DEPARTMENT *of* NATURAL RESOURCES
ZACK D. CRAVEY, *Commissioner*

DIVISION OF MINES, MINING AND GEOLOGY
425 State Capitol
ATLANTA, GEORGIA

GARLAND PEYTON, *Director*

MAGNETIC ROASTING TESTS
on
CARTERSVILLE MANGANESE ORES

(Preliminary Report)

AUTHORS

L. L. MCMURRAY, *Assistant Mining Engineer*
S. D. BROADHURST AND M. T. PAWEL

In Collaboration with
H. S. RANKIN, *Senior Mining Engineer*

Under the General Direction of
W. HARRY VAUGHAN, *Chief, Regional Products Research Division*
Tennessee Valley Authority

Published in cooperation with the Tennessee Valley Authority

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FOREWORD

This preliminary report concerns some research and tests in connection with magnetic roasting of Cartersville (Ga.) manganese ores. This work was done at the request of the Georgia Division of Mines, Mining and Geology, and was performed in cooperation with them at the Minerals Testing Laboratory of the Tennessee Valley Authority at Norris, Tennessee, between the months of May and November, 1941. It is believed that the results submitted herewith may be useful in connection with the urgent need for additional supplies of manganese during the present national emergency.

This experimental work does not represent an exhaustive study of the problem of the separation of manganese from manganese-iron ores. Instead, it represents a brief practical study of the problem of improving the quality of manganese from low grade manganese concentrates from the Cartersville district. It is reasonable to expect that further research into the subject would result in further improvements. However, it is believed that the results to date may warrant serious consideration and investigation by commercial interests. Moreover, it appears hardly likely that further research would result in diminishing the value of the work covered by this report.

While this report does not present figures representing operating costs based on actual tests of full-sized commercial equipment, it does include some data from which competent operators may fairly estimate such costs.

Therefore, it is expected that those who are interested in the subject matter will draw their own conclusions concerning the value of the procedures outlined and the possible commercial application of the process.

We wish to acknowledge the interest and assistance which has been received from the Division of Mines, Mining and Geology of the Georgia Department of Natural Resources and from several manganese producers in the Cartersville, Georgia, area.

Preliminary Report

MAGNETIC ROASTING TESTS ON CARTERSVILLE MANGANESE ORE

ABSTRACT OF RESULTS

These tests were carried out on washed concentrate ore from the Cartersville (Ga.) district which had the following approximate analysis: manganese 21.4 per cent, iron 27.0 per cent, insoluble 11.2 per cent. The results of magnetic roasting and subsequent magnetic separation indicated that 61 per cent of the roasted ore can be separated into manganese and iron concentrates.

The combined roasted product constituted 85.7 per cent by weight of the original washed concentrate ore and analyzed as follows: manganese 25.42 per cent, iron 31.41 per cent, insoluble 12.0 per cent.

By closely controlling the jigging of the manganese concentrate, we obtained the following three fractions:

(1) Manganese concentrate after jigging 32.0 per cent by weight (loss in jigging 3.7 per cent by weight). This concentrate analyzed as follows: manganese 45.10 per cent, iron 6.41 per cent, insoluble material 12.0 per cent.

(2) Iron concentrate 25.3 per cent by weight. This concentrate analyzed as follows: manganese 8.74 per cent, iron 55.1 per cent, insoluble material 8.1 per cent.

(3) Middlings 39.0 per cent by weight. This concentrate analyzed as follows: manganese 23.3 per cent, iron 34.16 per cent, insoluble material 12.2 per cent.

All of the products separated are believed to be marketable under

present conditions.

It must be understood that the foregoing represents the result of tests under one set of conditions. In order to evaluate the work covered by this report in terms of commercial application, the report must be studied in its entirety.

Commercial Application

The results represent conditions of roasting, magnetic separation and jigging of the manganese concentrate considered optimum, but not beyond the limits of ordinary mill operations. Commercially, close control of the several operations is imperative. Moreover, there are certain features which require particular attention. Among these are:

(1) The roasting furnace must have an air-tight reducing chamber.

(2) Reasonably accurate control of the temperature and reducing agent are required.

(3) The rate of processing must be carefully regulated by the ore discharge in order to allow sufficient time for heating and reducing the ore.

(4) Means must be provided for cooling the roasted ore without contact with the atmosphere. This may be done by quenching in water.

(5) Magnetic separators with controlled magnetic intensities must be provided, by the use of which the production of the middling product may be regulated.

(6) The jigging of the feed to the furnace or the manganese concentrate must be closely controlled. By this operation, silica and iron, contained in the insoluble particles, are removed from the manganese concentrate.

Estimated Costs and Profits

It is estimated that the costs of magnetic roasting with a furnace of two tons per hour capacity should not exceed $1.50 per ton.

It is not unreasonable, under present market conditions, to expect a profit of $2.00 per ton of ore processed by the method outlined in this report, assuming a steady processing of 90 per cent capacity in a furnace designed for the production of two tons per hour.

Remarks

This preliminary report will include some details and data by the examination of which the foregoing has been estimated.

Substantiating Tests on Commercial Size Equipment

The large scale tests on the manganese-iron ores were confined to the roasting step and only small-scale laboratory magnetic separation testing was applied. In order to check the results of the magnetic separation on commercial size equipment, roasted ore samples were sent to various manufacturers for testing on magnetic separation equipment. These results, while not complete, indicate that the laboratory magnetic separations given herein can be equaled or improved on commercial separators.

INTRODUCTION AND DISCUSSION

Ores of manganese containing iron in excessive amounts are not suitable for use in the production of ferro manganese. Many of the manganese ore deposits in the Cartersville district of Georgia contain iron as an ingredient which may be present in quantities up to 27 per cent. Economic separation of this iron from the manganese has been studied, and the principal results of this work, to date, are reduced in this report.

Careful review of previous work performed by the United States Bureau of Mines indicated that magnetic roasting, with subsequent magnetic separation of the synthetic magnetite, offered promise of success. Preliminary small scale tests were made, and favorable separations of the manganese and iron, by the method suggested, were indicated.

As a result of these studies, a pilot reduction roasting furnace, with a capacity of 500 pounds of ore per hour, was constructed. This furnace was of the vertical shaft type, and was designed to provide complete control over the various phases of the roasting process. The furnace operating results indicate that 97 per cent of the iron in the material fed into the furnace was made magnetic.

Having thus made the iron magnetic, the method of magnetic separation of the iron from the maganese in the product discharged from the pilot furnace was undertaken. In this operation it was discovered that this separation is by no means complete, and that a large percentage of the manganese minerals are removed with the synthetic magnetite. However, the separation is partially complete, and it is possible that it is sufficiently complete to warrant the use of the process commercially. Apparently the manganese, at least to some degree, develops magnetic characteristics during the roasting, and several reasons for this condition of the manganese minerals are discussed in this report.

This report describes the work to date on magnetic roasting of Cartersville, Georgia, manganese-iron ores with a view to concentrating both the iron and manganese by subsequent magnetic separation. This work has been performed during the period from May to November, 1941, at the Minerals Testing Laboratory of the Tennessee Valley Authority at Norris, Tennessee.

Little or no separation of the two minerals in the crude state of pyrolusite (or psilomelane) and hematite (or limonite) is possible by magnetic means until magnetic roasting is performed. This roasting converts the iron oxide hematite ($Fe_2O_3.nH_2O$) to magnetite (Fe_3O_4, composed of 31.0% FeO and 69.0% Fe_2O_3 (1)). The following table shows the relative magnetic strength of various minerals which might be associated with the Cartersville manganese ores in the crude state or after being roasted.

TABLE I

RELATIVE MAGNETIC FORCE OF MINERALS WHICH MIGHT BE MADE IN MAGNETIC ROASTING MANGANESE ORE [(a)]

Mineral	Formula	Relative Force
Iron	Fe	100.00
Magnetite	Fe_3O_4	40.18
Manganese	Mn	8.93
Hausmannite	Mn_3O_4	0.88 *
Hematite	Fe_2O_3	1.32
Limonite	$Fe_2O_3.2H_2O$	0.84
Pyrolusite	MnO_2	0.71
Manganite	$Mn_2O_3.H_2O$	0.52
Manganosite	MnO	0.65 *

(a) Table from Catalogue No. 77, Dings Magnetic Manufacturing Company, Page 8.

* Calculated from data given in International Critical Tables. These data are in specific susceptibilities; with MnO_2 given as 69.0 and Mn_3O_4 as 55.8 (both as 21° C). Thus: $\frac{69.0}{55.8} \times 0.71 = 0.88$.

Chemical Reactions

Theoretically, the reactions, involved in roasting under various conditions of reducing agent and temperatures, are represented by the following equations:

1. $3\ Fe_2O_3 + CO \rightleftharpoons 2\ Fe_3O_4$ (i.e. $2(FeO.Fe_2O_3)$ $+ CO_2$
   (Hematite) (Magnetite) (31.0% 69.0%)

2. $3\ Fe_2O_3 + H_2 \rightleftharpoons 2\ Fe_3O_4 + H_2O$

3. $MnO_2 + CO \rightleftharpoons MnO + CO_2$
   (psilomelane) (pyrolusite) (Manganosite)

4. $MnO_2 + H_2 \rightleftharpoons MnO + H_2O$

5. $3\ MnO_2 + 2\ CO \rightleftharpoons Mn_3O_4 + 2CO_2$
   (Hausmannite)

6. $Fe_2O_3 + CO \rightleftharpoons 2\ FeO + CO_2$
   (Ferrous Oxide)

7. $3\ FeO + H_2O \rightleftharpoons Fe_3O_4 + H_2$

8. $FeO + CO \rightleftharpoons Fe + CO_2$

9. $MnO + CO \rightleftharpoons Mn + CO_2$

10. $2\ CO + O_2 \rightleftharpoons 2\ CO_2$

11. $3\ FeO + CO_2 \rightleftharpoons Fe_3O_4 + CO$

Discussion of Reactions

If equations 1, 2, 3, 4, and 5 are allowed to proceed to the right, magnetite and either manganosite or hausmannite are produced, the specific oxide depending upon roasting conditions. To allow these equations to proceed to the right, two primary conditions are necessary:

(1) Sufficient temperature for the reaction to take place.

(2) Sufficient vapor pressure of reducing agent.

The most satisfactory temperature limits were found to lie between 500° C. and 1000° C. At convenient ore sizing and temperatures below 500° C., reducing periods are too long to be practical. At temperatures above 1000° C., sintering may be encountered, which is an undesirable condition. For all practical considerations, we have found the reduction of the iron oxides to magnetite may be accomplished at a temperature of 600° C. in one half hour, with the ore particles sized to 7/8 inch or smaller. Even though shorter reducing periods can be realized by higher temperatures than 600° C., the decrease in time is not wholly warranted due to added costs of operation and more difficult problems of furnace design.

To maintain sufficient vapor pressure of reducing agent, it has been found practical to perform the reduction in a closed chamber and allow the gaseous products of reduction, CO_2 and H_2O, to escape. This may be done by passing the reducing gas over the ore. In addition, after the reduction has taken place, means to keep the reaction from reversing are necessary. This can be done by quenching the ore in water or passing the ore through a cool inert atmosphere.

Means to control the reaction are also desirable. The reduction of hematite to magnetite, if continued, may produce ferrous oxide. The formation of this compound represents a loss of reducing agent and should be avoided. If the reaction continues after ferrous oxide is produced, metallic iron may be made, as shown in equation 8. The reduction to metallic iron, however, requires a more intense reducing action than that obtained using a reducing gas and temperatures around 600° C. For the production of sponge iron solid carbon plus a reducing gas and prolonged heating at approximately 950° C have been found necessary (2). Likewise, the production of metallic manganese as shown in equation 9 is not possible under the conditions employed.

To control the roast to yield magnetite of a composition approaching the theoretical, conditions were controlled to utilize the reaction in equation 7. The reaction in equation 11 also allowed some oxidation of the ferrous iron, but design of the reducing furnace prevented this reaction from being very effective. The use of steam in connection with such roasting was suggested by Davis (3) and proved very effective in the Cartersville ore roasting tests. The steam required was obtained by quenching the hot ore upon discharge from the furnace.

Ore Sizing

The ore size is an important variable in roasting technique. Fine ore generally permits shorter reducing periods than coarse ore, but the Cartersville ores used in these tests were sufficiently porous to allow rapid and complete reduction at jig sizes. The use of coarse ore overcomes several difficulties in roasting and also produces finished concentrates not requiring sintering for furnace use. Particle liberation was found to be relatively complete at sizes of -1/4 inch, but was never entirely complete, even on grinding to -200 mesh. It appears that some iron (3 per cent to 4 per cent) is intimately associated with the manganese and could not be liberated at any practical sizing.

Reducing Agent

As a reducing agent, a gas is almost a necessity. Reduction can be obtained by intimately mixing carbon and ore, but this solid to solid reaction is poor. Generally, reduction by solid carbon is caused by the presence of some air, thus forming CO, which is a very effective reducing agent. Many types of reducing agents may be used, but their effectiveness depends wholly upon their available carbon monoxide or hydrogen. Producer gas and coke oven gas are particularly good as they are mixtures of both carbon monoxide and hydrogen. Hydrocarbon gases such as propane and methane are compounds of hydrogen and carbon, and are not satisfactory reducing agents until they have been converted to carbon monoxide and hydrogen. Hot iron oxide is a fairly good catalytic agent for breaking down these compounds. Superheated steam converts the carbon to carbon monoxide: $C + H_2O \longrightarrow H_2 + CO$. Thus, the steam aids effectively in producing a reducing agent as well as controlling the roasting. Ordinary fuel oil may be gasified at a temperature of about 375° C, and the gas thus produced is a mixture of hydrocarbons and can be made an effective reducing agent by the means described. The low cost of fuel oil, combined with its ease of handling and measuring, made it attractive for use in the pilot-furnace.

The roasting furnace used in these tests, involving the scheme described above, proved efficient and practical, making over 95 per cent of the iron in the ore into magnetite.

ROASTING

Furnace Design and Operation

After small batch preliminary testing had indicated promise for this method of treating the Cartersville ore, a pilot furnace for continuous roasting was constructed. Since it was not possible to control the roast in the preliminary tests, the results of magnetic separation were of doubtful value and the process could not be evaluated by these small tests. As a shaft-type furnace had proved effective and economical in magnetic roasting of Mesabi hematite (3), this type was adopted for roasting these ores.

Description and Operation of Furnace

The accompanying sketches show the principles of construction of the pilot furnace erected at the laboratory. The essential details consist of a shaft or cupola made of circle fire brick surrounded by a metal shell built in halves and fastened around the brickwork. A separate fire box of regular firebrick, in which the gaseous products from the oil burner were completely burned, adjoined the cupola. By means of an exhaust fan these hot gases were drawn through a bed of ore eighteen inches thick. The heat intake and exhaust pipes were of extra heavy cast iron pipe in the form of a "T" with holes along the bottom of both for spreading the gases throughout the cupola cross-section to provide uniform heating. A skirt was provided over the exhaust pipe to prevent small ore particles from being drawn out through the exhaust. The reducing chamber was immediately below the heating zone. The reducing agent as a gas or in the form of gaseous crude oil was introduced into a 1-inch cast iron ring, which distributed the reducing agent over the furnace area. A quenching hopper was located below the cupola proper, and the open end was sealed by water to prevent air from entering the furnace. A rotary disc ore discharge was used to provide a uniform discharge from the furnace. As the normal furnace capacity of crude -7/8 inch ore was 500 pounds per hour, an elevator was built to facilitate ore handling. Thermocouples were installed to permit accurate temperature measurements in the cupola.

In operation, two defects in the original furnace were noted:

(1) Objectionable air leaks developed in the single brick cupola.

(2) The reducing chamber should have been much longer, thus providing a greater furnace capacity at very little additional expense.

To prevent the air leaks the furnace was rebuilt after a few tests. A layer of asbestos refractory cement was plastered on the outside of the cupola, and the sheet iron shell was firmly fastened and all leaks plugged in the shell openings. This provided a good seal, but a double brick furnace with interspersed impervious cement is recommended.

When the furnace was properly regulated, one man could carry out the operation easily. Fuel consumption and other pertinent data are given later in this report.

Heating Unit

The heat capacity required varied greatly with the ore moisture content, and thus a flexible heating unit was necessary. A Johnson Series 520 oil burner proved satisfactory. The capacity of this burner is from 0.65 gallons/hour to 7.5 gallons/hour, with an air blower furnishing air at from 100 to 350 cubic feet/minute at 10 ounces to 16 ounces pressure. This blower was arranged in series with a rheostat so that the air volume was variable at will. With a total moisture content of 10 per cent, the heat requirement was calculated to be 340 Btu/pound; if the moisture content increased to 18 per cent, 445 Btu were required. The heat value of the fuel oil used was 18,000 Btu/pound so that with 10 per cent moisture, 9.5 pounds of oil/hour was required. In normal operation this amount was close to 11.6 pounds/hour due to radiation and other items not used in the calculations. The high coefficient of heat transfer of the ore should be noted. The fact that the heat of the gases could be dissipated in passing through 18 inches of ore in no small way affects the cost of such a roasting scheme.

Exhaust Fan

Due to resistance of gas flow, the horsepower required for the exhaust fan increases rapidly as the height of ore column is increased. The height of this ore column was determined from actual test data given by Davis (3) in heating Mesabi iron ores. The specific heats of the manganese and iron oxides are so nearly the same, and with uniform size of the ore, these values could be used directly. The hot gases entered at a temperature of approximately 950° C, and the exhaust temperature remained relatively near 90° C.

As no test data were available to determine the fan capacity required for drawing the correct amount of hot gases through the ore, a variable speed for the fan was provided and a gate valve was inserted in the exhaust line. By these means the correct amount of hot gases could be drawn through the charge, and at the same time a suitable balance between the oil burner blower and the exhaust fan could be maintained.

Reducing Oil

The amount of reducing oil used was regulated by a needle valve which had been calibrated. The needle valve reading was checked by direct measurement in the oil storage reservoir. This oil was introduced into the furnace in the raw state or vaporized. Generally a vacuum of 1/4 inch of water existed at the reducing oil entry level. Introduction of the raw oil absorbed heat during vaporization, but as the subsequent reaction was exothermic, very little total heat was lost by using the crude oil direct.

Regulation of Ore Discharge

The ore discharge was closely regulated by the ore discharge disc. The ore discharge rate determined the time the ore was in the heating and reducing zones. The quantity of ore discharged also determined the amount of steam made in quenching although the ratio of steam produced and ore discharged remained constant. By a study of the $FeO-Fe_3O_4-H_2O$ equilibrium conditions, Davis (3) determined that a temperature of 600° C it was desirable to have in excess of 80 per cent by weight of steam in the atmosphere in the reducing chamber. Our calculations indicate that this amount of steam was present at all times. A sample calculation will show the following:

At a feed rate of 500 pounds/hour, 428 pounds/hour were discharged, the difference being loss of moisture (50 pounds at 10 per cent water) and oxygen (22 pounds). With a heat capacity of 208 Btu/pound of ore (assuming specific heat of MnO and Fe_3O_4 as 0.20 : Q = (1112° F - 70° F) x 0.20 x 1 pound = 208 Btu/pound). The heat
(1112°F = 600° C)
required was 208 x 428 pounds = 89,000 Btu. Of this amount of heat 11,500 Btu were required to heat 2200 pounds of water 5° F every hour in the quenching tank (2200 x 5 = 11,500 Btu.). 89,200 - 11,500 = 77,770 Btu available for steam production. To superheat steam to 1112° F, 1531 Btu. per pound are required. 77,770 ÷ 1531 = 50.7 pounds water. Generally it was shown that the reducing oil used amounted to 3.0 pounds/hour. Thus 50.7 + 3.0 = 53.7.

50.7 + 53.7 = 94.5 per cent steam.

Losses due to radiation of heat by the ore were not included, but it is obvious that an excess of steam was available. This steam aided the thermal balance of the unit as the heat of this rising steam aided in heating the ore, but, as previously indicated, its main purpose was to crack the gases and prevent the formation of ferrous oxide.

TESTS

Preliminary Tests

The Bureau of Mines, Report of Investigations 2936 (4), gives preliminary results of small batch tests made on roasting Cartersville ores and then magnetically separating the roasted product. The results of treating one Cartersville jig concentrate is shown in Table II.

This ore was roasted in a batch revolving drum for thirty minutes. The nature of reducing gas was not disclosed. The ore was a clean jig concentrate between one inch and one-half inch in size. After roasting, the magnetic portion was removed with a hand magnet. While these test results are very good, it appears that this ore must have been quite different in character from the ore samples used in our tests. The results of the Bureau were limited in scope, and as no further work has been published by the Bureau in connection with these tests, performed in 1929, it may be assumed that the ore used in these tests was not representative of that now available in the field. The ore samples taken in this district for the roasting tests shown in this report have not allowed such complete separation as that shown in Table II.

Batch testing on Cartersville ore covered in this report may be shown in Table III, which is typical of the results obtained. This ore was roasted in a crucible with 10 per cent -200 mesh coke at 600° C for one hour. The ore was crushed and passed through 1/4 inch screen. The products representing various magnetic susceptibilities were kept separate and combined for final products. The magnetic separator was a Stearn's

TABLE II

ROASTING OF CARTERSVILLE ORE *

Product	Per Cent Weight	Analysis, Per Cent Mn	Fe	Insol.	Per Cent total Mn	Fe	Insol.
Unroasted Conc.	-	32.8	17.9	7.4	-	-	-
Magnetic Portion	38.7	12.4	45.5	12.2	13.2	92.6	60.7
Nomag. Portion	61.3	51.7	2.3	5.0	86.6	7.4	39.3
Composite (roasted)	100.00	36.5	19.0	7.8	100.0	100.0	100.0

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* The Bureau of Mines, Report of Investigations 2936 (4)

TABLE III

BATCH ROASTING TEST OF CARTERSVILLE MANGANESE

Product	Per Cent Weight	Analysis, Per Cent			Per Cent Total			Magnet Resistance
		Mn	Fe	Insol.	Mn	Fe	Insol.	
Mag. Conc. #1	18.6	1.10	66.91	7.56	-	-	-	7,000 ohms
Mag. Conc. #2	28.3	3.96	54.19	11.42	-	-	-	5,000 ohms
Mag. Conc. #3	32.1	39.68	23.23	14.54	-	-	-	2,000 ohms
Mag. Conc. #4	14.4	45.80	6.08	15.04	-	-	-	500 ohms
Tails	6.6	44.10	1.93	18.50	-	-	-	
Combined Conc.	46.9	2.82	59.3	-	5.5	76.6	-	
Combined Midds	32.1	39.68	23.2	-	54.0	20.5	-	
Combined Tails	21.0	45.20	4.8	-	40.5	2.9	-	
Heads (Calc.)	100.0	23.53	36.4	-	100.0	100.0	-	

Type "KS" d.c. separator (dry material required) and the resistance inserted in the magnet circuit was taken as the standard method of determining the magnet strengths. By assuming these standards of magnet strengths the tests could be compared as the same resistance produced the same magnet strength each time. In the batch using coke as the reducing agent, the roast was more intensely reducing than in the pilot furnace, and the results are not very reliable.

Pilot Plant Tests

In the pilot roasting furnace many test runs were made, and after the furnace was properly adjusted, all gave very similar results. In order to avoid unnecessary duplication, only Test 12, typical of other results, is given in full.

Test Number 12

Conditions of Test:

Sample Number, Feed--Sample No. 8a. -7/8 inch Cartersville Ore,
Jig Concentrate (See Screen Analysis)
Feed rate-- 500 pounds per hour
Solids removed from furnace--428 pounds per hour
Time of test-- 12 hours. Samples collected over one-half hour periods after furnace running smoothly. 12 samples collected.
Temperature range of ore--585° C to 630° C.
Reducing fuel oil, average--3.0 pounds per hour
Heating fuel oil, average--1.0 gallon per hour
Temperature intake gas., average--950° C.
Temperature exhaust gas., average 93°C.
Vacuum in reducing chamber--1/4 inch water
Vacuum in steam chamber--1/8 inch water
Temperature rise in quenching water--5°F, measured in first three hours after discharge of hot ore.

TABLE IV

SCREEN ANALYSIS OF PRODUCTS IN FURNACE; TEST NO. 12

Screen Analysis of Feed			Screen Analysis of Discharge		
-7/8"	+3/4"	9.0	-7/8"	+3/4"	4.7
-3/4"	+1/2"	16.1	-3/4"	+1/2"	18.4
-1/2"	+1/4"	43.7	-1/2"	+1/4"	50.0
-1/4"	+10 mesh	17.4	-1/4"	+10 mesh	16.6
-10 mesh	+20 mesh	7.6	-10 mesh	+20 mesh	4.5
-20 mesh	+48 mesh	4.3	-20 mesh	+48 mesh	5.5
-48 mesh		1.9	-48 mesh		0.3
		100.0			100.0

Screen Analysis--Feed to Magnetic Separator
Furnace Discharge Crushed to -4 Mesh

-4 mesh	+ 10 mesh	60.5
-10 mesh	+ 20 mesh	21.9
-20 mesh	+ 48 mesh	10.8
-48 mesh		6.8
		100.0

TABLE V

RESULTS ON SEPARATION OF FURNACE DISCHARGE
SAMPLES COMBINED AND CRUSHED TO -4 MESH
SEPARATED DRY ON "KS" MAGNETIC SEPARATOR

Product	Per Cent	Analysis, Per Cent			Per Cent Total			Magnet
	Weight	Mn	Fe	Insol.	Mn	Fe	Insol.	Resistance
Magnetic #1	25.3	8.74	55.10	8.1	8.3	45.2	16.8	5,000 ohms
Magnetic #2	39.0	23.30	34.16	12.2	34.1	43.0	39.0	2,000 ohms
Magnetic #3	17.6	42.22	12.95	14.8	27.7	7.4	21.1	500 ohms
Nonmagnetic	18.1	43.79	8.27	15.6	29.9	4.4	23.1	-
Heads (Calc.)	100.0	26.68	31.04	12.2	100.0	100.0	100.0	
Heads (Analysed)	100.0	25.42	31.41	12.0	100.0	100.0	100.0	
Combined Fe Conc.	25.3	8.74	55.10	8.1	8.3	45.2	16.8	5,000 ohms
Combined Middling	56.6	29.20	27.58	13.0	61.8	40.4	60.1	500 ohms
Combined Mn Conc.	18.1	43.79	8.27	15.6	29.9	4.4	23.1	-

TABLE VI

RESULTS OBTAINED BY COMBINING MAGNETIC PRODUCT #3 AND NONMAGNETIC PRODUCT SHOWN IN TABLE V

Product	Per Cent Weight	Analysis, Per Cent			Per Cent Total			Magnet Resistance
		Mn	Fe	Insol.	Mn	Fe	Insol.	
Combined Fe Conc.	25.3	8.74	55.10	8.1	8.3	45.2	16.8	5,000 ohms
Combined Mdds	39.0	23.30	34.16	12.2	34.1	43.0	39.0	
Combined Mn Conc.	35.7	43.10	10.60	15.2	57.6	11.8	44.2	
Heads (Calc.)	100.0	26.68	31.04	12.2	100.0	100.0	100.0	

Table V shows that in Test No. 12, 45 per cent of the iron in the furnace discharge was recovered in an iron concentrate analyzing:

55.10% Fe 8.74% Mn 8.1% Insoluble

Also that 29.9 per cent of the manganese in the furnace discharge was recovered in a product analyzing:

43.79% Mn 8.27% Fe 15.6% Insoluble

By combining magnetic concentrate No. 3 with the non-magnetic portion, the results would be as in Table VI, where the manganese concentrate has an analysis of:

43.10% Mn 10.60% Fe 15.2% Insoluble; with a recovery of 57.6% of the manganese in the ore.

The total iron made magnetic (at the magnet strength existing when 500 ohms resistance was inserted in the magnet circuit) was 95.6 per cent. The remaining 4.4 per cent iron, not magnetic, remained in the manganese concentrate. This iron has been found to be in the insoluble portion of the ore, and due to the impervious nature of this cherty insoluble material, it cannot be properly roasted in the pilot furnace. Tests have established that for each unit of insoluble material, present in the non-magnetic portion, 0.266 per cent iron oxide cannot be magnetically roasted. Applying this knowledge to the above results it shows that 97.5 per cent of the iron available for roasting was made magnetic. Thus the poor separation results obtained cannot be chargeable to poor furnace roasting.

It should be noted that in the batch tests (Table III) the iron portion in the manganese concentrate was much lower due, no doubt, to the more intense roast available with solid carbon and limited oxygen so that the iron associated with the insolubles was roasted to the magnetic oxide.

To determine if this insoluble portion of the manganese concentrate could be effectively removed by jigging, a sample of ore -7/8 inch in size was jigged in the laboratory with an 8-inch by 12-inch jig. The results are tabulated in Table VII.

These jigging results represent close regulation of the jig and of course this was necessary in order to perform the task of removing only a small amount of tailings from such a rich feed.

Applying these results to the total recovery, the results of this process in separating the manganese from the iron are shown in Table VIII.

TABLE VII

JIGGING TEST ON MANGANESE CONCENTRATE

Product	Per Cent Weight	Analysis, Per Cent			Per Cent Total		
		Mn	Fe	Insol.	Mn	Fe	Insol.
Concentrate	89.7	45.10	6.41	12.0	92.2	54.2	68.9
Tails (Calc.)	10.3	32.91	47.2	47.1	7.8	45.8	31.1
Heads (Calc.)	100.0	43.10	10.60	15.2	100.0	100.0	100.0

TABLE VIII

TOTAL RECOVERY AND GRADE OF MANGANESE FROM PILOT FURNACE

Product	Per Cent Weight	Analysis, Per Cent			Per Cent Total		
		Mn	Fe	Insol.	Mn	Fe	Insol.
Feed to Furnace	100.0	21.40	27.05	11.18	100.0	100.0	100.0
Roasted Product	85.7	25.42	31.41	12.0	101.8	99.5	92.3*
Magnetic Separation:							
Fe Concentrate	25.3	8.74	55.10	8.1	8.3	45.2	16.8
Middlings	39.0	23.30	34.16	12.2	34.1	43.0	39.0
Mn Concentrate	35.7	43.10	10.60	15.2	57.6	11.8	44.2
Jigging:							
Jig Mn Concentrate	30.6	45.10	6.41	12.0	53.1	6.4	34.0
Jig Mn Tails	5.1	32.91	47.2	47.1	4.5	5.4	10.2

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* Theoretically this should total 100 per cent. The discrepancy is due to error in weighing and sampling the many products to make up the furnace feed. For per cent totals of separations subsequent to roasting, 100 per cent was used.

OPERATING COSTS

Operating costs from which a commercial operator could draw any conclusions with reasonable certainty are not available. However, the following data are submitted, together with some comments, by the interpretation of which anyone familiar with the operations of roasting furnaces may compile reasonably accurate estimates which may apply to any specific condition.

The cost of roasting in the laboratory furnace, not including the magnetic separation, crushing, and jigging, follow:

Labor (one man @ $5.00/8 hour shift)	$2.50	per ton
Fuel Oil (heating and reducing 1.6 gallon/hour @ 9¢)	.14	" "
Power (2-1/4 H. P.)	.04	" "
Miscellaneous	.04	" "
Total	$2.72	per ton

The low pilot furnace capacity of two tons per eight hour shift makes the labor item badly out of proportion as compared with a furnace of larger capacity. Since one man can operate with equal ease a furnace with a capacity of two tons per hour, the labor cost would be reduced to 32¢ per ton.

In a report of the operation of the Mesabi Magnetic Roasting Furnace (3), which was of shaft-type construction, the following costs are given:

Number of operating days (September, 1935)	30
Operating hours	692
Lost time, per cent	3.89
Tons of feed	5,802
Total gallons of oil	55,182
Number of men per shift	1.3
Electric power per ton of feed, kilowatt hours	19,050
Gallons oil per ton of feed	9.5
Electric power per ton of feed, kilowatt hours	3.3
Cost per ton of feed:	
Oil	$0.555
Power	0.050
Labor	0.072
Total	$0.677

An operation at Anzau, South Manchuria, described in the same report, where 120 tons of iron oxides per day were magnetically roasted in a shaft-type furnace, showed the following costs:

Cost per ton:	
Combustion fuel-pulverized coal	$0.124
Reduction fuel-coke oven gas	0.477
Power and electricity	0.033
Total	$0.634

Both of the above furnaces are of a type applicable for roasting Cartersville manganese-iron ores. The magnetic roasting of iron ores is not essentially different from the roasting of manganese-iron ores, provided both have the general physical characteristics required for shaft furnace operation. Therefore, these costs can be considered as representative of comparable operations on the Cartersville ore. Operating costs will vary with the capacity of the furnace. Computations based on the above large scale commercial operations and the small pilot-furnace tests indicate that for a roasting furnace of two tons per hour capacity, the cost of operating would be less than $1.50 per ton.

Additional Magnetic Separation Tests

In an effort to improve the magnetic separations , a large number of small scale laboratory separators were made using various ore sizings and alternating current as well as direct current separators. The results of some of these tests are given and discussed in this section of the report.

The failure of the two metal oxides to completely separate is difficult to explain. The question of locked grains has been studied and the results show that good liberation is obtained even in sizes as coarse as one-half inch with 95 per cent liberation at -4 mesh. Complete liberation is not attained by grinding to very fine sizes and this 4 or 5 per cent of iron in the manganese is thought to be intimately associated with the manganese and not capable of being liberated at any practical ore size.

Wet Tube Separator Tests

A separation of the roast of pilot-furnace Test No. 4 (very similar to Test No. 12), which was ground to pass through a 200 mesh screen, is shown in Table IX. This separation was made in a modified Davis Tube Wet Separator (5). This separator consisted of an inclined tube filled with water with the poles of a strong magnet resting against the

TABLE IX

WET TUBE SEPARATION OF ROASTED ORE NO. 4

Product	Per Cent Weight	Analysis, Per Cent			Per Cent Total		
		Mn	Fe	Insol.	Mn	Fe	Insol.
Magnetic No. 1	12.4	13.63	47.07	10.02			
Magnetic No. 2	14.3	21.13	35.71	14.24			
Magnetic No. 3	23.8	38.38	18.94	19.78			
Magnetic No. 4	14.2	43.88	10.82	25.58			
Nonmagnetic	35.3	43.88	14.34	15.52			
Combined Mag. Conc.	12.4	13.63	47.07	10.02	4.8	26.5	7.8
Middlings	38.1	32.2	25.2	17.6	35.5	43.5	39.0
Combined Nonmag.	49.5	43.8	13.3	18.2	60.7	30.0	53.2
Heads (Calc.)	100.0	35.8	22.02	17.10	100.0	100.0	100.0

sides of the tube. The ore was made into a slurry and poured through the water-filled tube with the magnet at different intensities. In settling through the magnetic zone, the magnetic particles stick to the sides of the tube and the non-magnetic material settles to the bottom of the tube and is drawn off. By using sufficient magnet strength, the tube can be rotated, allowing the particles to roll over one another, liberating entrapped non-magnetic particles. Washing can also be performed. In this way clean separations are possible. This separator has been used with remarkable success by many investigators and is especially valuable in testing fine ores.

Note in Table IX that no greater selection in the separation is possible even in this fine size. It was also found that dry separations in the "KS" Separator at fine sizes did not improve the separation over dry separations at -4 mesh. Therefore, it appears that close sizing of the product does not improve the separations appreciably.

Alternating Current Separator Tests

Two primary causes for the relatively poor separations have been advanced as a result of study of our test results:

(1) The high permeability and high coercive force of the manganese minerals causes the manganese to be removed in the magnetic fractions.

(2) The high permeability of the synthetic magnetite causes induced magnetism in the manganese and it is removed along with the iron.

In many instances an alternating current separator has given improved results over a direct current separator when separating minerals with high permeabilities (6), (7), and (8).

To determine if an alternating current separator would allow improved results, a laboratory model was constructed. This separator consisted of an alternating current relay with a laminated core in series with a variable transformer which was in turn in series with a 120-volt, 60-cycle line. The separator permitted sufficiently accurate control to permit regulating the magnet intensity and the distance of the ore from the magnet, thus removing products of decreasing susceptibility. Table X shows the results of a typical separation with this alternating current separator. Roasted ore, -4 mesh, from furnace Test No. 12 was used as the feed. Three magnetic fractions were removed and the products were analyzed and combined without a middling product to give the results shown in Table X.

To determine the influence of cycle changes in using an alternating current magnet, the laboratory magnet and variable transformer were placed in series with a rotary converter and the results are tabulated in Table XI. No improvement in separation was apparent.

Variations in Reducing Roast to Improve Separation

A study of the possibilities of improving the separation by a more intense reducing roast with production of sponge iron was made. In this test -4 mesh ore was roasted with 35 per cent of -200 mesh coke in a muffle furnace. The charge was heated for three hours at 950° C. The results obtained by the magnetic separation of this product are shown in Table XII.

TABLE X

A.C. MAGNETIC SEPARATION

Product	Per Cent Weight	Analysis, Per Cent			Per Cent Total		
		Mn	Fe	Insol.	Mn	Fe	Insol.
Magnetic	59.9	15.47	42.98	12.12	35.3	86.0	49.0
Nonmagnetic	40.1	42.34	10.47	18.78	64.7	14.0	50.9
Heads (Calc.)	100.0	26.3	30.00	14.8	100.0	100.0	100.0

TABLE XI

EFFECT OF CYCLE CHANGES ON A. C. SEPARATION

Product	Cycles	Voltage	Per Cent Weight	Analysis, Per Cent Mn	Fe	Insol.
A. Mag. Conc. No 1	21	20	18.9	5.28	54.97	7.46
Mag. Conc. No. 2	21	45	20.0	6.60	52.51	9.84
Mag. Conc. No. 3	21	40	14.9	24.42	30.08	14.82
Tails	-	-	46.2	38.50	9.30	18.82
B. Mag. Conc. No. 1	60	55	22.5	5.38	57.3	7.96
Mag. Conc. No. 2	60	70	19.5	10.08	50.1	11.36
Mag. Conc. No. 3	60	100	12.0	25.42	31.4	13.98
Mag. Conc. No. 4	60	110	17.2	37.41	16.5	16.66
Tails	-	-	28.8	40.88	7.4	20.40
C. Mag. Conc. No. 1	114	55	20.9	6.16	55.52	7.26
Mag. Conc. No. 2	114	70	16.4	6.93	51.97	9.78
Mag. Conc. No. 3	114	75	17.2	23.42	31.73	14.20
Tails	-	-	45.5	38.72	9.85	20.20

TABLE XII

MAGNETIC SEPARATION OF SPONGE IRON ROAST

Product	Per Cent Weight	Analysis, Per Cent Mn	Analysis, Per Cent Fe	Analysis, Per Cent Insol.	Per Cent Total Mn	Per Cent Total Fe	Per Cent Total Insol.	Magnet Resistance
Magnetic No. 1	5.3	4.03	82.79	9.04	0.7	12.5	2.6	10,000 ohms
Magnetic No. 2	29.8	6.94	72.18	14.15	7.2	61.3	21.9	5,000 ohms
Magnetic No. 3	15.7	27.33	32.51	21.50	14.8	14.5	17.7	2,000 ohms
Magnetic No. 4	22.5	43.12	13.78	19.50	33.5	8.9	22.9	500 ohms
Nonmagnetic	26.7	47.26	3.58	23.86	43.8	2.9	34.9	
Heads (Calc.)	100.0	28.9	35.1	19.2	100.0	100.0	100.0	

Inspection of Table XII indicates that an appreciable amount of metallic iron was made. The amount of metallic iron here cannot be determined accurately due to the fact that analysis for metallic iron, ferrous oxide, and ferric oxide are confused by the oxidization effect of the manganese oxide present. In some attempts to make such an analysis, it was found that the amount of oxidization during volumetric analysis was dependent upon the amount and type of manganese oxide present in the sample. Metallic manganese had little or no effect. A study of other methods of analysis for these products revealed lengthy and somewhat doubtful successes, so that further attempts were abandoned.

A calculation of analytical percentages does reveal the metallic iron present. Calculating the manganese present as MnO and leaving the iron as metallic iron gives: Concentrate No. 1, 97.03; Concentrate No. 2, 95.28; Concentrate No. 3, 89.31. Assuming that the undetermined constituent of the concentrates is oxygen, it follows that the first two concentrates are almost wholly metallic iron, and the other concentrate probably contains an appreciable percentage of metallic iron. The charge is probably "over roasted." This intense reduction allowed no better selection in the magnetic separation than when only magnetite is made. The concentration was essentially the removal of oxygen from the iron. To produce such a product commercially would be very expensive and would offer many difficulties.

Magnetic Separation Tests on Hand-Picked Sample

An interesting test was made by hand picking manganese minerals from crude ore Sample No. 8a (feed to pilot-furnace Test No. 12) which were entirely free from iron viewed under the microscope. This sample was crushed to -4 mesh and resampled. This material was given a roast with 10 per cent -200 mesh coke in a muffle furnace for a time of one hour. The results upon magnetic separation are shown in Table XIII.

Note in Table XIII how the iron content of the manganese decreases with decreased magnetic susceptibility. This test indicates that 40 per cent of the manganese minerals are "magnetic." Grinding this sample to -200 mesh and separating in the Davis Tube at very high magnet intensity gave the results shown in Table XIV.

In Table XIV note that much more manganese was removed at the high magnet intensity than in Table XIII. Thus it appears that only the very purest manganese minerals are "non-magnetic." However, caution should be exercised in stating that this iron content of the manganese alone is the cause of poor manganese-iron separations. It must be remembered that the liberated magnetite has a relative magnetic strength of at least forty times the relative magnetic strength of pure manganese minerals (see Table I). The influence of this unliberated magnetite contained in the manganese minerals (without bringing other forces into play, such as permeability and coercive force) cannot influence the magnetism of the manganese greater than the extent of its iron content. To approximate the influence of the magnetite content of the manganese minerals, we can assume that the manganese containing 18.75 per cent Fe, or 25.8 per cent Fe_3O_4(of which only 5.2 per cent exists as shown in Table XIII, Magnetic Concentrate No. 1) would have a relative magnetic strength of:

40.18 x 25.8% or 10.3 (see Table I, where relative magnetic strength of magnetite is given as 40.18 and MnO as 0.65)

10.3 plus (74.2% x 0.65) or 10.8

TABLE XIII

A. C. SEPARATION OF HAND-PICKED MANGANESE MINERALS

Product	Cycles	Voltage	Per Cent Weight	Analysis, Per Cent Mn	Fe	Insol.
Mag. Conc. No. 1	60	100	5.2	41.72	18.73	6.92
Mag. Conc. No. 2	60	70	9.1	48.72	11.02	7.36
Mag. Conc. No. 3	60	50	11.7	54.60	6.06	6.02
Mag. Conc. No. 4	60	40	13.9	57.12	4.41	5.54
Non-magnetic			60.1	59.36	1.65	5.38

TABLE XIV

WET SEPARATION OF -200 MESH HAND-PICKED MANGANESE MINERALS

Product	Per Cent	Analysis, Per Cent			Per Cent Total		
		Mn	Fe	Insol.	Mn	Fe	Insol.
Magnetic	75.0	53.33	5.53	5.79	72.4	93.7	90.7
Non-magnetic	25.0	61.05	1.11	1.80	27.6	6.3	9.3

This value of relative magnetic strength is still only one-fourth as much as pure magnetite. If, however, the magnetite contained 75.2 per cent unliberated pure manganous oxide, its relative magnetic strength would be approximately the same as the manganese oxide containing 25.8 per cent magnetite. It hardly seems probable that this is the cause of such poor separations. As we have expressed, they are more due probably to the high permeability of the iron or the manganese minerals themselves. To determine this fact is quite out of the scope of our laboratory investigations.

Various other schemes have been tried for improving the separations. Regrinding of the middling gives no improvement. Schemes involving the use of both alternating current and direct current magnets intermittently have not indicated a promising trend. To obtain improved results over those obtained at present, appears impossible until more information can be gathered so that the cause of poor separations will be pinned down to one known condition and a practical means adopted to overcome this condition. For instance, if it were definitely determined that the high permeability of the manganese minerals were the cause of the failure to make a clean separation, a study to either reduce this high permeability, inherent in the roasted product, or to nullify its effect by using a specially designed magnetic separator might solve the problem.

In regard to the reduction of the effect of high permeability, it may be stated that the effect of temperature of roasting influences this condition and a study of temperature versus permeability might be enlightening.

In regard to the type of magnetic separator adaptable, R. S. Dean and C. W. Davis (8) discuss the use of magnetic separators involving separation by magnetic remanence alone. Because of the variable existing in such a study, a practical solution appears doubtful.

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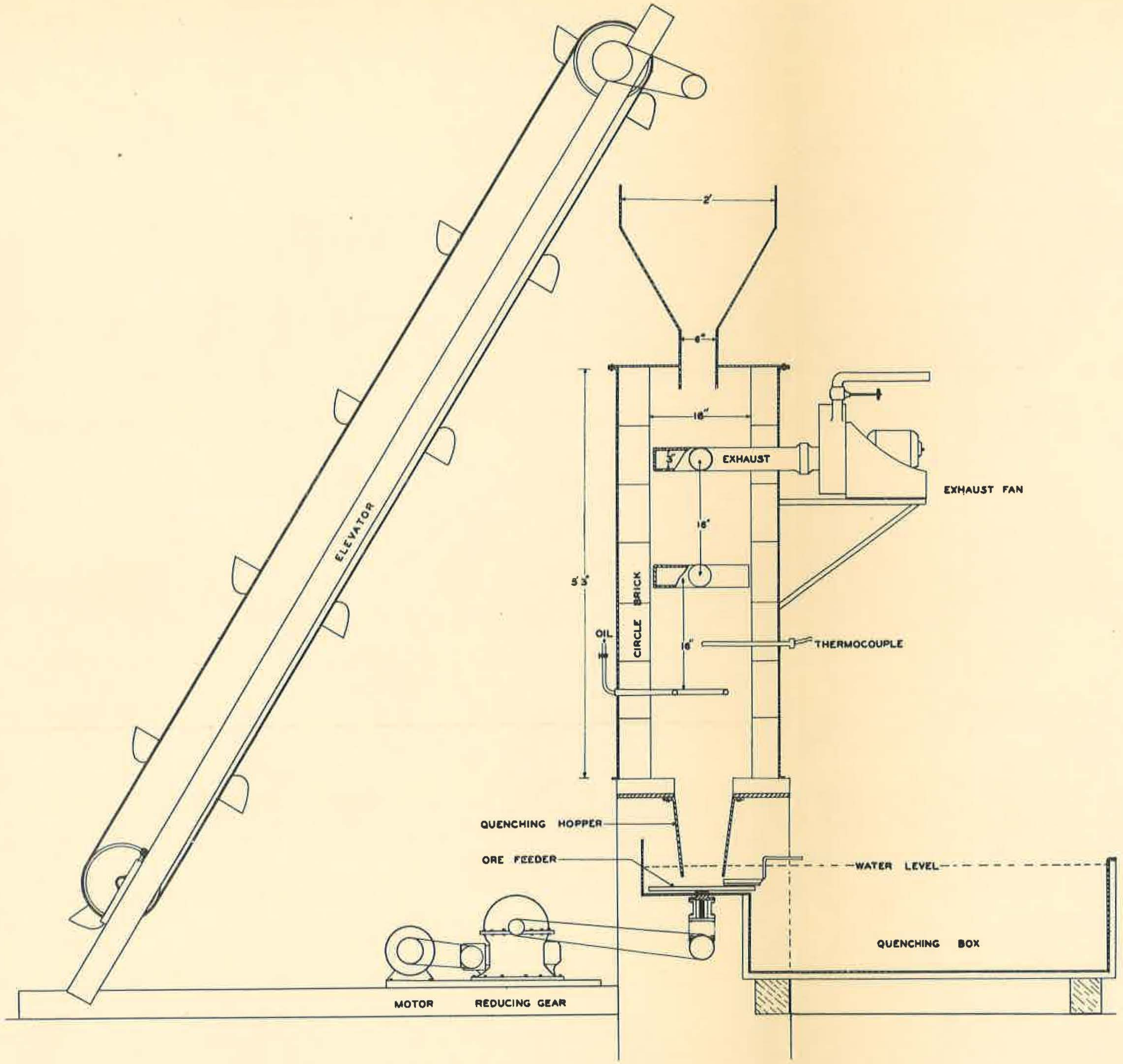

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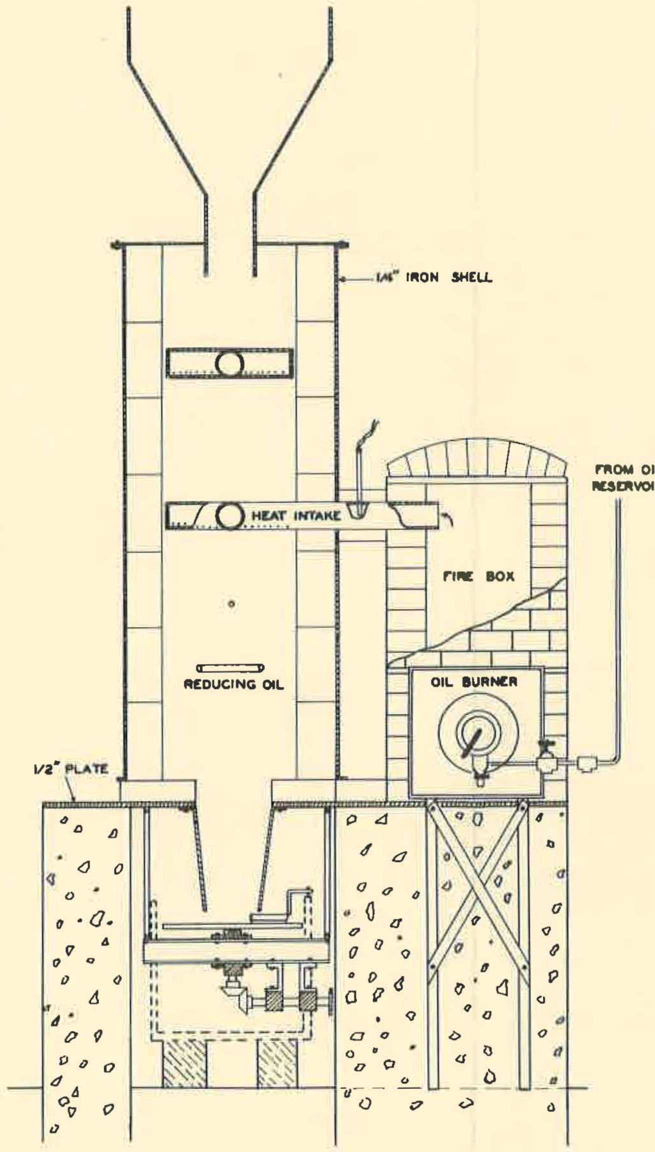

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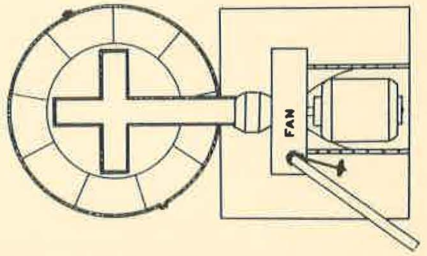

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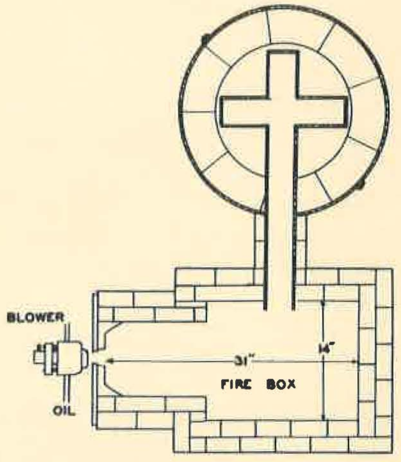

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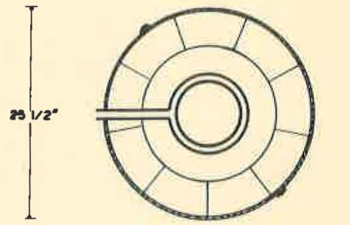

REDUCING OIL RESERVOIR

SCALE 1" = 1'
DRAWING REDUCED TO
APPROXIMATELY 1/2

MANGANESE CONCENTRATION

MAGNETIC ROASTING FURNACE

TENNESSEE VALLEY AUTHORITY
COMMERCE DEPARTMENT

SUBMITTED	APPROVED	RECOMMENDED
L. L. McMurray Nov. 1941		