of concentration	1.79 : 1	1.75 : 1	1.73 : 1
Iron recovered ... per cent	92.33	93.06	93.55
Insoluble rejected ... do	79.32	78.76	78.04

NOTE.—The ore was crushed to 4 mesh and roasted at 550° C. for 30 minutes. Magnetic-tube tests were made at minus 300 mesh.

EFFECT OF VARYING STRENGTH OF MAGNETIC FIELD

In a search for other methods of improving the concentrates tests were made with the magnetic-tube separator operated at varying strengths of magnetic field. The magnetic coils are generally used with the direct-current generator operating at 110 volts, but this can be controlled as desired, as the magnetic strength is directly proportional to the voltage. It was thought that if the tube were run in a weaker magnetic field the free gangue in the ore would be removed more easily, because the grains of magnetite might not hold the entrained gangue material so tightly. Results of experiments made to test this theory were a little disappointing. When the tube was run at voltages down to 10 there was a slight difference in the grade of concentrate produced and in the extraction of iron. When the voltage was reduced from 10 to 5 there was fair improvement in the concentrate, but the recovery of iron dropped to less than 10 per cent.

Obviously, therefore, lessening the strength of the magnetic field does not have a favorable influence on the process of concentration, for the percentage of iron recovered is affected too much. The results of the series of tests given in Table 9 bring out clearly the points discussed in the preceding paragraph.

TABLE 9.—*Effect of reducing the strength of the magnetic field of the magnetic-tube separator*

	Generator voltage			
	110	70	10	5
Tube feed:				
Iron ... per cent..	33.0	33.0	33.0	33.0
Insoluble ... do...	22.0	22.0	22.0	22.0
Lime ... do...	13.3	13.3	13.3	13.3
Tube concentrate:				
Weight ... do...	56.87	56.42	54.46	4.67
Iron ... do...	53.4	53.7	53.9	55.7
Insoluble ... do...	10.6	10.5	9.6	8.1
Lime ... do...	4.7	4.3	4.3	4.1
Tube tailing:				
Iron ... do...	6.1	6.2	8.0	31.9
Insoluble ... do...	37.0	36.9	36.8	22.7
Lime ... do...	24.7	24.9	24.1	13.8
Ratio of concentration	1.76:1	1.77:1	1.84:1	21.41:1
Iron recovered ... per cent..	92.03	91.81	88.95	7.88
Insoluble rejected ... do...	72.54	73.10	76.23	98.27
Lime rejected ... do...	80.10	81.59	82.41	98.57

NOTE.—Ore was crushed to 4 mesh for roasting at 500° C. for 30 minutes. Roasted ore was crushed to minus 100 mesh for the magnetic tube.

The data obtained from many tests, some of which are presented in the preceding tables, are very good evidence of the fact that there is a limit to the grade of concentrate that can be produced by concentration. This limit is not as high as could be desired, although it is high enough to make a desirable blast-furnace feed. Many of the iron ores of this country can be concentrated into a product containing as high as 68 per cent of iron, but the red ores of the Birmingham district have not yielded a concentrate much higher than a 56 per cent concentrate, even after crushing to minus 300 mesh.

IMPURITIES REMAINING IN MAGNETIC CONCENTRATES

The impurities which remain in the concentrates and are so intimately mixed with the iron mineral as to be inseparable by any practicable mechanical process of concentration consist mainly of silica, alumina, and lime, the alumina being mainly in the form of the clay mineral kaolinite. Of these three impurities, the amount of alumina which is present in the concentrates produced from representative samples of ore is most persistent. A series of magnetic-tube concentrates produced from 11 representative samples of red ore (see Table 10) showed an average of 4 per cent of alumina. The minimum percentage of alumina in these concentrates was 3 per cent and the maximum 4.9 per cent. These concentrates were produced under identical conditions from representative samples of ore the iron content of the samples ranged from 25 to 40.3 per cent. This average of four units of alumina (Al_2O_3) in the concentrates, presumably as the clay mineral kaolinite ($H_4Al_2Si_2O_9$), represents an average of about 10 units of clay. The variation from the average of 10 units would not be over 2.5 units one way or the other in any of the 11 samples of magnetic-tube concentrates just mentioned. With very few exceptions, it seems to be a rule that the red ores of the Birmingham district contain a certain amount of inherent clay which stays with the iron mineral throughout any mechanical concentration process, therefore the concentrates contain as one of their impurities clay material amounting to about 10 units.

Impurities in the concentrates, besides this fairly constant percentage of inherent clay, are mainly lime and silica. The lime and silica do not appear in the concentrates in fairly regular proportions, as the alumina does, but vary between wide limits. Where the percentage of alumina in the 11 different concentrate samples varied between 3 and 4.9 per cent the silica ranges from 5 to 15.3 per cent and the lime from 1.7 to 5 per cent. In spite of these wide variations in silica and lime the iron remains fairly constant, the lowest-grade concentrates assaying 50.1 and the highest-grade 55.5 per cent of iron. This consistency is accounted for by the fact that ordinarily the silica content will be relatively low, where the lime content of the concentrates is unusually high, and vice versa. It would be difficult to offer a satisfactory explanation for this behavior of the lime and silica, except on the basis of the physical characteristics of the ore. It appears that, on account of certain differences in the physical characteristics, some samples will permit more thorough liberation of the lime, silica, or both, than others.

TABLE 10.—*Impurities which affect the grade of magnetic-tube concentrates from red ores*

[Values in per cent]

Sample	Feed				Concentrate					Iron recovered	Rejected		
	Iron	Silica	Alumina	Lime	Weight	Iron	Silica	Alumina	Lime		Silica	Alumina	Lime
1	25.0	2.8	2.3	27.4	43.22	51.4	5.0	4.3	4.1	88.86	21.43	21.74	49.43
2	27.9	41.9	2.2	7.6	47.88	55.5	10.4	3.7	1.7	94.39	88.07	18.18	89.47
3	31.9	31.6	3.1	8.1	58.97	51.1	15.3	4.8	2.5	94.46	71.52	9.68	81.48
4	31.9	28.7	2.6	9.2	60.61	50.1	15.5	3.5	2.2	95.19	67.25	19.23	85.87
5	33.1	31.1	2.8	7.3	59.47	52.8	12.0	4.1	1.6	94.86	77.17	14.29	86.30
6	33.4	11.4	2.7	17.5	58.12	53.5	7.8	3.6	5.0	93.10	60.53	22.22	83.43
7	36.8	25.8	2.5	7.1	64.35	53.2	10.3	3.3	3.5	93.03	74.42	16.00	67.61
8	38.0	12.1	2.6	14.5	68.07	54.0	7.5	3.0	3.0	96.73	57.85	23.08	86.20
9	38.6	5.0	4.1	14.9	65.30	52.1	6.0	4.9	4.1	88.13	22.00	21.95	81.88
10	39.2	20.8	3.0	8.1	71.28	53.3	10.7	3.5	2.4	96.92	63.46	16.67	79.01
11	40.3	19.6	3.5	7.6	72.67	53.5	10.6	4.2	1.9	96.47	60.71	12.86	81.58

The most striking feature of Table 10 is the percentage of alumina rejected during magnetic concentration. Except for two high-lime ores (Nos. 1 and 9), the amount of alumina rejected was very much lower than that of either silica or lime. There can be no question, therefore, but that the alumina, in the form of kaolin, is the biggest obstacle to the concentration of high-silica red ores.

PHOSPHORUS IN RED ORES

The red ores of the Birmingham district contain an average of 0.3 to 0.4 per cent of phosphorus, although some ores contain more and others less than the average mentioned. The phosphorus occurs in the ore in such condition as to make good mechanical separation impossible. R. E. Head, microscopist, Bureau of Mines, made a microscopic examination of a sample of typical high-silica red ore and reported that no definite phosphorus mineral was identified and that microchemical tests of carefully picked or suspicious material did not isolate any one phosphorus-bearing individual.

Magnetic-tube tests of many samples of red ore showed only fair rejection of phosphorus in the tailing. Table 11 includes some interesting figures on the units of phosphorus per unit of iron in the feed, concentrates, and tailings of magnetic-tube tests. The units of phosphorus per unit of iron were about 50 per cent less in the concentrate than in the feed.

The percentage of phosphorus rejected ranges from 29.44 to 49.65. Ordinarily, however, 41 to 49 per cent is rejected.

TABLE 11.—*Relation of phosphorus to iron in magnetic-tube products*

Sample	Feed (per cent)		Concentrates (per cent)		Tailings (per cent)		Units of phosphorus per unit of iron			Phosphorus rejected (per cent)
	Iron	Phosphorus	Iron	Phosphorus	Iron	Phosphorus	Feed	Concentrates	Tailings	
1	25.0	0.26	51.4	0.37	4.9	0.19	0.0104	0.0072	0.0388	41.49
2	27.9	.18	55.5	.19	3.0	.17	.0065	.0034	.0566	49.65
3	31.9	.22	51.1	.19	4.3	.26	.0069	.0037	.0604	48.49
4	31.9	.30	50.1	.34	3.9	.24	.0094	.0068	.0615	31.51
5	33.1	.23	52.8	.22	4.2	.24	.0069	.0042	.0571	42.29
6	33.4	.37	53.5	.33	5.5	.43	.0111	.0062	.0782	48.67
7	36.8	.43	53.2	.38	7.2	.52	.0117	.0071	.0722	43.11
8	38.0	.40	54.0	.40	3.9	.41	.0105	.0074	.1051	32.74
9	38.6	.49	52.1	.45	13.2	.57	.0127	.0086	.0432	40.37
10	39.2	.41	53.3	.41	4.2	.41	.0102	.0077	.0976	29.44
11	40.3	.40	53.5	.38	5.2	.44	.0099	.0071	.0846	30.00

RESULTS OF TESTS OF DIFFERENT TYPES OF ORES

During the investigation of high-silica red ores many samples representing different locations and beds were tested. To clarify the response of different ores to roasting and magnetic concentration, a table was prepared showing the results of tests of 17 different samples, all treated under the same conditions. Of the 17 samples treated 8 were leached and 6 unleached high-silica ores and the other 3 self-fluxing ores. The ores ranged from sandstone carrying only

18.2 per cent of iron to self-fluxing ores containing as much as 38 per cent of iron. With one exception the concentrates produced from these ores ranged between narrow limits in grade. In all but two samples—very low-grade ores—the extraction of iron was consistently high, averaging about 95 per cent.

The results presented in Table 12 were obtained by roasting minus ¼-inch ores at 500° C. for 30 minutes. The roasting was followed by magnetic-tube tests at minus 100 mesh.

TABLE 12.—*Results of magnetic-tube tests of various red iron ores of the Birmingham district*

Ore	Bed	Feed, per cent			Concentrate, per cent				Tailing, per cent			Iron recovered, per cent	Insoluble rejected, per cent	Lime rejected, per cent
		Iron	Insoluble	Lime	Weight	Iron	Insoluble	Lime	Iron	Insoluble	Lime			
LEACHED HIGH-SILICA RED ORE														
Milner Heights	Ida	40.9	39.4	Trace.	64.42	61.5	11.3	--------	3.6	90.2	--------	96.87	81.50	--------
Do	Irondale	40.7	17.6	11.0	69.20	56.5	13.0	2.0	5.2	27.9	31.2	96.06	48.87	87.27
Do	Hickory Nut	37.6	41.6	Trace.	62.66	58.4	11.2	--------	2.7	92.7	--------	97.32	83.17	--------
Do	Big Seam [1]	37.2	38.1	2.4	62.02	57.1	13.2	.7	4.7	78.9	5.2	95.20	78.48	83.33
Do	do.[2]	25.9	53.2	1.9	42.09	54.1	18.4	.5	5.4	80.2	3.0	87.92	85.53	89.47
Do	Sandstone	18.2	69.7	Trace.	27.59	57.3	15.0	--------	3.3	90.6	--------	86.39	94.12	--------
Ruffner	Big Seam	31.9	34.7	8.1	58.97	51.1	20.1	2.5	4.3	55.7	16.1	94.46	65.71	81.48
Do	Ida	27.9	44.1	7.6	47.88	55.0	14.1	1.7	3.0	71.7	13.0	84.39	84.69	89.47
UNLEACHED HIGH-SILICA RED ORE														
Ruffner	Irondale	40.3	23.1	7.6	72.67	53.5	14.8	1.9	5.2	45.0	22.8	96.47	53.25	81.58
Redding	Big Seam [3]	39.2	23.8	8.1	71.28	53.3	14.2	2.4	4.2	47.7	22.2	96.92	57.57	79.01
Do	do.[4]	25.3	40.2	10.2	45.93	49.9	17.8	4.0	4.4	59.2	15.5	90.59	79.60	82.35
Valley View	do	37.0	28.3	7.3	65.84	53.7	13.8	3.5	4.8	56.2	14.6	95.56	67.83	68.32
Walkers Gap	do	34.0	26.6	10.9	60.80	52.7	13.3	4.8	5.0	47.2	20.5	94.24	69.54	70.64
Spaulding	do	33.0	22.0	13.3	56.87	53.4	10.6	4.7	6.1	37.0	24.7	92.03	72.54	80.10
SELF-FLUXING RED ORE														
Redding	Big Seam	38.0	14.7	14.5	68.07	54.0	10.5	3.0	3.9	23.8	39.1	96.73	51.70	86.20
Hammond	Irondale	37.4	14.9	13.7	63.24	54.9	8.6	3.8	7.3	25.8	30.7	92.83	63.75	82.37
Raimund	Big Seam	32.9	13.9	16.0	57.60	51.6	10.2	4.4	7.5	18.4	31.1	90.34	57.55	84.37

[1] Upper bench of Big Seam.
[2] Lower bench of Big Seam.
[3] Upper portion of lower bench, Big Seam.
[4] Lower portion of lower bench, Big Seam.

FLOTATION OF LIMESTONE FROM MAGNETIC LOG-WASHER TAILINGS

One disadvantage in the roasting and magnetic concentration of limy red hematite ores is that much of the lime in the original ore is lost in the tailing. As the concentrate produced contains a high excess of silica and alumina over lime, limestone would have to be added at the furnace to flux off this excess.

If the loss of lime could be prevented, some ores, though low in iron and high in insoluble matter, would contain enough lime to make their concentrates self-fluxing. As this loss in the magnetic log washer can not be avoided, the lime must be recovered from the tailing by some method and added to the magnetic iron concentrate before sintering. Then the resulting concentrate will be self-fluxing.

During a search for suitable means of treating the tailing for recovery of lime, flotation was tried. This method at once showed possibilities. Cresol was the first reagent used; it made possible the recovery of a fairly good lime concentrate, although the percentage recovered was low. A soap solution made from common soap was next tried, with decidedly better results. In fact, they constituted an important clue and led to tests of such reagents as oleic acid and sodium oleate. Later cresol, creosote, coal tar, and similar reagents were tested in combination with the oleic acid and soap solutions. Repeated experiments have shown that a mixture of approximately equal amounts of cresol and oleic acid gives the most efficient results. The amount of oil added in making a standard test of a 500-gram sample of tailing amounted to one-third gram of cresol and an equal amount of oleic acid.

As the iron ore had been ground in a ball mill to 100 mesh for magnetic concentration, the bond between the lime carbonate and the other constituents of the tailing was well broken. For this reason the tailing from the magnetic log washer is in excellent physical condition for flotation.

All experiments were performed in flotation machines of the mechanical agitation type. Fair results may be obtained by one-stage flotation. However, the work is more efficient when the roughing-cleaning system is followed; the tailing from the cleaner is returned to the rougher.

TABLE 13.—*Flotation of limestone from tailings*

[Values in per cent]

Ore	Magnetic log-washer tailing (flotation feed)				Flotation concentrates				
	Lime	Magnesia	Insoluble	Iron	Weight	Lime	Magnesia	Insoluble	Iron
1	33.4	1.1	24.5	5.6	59.4	48.7	1.00	3.2	4.0
2	28.2	.30	36.8	5.2	45.0	48.6	.60	3.0	2.5
3	24.6	.54	40.4	8.2	39.3	49.7	1.18	2.4	2.6
4	19.1	.50	58.2	2.9	31.6	46.7	1.00	3.4	2.4

TABLE 13.—*Flotation of limestone from tailings*—Continued

Ore	Flotation tailings				Lime recovered	Magnesia recovered	Iron recovered	Insoluble rejected
	Lime	Magnesia	Insoluble	Iron				
1	11.1	1.2	55.7	8.7	86.5	54.0	34.8	92.3
2	11.5	.06	64.5	7.4	77.6	90.0	21.6	96.3
3	8.3	.13	65.0	8.0	79.5	85.9	12.5	97.7
4	6.3	.27	83.5	3.1	77.5	63.2	25.9	98.1

Table 13 shows how freely lime floats in the presence of siliceous gangue. The amount of lime in the various samples tested ranged between rather wide limits, but, as the table indicates, the grade of lime concentrates obtained was much the same. The log tailing contains a small amount of magnesia which is retained in the flotation concentrate in much the same way as the lime. Magnesia has much the same fluxing properties as lime, and the percentage in the concentrate averages about 1 per cent.

The concentrates obtained in this process compare favorably with the limestone now utilized as flux. The average analysis of the limestone in use in the Birmingham district is: Insoluble, 3.5 per cent; iron, 0.5 per cent; and lime, 53 per cent. Dolomite is used extensively as a flux; it averages 1.5 per cent of insoluble, 0.5 per cent of iron, 30.3 per cent of lime, and 20.7 per cent of magnesia. The lime concentrate is somewhat higher in iron than the commercial stone, but as the purpose of smelting is to recover iron this feature is not undesirable.

Small-scale tests indicate that about equal quantities of cresol and oleic acid give the most satisfactory results. The amount of reagents required is not excessive, amounting to approximately 1.5 pounds for each ton of tailing handled.

SUMMARY

Small-scale laboratory tests made with a small cylindrical roasting drum and a Davis magnetic tube indicated the theoretical limits in the magnetic concentration of Birmingham district red ores, both as to grade of concentrates obtainable and possible extraction or efficiency. Later it will be shown that the results obtained with semicommercial machines approached these limits very closely. The results of small-scale tests of representative samples of ore ordinarily show an extraction of about 95 per cent of the iron in concentrates that assay about 52 to 55 per cent of iron before sintering. These results are obtainable with ore crushed to 100 mesh. The impurities remaining in the concentrates are so thoroughly combined with the iron mineral that fine grinding to 300 mesh does not liberate them;

indeed, concentrates obtained from ore crushed to 300 mesh are little better than those from ore crushed to 100 mesh.

That tailings of ores which contain appreciable amounts of lime and magnesia can be treated successfully by flotation was established; the floated lime is mixed with the iron concentrate. Self-fluxing concentrates can thus be produced from certain high-silica red ores. The advantage of doing so is that the limestone is in intimate contact with the iron mineral, thus making reduction of the ore more rapid.

LARGE-SCALE TESTS

The small-scale tests constituted a preliminary study of the various samples of ore tested during the investigation. With the preliminary results as a guide to the limitations of individual ores, large-scale tests could be made with a definite goal. The large-scale tests were made in equipment of semicommercial size installed and operated to make a complete pilot mill handling a continuous feed. The work is thought to be indicative of what can be done on a commercial scale in actual practice.

DESCRIPTION OF MACHINES

Coarse crushing.—The ore as received from the mine was ordinarily quite coarse. It was reduced to ¼ inch by being put through jaw crushers and a pair of rolls. As both machines are standard, they require no discussion.

Roasting furnace.—The ¼-inch ore was fed to a multiple-hearth roasting furnace. (See fig. 3.) The six hearths are 36 inches in diameter, and the wall of the furnace is lined with 9 inches of fire brick. The central shaft and the rabble arms attached to it are air cooled. The ore is fed to the top of the furnace, where the first set of rabbles moves it over the preheating hearth to an opening at the outer edge, through which it drops to the next hearth. Here the ore travels in the opposite direction—that is, toward the center of the furnace. After passing over the six hearths of the furnace in this manner the ore is discharged at the bottom through a 3-inch pipe. By-product gas is used to heat and reduce the ore. The gas enters the furnace above the bottom hearth and rises through the two lower hearths that constitute the reducing zone. Virtually no air is admitted to these two hearths. In the hearths above the reducing zone the gas comes in contact with air, and in burning it heats the ore to the desired temperature. A temperature of 500° to 600° C. is ordinarily maintained. The roasted ore, which has become quite soft and porous, is discharged into water to prevent reoxidation.

Mechanical rake classifier and ball mill.—A duplex rake classifier is operated in closed circuit with a conical ball mill. The roasted

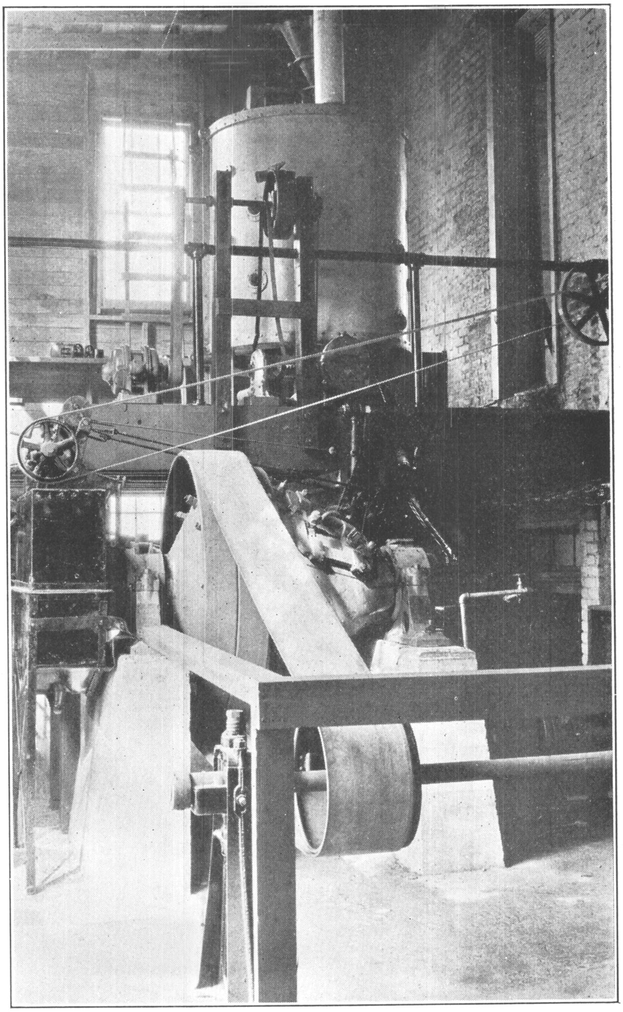

FIGURE 3.—Roasting furnace and ball mill

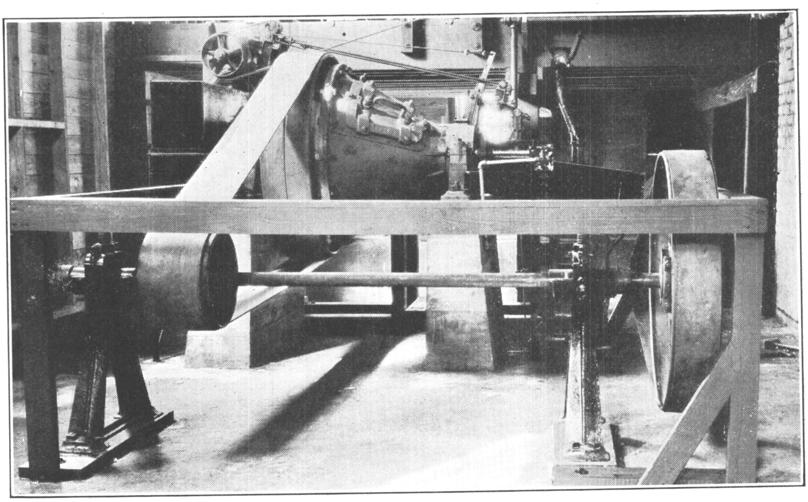

FIGURE 4.—Ball mill

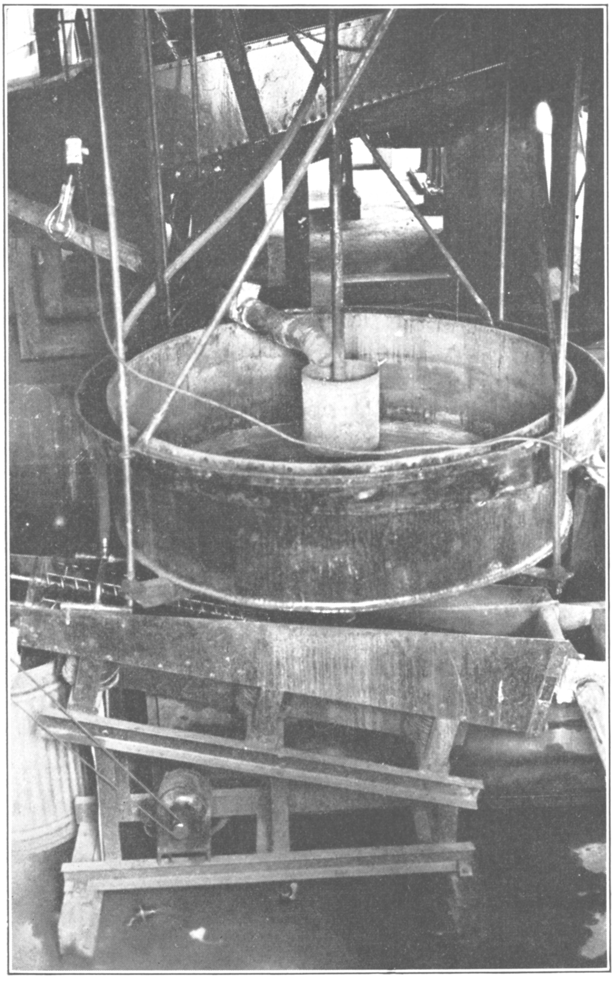

FIGURE 5.—Thickener and magnetic log washer

ore from the furnace is discharged below the water level in the classifier. The function of the classifier is to separate the fine material from the coarse; the fines overflow the lower end and the coarse ore is raked to the upper end of the classifier, where it discharges into a ball mill 36 inches in diameter. Figure 4 shows the ball mill below the roasting furnace.

Mechanical thickener.—The pulp overflowing the classifier is too thin to be fed directly to the magnetic log washer and must therefore be partly dewatered. The mechanical thickener used for this purpose is suspended immediately above the magnetic log washer. It is 48 inches in diameter and 18 inches deep. In Figure 5 the magnetic log washer is underneath the thickener, and the rake classifier may be seen in the background.

Magnetic log washer.—The magnetic log washer is a machine for concentrating finely ground ore. It was developed by E. W. Davis, superintendent, Minnesota School of Mines Experiment Station, and used successfully at the plant of the Mesabi Iron Co., Babbitt, Minn. Material as course as 48 mesh can be handled, but the finer the ore is crushed the better the machine operates. The washer is similar in principle to log washers commonly used for washing brown ores, except that the bottom of the inclined trough is in a magnetic field because electromagnets are attached beneath the machine. The discharge from the mechanical thickener feeds into the magnetic log washer slightly below the center of the machine and settles at once into the magnetic field. The particles of magnetic iron mineral, as well as some locked nonmagnetic particles, cling to the bottom of the trough. Two copper spirals that serve as screw conveyors stir and draw the ore to the upper end of the slope. Wash water entering the top of the inclined trough flows down through the mass of concentrate and carries with it the particles of gangue liberated by the action of the spirals. The two machines used for testing are each 5 feet long and have two spirals. Commercial machines are built as large as 6 feet wide by 18 feet long and have four spirals.

Sinter pan.—The concentrates produced by the magnetic log washer are very fine and require agglomerating; in these tests a single-unit sinter machine was used to agglomerate them. The pan is 10 inches square, is 5 inches deep, and has a grate bottom. It is connected to a vacuum pump which supplies the necessary suction for a down draft. After the moist concentrate is mixed with the proper amount of finely crushed coal or coke, generally about 6 to 8 per cent by weight, it is placed in the sinter pan. An igniter, burning gas, is passed over the surface of the bed of material in the pan and ignites the fuel. The suction pump causes a current of air to travel down through the bed of ore, and the coal therefore burns at a high temperature and in intimate contact with the ore. In consequence, the ore is agglomerated into a firm cellular mass that will not readily disintegrate. The ore undergoes a chemical as well as a physical change. Oxygen and chemically combined water are driven off, and when lime is present CO_2 is also eliminated. Most of the iron is reduced to FeO.

METHOD OF TREATMENT

The discussion of the method of treatment will be confined to the general flow sheet developed and its use in practice. If variations in the adjustment of individual machines are disregarded, the flow sheet is the same for all the red ores, unless an ore is magnetically concentrated in three stages instead of the customary two. The method duplicated that developed for the treatment of high-silica gray hematite. (See pp. 11 and 12.)

In the treatment of some ores the tailing from the magnetic log washers was recovered and dried. A sample was cut from this and treated in flotation machines, which recovered a large part of the limestone as a good lime product and returned it to the iron concentrate of the log washers in amounts sufficient to make the resulting sinter self-fluxing.

RESULTS OF LARGE-SCALE TESTS

During the investigation many tests were made in the pilot or miniature mill composed of machines of semicommercial size. The first few tests were made with only one magnetic log washer, but tables were used to re-treat the tailing from it. None of the early tests were satisfactory, because a large percentage of iron was lost in the tailing. A second magnetic log washer was installed, and the succeeding work showed a decided improvement, not only in the percentage of iron recovered but in the grade of concentrate produced. After the various machines had been properly adjusted for treating one of the red ores only a few minor changes were necessary when new ores were tested. These changes were made principally in the two magnetic log washers, where the slope, speed of the spirals, and amount of wash water were adjusted.

A number of different ores were run through the pilot mill, and several tests were made of each. As a result it was concluded that the flow sheet developed for one ore could be safely used for another by slightly changing the mechanical conditions of operation. Table 14 was prepared to show the results of a typical test of each of six ores that contained at least a fair percentage of lime and ranged from

33.3 down to 15.5 per cent of insoluble. As the insoluble content decreases the lime increases, so that the six samples included in the table cover almost the entire range of red ores of the Birmingham district. Although it is not logical to assume that self-fluxing ores will ever be concentrated, the results with ore 6, which is almost self-fluxing, are given to show what might be accomplished.

TABLE 14.—*Large-scale tests of a variety of high-silica and limy red ores*

[Values in per cent]

Ore	Roasted ore				Magnetic concentrate				
	Iron	Insoluble	Lime	Phosphorus	Weight	Iron	Insoluble	Lime	Phosphorus
1	32.6	33.3	8.0	0.24	58.40	52.9	17.4	2.7	0.22
2	35.8	28.6	8.9	.33	67.50	50.9	14.2	4.5	.44
3	33.4	28.2	11.9	.32	62.54	51.2	14.1	4.7	.35
4	35.1	22.4	12.1	.36	60.65	52.1	12.8	4.5	.34
5	36.7	20.7	12.3	.37	67.68	51.2	13.6	4.8	.38
6	36.3	15.5	14.5	.43	68.84	50.2	12.8	6.1	.43

Ore	Sinter				Iron recovered	Insoluble rejected	Lime rejected
	Iron	Insoluble	Lime	Phosphorus			
1	55.6	17.9	2.8	0.22	94.76	69.5	80.3
2	53.9	14.6	5.0	.45	95.97	66.5	65.9
3	54.2	15.5	4.9	.37	95.87	68.7	76.3
4	54.6	13.4	4.7	.36	90.02	66.8	77.5
5	54.8	15.8	5.7	.39	94.41	55.6	74.6
6	52.9	13.6	6.4	.45	95.20	43.2	71.0

All tests, with the exception of those of ore 1, were made with two magnetic log washers according to a flow sheet similar to that given as Figure 6. Ore 1 (see Table 14) would not give up enough gangue material in two stages of treatment, and a third log washer had to be added to get desirable results.

Flow sheet for two-stage concentration.—Figure 6 gives detailed information on two-stage concentration of a high-silica ore. The ore was fed to the roasting furnace at the rate of 255 pounds an hour, and the lower hearths of the furnace were maintained at an average temperature of 530° C. The ball mill and classifier circuit discharged a pulp in which 85 per cent of the ore passed a 300-mesh screen and all passed a 100-mesh screen. Table 15 is a screen analysis of the feed to the magnetic log washer.

The treatment of the ore gave a sintered concentrate carrying 53.9 per cent of iron, 14.6 per cent of insoluble, and 5.0 per cent of lime. The recovery of iron was 95.97 per cent and of lime 34.1 per cent. A little over 66 per cent of the insoluble matter was rejected in the tailing.

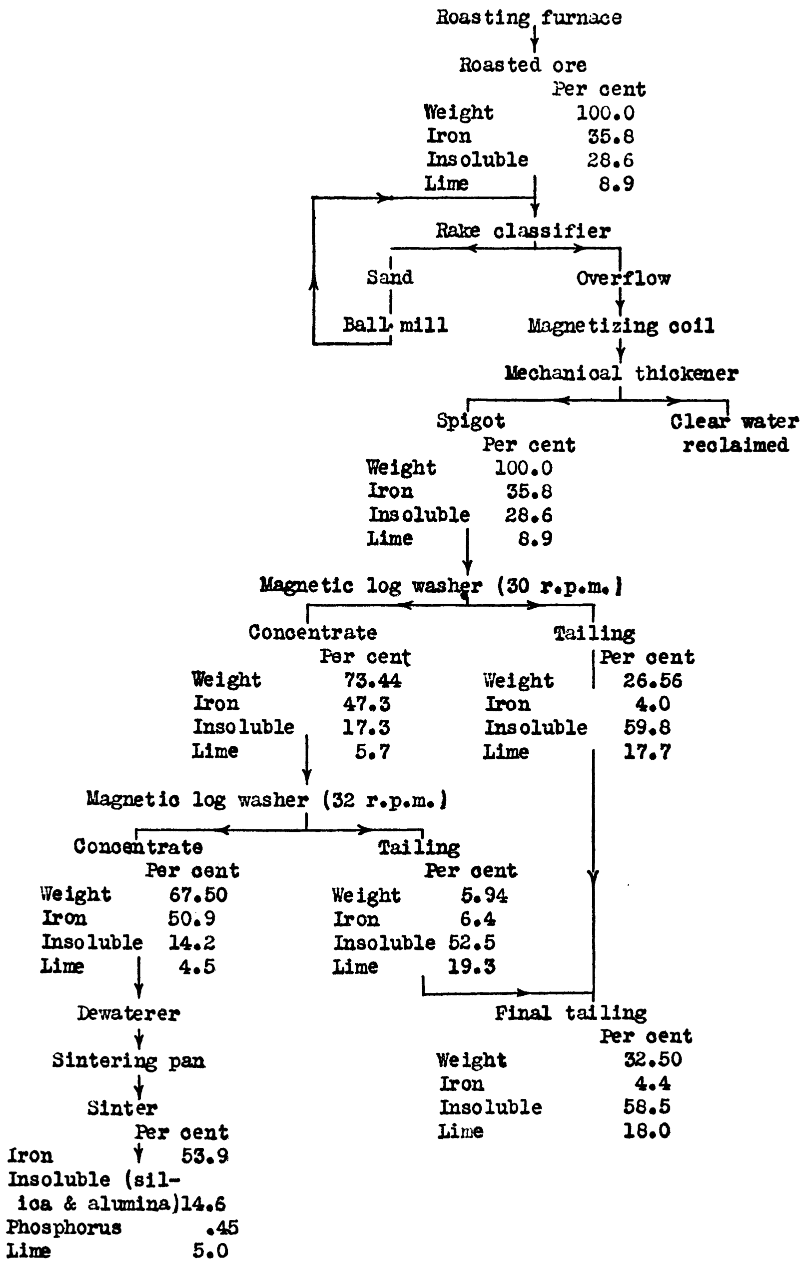

FIGURE 6.—Flow sheet for roasting and two-stage magnetic concentration of high-silica red ore. Ratio of concentration, 1.48 : 1; iron recovered, 95.97 per cent; insoluble rejected, 66.5 per cent

TABLE 15.—*Screen analysis of feed to magnetic log washer*

Weight			Iron	Insoluble	Lime
Mesh	Per cent	Cumulative per cent			
			Per cent	*Per cent*	*Per cent*
Plus 200	6.1	6.1	15.0	56.8	9.4
Plus 250	3.5	9.6	20.4	48.6	9.2
Plus 300	5.3	14.9	24.7	41.2	10.0
Minus 300	85.1	85.1	38.7	24.8	8.5
Total	100.0	100.0	35.9	28.5	8.7

Flow sheet for three-stage concentration.—A flow sheet was prepared of a test of one other high-silica red ore in which three stages of magnetic concentration were employed. A comparison of two and three stage treatment can be obtained direct from the flow sheet, Figure 7. The reader will see that the third magnetic log washer raised the grade of the concentrate from 50.8 to 52.9, an increase that is believed to justify its use. A loss of 1 per cent of the iron resulted from the extra step. This particular ore was more difficult to concentrate than the average ore, in that the silica and alumina were hard to eliminate in the customary two stages of treatment. Although the final concentrate contained 55.6 per cent of iron after sintering, it still held 17.9 per cent of insoluble and 2.8 per cent of lime. More than 69 per cent of the insoluble was rejected. Tables 16 and 17 give the screen analyses of the feed to the magnetic log washers and the concentrate from the second magnetic log.

TABLE 16.—*Screen analysis of feed to magnetic log washer*

[Values in per cent]

Screen size (mesh)	Weight	Iron	Silica	Alumina	Lime	Phosphorus
Plus 200	3.5	9.0	62.4	1.4	11.3	0.17
Minus 200 plus 300	9.9	18.5	47.7	2.3	10.5	.22
Minus 300	86.6	35.2	27.1	3.0	7.6	.25
Total	100.0	32.6	30.4	2.9	8.0	.24

TABLE 17.—*Screen analysis of second magnetic log-washer concentrate*

[Values in per cent]

Screen size (mesh)	Weight	Iron	Silica	Alumina	Lime	Phosphorus
Plus 200	2.3	36.6	31.0	3.2	4.9	0.22
Minus 200 plus 300	9.6	44.6	22.3	3.8	3.4	.27
Minus 300	88.1	51.8	13.4	4.3	3.1	.26
Total	100.0	50.8	14.7	4.2	3.2	.26

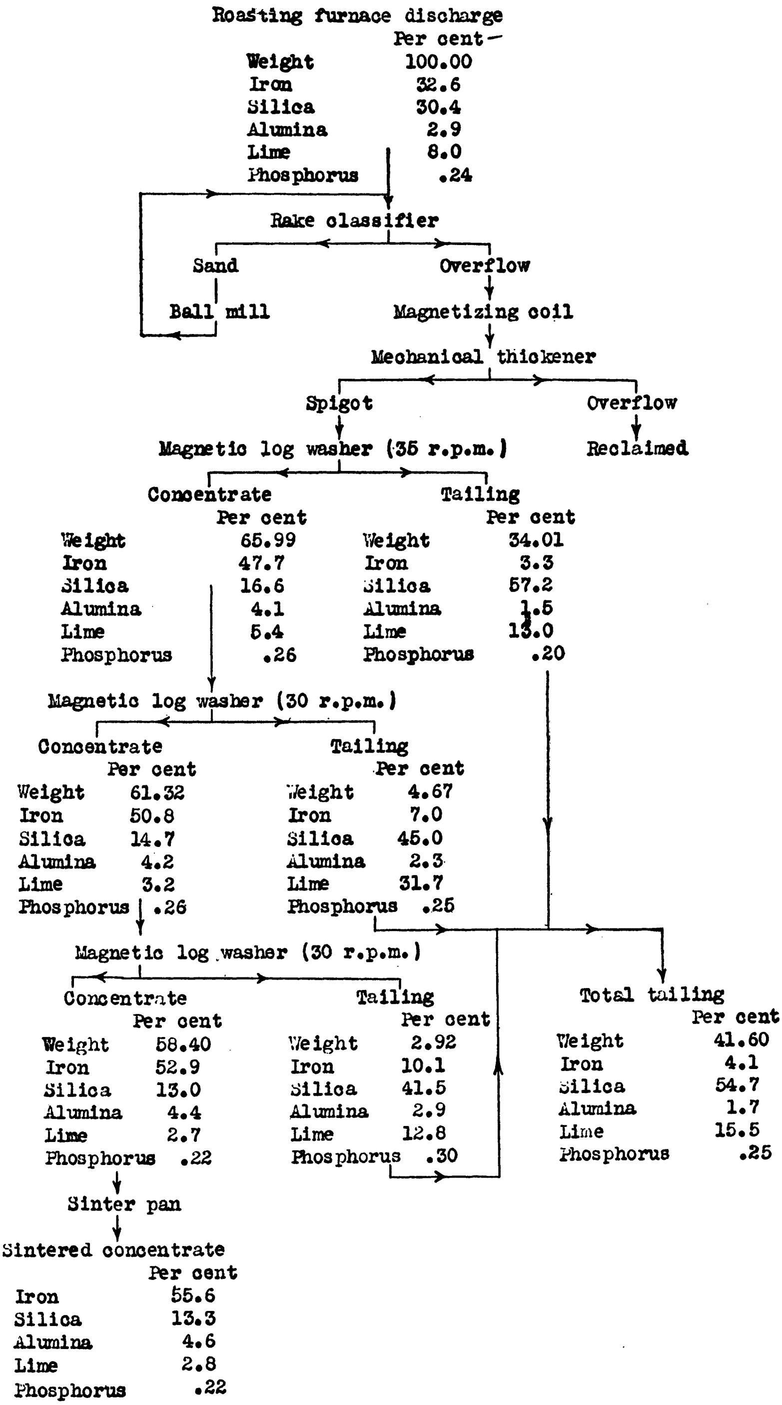

FIGURE 7.—Flow sheet for roasting and three-stage magnetic concentration of high-silica red ore. Ratio of concentration, 1.71 : 1; iron recovered, 94.76 per cent; insoluble rejected, 69.5 per cent

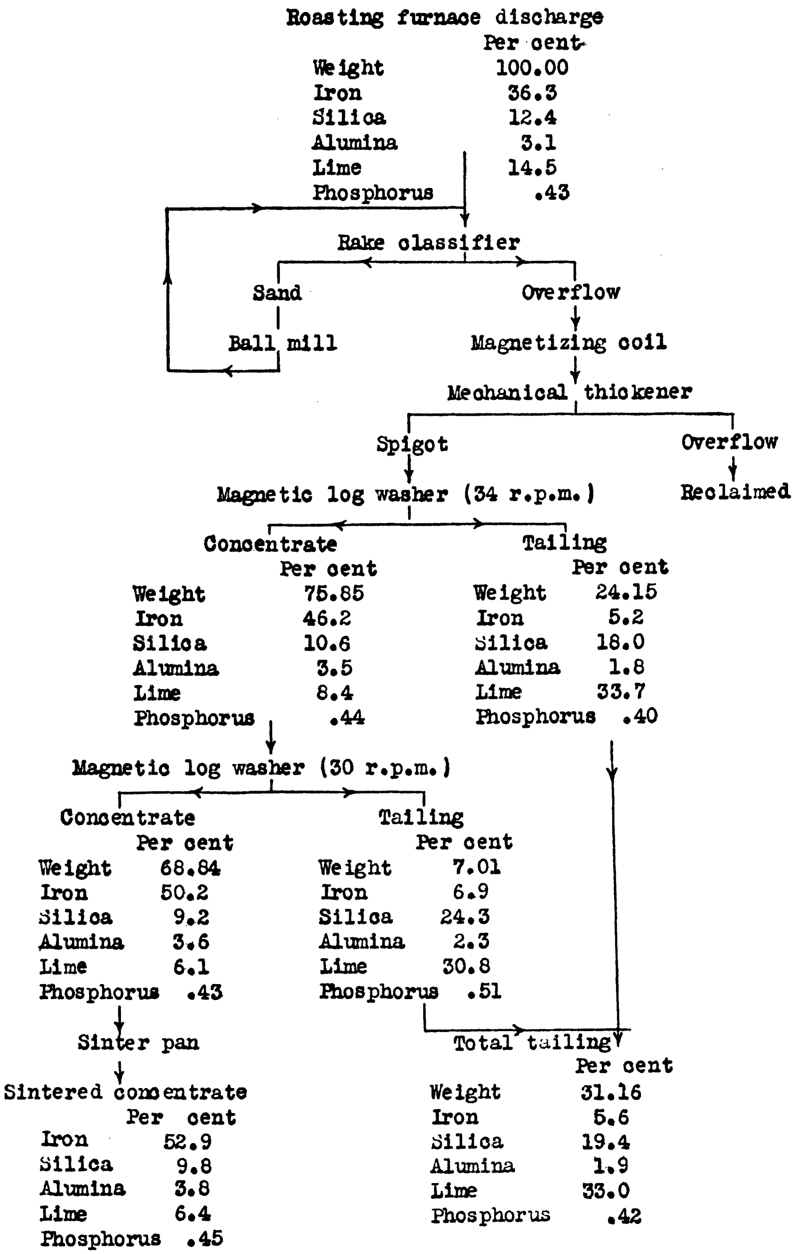

FIGURE 8.—Flow sheet for roasting and two-stage magnetic concentration of limy red ore. Ration of concentration, 1.45 : 1; iron recovered, 95.20 per cent; insoluble rejected, 43.2 per cent

Flow sheet for two-stage concentration of limy ore.—Two tests of high-silica red hematites were described in Figures 6 and 7. As a matter of general interest the flow sheet (fig. 8) is presented to show the results obtainable by the roasting and magnetic concentration of an ore that is practically self-fluxing. The ore was delivered to the roasting furnace at the rate of 250 pounds an hour. The temperature of the reducing zone of the furnace averaged 535° C. for the entire run. Results showed that 1 ton of concentrate could be produced from every 1.45 tons of ore treated. In producing a sintered concentrate assaying 52.9 per cent of iron, 13.6 per cent of silica plus alumina, and 6.4 per cent of lime, 95.20 per cent of the iron was recovered. This concentration was accomplished by removing 43.2 per cent of the insoluble (silica plus alumina). Virtually 29 per cent of the lime in the ore was held in the concentrate.

The flow sheet as perfected was well standardized for treating red ores of the Birmingham district. Few changes were necessary, as the percentage of iron in the ores ranged between narrow limits, and the magnetic machines were designed to recover the iron. The varying proportions of silica and lime in the ores affected the grade of the concentrate and the extraction of iron very little.

General operating data.—Table 18 presents general operating data for typical tests and may be considered representative of average operation. No machine was ever run at its full capacity, as the testing of larger samples of ore was unnecessary and expensive. The quantity of ore treated with a continuous feed was large enough to insure accurate data. Results of steady operation on a commercial scale would probably be even better than those obtained from the tests discussed in this report.

TABLE 18.—*General operating data from roasting and magnetic concentration tests of red ores*

Rate of feed, 250 to 280 pounds per hour.
Size of feed, ¼ inch.
Roasting furnace:
- Number of hearths, 6.
- Speed of rabble arms, 52 revolutions per hour.
- Temperature of reducing zone, 500 to 575° C.
- Gas consumption for heating and reducing, 500 to 600 cubic feet per hour.

Duplex rake classifier:
- Slope of bottom, 2.8 inches per foot.
- Speed of rakes, 17½ strokes per minute.
- Water consumption, 4 to 5 gallons per minute.

Conical ball mill:
- Ball load, 900 pounds.
- Size of balls, 1 and 2 inches.
- Speed, 37 revolutions per minute.

Mechanical thickener:
- Speed, 15 revolutions per hour.
- Spigot discharge, 40 to 60 per cent of solids

Magnetic log washers:
- Speed, 34 and 30 revolutions per minute.
- Slope, 2.9 inches per foot.
- Ampere for magnetic coils, 0.30 kilowatt.
- Wash water, 3½ to 4½ gallons per minute.

Sintering machine:
- Amount of coke used for fuel, 6 to 8 per cer t by weight.
- Amount of moisture in feed, 12 to 18 per cent by weight.
- Ignition, by gas flame.

FLOTATION OF LIMESTONE IN TAILING

Flotation of the limestone was developed in laboratory-size machines, as it was not feasible to attempt work on a large scale. The results of two small-scale tests are given in Tables 19 and 20 to show what the flotation of magnetic-concentrator tailing to recover limestone would mean to general concentrating practice.

Samples cut from the tailings of the magnetic log washers during two large-scale tests were treated in the flotation cells, and the limestone recovered was mixed with a cut sample of iron concentrates before sintering. These results should be included in this account of large-scale tests to indicate the possibilities of commercial use. Although it is true that the amount of iron in the sinter is 2 or 3 per cent lower than that in the concentrate from the log washer, this decrease is compensated for because the resulting sinter is self-fluxing and the recovery of iron is increased. A self-fluxing sinter would, no doubt, reduce very rapidly in a blast furnace and thereby allow the capacity of the furnace to be increased decidedly.

TABLE 19.—*Production of a self-fluxing concentrate from low-grade self-fluxing ore*

[Values in per cent]

Product	Iron	Insoluble	Lime	Magnesia	Iron recovered	Lime recovered	Magnesia recovered	Insoluble rejected
Ore	36.3	15.5	14.5	0.70				
Iron concentrate	50.2	13.0	6.1	.30	95.2			
Tailing to flotation	5.6	24.5	33.4	1.1				
Flotation concentrate	4.0	3.2	48.7	1.0				
Sintered concentrate	48.0	13.5	13.9	.40	96.6	77.1	59.3	38.8

TABLE 20.—*Production of a self-fluxing concentrate from high-silica ore*

[Values in per cent]

Product	Iron	Insoluble	Lime	Magnesia	Iron recovered	Lime recovered	Magnesia recovered	Insoluble rejected
Ore	35.1	22.4	12.1	0.36				
Iron concentrate	52.1	12.8	5.6	.22	90.95			
Tailing to flotation	8.2	40.4	24.6	.54				
Flotation concentrate	4.2	3.1	48.9	1.18				
Sintered concentrate	49.0	12.8	12.7	.38	91.9	76.0	82.3	63.8

SINTERING

In recent years the sintering process of making fine iron-bearing materials suitable for blast-furnace feed has been increasingly used. Once it was thought that sintering could only be applied economically to material that was too fine or contained too large quantities of such impurities as sulphur and moisture to permit the smelting of it in a natural state in a blast furnace; in other words, to material which had to be sintered before smelting. In recent years, however, experience with sinter as a blast-furnace feed has changed this attitude. The advantages of sinter over raw ore as a blast-furnace feed have been found so pronounced and so convincing that a large amount of iron ore is being sintered to-day which would have been smelted directly a few years ago.

Magnetic log-washer concentrates form a porous cellular mass when sintered. In the blast furnace such a product, because of the large area exposed to the hot reducing gases, is reduced from iron oxide to metallic iron more readily and also melts more easily than lumps of raw ore. In operating a blast furnace about 8,000 tons of air a day is forced up through the charge. When the furnace is running on a sinter feed the forcing of this large volume of air through the charge is greatly facilitated because of the porous, open nature of the burden. This also makes possible increasing the rate of driving and the smelting of more ore in a day. Losses in flue dust are practically eliminated when a furnace runs on a sinter feed, for there was no appreciable amount of fines in the sinter. A result such as this would allow a noteworthy saving in districts where the flue dust produced is so high in carbon and low in iron as to make its reclamation by the usual methods impractical.

In a recent article on iron ore sintering in the East, Kreutzberg[5] says:

> A broader application of the sintering process is the most important development in the eastern iron-ore industry in many years. Two or three years ago certain eastern furnaces modified their impression of sintering as strictly a blast-furnace flue-dust reclamation process and experimented in sintering iron ore. The results were such as to bring about an increased application of the sintering process to iron ore. Developments during 1925 indicate that sintering of ore may be the general practice in the East in a comparatively short period.
>
> Results obtained by operating furnaces on sintered ore have proved remarkable. Observations at furnaces using sinter exclusively show that there is an average saving in coke consumption of at least 10 per cent. Likewise, there has been an average increase of at least 10 per cent in the tonnage of iron produced. In some instances much better results have been obtained than indicated by these figures. One furnace operating on sinter for a time reduced its coke consumption to less than 1,700 pounds per ton of foundry pig iron.

[5] Kreutzberg, E. C., "Iron ore sintering spreads in East"; Iron Trade Rev., vol. 78, Mar. 11, 1926, pp. 641–643.

Concerning the advantages of running a blast furnace on sinter, Dwight Woodbridge[6] says:

Furnace operators are more insistent on uniformity of raw materials. * * *. Recent results from the use of sintered ores indicate a solution of the uniformity problem. One hundred per cent sintered ore in the furnace burden is quite new. A careful run in an eastern furnace in 1925 proved that, at that plant at least, the use of a sintered magnetite increased the output of iron by more than 60 per cent and reduced the coke per ton by more than 40 per cent. Coke had been used in excessive amount in this furnace, and a fairer proportion of coke saving perhaps would be 15 per cent. * * *. There can be no doubt that, in the future, sintered ores will be in great demand if these early results are confirmed and extended. It is probable that among forthcoming mechanical improvements at mines will be sintering equipment, not alone for those ores that must be so treated to become merchantable, but also for those ores that are physically capable of being made into a sinter. Indeed, plants for this work may become as common in Minnesota as washeries are now; not necessarily for treating concentrates, but for any fine-mesh, wet, or dusty ore.

Advantages of sintering.—Sinter as a blast-furnace feed undoubtedly has a number of good features which have not been fully appreciated, but in weighing the probable advantages and disadvantages of concentrating low-grade ores, such as those occurring in the Birmingham district, the principal item would be the relatively high percentage of iron in sintered concentrates produced from these ores. When a blast furnace is running on an average grade of Birmingham red ore about 3 tons of material must be smelted to produce 1 ton of pig iron, whereas if a furnace could take the sintered magnetic concentrates produced from such an ore about 2 tons of material smelted would produce 1 ton of pig iron. On this basis alone the pig-iron output of a furnace would be increased 50 per cent. The lower percentage of slag-forming impurities in the sinter as compared with the natural ore would allow substantial decrease in consumption of coke per ton of material smelted and a still larger decrease in consumption of coke per ton of pig produced. In addition to this increase in the capacity of the furnace and decrease in comsumption of coke, computed on the basis of chemical constituents in the feed, there would be a further increased capacity and decreased consumption of coke, due to such factors as an increased rate of driving and a feed material that would be less refractory and more easily reduced.

SUMMARY

In the Birmingham district the Clinton formation contains large quantities of high-silica red ores which are not termed merchantable because they can not be smelted profitably. It is probable that a

[6] Woodbridge, Dwight, "Iron ore mining": Eng. and Min. Jour.-Press, vol. 121, Jan. 16, 1926.

suitable method of concentration soon will make these ores economically important.

The ores are mostly oölitic hematites, but there is also some fossiliferous ore, which is generally of such character that its concentration is unnecessary. The iron mineral and the gangue are so intimately associated in the ores that they can be liberated only by fine grinding. It was clearly demonstrated that minus 100 mesh is the critical point of liberation.

Finely crushed ore can not be concentrated efficiently by present methods of gravity concentration. Magnetic concentration, however, is ideal for finely crushed ore if the iron mineral is in the form of magnetite.

Inasmuch as the red ores are hematites, some method of artificial magnetization must be employed. Roasting coarse sizes of ore in a reducing atmosphere at 500 to 600° C. was found to be an efficient method of converting the hematite to magnetite.

Fine grinding is not attempted unless absolutely necessary because it is generally expensive. Roasting the red ores makes them soft and porous and the problem of fine grinding was so simplified that it need not be considered with apprehension.

The finely crushed ore in the form of wet pulp can ordinarily be concentrated in two stages of magnetic concentration. A third stage was necessary in one test. The average high-silica red ore containing 32 to 36 per cent of iron can readily be concentrated into a product assaying 51 to 53 per cent of iron before sintering, with a recovery of 95 per cent of the iron. To accomplish this, 50 to 65 per cent of the gangue material is removed in the tailing.

A determined effort was made to decrease the silica and alumina content to such a point that the product would contain 60 per cent or more of iron, but because of the alumina in the ore this result could not be attained with a high percentage of extraction. The alumina is present as kaolin and is so associated with the iron mineral that separation by mechanical means is extremely difficult. Inasmuch as the alumina content in the average concentrate runs from 3 to 4.9 per cent, the kaolin of which the alumina is a part must run from 7.5 to more than 12 per cent. Moreover, the concentrate always contains some silica free from alumina; hence the percentage of gangue in the concentrate is relatively high.

The concentrate is so finely divided that some form of agglomeration is essential. The physical character of the sintered product indicates that sintering is the most suitable method. The porous, honeycombed mass makes an ideal blast-furnace feed because a large surface area is exposed to the reducing gases of the furnace.

Sintering of the red ore concentrates is best done with 6 to 8 per cent of fuel, either finely crushed coal or coke. In mixing the concentrate and the fuel about 16 per cent of moisture is added to bond the material lightly. Concentrates that generally assay 51 to 53 per cent of iron have their iron content increased to 53 to 55 per cent by sintering because of the removal of moisture, oxygen, and, if calcium carbonate is present, carbon dioxide (CO_2).

Some high-silica red ores contain appreciable amounts of limestone, most of which escapes in the tailing during concentration. A flotation method was developed for recovering the limestone from the tailing and returning it to the concentrate. From ores that contain enough limestone a self-fluxing sintered concentrate can be produced that will assay 48 to 50 per cent of iron.

CONCLUSIONS

The results obtained during this investigation show quite conclusively that it would be possible to apply roasting and magnetic concentration on a commercial scale to the red ores of the Birmingham district and obtain good metallurgical results. The question as to whether or not it would be a sound and advantageous economic policy for operators in the district to adopt this process deserves serious consideration. To be economically successful the process would have to yield benefits substantial enough to offset the cost of building and operating the concentrating plants. The benefits which would be derived from concentration of the iron ores include two principal items of importance: (1) There would be a substantial decrease in blast-furnace costs on the basis of pig iron produced and (2) concentration would have a vital effect on the future of the Birmingham district because it would make available enormous amounts of ore that is now too low grade for profitable smelting.

There is no doubt that the "per ton" value of smelting ores of good grade is increasing from year to year in the Birmingham district as the available supplies of such ores are gradually depleted. The further this process of depletion proceeds the greater will be the demand for good-grade material for smelting and the more urgent will be the need of a process such as magnetic concentration, whereby low-grade ores may be utilized and high-grade feed obtained for the blast furnaces.

MAGNETIC CONCENTRATION OF HIGH-SILICA GRAY HEMATITE OF TALLADEGA COUNTY, ALA.

By Oscar Lee, B. W. Gandrud, and F. D. De Vaney

INTRODUCTION

The gray iron ores of Talladega County, Ala., have been known for many years; as long ago as 1858 Dr. M. Tuomey, then State geologist, mentioned them in his field notes. At various times the ores have been considered as a source of iron but, except for a short period before 1907, they have never been mined on a commercial scale.

Although the ores average fairly high in iron they usually contain much silica, and this high content of silica has discouraged the operators from mining them on a commercial basis. Beneficiation has been considered for a number of years, but no determined attempt to devise a method was made until 1923. In that year the Southern experiment station of the Bureau of Mines undertook to study concentration of the ores with the object of developing a process that would make the ores available for smelting in the blast furnace. After two years of work the investigation was concluded; its results are embodied in this report.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the hearty cooperation of the officials of the Gray Ore Iron Co. and the Alabama Ore & Iron Co. Thanks are especially due W. R. Crane, superintendent of the Southern station, and W. H. Coghill, metallurgist, of the Bureau of Mines, for many helpful suggestions during the investigation and the preparation of this report.

OCCURRENCE OF GRAY ORES

Smith[1] and Grasty[2] have described the gray ores, and the following discussion of their occurrence and character is in part an abstract of their papers.

[1] Smith, P. S., "The gray iron ores of Talladega County, Ala."; Contributions to Economic Geology, 1906: U. S. Geol. Survey Bull. 315, 1907, pp. 161–184.

[2] Grasty, J. D., "Cambrian gray and red hematites of east Alabama": Manufacturers Record, May 31, 1906, vol. 49, pp. 550–563.

In Alabama the gray iron ores occur almost entirely in Talladega County, and the workable ores are confined mainly to the northern and northeastern part of the county. Probably the two most important districts are the Tallaseehatchee and the Weewoka, and of these the Tallaseehatchee has received more attention. The two districts lie about due north of the town of Sylacauga and 4 to 8 miles from it.

Much prospecting has been done in the Weewoka Hills at Heacock and Riser Mountains, most of it on the property of the Alabama Ore & Iron Co. At the Heacock property the exploration consisted of a series of pits and trenches that exposed the ore well. Figure 9 shows one of the open cuts. The several beds of ore occur in arenaceous schists and slates.

The Riser Mountain property, on which comparatively little development work has been done, is about 1 mile south of Heacock Mountain and on the eastern side of Weewoka Creek. A few shallow pits like that shown in Figure 10 were dug, and a small amount of trenching was done. The ore is fairly well exposed, however, so that something is known of its occurrence. The summit of Riser Mountain is a heavy quartzitic sandstone, and on the lower slopes a series of metamorphosed beds are exposed. The ores at Riser Mountain show intimate connection with the quartzitic sandstone but are of somewhat lower grade than those of Heacock Mountain.

About 20 years ago the Gray Ore Iron Co. worked the Emauhee and Tallaseehatchee mines for a short time. These mines, in the Tallaseehatchee district, are on Emauhee and Tallaseehatchee Creeks, from which they take their names. The ore was mined chiefly by opencuts, although a considerable amount of ore was mined underground to a depth of more than 300 feet along the slope. Figures 11 and 12 show two openings in the ore beds.

The ore occurs in a series of slates and quartzites. There are two forms of ore—one is hard and quartzitic, the other soft and slaty. The soft ore is the easier to mine and usually contains a higher percentage of iron. The hard ore breaks into angular blocks, which on fresh surfaces show bright grains of iron mineral intimately mixed with quartz. The quartz grains are flat and elongated.

The thickness of the ore beds at the different points mentioned is variable. The range of thickness of the beds from which samples were obtained for this investigation was 3 to 9 feet.

CHARACTER OF ORE

The gray ore of Talladega County is mainly hematite, but has often been termed magnetite because in places it is somewhat magnetic. The ore contains from a small percentage to quite an appreciable

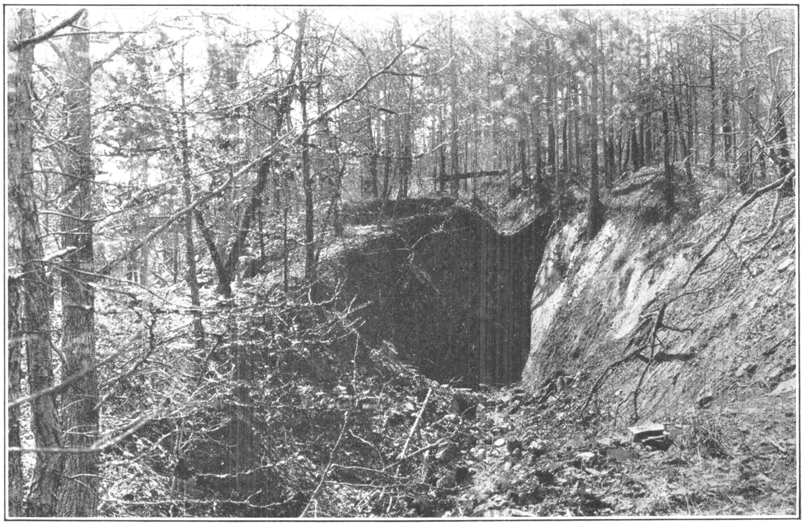

FIGURE 9.—Opencut in upper bed of Heacock Mountain

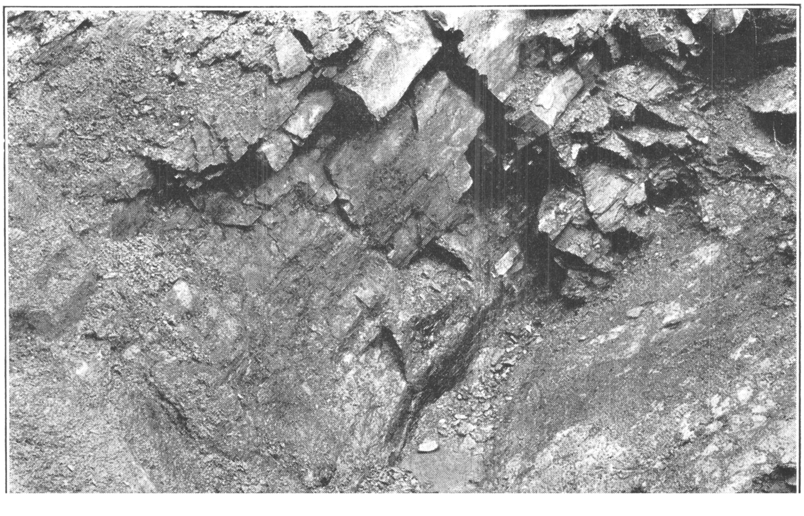

FIGURE 11.—Old drift in ore in Emauhee mine

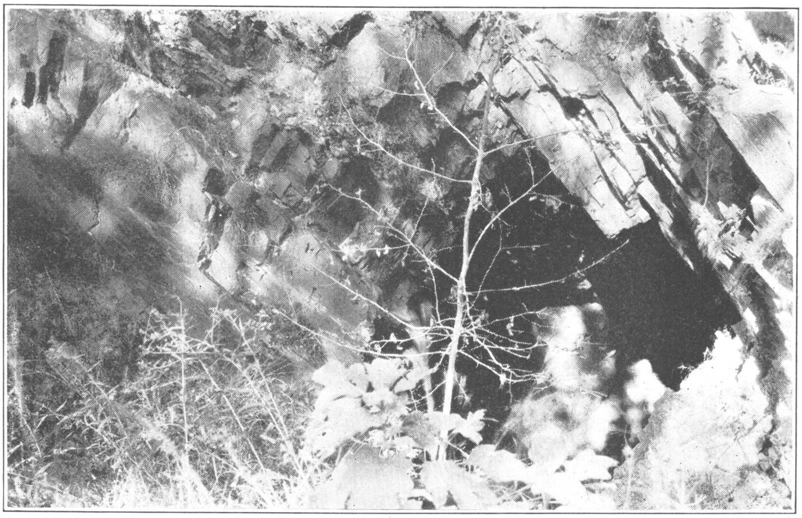

FIGURE 12.—Old opening in ore at Tallaseehatchee mine

amount of magnetite (see Table 26), and in one bed almost two-thirds of the iron mineral is magnetite.

When first mined, the ore is almost black, but on exposure to weather it becomes light gray. As the ore is a mixture of hematite and magnetite and is gray, the term " gray ore " is not only appropriate but also distinguishes it from the red and brown ores of Alabama.

Thin sections of the ore contain, in addition to the iron minerals, a great deal of quartz, which is the main source of the silica content. There is some feldspar, mainly soda-lime feldspar, although there is also some microcline. Mica, as a secondary product, is represented by scattered blocks of muscovite. Biotite is practically absent.

The main constituents of the ore are quartz and iron. The hematite is in scaly and apparently sheared aggregates, while the magnetite is generally in well-formed, sharp crystals, which have apparently been formed later than the hematite. In a very few thin sections iron sulphide has been recognized. The quartz occurs in two distinct forms—as an original mineral very much strained and shattered and as a secondary mineral showing no optical stress. This secondary quartz includes many crystals of magnetite, the relations of these minerals showing the relative age of crystallization of the magnetite and the later quartz. Mica was apparently contemporaneous with the later quartz. The magnetite, the later quartz, and the mica were probably formed at the close of the period of dynamic metamorphism during which the mountains were built.[3]

The iron minerals are minutely disseminated through the ore, and fine grinding is necessary to free them.

SAMPLING OF ORE

The sample of ore used at the start of the investigation had been taken by E. C. Eckel a number of years ago; it was from an outcrop and was weathered. A few tests yielded enough general information to serve as a basis for work on a larger scale.

In the fall of 1923 a visit was made to the Heacock Mountain and Riser Mountain properties of the Alabama Ore & Iron Co. to select the most suitable places for sampling. As a result, arrangements were made to remove the overburden and some 15 feet of ore at four points. Four samples of ore weighing about 2½ tons each were obtained. They represented the upper and lower beds at the Heacock Mountain and Riser Mountain properties. At the points of sampling the beds had lost some of their original content of lime, but to obtain samples below the weathered zone was impracticable.

Investigation of the gray ores of the Emauhee and Tallaseehatchee mines of the Gray Ore Iron Co. was not undertaken until the work on the ores from Heacock and Riser Mountains was completed. In the spring of 1925 samples were taken at two places at the Emauhee

[3] Smith, P. S., "The gray ores of Talladega County, Ala."; Contributions to Economic Geology, 1906: U. S. Geol. Survey Bull. 315, 1907, pp. 161–184.

mine and four places at the Tallaseehatchee. One of the six samples was taken in an opencut at the Tallaseehatchee, but all the others were mined from old stopes and immediately above water level. All the ore obtained underground was very hard, but as all the stopes sampled were only about 100 feet from the surface it is probable that the ore is from the zone of weathering. Each sample weighed 2½ tons.

GRADE OF ORES TESTED

Table 20 gives partial analyses of the 10 samples of ore—4 from the Weewoka district and 6 from the Tallaseehatchee district. The samples obtained from the Weewoka area are of higher grade, but none contains less than 26 per cent of insoluble. All are low in manganese and lime.

TABLE 21.—*Partial analyses of samples of gray ore*

[Values in per cent]

Mine and bed	Iron	Insoluble	Lime	Phosphorus	Manganese
Heacock Mountain:					
Upper bed	46.1	29.8	0.3	0.30	0.1
Lower bed	47.7	26.0	.2	.36	.1
Riser Mountain:					
Upper bed	41.6	34.6	.4	.65	.1
Lower bed	44.6	29.4	.5	.38	.1
Emauhee mine:					
Upper bed	44.4	27.6	.2	.33	.1
Lower bed	31.4	44.7	.3	.23	.2
Tallaseehatchee mine:					
Upper bed	38.4	38.5	Trace.	.33	.1
Second bed	43.0	31.3	Trace.	.36	.1
Third bed	35.7	40.1	1.0	.56	.2
Lower bed	42.3	31.8	.6	.36	.1

In Table 21 the ores are listed according to the geographic order of the places from north to south; Heacock Mountain represents the northern end of one district and the Tallaseehatchee mine the southern end of the adjoining district. The ores tend to become leaner toward the south.

PRELIMINARY TESTS

METHODS USED

The microscope was used in studying the physical character of the ores. Samples of the various screen sizes were examined for the amount of clean mineral and gangue in the different sizes. After being crushed to 4 mesh all the samples were subjected to screen analysis. The standard scale of screen sizes was used.

Magnetic assays were made of raw ore crushed to 100 mesh. The Davis magnetic tube, shown in Figure 2 and described on page 5, was used in making these tests. Magnetic-roasting tests were made in a small roasting drum, shown in Figure 1 and described on page 5.

PHYSICAL CHARACTERISTICS OF ORES

The samples are much alike. Microscopic examination reveals that the component minerals are in fine grains and the iron mineral is minutely disseminated; moreover, the ore has a foliated structure caused by pressure, and the mineral grains are flaky.

SCREEN ANALYSES

As the screen analyses in Tables 22 to 25 show, the distribution of the iron in the ores is remarkably uniform. The highest and lowest grades of ore were selected from the Weewoka and Tallaseehatchee districts. All of the samples are as uniform as those listed in the tables. Microscopic study of the screen sizes indicated that crushing to 100 mesh would be required to liberate the iron.

TABLE 22.—*Screen analysis of ore from lower bed of Heacock Mountain*

[Values in per cent]

Screen size (mesh)	Weight	Content of—		
		Iron	Insoluble	Phosphorus
Plus 4	1.0	49.2	25.1	0.40
Minus 4 plus 8	21.7	48.3	25.4	.38
Minus 8 plus 10	10.7	48.3	25.5	.37
Minus 10 plus 14	8.4	48.5	25.0	.34
Minus 14 plus 20	6.0	48.5	25.0	.35
Minus 20 plus 28	6.7	48.0	25.4	.35
Minus 28 plus 35	6.3	48.0	26.1	.33
Minus 35 plus 48	4.9	48.4	26.1	.32
Minus 48 plus 65	3.7	48.4	25.1	.30
Minus 65 plus 100	4.1	48.2	23.9	.29
Minus 100	26.5	45.7	27.3	.34
Composite	100.0	47.6	25.9	.35
Original ore		47.7	26.0	.36

TABLE 23.—*Screen analysis of ore from upper bed at Riser Mountain*

[Values in per cent]

Screen size (mesh)	Weight	Content of—		
		Iron	Insoluble	Phosphorus
Plus 4	0.7	41.5	34.8	0.74
Minus 4 plus 8	20.4	41.6	34.7	.73
Minus 8 plus 10	10.9	41.6	34.5	.73
Minus 10 plus 14	7.5	41.3	34.7	.64
Minus 14 plus 20	6.7	41.4	35.0	.59
Minus 20 plus 28	6.6	41.5	34.7	.55
Minus 28 plus 35	6.2	41.7	34.9	.50
Minus 35 plus 48	4.9	42.0	34.8	.49
Minus 48 plus 65	3.9	42.7	33.9	.47
Minus 65 plus 100	4.5	44.3	32.0	.45
Minus 100	27.7	40.9	35.0	.46
Composite	100.0	41.6	34.6	.58
Original ore		41.6	34.6	.55

TABLE 24.—*Screen analysis of ore from upper bed of Emauhee mine*

[Values in per cent]

Screen size (mesh)	Weight	Content of—		
		Iron	Insoluble	Phosphorus
Plus 4	16.9	44.4	26.8	0.35
Minus 4 plus 8	26.4	44.3	27.3	.36
Minus 8 plus 10	11.4	44.1	27.4	.35
Minus 10 plus 14	8.0	43.9	27.6	.34
Minus 14 plus 20	6.1	43.7	27.7	.36
Minus 20 plus 28	4.5	42.9	28.5	.33
Minus 28 plus 35	4.3	42.3	29.6	.31
Minus 35 plus 48	3.2	41.4	30.1	.31
Minus 48 plus 65	2.0	41.1	30.8	.30
Minus 65 plus 100	3.0	42.6	29.3	.31
Minus 100	14.2	45.9	25.1	.30
Composite	100.0	44.1	27.3	.34
Original ore		44.4	27.6	.33

TABLE 25.—*Screen analysis of ore from lower bed of Emauhee mine*

[Values in per cent]

Screen size (mesh)	Weight	Content of—		
		Iron	Insoluble	Phosphorus
Plus 4	19.8	32.0	43.8	0.21
Minus 4 plus 8	26.3	32.0	44.2	.21
Minus 8 plus 10	9.9	31.9	44.4	.23
Minus 10 plus 14	6.8	32.0	45.4	.22
Minus 14 plus 20	5.4	31.4	45.2	.23
Minus 20 plus 28	4.3	30.9	46.5	.24
Minus 28 plus 35	4.5	30.3	47.6	.24
Minus 35 plus 48	3.7	29.6	46.7	.22
Minus 48 plus 65	2.6	29.3	47.2	.25
Minus 65 plus 100	3.4	29.8	46.6	.21
Minus 100	13.3	31.8	43.6	.20
Composite	100.0	31.6	44.7	.22
Original ore		31.4	44.7	.23

MAGNETIC PROPERTIES OF ORES

That the gray ores contain magnetite has long been known, but data on the actual proportions of hematite and magnetite have been scanty. By means of the magnetic tube the authors obtained information as to the proportion of magnetite in the samples studied. The samples were crushed to pass 100 mesh; during the crushing a large part of each sample was unavoidably reduced to 300 mesh.

Table 26 gives the data from the tests with the magnetic tube. The percentage of iron recovered represents the proportion of the total iron that is recoverable as magnetite in the natural ore. The ores were so finely crushed that iron mineral caught by the magnet would, of course, be magnetite. Apparently the ores of lower grade contain the largest percentage of magnetite. As already pointed out, the ores in the southern end of the field are leaner than those the northern end, but, as Table 26 shows, the percentage of magnetite is higher in the southern ores. Smith refers to this fact in his report cited on page 35. He says: "In the range near Mesaba (Tallaseehatchee) and Emauhee the rocks are more metamorphosed and the magnetite increases perceptibly." The highest-grade concentrates were recovered from ores containing the larger percentages of iron and the lowest grade from the ores having the lower percentages of iron.

TABLE 26.—*Magnetic assays of raw gray ores*

[Values in per cent]

Source	Raw ore		Magnetic concentrate			Magnetic assay	Iron recovered
	Iron	Insoluble	Weight	Iron	Insoluble		
Heacock Mountain:							
Upper bed	46.1	29.8	10.93	68.1	2.4	7.44	16.15
Lower bed	47.7	26.0	10.50	67.4	2.5	7.08	14.20
Riser Mountain:							
Upper bed	41.6	34.6	15.68	65.8	5.8	10.32	24.81
Lower bed	44.6	29.4	10.04	67.9	2.3	6.82	15.29
Emauhee mine:							
Upper bed	44.4	27.6	38.26	66.5	5.7	25.44	57.30
Lower bed	31.4	44.7	33.86	60.6	12.0	20.49	65.24
Tallaseehatchee mine:							
Upper bed	38.4	38.5	27.01	61.9	10.4	16.72	43.54
Second bed	43.0	31.3	28.57	66.5	4.7	19.00	44.19
Third bed	35.7	40.1	26.61	63.0	8.1	16.76	46.96
Lower bed	42.3	31.8	29.08	64.0	8.3	18.61	44.00

At first glance there seems to be enough magnetite in some of the ores to affect the choice of a method of concentration. Details given on later pages will show, however, why the presence of natural magnetite is practically of no advantage.

MAGNETIC ROASTING

That hematite can be changed to magnetite by exposing it at red heat to carbon has been known for many years. Coke-oven or any other gas containing appreciable amounts of carbon monoxide and hydrogen will also serve the purpose. Removal of the oxygen makes the ore soft and porous and lowers its specific gravity.

The possibility of converting hematite to magnetite by roasting and of then separating the magnetite by magnetic concentration has been generally recognized. Davis[4] says:

> It is apparent that magnetic roasting and concentration is an old process which has been applied with little commercial success to various low-grade iron ores. From the available information it would seem that all attempts had failed, as effective magnetic roasting was not accomplished commercially. In all of these attempts a considerable part of the ore passing through the roasting furnace was not rendered magnetic. This seems to be the fault of the furnace rather than of the process.

[4] Davis, E. W., Magnetic Concentration of Iron Ore: Bull. 9, Minnesota Sch. Mines Expmpor 1921, p. 37.

Most of the attempts at roasting and magnetic concentration of iron ores were made before the enormous deposits of the Mesabi range dominated the price of ore. From that time until within a few years there has been little interest in the large-scale concentration of iron ore. Since 1900 roasting furnaces and roasting practice have improved greatly. The copper smelters of the Western States are now roasting copper ores on a large scale and are successfully employing methods that in a mechanical way are much like those required for roasting iron ores, hence there seems to be no reason why roasting can not be successfully applied to the gray iron ores of Alabama.

Table 25 shows that the gray ores are a combination of hematite and magnetite, hematite predominating in most of the samples. The magnetite was recovered by magnetic concentration after fine grinding, but the hematite escaped in the tailing. As magnetic concentration is generally acknowledged to be the most feasible method of beneficiating iron ores that are finely crushed, it is necessary to convert the hematite in the tailing to magnetite by roasting.

Ores that are to be roasted should be fairly coarse. Finely crushed ores cause high losses in furnace dust; moreover they pack and prevent free circulation of the reducing gases. The wet tailing from concentration would have to be partly dried before going to the roasting furnace. Another objection to recovering the natural magnetite in the ore before roasting is that fine grinding of raw ore would be more difficult and costly. On the other hand, fine grinding of roasted coarse ore would be comparatively simple because of the ore being softer and more porous. Reoxidation can be prevented by discharging the roasted ore into water. This sudden cooling of the hot ore causes it to crack and break up. Much of the roasted ore is soft enough to be broken with the fingers.

MAGNETIC-ROASTING TESTS

A series of preliminary roasting tests was made with 4-mesh samples of ore. The roasting drum (fig. 1) previously described was employed in the tests, which were run at 500° C. By-product coke-oven gas was used both as a heating and reducing agent. It is an efficient reducing agent and because so much of this type of gas is produced cheaply in the district no other was considered for testing purposes. Table 27 gives an average analysis of the gas.

TABLE 27.—*Analysis of reducing gas*

	Per cent		Per cent
Carbon dioxide (CO_2)	2.2	Nitrogen (N_2)	5.9
Oxygen (O_2)	.5	Illuminants	2.2
Carbon monoxide (CO)	4.9		
Methane (CH_4)	31.2		100.0
Hydrogen (H_2)	53.1		

NOTE.—Heating value, 552 B. t. u. per cubic foot.

The effective reducing agents in the gas are carbon monoxide and hydrogen; they have almost the same reducing efficiency. The roasted ore was crushed to 100 mesh for the magnetic assay, which determined the efficiency of roasting.

Table 28, which gives results of the roasting and magnetic-tube tests, shows that a large proportion of the iron was recovered by the magnetic tube and that the roasting was satisfactory. The best results were obtained with the Heacock Mountain ores, and the poorest concentrate was from the ore of the lower bed at the Emauhee mine. Table 26 (p. 41) shows that the Heacock Mountain ores contained the least magnetite, whereas more than 65 per cent of the iron in the lower bed of the Emauhee mine is magnetite. The results of the roasting tests indicate that, in general, the better grades of concentrate were obtained from the ores containing the higher percentages of iron; the iron in these ores carried the smaller proportions of natural magnetite.

Attention is called to the results of the magnetic-tube tests of the ore from the lower bed of the Emauhee mine. The concentrate contained only 51.1 per cent of iron in contrast to the much higher-grade concentrates from the other tests. The relatively poor quality of this one concentrate is attributed partly to the fact that the original low-grade ore contained 6.4 per cent of alumina and the resulting magnetic concentrates 3.7 per cent. The other nine samples shown in Table 28 contain 3.8 to 4.4 per cent of alumina, and the magnetic concentrates produced from them contain 1.6 to 1.8 per cent. As the alumina occurs as clay in intimate contact with the iron mineral, its separation is difficult. To determine whether or not extremely fine grinding would be beneficial, a sample of the high-alumina ore was crushed to 300 mesh before treatment in the magnetic tube.

TABLE 28.—*Magnetic assays of roasted gray ores*

[Values in per cent]

	Raw ore		Roasted ore		Magnetic concentrate			Iron recovered	Insoluble rejected
	Iron	Insoluble	Iron	Insoluble	Weight	Iron	Insoluble		
Heacock Mountain:									
Upper bed	46.1	29.9	46.7	30.9	66.87	68.0	4.0	97.37	91.3
Lower bed	47.7	26.0	49.4	26.4	71.56	67.8	5.4	98.21	85.3
Riser Mountain:									
Upper bed	41.6	34.6	42.7	34.7	67.45	62.0	6.7	97.94	87.0
Lower bed	44.6	29.4	46.0	29.7	67.44	67.0	4.1	98.23	90.7
Emauhee mine:									
Upper bed	44.4	27.6	45.6	28.1	71.45	62.1	11.6	93.30	70.5
Lower bed	31.4	44.7	32.9	45.6	61.68	51.1	24.5	95.80	67.0
Tallaseehatchee mine:									
Upper bed	38.4	38.5	39.7	38.4	59.47	64.3	10.7	96.32	84.5
Second bed	43.0	31.3	44.1	31.6	68.22	63.2	11.2	97.77	75.8
Third bed	35.7	40.1	36.0	40.6	57.19	60.7	13.4	96.42	81.2
Lower bed	42.3	31.8	43.1	32.0	66.78	63.0	11.3	97.61	76.4

The tube concentrate was substantially higher in iron (59 per cent) and lower in insoluble (14 per cent). The extraction of iron was 95 per cent and the insoluble rejected 83.7 per cent.

EFFECT OF FINE GRINDING

As previously stated, microscopic examination of the products of screen sizing revealed that all sizes coarser than 100 mesh contained unclean particles of mineral. A series of magnetic-tube tests of ore crushed to different sizes proved conclusively that grinding to 100 mesh was necessary to produce a good grade of concentrate from all of the samples.

Table 29 was prepared to show the advantage of fine grinding. All the samples gave better results when the grinding was increased from 28 to 48 mesh and from 48 to 100 mesh. Only four sets of tests are, therefore, given to illustrate the trend of the results. A test at minus 300 mesh of the ore from the lower bed of the Emauhee mine is included, for reasons already discussed.

TABLE 29.—*Effect of fine grinding on magnetic-tube concentration*

[Values in per cent]

	Roasted ore		Concentrate			Iron recovered	Insoluble rejected
	Iron	Insoluble	Weight	Iron	Insoluble		
Riser Mountain, upper bed:							
At minus 28 mesh	42.7	34.7	77.17	54.0	21.5	97.59	52.2
At minus 65 mesh	42.7	34.7	70.81	58.9	16.0	97.59	67.4
At minus 100 mesh	42.7	34.7	67.45	62.0	6.7	97.94	87.0
Emauhee mine, lower bed:							
At minus 28 mesh	32.9	45.6	81.84	39.2	36.1	97.51	35.2
At minus 48 mesh	32.9	45.6	76.23	42.1	33.5	97.54	44.0
At minus 100 mesh	32.9	45.6	61.68	51.1	24.5	95.80	67.0
At minus 300 mesh	32.9	45.6	52.97	59.0	14.0	95.00	83.7
Tallaseehatchee mine, second bed:							
At minus 28 mesh	44.1	31.6	85.41	50.9	24.4	93.58	34.0
At minus 48 mesh	44.1	31.6	80.44	53.8	21.8	98.13	44.5
At minus 100 mesh	44.1	31.6	68.22	63.2	11.2	97.77	75.8
Tallaseehatchee mine, third bed:							
At minus 28 mesh	36.0	40.6	81.96	43.0	31.8	97.89	35.8
At minus 48 mesh	36.0	40.6	72.81	48.1	28.5	97.28	48.9
At minus 100 mesh	36.0	40.6	57.19	60.7	13.4	96.42	81.2

The percentage of iron recovered is almost the same in all of the tests. The effect of grinding to certain sizes is shown by the grade of concentrate and the percentage of insoluble rejected; fine grinding makes it possible to have high-grade concentrates low in insoluble.

SUMMARY

A brief summary of the information obtained in the preliminary tests follows:

1. The iron and insoluble contents of the gray ores range from 31.4 and 44.7 per cent, respectively, in ore of the poorest grade to 47.7

and 26 per cent, respectively, in the best ore. Even the sample richest in iron contained an excessive amount of insoluble. (See Table 21.)

2. The ores are a mixture of hematite and magnetite, the larger part ordinarily being hematite. (See Table 26.)

3. The presence of magnetite in the ore has no economic effect upon the method of concentration, except in isolated instances.

4. The roasting of coarse ore at a temperature of 500° C. or higher is necessary to convert the hematite to magnetite and allow the use of magnetic concentration.

5. Roasting makes the ore soft and easy to grind.

6. Fine grinding (minus 100 mesh) is necessary for satisfactory liberation of iron mineral from gangue. (See Table 29.)

7. Concentrates containing 60 per cent or more of iron can ordinarily be produced by magnetic concentration, with recovery of more than 95 per cent of the iron. (See Table 29.)

8. The preliminary tests indicate that the grade of the concentrate produced is governed somewhat by the grade of the ore treated. Thus Table 29 shows that the highest-grade concentrate was produced from the highest-grade ore and vice versa.

LARGE-SCALE TESTS

The data obtained from the preliminary tests were used as a guide for the large-scale tests. These tests also served as a maximum efficiency indicator. The large-scale tests were made with machines of semicommercial size, and about 1 ton of ore was generally used for a test.

MACHINES USED

To treat the ore a miniature mill was built. The flow sheet arranged for treating a continuous flow of ore included the following machines:

For coarse crushing, jaw crusher, rolls.
For coarse sizing, shaking screen.
For roasting, six-hearth roasting furnace.
For fine grinding, conical ball mill.
For fine sizing, rake classifier.
For pulp thickening, mechanical rake thickener.
For magnetic concentration, two magnetic log washers in series.
For agglomerating, down-draft sintering pan.

The machines are all of standard types now used successfully in ore dressing. As devices for coarse crushing have been pretty well standardized, nothing need be said about the jaw crusher and rolls used. It may be of interest, however, to discuss briefly the operation of the other machines used in treating the gray ores.

Roasting furnace.—The furnace has been shown in Figure 3 and described on page 20.

Mechanical rake classifier and ball mill.—The classifier and the mill have been described on page 20. The mill is shown in Figure 4.

Mechanical thickener.—The mechanical thickener has been described on page 21 and is pictured in Figure 5.

Magnetic log washer.—The magnetic log washer used has been described on page 21.

Sinter pan.—The fine concentrates were agglomerated in a single sinter pan, which has been described on page 21.

METHOD OF TREATMENT

Samples weighing about 3,000 pounds each were prepared by stage crushing to one-quarter inch. From a bin near the roasting furnace the ore was fed to a hopper which delivered it continuously and regularly to the preheating hearth of the furnace. The rate of feed was ordinarily 260 to 300 pounds an hour, although the furnace can handle much more than that. The lower three hearths of the furnace were generally kept at a temperature between 500 and 600° C.; by adjusting the valves for gas and air the temperature was easily controlled and maintained at any desired point. The temperatures were recorded with thermocouples and pyrometers. The furnace ran at a rabble speed of 52 revolutions per hour and the ore traveled through the furnace in less than one and one-half hours.

The roasted ore discharged through a 3-inch pipe into the overflow end of a duplex rake classifier and was immediately quenched to prevent reoxidation of the magnetite to hematite. The ball mill was loaded with 900 pounds of 1 to 2 inch iron balls and was run at a speed of 37 r. p. m. by a 7.5-hp. motor. The crushed ore passed from the ball mill into the rake classifier, whence the 100-mesh material overflowed into a launder which carried the wet pulp through a magnetizing coil and into a mechanical thickener. The function of the magnetizing coil is weakly to magnetize the particles of magnetite so that when they flow into the mechanical thickener more rapid settling will take place as a result of the magnetic mass action of the particles. The thickener delivers the thickened pulp to the magnetic log washer underneath it. The pulp ordinarily contains 40 to 60 per cent of solids. The clear water overflowing the top of the thickener can be reused as wash water in the magnetic log washers.

As already stated the magnetic log washer can be adjusted to suit the conditions necessary for handling different grades of ore. Average operating conditions required the spirals to rotate at 30 to

35 r. p. m., a slope of 2 to 3 inches per foot, and a consumption of 0.25 to 0.35 kilowatt for field excitation. The 5-foot machine handled an average of about 275 pounds of dry gray ore an hour. The thick pulp enters the log washer a little below the center of the machine. The first log washer of two in series may be run to produce a clean tailing and a fair grade of concentrate. The latter goes to a second machine of the same type, where more gangue is removed, raising the grade of the final concentrate. Another method is to make a partial recovery of concentrate in the first log and then re-treat the tailing in the second step. This arrangement is not particularly desirable in the treatment of the gray ores.

The concentrate from the magnetic machines ordinarily contains much water. Most of it was removed by settling, and the remaining thick pulp was dried. As it was impracticable to sinter the concentrate continuously in such small-scale tests, a sample was cut from the dried concentrate and mixed with the proper amounts of water and fuel. The mixture was sintered in the laboratory sinter pan.

RESULTS OF LARGE-SCALE TESTS

The first large-scale tests were made with the ores from Heacock and Riser Mountains. The results of several such tests did not equal the standard set by the later tests. General improvement in results that followed adjustments and changes in the method of treatment was recorded as the investigation proceeded. For example, a number of the earlier tests were made with only one magnetic log washer, operated in conjunction with a concentrating table. When a second log washer was added to the circuit, both the grade of concentrate produced and the percentage of recovery showed marked improvement; from then on the method was pretty well standardized.

Many tests of individual lots representing certain beds of ore were made. Good results were realized from all the individual samples treated during the later part of the investigation. The results obtained with the flow sheet finally developed are thought to be fairly representative of what might reasonably be expected of a commercial plant. Table 30 embodies the results of several typical tests of a number of ores. It may be observed that all but two of the sintered products contained 60 per cent or more of iron. One of the two was from the lower bed of the Emauhee mine; it gave trouble even in the magnetic tube. The recovery of iron was invariably high, only two of the seven tests yielding less than 95 per cent.

The results of the work with the composite samples (later shown) are regarded as more representative of commercial practice, as the ore mined in different parts of the deposits owned by a company would undoubtedly be combined before treatment. The quantities of ore used in the composite samples are all in direct proportion to the thickness of the ore beds at the points of sampling.

TABLE 30.—*Large-scale roasting and magnetic-concentration tests of samples from several ore beds*

[Values in per cent]

	Raw ore		Sintered concentrate		Iron recovered	Insoluble rejected
	Iron	Insoluble	Iron	Insoluble		
Heacock Mountain, upper bed	46.0	29.8	62.0	13.8	95.3	67.2
Riser Mountain, upper bed	41.6	34.6	60.3	15.0	92.7	72.4
Emauhee mine:						
Upper mine	44.4	27.6	60.2	13.7	98.2	63.8
Lower mine	31.4	44.7	50.4	23.9	96.7	68.5
Tallaseehatchee mine:						
Upper bed	38.4	39.0	58.8	16.6	96.9	73.2
Second bed	43.0	31.1	61.0	14.1	96.5	68.2
Lower bed	35.7	40.1	60.0	15.2	91.7	80.3

In only one test was a sample of ore concentrated on a large scale without roasting. Magnetic-tube tests had shown that the raw ore from the lower bed of the Emauhee mine could be raised from 31.4 to 60.5 per cent of iron, with a recovery of over 65 per cent of the iron. This ore had failed to yield to the roasting and magnetic-concentrating treatment which was applicable to the other ores on the property of the Gray Ore Iron Co. A concentrate comparable with that of the others could be obtained from the roasted ore only after crushing to 300 mesh. (See Table 29.)

The results of the large-scale test of the raw ore resulted quite favorably. Comparing the results with those of the magnetic-tube test, it will be found that while the concentrate produced by the large-scale test was a little lower in iron the percentage of recovery was 4 per cent higher. Table 31 compares the results of the two tests.

TABLE 31.—*Comparison of large-scale test with magnetic-tube tests of ore from lower bed of Emauhee mine*

[Values in per cent]

	Unroasted ore		Unsintered concentrate			Iron recovered	Insoluble rejected
	Iron	Insoluble	Weight	Iron	Insoluble		
Magnetic-tube test	31.4	44.7	33.86	60.5	12.0	65.24	90.9
Large-scale test	31.4	44.7	37.56	57.9	14.9	69.25	87.5

TESTS OF COMPOSITE SAMPLES

Flow sheet for ore from Heacock and Riser Mountains.—The final large-scale tests used composite samples, the first being mixed ore from Heacock and Riser Mountains. The flow sheet (fig. 13) shows in detail the travel of the ore from the time it was discharged by the roasting furnace until it was delivered as a sintered concentrate. The ore was crushed to one-quarter inch and roasted. The concentrate from the magnetic log washers was dried and mixed with 20-mesh coke and with water. The resulting feed to the sinter pan contained 7 per cent of coke and 12 per cent of moisture.

The composite sample of ore discharged by the furnace contained 46.5 per cent of iron, but in spite of its fairly high content of iron it contained 30.2 per cent of insoluble. The treatment outlined in the flow sheet removed 75.1 per cent of the insoluble and thereby increased the iron in the sintered concentrate to 62.9 per cent, with a recovery of 93.5 per cent. For every ton of concentrate produced 1.43 tons of ore were treated.

Flow sheets for ore from six and from five beds.—The ores of the Emauhee and Tallaseehatchee mines were combined in two ways for final treatment. One method of combining and treating the ores is outlined in the flow sheet (fig. 14), in which a composite of all of the six beds was given a magnetizing roast. The second method of handling the ore is shown in the flow sheet. (Fig. 15.) Here the ore from only five of the six beds was combined and roasted. To the roasted ore was added raw ore from the lower bed of the Emauhee, and from this point on the method of treatment was the same as that shown in Figures 13 and 14.

In roasting the combined ore from six beds no advantage was taken of the fact that one of the ores contained the iron mineral, chiefly as magnetite. It will be observed that the sintered concentrate from this run assayed 58.8 per cent of iron and 15.2 per cent of insoluble. In recovering 94.63 per cent of the iron in the ore 73.2 per cent of the insoluble was rejected in the tailing. The ratio of concentration was 1.59 into 1. The ore from the lower bed of the Emauhee mine comprised over 25 per cent of the composite. Because previous tests had shown the difficulty of concentrating this particular lot of ore, it was expected that the results of the test of the composite sample would be affected.

Figure 15 illustrates the advantages and disadvantages of treating the raw ore from the Emauhee in combination with roasted ore from the other beds of the two mines. The test of the unroasted ore from the Emauhee showed that a good grade of concentrate could be produced, but with a recovery of only 69 per cent of the iron. It is obvious, therefore, that the recovery of iron would be decreased when this ore is mixed raw with the roasted ores from the other five beds. A recovery as low as 90.35 per cent is therefore not surprising. The sintered concentrate contained 59.9 per cent iron and 14.8 per cent insoluble, a fair improvement over the results of the previous test, shown in Figure 14.

Although the results of this test are very interesting, it is doubtful whether handling the ore in that way would be feasible. Grinding the raw ore would cost more than grinding roasted ore. The loss of

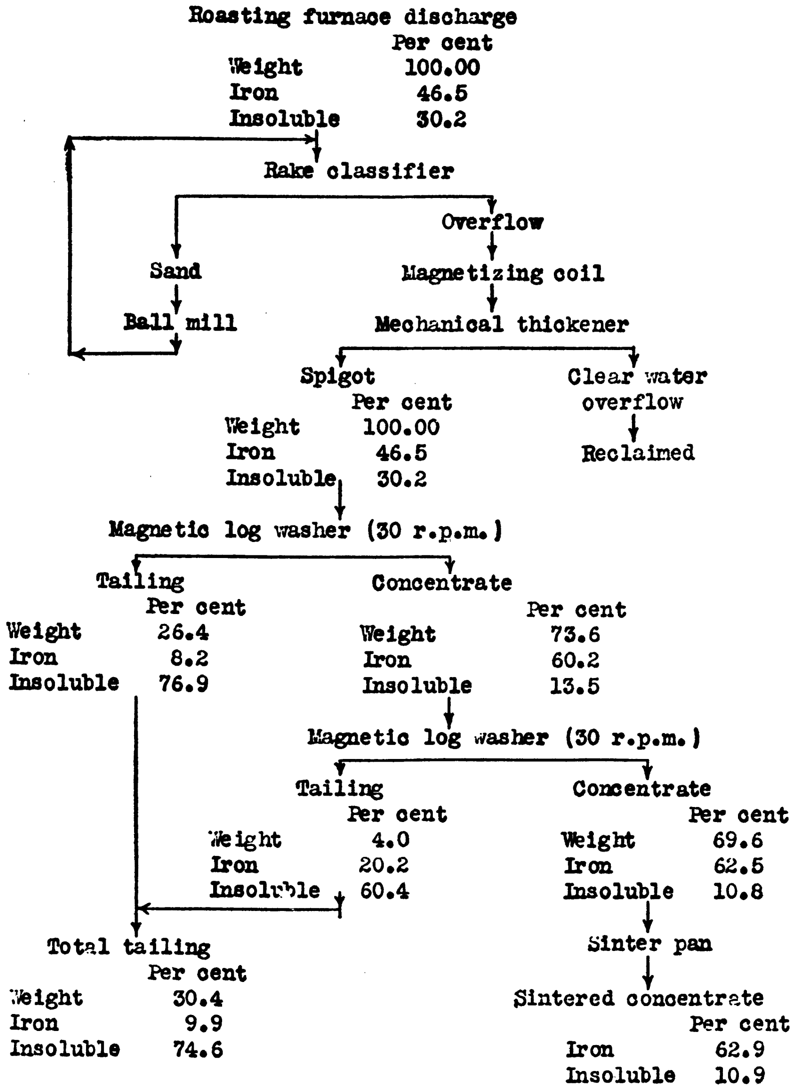

FIGURE 13.—Flow sheet for roasting and magnetic concentration of ore from Heacock and Riser Mountains. Ratio of concentration, 1.43 : 1; iron recovered, 93.5 per cent; insoluble rejected, 75.1 per cent

iron would also be higher than is allowable. The grade of the concentrate would be a little better, but the difference is probably not enough to offset the disadvantages.

General operating data.—The three tests of composite ores were made under standardized conditions. Table 32 gives the operating data obtained during the test shown in the flow sheet. (Fig. 14.)

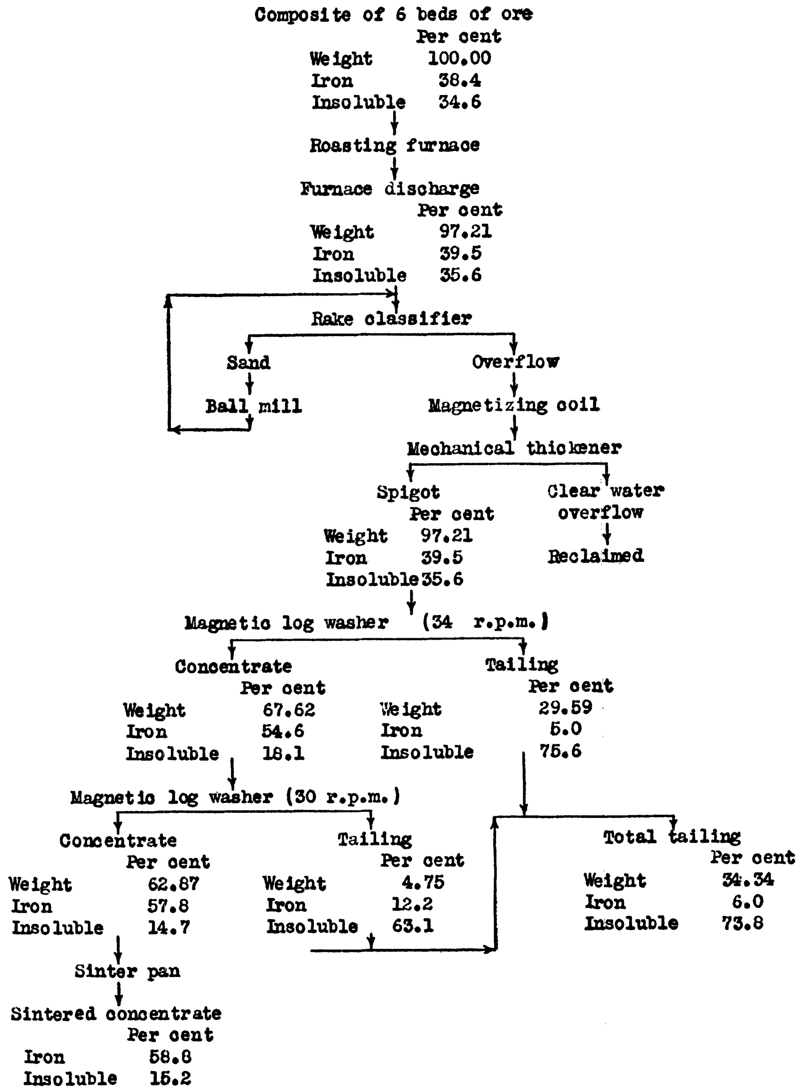

FIGURE 14.—Flow sheet for roasting and magnetic concentration of ore from the Emauhee and Tallaseehatchee mines. Ration of concentration, 1.59 : 1; iron recovered, 94.63 per cent; insoluble rejected, 73.2 per cent

These data are representative of the average conditions of the other tests.

The several machines were adjusted to comply with conditions for the tests under a limited rate of feed. Because of the expense involved no attempt was made to run them at capacity. A large enough quantity of ore was treated with a continuous feed to insure reliable results, therefore, conditions would be far different in com-

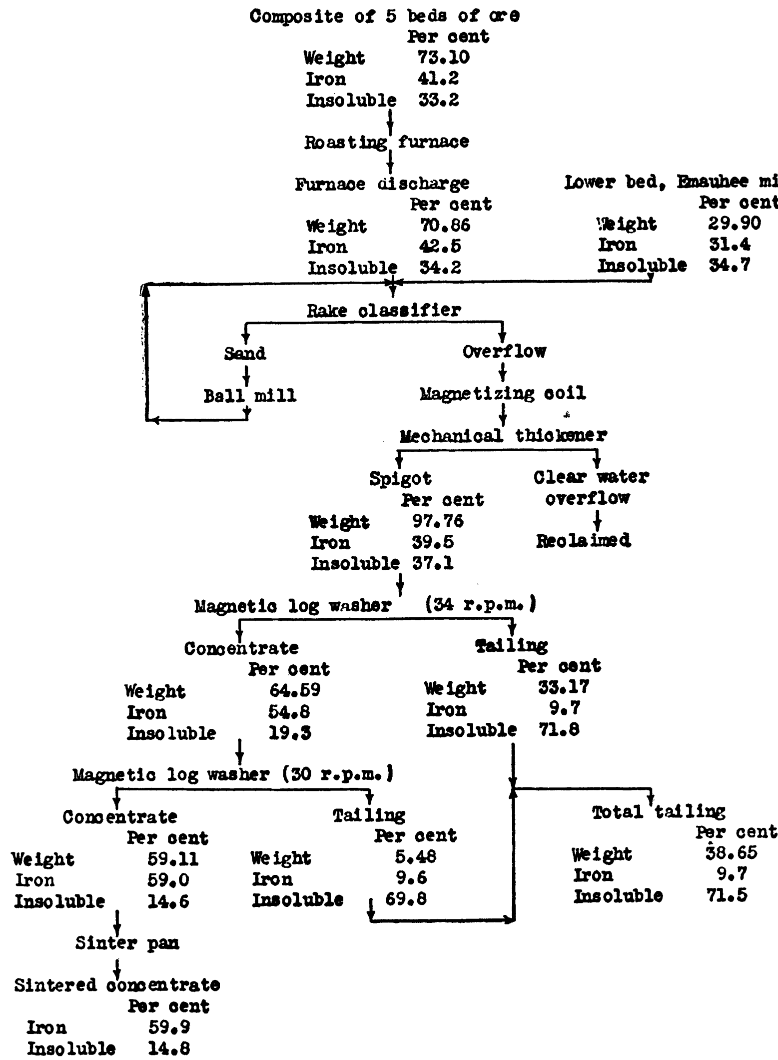

FIGURE 15.—Flow sheet for roasting and magnetic concentration of ore from the Emauhee and Tallaseehatchee mines. Ratio of concentration, 1.69 : 1; iron recovered, 90.35 per cent; insoluble rejected, 76.1 per cent

mercial practice, where, with steady operation over long periods of time, the results would probably be even better than those shown in this report.

TABLE 32.—*General operating data from roasting and magnetic concentration tests of gray ores*

Rate of feed, 247 pounds an hour.
Size of feed, ¼ inch.
Roasting furnace:
- Number of hearths, 6.
- Speed of rabble arms, 52 revolutions per hour.
- Temperature of reducing zone, 560° C.
- Gas consumption for heating and reducing, 500 cubic feet per hour.

Duplex rake classifier:
- Slope of bottom, 2.8 inches per foot.
- Speed of rakes, 17½ strokes per minute.
- Water consumption, 4 gallons per minute.

Conical ball mill:
- Ball load, 900 pounds.
- Size of balls, 1 and 2 inches.
- Speed, 37 revolutions per minute.

Mechanical thickener:
- Speed, 15 revolutions per hour.
- Spigot discharge, 40 to 60 per cent of solids.

Magnetic log washers:
- Speed, 34 and 30 revolutions per minute.
- Slope, 2.9 inches per foot.
- Power for magnetic coils, 0.30 kilowatt.
- Wash water, 4½ gallons per minute.

Sintering machine:
- Amount of coke used for fuel, 7 per cent by weight.
- Amount of moisture in feed, 12 per cent by weight.
- Ignition, by gas flame.

Table 33 contains screen analyses of the overflow of the rake classifier and the concentrate produced by the magnetic log washers during the test shown in Figure 14. About 95 per cent of each of these products passed a 300-mesh screen. This extreme fineness is attributed to roasting, which makes the ore very soft and in turn makes fine grinding simple. Such fine grinding is generally viewed with disfavor where gravity concentration is practiced, but for magnetic concentration it is far from being a handicap, for the magnetic log washer works best when handling extremely fine material.

The material in the concentrate coarser than 300 mesh is comparatively low grade, but its amount is so small that it has no appreciable effect on the quality of the concentrate produced.

TABLE 33.—*Screen analysis of concentrator products*

A.—RAKE-CLASSIFIER OVERFLOW (MAGNETIC LOG-WASHER FEED)

Mesh	Weight	Iron	Silica	Alumina	Phosphorus
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Minus 100 plus 200	0.5	31.2	39.7	4.5	0.28
Minus 200 plus 300	3.6	25.2	50.4	5.2	.25
Minus 300	95.9	40.2	30.5	4.3	.40
Total	100.0	39.5	31.2	4.4	.39

B.—MAGNETIC LOG-WASHER CONCENTRATE

Mesh	Weight	Iron	Silica	Alumina	Phosphorus
Minus 100 plus 200	0.8	32.2	39.0	6.1	0.26
Minus 200 plus 300	4.8	40.6	31.2	4.5	.23
Minus 300	94.4	58.9	11.5	1.9	.19
Total	100.0	57.8	12.7	2.0	.19

SUMMARY

The gray ores of Talladega County used in this investigation were obtained from Heacock and Riser Mountains in the Weewoka district and from the Emauhee and Tallaseehatchee mines of Tallaseehatchee district. Ten samples were analyzed; they contained varying proportions of hematite and magnetite, with hematite predominating in all but two samples. The magnetite in the ores contained from 14.2 per cent to as high as 65.24 per cent of the total iron. These figures were obtained with the assistance of a Davis magnetic-tube separator.

The total iron content of the ores varied between rather wide limits. The poorest ore came from the lower bed of the Emauhee mine and assayed 31.4 per cent of iron and 44.7 per cent of insoluble. The best ore, which contained 47.7 per cent of iron and 26.0 per cent of insoluble, represents the lower bed of Heacock Mountain. None of the ores contained more than 1 per cent of lime, and the phosphorus, which ranges from 0.23 to 0.65 per cent, follows no particular trend. Only a fraction of 1 per cent of manganese is present.

Grinding to 100 mesh is essential to clean liberation of iron mineral from gangue. Gravity concentration is not suitable for beneficiating such finely crushed iron ores. Roasting and magnetic concentration give desirable products.

As the ores do not carry enough magnetite to permit magnetic concentration of the unroasted ore, roasting is necessary to convert the hematite to magnetite. Roasting not only reduces the ore but makes it soft and crumbly, therefore fine grinding is comparatively simple.

In fine grinding the aim is to deliver a minus 100-mesh product to the magnetic concentrators, but to do this the bulk of the material is crushed to 300 mesh. As the ore is ground easily, this fact is not regarded with any alarm when costs are considered.

Magnetic concentration is best handled in two stages; the first stage is a roughing treatment. The resulting concentrate is retreated in the second stage.

The assumption was made that a high extraction of iron is essential in the treatment of gray ores. In treating the individual lots of ores there was ordinarily no difficulty in producing a 60 per cent concentrate with a recovery of over 95 per cent of the iron. The ore from the lower bed of the Emauhee mine was, however, a conspicuous exception. This ore was very low grade and in the large-scale tests of roasted ore would not yield a concentrate containing more than about 50 per cent of iron. A 59.4 per cent sinter was produced from the raw ore, but the recovery of iron was only 69 per cent. The composite sample of ore from Heacock and Riser Mountains responded to the treatment with a 52.9 per cent sinter and a recovery of 93.5 per cent of the iron.

The composite samples of ore from the Emauhee and Tallaseehatchee mines were concentrated in two ways. The first method consisted in roasting the ore from all of the six beds, but in the other method the ore from only five of the beds was roasted and that from the sixth (lower Emauhee) bed was added in the natural state. A 58.8 per cent sinter was produced by the first method, with a recovery of 94.6 per cent of the iron. The second method resulted in a 59.9 per cent sinter, but the recovery of iron dropped to 90.4 per cent.

The grade of concentrate can be controlled to some extent by proper mixing of the ores, because richer concentrate can be produced from some ores than from others.

Much of the phosphorus is eliminated by concentration. The flow sheets (figs. 13 to 15) show that in the composite sample of ore the actual percentages of phosphorus in the sintered concentrate are 0.13, 0.19, and 0.16. The corresponding ores before concentration contained 0.31, 0.39, and 0.35 per cent of phosphorus. In view of the fact that there was an increase in the iron content of the concentrate, the reduction of the phosphorus per unit of iron was appreciable.

Sintering is preferably done with coke as a fuel. As a higher temperature is obtainable, a more compact sinter cake can generally be produced when coke is used. A slight increase in iron, due to the removal of oxygen, is shown in the sinter. The porosity of sinter makes it an ideal blast-furnace feed. A larger surface is exposed to the action of heat and reducing gases, consequently smelting is more rapid and less fuel is required.

CONCLUSIONS

Although the gray iron ores carry a fair percentage of iron, they are too high in silica and alumina to be smelted profitably. Concentration is a satisfactory remedy.

The investigation has shown conclusively that a good grade of concentrate can be produced from the gray ores by a process involving roasting and magnetic concentration. The four principal steps in the process are roasting, fine grinding, magnetic concentration, and sintering.

A concentrate containing 60 per cent of iron can be produced from the average gray ores with an extraction of approximately 94 to 95 per cent of the iron. The grade of the concentrate produced will depend to some extent upon the proper mixing of the ore going to the concentrator to maintain a uniform feed.

The finished product of the concentrator is in the form of sinter, an excellent blast-furnace feed.

FLOTATION OF LIMESTONE FROM SILICEOUS GANGUE

By Oscar Lee

INTRODUCTION

Flotation is generally regarded as a process applicable to metallic minerals only. However, its scope is now known to be wider, because some of the nonmetallic minerals, including graphite, sulphur, and fluorite, are floatable; and recent observations show that limestone may be added to the list by reason of work done on a laboratory scale at the Southern experiment station of the Bureau of Mines, Tuscaloosa, Ala., where experimental magnetic concentration of the low-grade iron ores of the Birmingham district has been under way. Certain experiments demonstrated that lime may be floated from the magnetic log-washer tailing and then incorporated in the iron concentrate. Throughout this work W. H. Coghill acted as adviser.

If loss of lime could be prevented, some ores, though low in iron and high in insoluble, would contain enough to make their concentrates self-fluxing. Inasmuch as this loss in the magnetic log washer can not be avoided, the lime must be recovered from the tailing by some method and added to the magnetic iron concentrate before sintering. The resulting concentrate will then be self-fluxing.

During a search for a suitable method of treating tailing to recover line, flotation was tried. That this method had possibilities was at once evident. During the early part of the investigation soap solution made from common soap was the flotation reagent. The froth obtained was a fairly good lime concentrate. This result gave an important clue and led to the use of such reagents as oleic acid and sodium oleate. Later, cresol, creosote, coal tar, and similar flotation reagents were used in combination with the oleic acid and soap solutions. Oleic acid and cresol used together proved satisfactory.

The tailing from the magnetic log washer was in excellent physical condition for flotation. The iron ore had been ground in a ball mill to 100 mesh for magnetic concentration, hence the bond between the lime carbonate and the other constituents of the tailing was well broken.

Fair results were obtained by one-stage flotation, but the roughing and cleaning system was more efficient; the tailing from the cleaner was returned to the rougher.

RESULTS OF TESTS

The results of two typical tests will suffice to show how freely the lime floats in the presence of the siliceous gangue. The tailings from two ores were used. One had a tenor of 24.6 and the other 33.4 per cent of CaO. The tests were made under similar conditions by the roughing and cleaning system with the same reagents. The only difference in the two tests was in the amount of reagents.

TABLE 34.—*Flotation of limestone from siliceous gangue*

SAMPLE A

[Values in per cent]

Product	Weight	Lime	Insoluble	Iron	Lime recovered	Insoluble rejected
Feed	100.0	24.6	40.4	8.2		
Concentrate	39.3	49.8	2.4	2.6	79.5	
Tailing	60.7	8.3	65.0	11.8		97.7

SAMPLE B

Product	Weight	Lime	Insoluble	Iron	Lime recovered	Insoluble rejected
Feed	100.0	33.4	24.5	5.6		
Concentrate	59.4	48.7	3.2	4.0	86.5	
Tailing	40.6	11.1	55.7	8.7		92.3

Although sample A was relatively lean, it yielded a concentrate as rich in lime as sample B. The recovery would probably have been lower if a tailing of low lime content was treated. The concentrate shown in Table 34, sample A, compared favorably with the limestones now utilized as flux. The average analysis of the limestone in use in the Birmingham district when the investigation was made was as follows: Insoluble, 3.5 per cent; iron, 0.5 per cent; and lime, 53 per cent. Dolomite was being used extensively as a flux and averages 1.50 per cent of insoluble, 0.5 per cent of iron, 30.3 per cent of lime, and 20.7 per cent of magnesium oxide. The lime concentrate was somewhat higher in iron than the commercial stone, but the purpose of smelting is to recover iron, hence this feature was not undesirable.

Inexpensive reagents were used, so the quantity necessary for good separation would not be prohibitive. The tests indicate that the amount required did not exceed 1.5 pounds for each ton of tailing treated. About equal quantities of oleic acid and cresol seemed to give the most satisfactory results. At prices then prevailing these two reagents cost 10 and 18 cents a pound, respectively.

To give a clear idea of the effect of adding the floated lime to the magnetic concentrate, a few figures are presented. (Table 35.) A typical ore was selected for the illustration.

Table 35.—*Result of adding floated lime to iron concentrate*

[Values in per cent]

Product	Iron	Insoluble	Lime	Iron recovered	Lime recovered	Insoluble rejected
Ore	35.3	23.2	11.9			
Iron concentrate	51.4	12.6	4.3	95.84		
Tailing to flotation	4.3	42.3	25.4			62.7
Flotation concentrate	3.0	3.0	48.5			
Final sintered concentrate	50.3	12.9	13.3	97.1	76.1	

The value of lime flotation is manifest in the above table. Not only is use made of the available lime for fluxing the gangue, but the recovery of iron is increased and the sintered concentrate rendered self-fluxing. Such a product would reduce very rapidly in a blast furnace, thereby increasing furnace capacity greatly.

MAGNETIC CONCENTRATION OF FLUE DUST OF THE BIRMINGHAM DISTRICT

By Oscar Lee, B. W. Gandrud, and F. D. DeVaney

INTRODUCTION

Flue dust from the smelting of ores containing appreciable quantities of fines is one troublesome product of iron blast-furnace practice. Gases issuing at high velocity from the furnaces carry small particles of coke, ore, and flux into dust-collecting chambers. These particles constitute flue dust. Losses of iron ore through the production of flue dust vary between wide limits at different furnaces and depend upon a number of factors, such as size and design of furnace, amount of fines in the ore, operating conditions, and blast pressure.

Blast-furnace operators of the Birmingham district realize this waste keenly. The ores are comparatively low grade and require more fuel than is ordinarily used elsewhere, hence the flue dust contains little iron and much coke, and is therefore unsuitable for direct sintering. In many other iron and steel centers direct sintering is a common practice. In the Birmingham district efforts have been made to prevent dust losses by recharging the dust into the furnace, but, as might be expected, a material fine enough to be blown out once will probably be carried over again.

In general, the flue-dust losses in the district average 250 pounds for each ton of pig iron produced, but at times the losses at different furnaces are substantially higher or lower. On the basis of the present rate of pig-iron production, the annual loss of flue dust exceeds 300,000 tons. The iron content of the dust probably averages 25 per cent, therefore about 75,000 tons (about 3 per cent) of the iron mined is wasted yearly in flue dust.

The operators of the district are endeavoring to prevent this waste, and this investigation was undertaken at their request.

The red ores of the district require very fine grinding to free the mineral from the gangue, hence gravity concentration is impracticable. As the important constituent of this flue dust is red ore, gravity concentration need be considered only for removing coke. On the other hand, if the iron mineral has been reduced to magnetite, magnetic concentration is desirable.

ACKNOWLEDGMENTS

Acknowledgment is due the several companies of the district who cooperated with the Southern experiment station in furnishing the samples of flue dust necessary for the investigation. Information on the operating conditions at the furnaces from which the samples were obtained was always freely given.

The authors wish to express their appreciation of the many helpful suggestions and criticisms of W. R. Crane, superintendent of the Southern station, and W. H. Coghill, metallurgist, of the Bureau of Mines.

PRELIMINARY TESTS

CHARACTERISTICS OF FLUE DUSTS

Samples of flue dust were obtained from the furnaces of seven operating companies. The great variation in smelting conditions is evidenced by the fact that the samples were so dissimilar. The differences are not surprising, however, when one considers the irregular nature of the furnace burdens and the conditions under which smelting is done.

The iron mineral in the ore charged to the furnaces is chiefly hematite, but some limonite ore is used. Some furnaces smelt self-fluxing red hematite ore exclusively, others a mixture of red and brown ores. Occasionally as much as 50 per cent of the burden is brown ore. Very often the operators smelt ores which are on hand regardless of whether they are red or brown, and this results in a continually changing burden. An abundance of red ore in the Birmingham area is low enough in insoluble to be used, but it is not self-fluxing. In smelting such ore limestone is added or the ore is mixed with other ores which contain an excess of lime. Limestone is also required when the charge carries a large proportion of washed brown ore.

The ore, whether red or brown, is crushed to pass a 3 or 4 inch opening, but crushing as fine as 2 inches is not uncommon. The crushing is done in gyratory crushers and produces fines; a large part of this fine material is blown out of the furnace later.

The size of coke particles escaping in the flue dust varies through a wide range. Sometimes they are fine enough to pass a 35-mesh screen, but more often a fairly large proportion is coarser than 35 mesh. At times much of the coke is as coarse as one-eighth to one-half inch and even larger.

The particles of ore and flux are finer than the coke as a result of the air classification of particles of different specific gravities. The average screen test will show a high carbon and a low iron content for the coarser sizes, a relation that is gradually reversed as size decreases.

The chemical contents of the flue dusts vary widely. The percentage of iron depends mainly upon the grade and kind of ore charged to the furnace. The flue dust of highest iron content generally comes from furnaces handling a large proportion of brown ore and the leanest dust from those smelting red hematite only.

All of the characteristics described in the foregoing paragraphs influence the problem of concentration. Moreover, the magnetic property of the iron minerals in the flue dust is another factor of importance. As will be shown, a flue dust which has been well reduced and hence contains a large proportion of the iron mineral as magnetite is readily amenable to concentration.

COMPOSITION OF FLUE DUSTS

Table 36 shows the composition of a variety of flue dusts investigated. The samples are designated by number and these numbers will be uniform throughout.

TABLE 36.—*Chemical analyses of a variety of flue dusts*

[Values in per cent]

Flue dust No.	Iron	Insoluble	Lime	Phosphorus	Sulphur	Carbon
1	21.6	11.9	13.2	0.22	0.16	30.6
2	22.1	17.8	9.6	.21	.17	26.5
3	24.3	17.5	6.7	.26	.18	30.1
4	29.6	20.2	10.9	.24	.10	11.6
5	30.0	18.6	11.4	.23	.13	18.1
6	36.8	13.8	7.8	.21	.28	15.2
7	45.8	14.0	2.9	.09	.18	10.8

Other samples were examined, but being from the same furnaces and much like those tabulated above, are not included. No two of these flue dusts are similar in composition, hence no one of these can be regarded as representative of the group. Only dust 1 is self-fluxing; the others are deficient in lime. In a general way the carbon content of the dust varies inversely as the iron.

SCREEN ANALYSES

Each of the seven samples was screened to determine the proportion of sizes present. The differences in the amount of the various sizes in the different flue dusts are shown in Table 37.

TABLE 37.—*Results of screen-sizing tests of flue dusts*

[Values in per cent by weight]

Screen size (mesh)	1	3	5	6	4	2	7
Plus 8	0.0	0.1	0.4	1.9	7.0	6.9	8.4
Minus 8 plus 10	.0	.1	.8	1.5	2.4	6.0	6.6
Minus 10 plus 14	.0	.3	1.5	1.9	2.8	6.9	8.0
Minus 14 plus 28	.0	5.3	14.3	12.8	13.0	27.4	28.1
Minus 28 plus 35	.5	10.2	13.4	14.1	12.2	15.5	14.4
Minus 35 plus 48	3.6	20.8	16.2	19.0	16.3	14.8	13.5
Minus 48 plus 65	11.8	19.6	12.6	17.0	14.0	9.2	8.0
Minus 65 plus 100	20.4	15.8	11.0	13.5	12.5	5.7	5.7
Minus 100	63.7	27.8	29.8	18.3	19.8	7.6	7.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The relationship between the screen sizes and the composition of the different flue dusts is indefinite because furnace operation is so irregular. The screen analysis and chemical content of a flue dust are affected by a number of things, such as (1) blast pressure, (2) kind and grade of ores charged to the furnace, (3) size of particles in the ore, (4) height of stock line, (5) amount of coke in charge, (6) size of coke particles, (7) amount of lime added to charge, and (8) size of limestone particles.

The poorest grade of flue dust available for investigation happened to be that containing a minimum of coarse sizes. The sample richest in iron represents the other extreme; that is, it contains a maximum of coarse material. In Tables 38 and 39 screen analyses are shown of these two flue dusts to illustrate that they vary between wide limits.

TABLE 38.—*Screen analysis of flue dust 1*

[Values in per cent]

Screen size (mesh)	Weight	Iron	Insoluble	Lime	Phosphorus	Sulphur	Carbon
Plus 8	0.0						
Minus 8 plus 10	.0						
Minus 10 plus 14	.0						
Minus 14 plus 28	.0						
Minus 28 plus 35	.5	1.5	5.6	0.6	0.04	0.20	83.0
Minus 35 plus 48	3.6	1.6	6.9	1.6	.03	.20	83.6
Minus 48 plus 65	11.8	5.4	8.0	6.2	.09	.25	68.7
Minus 65 plus 100	20.4	13.6	11.2	12.8	.17	.17	43.0
Minus 100	63.7	28.8	13.2	15.1	.29	.13	15.8
Composite	100.0	21.6	11.9	13.2	.22	.16	30.6

TABLE 39.—*Screen analysis of flue dust 7*

[Values in per cent]

Screen size (mesh)	Weight	Iron	Insoluble	Lime	Phosphorus	Sulphur	Carbon
Plus 8	8.4	24.6	14.1	0.25	0.04	0.20	37.1
Minus 8 plus 10	6.6	40.3	13.4	2.1	.05	.18	19.3
Minus 10 plus 14	8.0	45.7	13.5	1.8	.05	.16	13.3
Minus 14 plus 28	28.1	50.6	13.4	2.1	.05	.17	7.5
Minus 28 plus 35	14.4	49.3	15.2	3.2	.09	.17	6.1
Minus 35 plus 48	13.5	48.4	15.3	3.9	.09	.15	5.2
Minus 48 plus 65	8.0	47.0	14.3	4.5	.12	.19	6.7
Minus 65 plus 100	5.7	46.4	13.9	4.0	.17	.20	7.6
Minus 100	7.3	45.9	11.4	4.8	.10	.25	6.7
Composite	100.0	45.8	14.0	2.9	.09	.18	10.8

The screen analyses stress a marked contrast between the two samples. The other five samples, although differing from each other, are between the two extremes. Obviously no one procedure can be followed in the concentration of all of these flue dusts.

MAGNETIC PROPERTIES OF FLUE DUSTS

Flue dust may or may not have been exposed to the reducing atmosphere of the furnace long enough to convert the hematite particles to magnetite. After leaving the furnace the dust passes through the flues into dust-collecting chambers. Hot fumes also pass through the flues and may continue the reduction begun in the furnace. The completeness of reduction is dependent on a number of conditions, as follows: (1) Temperature of ore in top of furnace, (2) temperature of gases to which the iron mineral in the flue dust is exposed, (3) length of time of exposure to the reducing atmosphere, (4) size of ore particles in the flue dust, (5) amount of CO gas present, and (6) kind of ore smelted.

Operating conditions in the Birmingham district are such that the above factors are seldom constant at any given furnace. The top temperatures vary. In some furnaces the top is kept cool intentionally. The temperature of the gases ranges from 180 to 325° C. At a number of plants the dust is removed from the dust catcher every 24 hours, but at others it is collected as often as every two hours. As already stated, the ore burden at some furnaces contains ever-changing proportions of red and brown ore, whereas at others it is generally made up entirely of red ore. The percentage of CO gas present is fairly uniform. The blast pressures vary through about the same range at all of the furnaces from which flue-dust samples were obtained, hence the variable character of the different flue dusts is what would be expected when operating conditions are so irregular.

MAGNETIC ASSAYS OF FLUE DUSTS

Magnetic assays were made of each of the seven samples in their natural state and also after crushing to fine sizes. Some samples yielded a high extraction of iron, but others were in such condition that only a fair recovery could be obtained.

The so-called magnetic assays were made in a Davis magnetic-tube separator already described.

MAGNETIC-TUBE TESTS

This magnetic tube not only made possible accurate determination of the amount of magnetic iron in the flue dust but also the grade and amount of concentrate that could be produced from it at different sizes. Sizes obtained by the screen analysis of each sample were used for this work. Each screen product was divided into two parts—one tested in its natural condition and the other after crushing to 100 mesh. This series of tests demonstrated that the highest grade of concentrate was obtainable after crushing to 100 mesh. A good grade of concentrate, however, was usually accompanied by a low recovery of iron.

Tests of the natural flue dusts and the material crushed to 100 mesh show clearly that crushing makes possible the production of a higher grade of concentrate, but with a sacrifice in the percentage of iron recovered. The data from these last tests appear in Tables 40 and 41. For convenience the samples are arranged in the tables in the order of the percentage of iron recovered.

TABLE 40.—*Magnetic-tube tests of uncrushed flue dust*

[Values in per cent]

Flue dust No.	Feed					Weight	Concentrate				Iron recovered
	Total iron	Magnetic iron	Insoluble	Lime	Carbon		Iron	Insoluble	Lime	Carbon	
1	21.6	15.2	11.9	13.2	30.6	32.02	47.5	13.0	9.0	3.9	70.42
5	30.0	22.4	18.6	11.4	18.1	48.71	45.9	13.8	9.1	2.4	74.52
3	24.3	18.2	17.5	6.7	30.1	35.84	50.8	10.8	6.6	1.4	74.92
4	29.6	24.6	20.2	10.9	11.6	54.73	44.9	16.2	9.3	2.1	83.02
2	22.1	19.7	17.8	9.6	26.5	53.82	36.6	14.9	11.1	6.6	89.13
7	45.8	41.7	14.0	2.9	10.8	70.76	58.9	11.0	1.3	.8	91.05
6	36.8	34.0	13.8	7.8	15.2	59.92	56.8	8.2	4.6	.9	92.49

TABLE 41.—*Magnetic-tube tests of fine dust crushed to 100 mesh*

[Values in per cent]

Flue dust No.	Feed					Weight	Concentrate				Iron recovered
	Total iron	Magnetic iron	Insoluble	Lime	Carbon		Iron	Insoluble	Lime	Carbon	
3	24.3	15.4	17.5	6.7	30.1	24.95	61.6	7.7	2.7	1.2	63.25
1	21.6	14.7	11.9	13.2	30.6	25.47	57.6	11.6	4.9	1.8	67.92
5	30.0	20.7	18.6	11.4	18.1	35.29	58.6	9.1	3.8	.9	68.93
2	22.1	15.5	17.8	9.6	26.5	27.12	57.3	8.8	2.4	.8	70.31
4	29.6	24.0	20.2	10.9	11.6	41.61	57.8	11.1	3.4	.9	81.23
7	45.8	40.1	14.0	2.9	10.8	63.31	63.3	10.0	.3	.4	87.55
6	36.8	33.0	13.8	7.8	15.2	51.98	63.5	6.4	1.7	.9	89.57

If high recoveries are desired, the results obtained by concentrating uncrushed flue dust (Table 40) are preferable; if a high-grade concentrate is desired, fine grinding will be necessary. Comparison of Tables 40 and 41 shows that, although grinding to 100 mesh allows a richer concentrate to be produced, the percentage of recovery is reduced materially.

The magnetic-tube tests described showed encouraging enough results to justify arrangements for the testing of additional samples on a larger scale.

Before large-scale tests were attempted, however, screen analyses and magnetic-tube tests of the new samples were made. The results of this series of tests were disappointing because they were not up to the standard set by the tests of the first lot. Comparison of the two lots (see Table 42) with regard to their iron content, magnetic iron, grade of concentrate produced, and recovery of iron reveals that the work of each furnace is extremely variable. There is a noticeable difference in quality between the lots of flue dust coming from the same furnace. This lack of uniformity is unfortunate, because it would be extremely difficult to operate a commercial plant on feed so variable.

COMMENTS ON PRELIMINARY TESTS

The preliminary tests showed that there is a decided difference between the flue dusts of various furnaces and also between the flue dusts produced at the same furnace at different times.

The investigation was started with seven samples from as many furnaces. Later, additional samples were obtained from five of the furnaces from which the first samples were taken. Table 43 shows how different were the magnetic properties of the two lots of flue dust. Some of the first flue dusts yielded results which would be satisfactory under uniform operating conditions. But the results of tests of the second series did not prove so satisfactory. However, the preliminary tests do show that the flue dust can be satisfactorily beneficiated if the hematite in the dust has been properly reduced before being discharged by the blast furnace. The lack of uniformity in the character of the flue dust makes it doubtful whether any single concentrating procedure developed would meet the demands.

LARGE-SCALE TESTS

Testing on a small laboratory scale provided the data necessary for a good understanding of the physical properties of flue dust with respect to concentration. Although the small-scale laboratory results were not entirely satisfactory, a flue dust which was in proper condition was chosen to show that magnetic concentration might be applied on a large scale.

MACHINES USED

All large tests were made in machines of semicommercial size. Three types were employed, namely: A dry magnetic separator for coarse ore, a wet magnetic cobber for coarse ore, and a wet magnetic log washer for finely crushed ore.

Dry magnetic separator.—This type of separator is adapted to the treatment of coarse ore (as large as ½ inch) containing a minimum of fine material. It is ineffective for 100-mesh fines. Ore fed to this device is distributed evenly on a thin brass belt which carries it past a series of electromagnets. The first magnet is the most powerful and the last is the weakest. At the first magnet in the head pulley a tailing consisting of nonmagnetic minerals is discarded into a hopper. The remaining ore passes beneath the succeeding magnets, and as each magnet is weaker than the preceding one the ore is graded according to its magnetic strength. Hence the material discharged under the last and weakest magnet is the most strongly magnetic. The small portion of the tailing entrained with the magnetic material is shaken off by the sustaining action and the changing polarity of the magnets. A number of products may be made with this machine; ordinarily intermediate ones are re-treated.

Wet magnetic cobber.—This device, designed at the Minnesota State Mine Experiment Station, is used for treating coarse material. It is most effective for material between 8 and 100 mesh. Absence of slime is desirable. The cobber consists of a revolving brass drum within which are powerful stationary magnets of reversing polarity. The lower part of the drum is submerged in a tank of water. The strength of the magnetic field can be controlled by a rheostat.

TABLE 43.—*Comparison by magnetic-tube test of flue dusts crushed to 100 mesh*

[Values in per cent]

Flue dust No.	Feed										Concentrate			
	Iron		Magnetic iron		Insoluble		Lime		Carbon		Iron		Iron recovered	
	Lot 1	Lot 2	Lot 1	Lot 2	Lot 1	Lot 2	Lot 1	Lot 2	Lot 1	Lot 2	Lot 1	Lot 2	Lot 1	Lot 2
1	21.5	31.1	14.7	15.3	11.9	17.8	13.2	11.0	30.6	11.8	57.6	65.1	67.92	49.30
2	22.1	26.2	15.5	22.9	17.8	17.0	9.6	11.9	26.5	21.6	57.3	53.4	70.31	87.36
3	24.3	------	15.4	------	17.5	------	6.7	------	30.1	------	61.6	------	63.25	------
4	29.6	19.6	24.0	14.0	20.2	19.2	10.9	9.5	11.6	34.0	57.8	58.8	81.23	71.64
5	30.0	------	20.7	------	18.6	------	11.4	------	18.1	------	58.6	------	68.93	------
6	36.8	29.0	33.0	16.5	13.8	17.2	7.8	5.4	15.2	24.2	63.5	52.7	89.57	56.80
7	45.8	35.2	40.1	23.2	14.0	17.6	2.9	4.5	10.8	16.2	63.3	56.3	87.55	65.90

The ore, with a small amount of water, is received by the drum at a point immediately above the first magnet. The magnetic field extends three-fourths of the way around the drum to a zone slightly below a riffled steel take-off roller revolving at high speed. Magnetism is induced in the roller by the last magnets inside the drum. As the ore moves with the drum into the tank of water the gangue is released and washed off because of the agitation produced by the reversing polarity. Magnetic particles cling to the drum until they pass out of the water into a zone between the last magnet and the take-off roller. The roller attracts the magnetic particles away from the surface of the drum, but in turn centrifugal force immediately throws them off into a receiving bin.

Magnetic log washer.—This machine also was developed at the Minnesota State Mine Experiment Station and is adapted to concentrating finely ground ore. Unlike the machine just described, it works best with fine sizes. It has already been described.

TESTS WITH DRY MAGNETIC SEPARATOR

Flow sheet for dry magnetic separator.—As magnetic treatment of poorly reduced material gives unsatisfactory results, a sample of flue dust of the most suitable magnetic properties was selected. As far as magnetic properties are concerned, the sample is representative of the flue dust discharged at favorable times by nearly all of the furnaces. The magnetic-tube tests of flue dust crushed to 100 mesh showed that a high-grade concentrate and a reasonably high extraction could be obtained. Results of this test appear in Table 43. Preliminary tests with the magnetic separator demonstrated that (1) a uniform feed rate is essential; (2) a high belt speed agitates the ore better and results in the production of a cleaner concentrate; (3) three products—namely, a concentrate, a middling, and a tailing—should be made and the middling returned for re-treating; and (4) the plus 10-mesh material should be removed from the feed; the removed portion is high in carbon and may be used as a sinter fuel. The final tests conformed to these conditions. Data recorded in the flow sheet, Figure 16, are representative of a number of tests and illustrate what can be done with one of the more suitable flue dusts.

The final sintered concentrate produced by this method is not of high grade, but is good enough to make the sinter desirable for blast-furnace feed; its porous nature is an asset. The lime content makes it about self-fluxing. All of the carbon and 55 per cent of the insolubles were removed. Virtually 88 per cent of the iron was recovered and the ratio of concentration was 1.7 into 1.

TESTS WITH WET MAGNETIC COBBER

Wet methods of concentration usually are preferred to dry methods. Although the work of the dry magnetic separator was quite satisfactory for the dusts tested, it seemed advisable for purposes of direct comparison to apply a wet concentrating process. As coarse uncrushed flue dust was used in making the dry magnetic-separator tests, the same class of material was utilized in the present tests. Trial runs supplied certain necessary data, such as (1) rate of feed, (2) amount of feed water, (3) position of last magnet with respect to the take-off roller, and (4) strength of magnetic field.

Flow sheet for wet magnetic cobber.—In the flow sheet, Figure 17, are shown representative results obtained in the work with the wet cobber. As was expected, the concentrate was cleaner than that produced by the dry magnetic grader; although the difference is small, it represents a slight improvement in the grade of the sintered product. In either case the concentrate lacks but little of being self-fluxing. The extraction of iron by both processes is practically the same. The ratio of concentration in the wet cobber test was 1.8 into

1; this means that 1.8 tons of flue dust was required for the production of 1 ton of sintered concentrate.

TESTS WITH MAGNETIC LOG WASHER

Finely crushed flue dust was treated in the magnetic log washer. After the proper conditions for treating any flue dust have been determined, the operation of this machine is easily controlled. The following factors are important: (1) Speed of the spirals, (2) rate

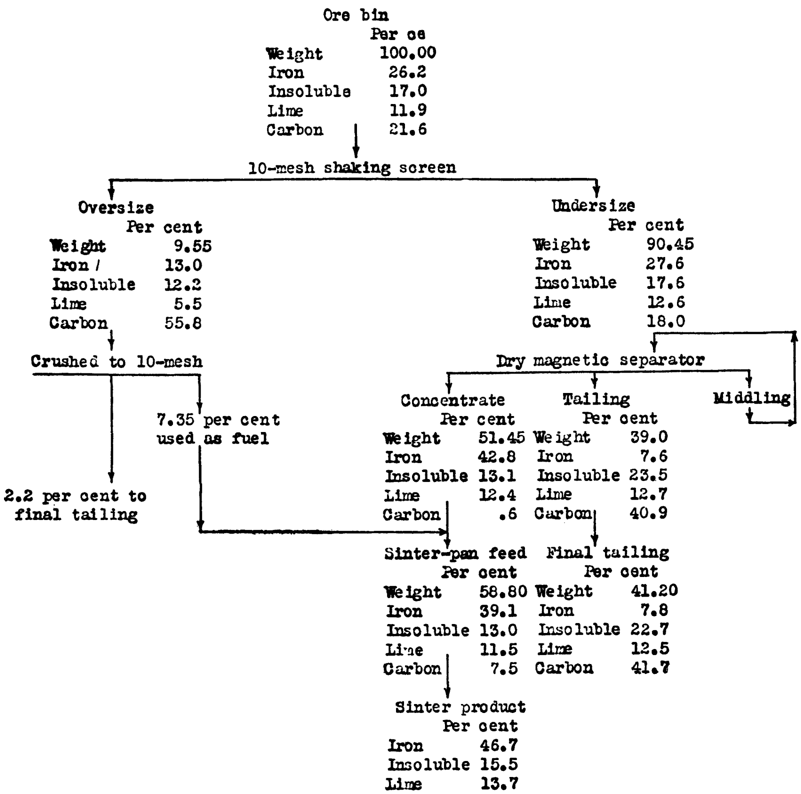

FIGURE 16.—Flow sheet for dry magnetic-separator concentration. Ratio of concentration, 1.7 : 1; iron recovered, 87.8 per cent; insoluble rejected, 66.0 per cent

and density of the feed, (3) slope of the trough, (4) strength of the magnetic field, and (5) amount of wash water.

Trial runs showed the most favorable conditions. The coarse flue dust was screened on 10 mesh to remove coarse coke. The minus 10-mesh product was delivered to a rake classifier working in closed circuit with a ball mill and was ground to 100 mesh. The classifier overflow passed through a magnetizing coil on its way to a mechanical thickener, where the excess water overflowed and the spigot product dropped directly into the magnetic log washer. The concentrate produced was mixed with the necessary amount of original material coarser than 10-mesh size, for fuel, and sintered.

The sinter thus produced is higher in iron but lower in lime than the products of either the dry magnetic separator or the wet cobber. Crushing to 100 mesh liberates lime which escapes during concentra-

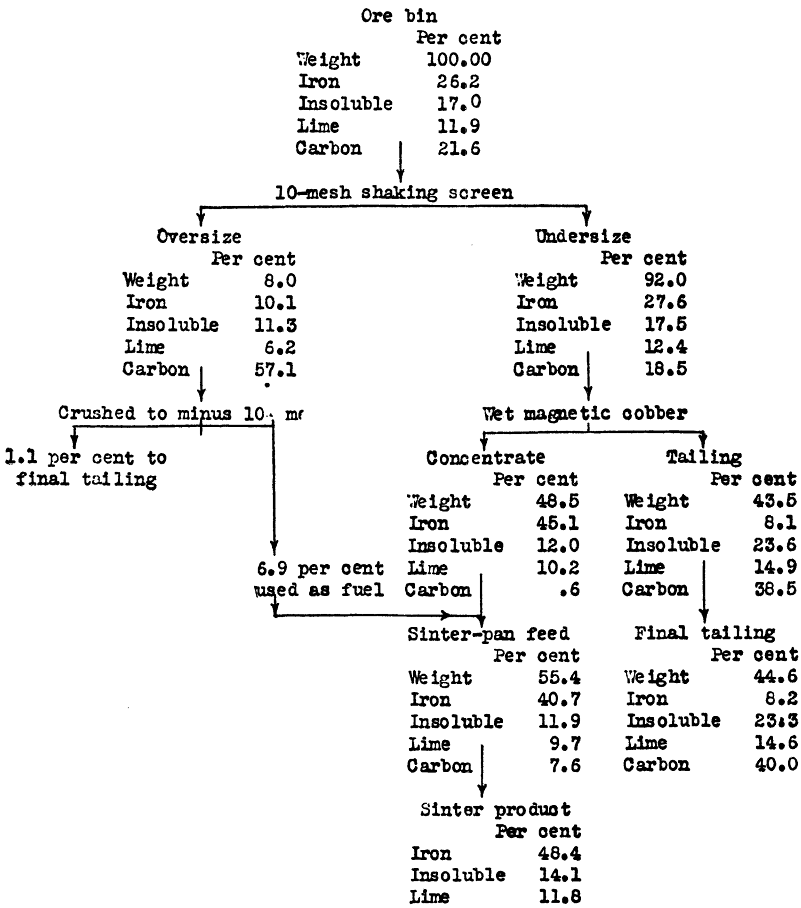

FIGURE 17.—Flow sheet for wet magnetic-cobber concentration. Ratio of concentration, 1.8 : 1; iron recovered, 86.1 per cent; insoluble rejected, 61.2 per cent

tion. The percentage of iron recovered is 88.7, which is slightly higher than that obtained by either of the other types of magnetic machines.

Flow sheet for magnetic log washer.—The flow sheet, Figure 18, details the test and shows that the process is a little more complicated than either of the two preceding ones.

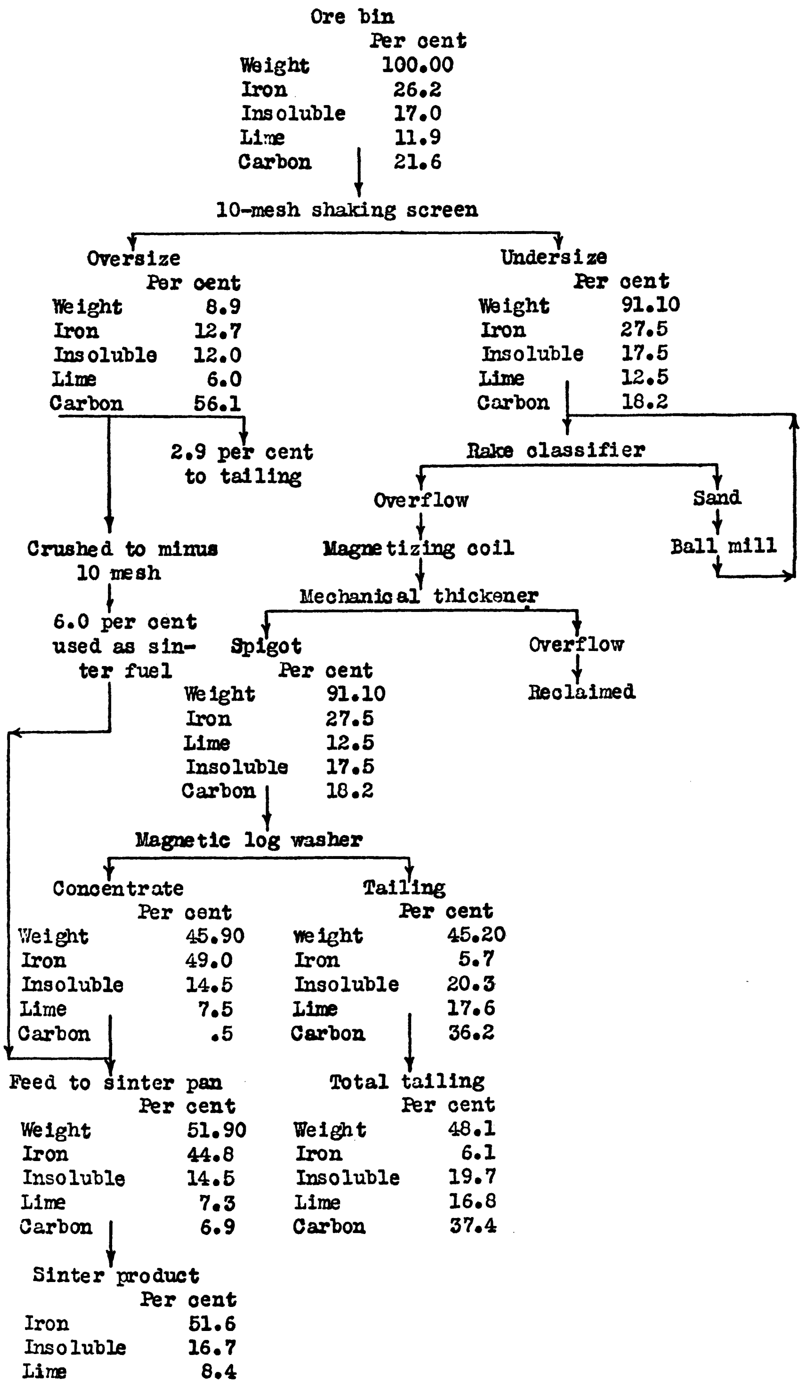

FIGURE 18.—Flow sheet for magnetic log-washer concentration. Ratio of concentration, 1.93 : 1; iron recovered, 88.7 per cent; insoluble rejected, 55.7 per cent

RELATIVE MERITS OF WET AND DRY CONCENTRATORS

Although good results were obtained from the respective machines, each has features which need discussion. Granted that fine grinding is necessary for the complete liberation of iron mineral from gangue, the work of both the dry magnetic separator and the wet cobber on flue dust through 10 mesh appears commendable. Comparatively high recoveries of iron were obtained by all of the machines, indicating that concentration of flue dust has possibilities under certain conditions previously outlined.

The advantages and disadvantages of the three different magnetic concentrators for treating flue dust are now considered.

Dry magnetic separator.—The dry magnetic separator has three disadvantages, which, under certain conditions, might prevent its use for concentrating flue dust: (1) It has a low capacity, because only a thin layer of ore should be carried on the brass belt; (2) it requires a dry feed, and this is undesirable because of dusting; (3) the brass belt is stiff and occasionally gives trouble. Because of the dust the bearings wear rapidly and hence require frequent attention. On the other hand, this machine has advantages, some of which follow: (1) It is easy to operate except for the effect of dust on wearing parts; (2) it is portable and hence can be set up anywhere; (3) it requires no water; (4) it produces a satisfactory though not high-grade product; (5) its power consumption is low.

Wet magnetic cobber.—Under some conditions the cobber might have certain disadvantages, such as (1) it requires use of water and this may make disposal of tailing more difficult, (2) it is not as portable as the dry separator because of water connections and the necessity of facilities for disposal of wet tailing, and (3) it produces a concentrate that must be dewatered before sintering.

Among the advantages of this machine are the following: (1) It is efficient and produces a clean concentrate, (2) it has a moderately large capacity, (3) it is easy to operate as compared to other stationary machines, (4) its power consumption is low, (5) it uses a wet feed and hence there is no dust, and (6) it requires little attention and few repairs.

Magnetic log washer.—The magnetic log washer is an excellent concentrator when handling material strongly magnetic and finer than 100 mesh. Nevertheless, this machine must operate under certain restrictions, such as (1) the necessity of fine grinding, which in turn requires ball mills, classifiers, and mechanical thickeners; (2) a comparatively large amount of water is needed; (3) a larger mill crew is required to operate the plant; and (4) the total power consumption exceeds that of a plant using either the dry separator or the wet cobber.

The magnetic log washer, however, has a number of desirable features: (1) It has large capacity, (2) it is easy to manipulate, (3) it is positive in its action, and (4) it gives a good grade of concentrate, with high recovery.

Table 44 shows a direct comparison of the results of the tests of the three types of machines. A study of this table stresses some important facts. In considering the quality of the concentrates produced it is obvious that the highest grade iron product came from the log washer. Unfortunately this product was obtained at the expense of the lime, the content of which is decidedly lower than in the products of the other two magnetic concentrators. On the other hand, the recovery of iron was slightly higher with the log washer. The wet cobber rejected a noticeably larger proportion of insoluble than either of the other machines, but it also rejected a larger percentage of iron, and thus its recovery of iron was lower.

The magnetic log washer treated the flue dust after it had been crushed to 100 mesh, whereas the other two handled the natural flue dust from which the dust coarser than 10 mesh had been removed. In this respect the magnetic log washer is at a disadvantage because of the cost of crushing to 100 mesh. The log washer also used a comparatively large amount of water, and the amount of power required to drive the plant of which the log washer was a part was decidedly larger than for the other two concentrators. The capacity of the log washer, however, was very much greater than that of the other machines.

The data in Table 44 indicate that the wet magnetic cobber is perhaps the best machine for concentrating these flue dusts.

TABLE 44.—*Résumé of results from the three methods of magnetic concentration*

	Dry magnetic separator	Wet magnetic cobber	Magnetic log washer
Sintered concentrate produced:			
Iron ... per cent	46.7	48.4	51.6
Insoluble ... do	15.5	14.1	16.7
Lime ... do	13.7	11.8	8.4
Weight of concentrate ... do	58.8	55.4	51.9
Ratio of concentration	1.7:1	1.8:1	1.9:1
Iron recovered ... per cent	87.8	86.1	88.7
Lime recovered ... do	56.8	45.1	31.8
Insoluble rejected ... do	55.0	61.2	55.7
Maximum size of particles treated ... mesh	10	10	100
Feed rate ... pounds per hour	45	120	250
Wash water used ... gallons per hour	----------	30	240
Power consumed in driving ... horsepower	½	½	⅛
Power consumed in driving entire flow sheet (not including sintering) ... horsepower	¾	¾	9⅝
Power consumed by magnetic coils ... kilowatt	.30	.25	.25

CONCLUSIONS

The high content of gangue in the average flue dust of the Birmingham district renders it unfit for treatment similar to that for dusts of other districts where direct sintering is enough to insure a satisfactory product.

The charge and the operating conditions at the various furnaces from which samples were obtained are so variable that no single sample of flue dust can be taken as representative. Likewise samples from the same furnace varied greatly in physical characteristics and in chemical composition; hence a successful concentration process must be capable of operating under a varying feed.

The coke can readily be removed by gravity concentration; for example, hydraulic classification. However, after the coke has been removed the remaining low-grade iron ore is not amenable to satisfactory concentration by ordinary methods, primarily because the intimate interlocking requires grinding to 100 mesh to liberate the hematite from the gangue. Material of such fineness is difficult to handle by gravity concentration.

In a number of the samples hot reducing gases in the blast furnace or in the dust catcher had converted the iron minerals from hematite or limonite into magnetite. When such an alteration had taken place, a good separation of the iron mineral from the gangue can be obtained by use of magnetic-concentration machines.

Magnetic concentrators of various kinds, such as a magnetic wet cobber, a magnetic dry concentrator, and a magnetic log washer, were used with flue dust in which the iron mineral had been converted into magnetite. The first two machines are built to handle coarse material, and the log washer is designed to handle fine material. The results obtained with these different machines show that a good concentrate and a high recovery can be made by the dry concentrator or the wet cobber without preliminary crushing. It is doubtful whether the added expense of fine grinding would be justified by the higher grade of concentrate obtainable in the magnetic log washer.

When a large proportion of iron is in the form of magnetite, a magnetic cobber will give excellent results at low cost and requires a relatively simple installation.

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