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ELECTRIC SMELTING OF TITANIFEROUS IRON ORES FROM ALASKA, MONTANA, AND WYOMING

By Wesley T. Holmes II and Lloyd H. Banning

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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ELECTRIC SMELTING OF TITANIFEROUS IRON ORES FROM ALASKA, MONTANA, AND WYOMING

by

Wesley T. Holmes II[1] and Lloyd H. Banning[2]

ABSTRACT

Electric-smelting studies were made on titaniferous materials obtained from the Klukwan and Snettisham, Alaska; Choteau, Mont.; and Iron Mountain, Wyo., deposits with the objective of determining the feasibility of producing pig iron and an enriched titania slag in one test series and pig iron alone in another test series. In addition, related studies were conducted to determine the amenability of Choteau crude ore to wet-magnetic separation and to determine the quality of steel that could be produced from the titaniferous pig iron.

The continuous smelting tests were made in a three-phase, submerged-arc, electric furnace, and the laboratory steelmaking tests were made in a single-phase electric-arc furnace. A continuous, belt-type, wet-magnetic separator was used in conjunction with a ball mill and a spiral classifier in recovering titaniferous magnetite from the crude Choteau ore.

Pig irons containing less than 0.05 percent phosphorus or sulfur were readily produced from the titaniferous materials; iron recoveries ranged from 92 to 98 percent. The Choteau ore was ground to minus 65-mesh to produce a concentrate containing 60 percent or more iron. The steel produced from the titaniferous pig iron was a high-quality product.

INTRODUCTION

To obtain information that might encourage development of domestic titaniferous iron ore resources, the Bureau conducted: (1) Laboratory and pilot-plant-scale wet-magnetic beneficiation studies on samples from Alaska and Montana; the pilot-plant tests were made to produce concentrates for electric-smelting tests; (2) continuous smelting tests on crude ores and concentrates

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of titaniferous magnetites with the objective of producing pig iron and high titania slag or pig iron only; and (3) laboratory-scale oxygen-blowing and steelmaking tests on titaniferous pig iron.

The Bureau of Mines program for developing mineral resources includes a study of methods for utilizing domestic titaniferous iron-bearing materials. Several potentially valuable titaniferous iron ore deposits, containing several million tons of ore each,are known in the United States; those in the Pacific Northwest include the Klukwan, Alaska, deposit which is situated near the Chilkat River and is about 23 miles by paved highway from the port of Haines; the Snettisham deposit which is about 30 miles southeast of Juneau, Alaska, on the margin of a deep-water harbor; the Choteau deposit which lies about 9 miles north of Choteau, Mont., by U.S. Highway 89 and is within 1-½ miles of the great Northern Railway branch line; and the Iron Mountain deposit which by road is 40 miles northeast of Laramie, Wyo., and is 9 miles northwest of the Farthing Station of the Chicago, Burlington, and Quincy Railroad.

The electric-furnace smelting method was chosen for this investigation. Iron ore blends containing more than 2 percent titania are not normally used in the blast furnace[3] because (1) slags produced may have pasty characteristics which will cause irregular furnace operation; (2) character of the hot metal may be adversely affected, resulting in excessive skulling of hot-metal ladles; and (3) titanium exhibits a slight tendency to combine with carbon and nitrogen to form an infusible titanium cyano-nitride which accumulates on furnace hearth and side wall.

The electric-furnace smelting tests were conducted under the direction of project leaders on a three-shift-per-day basis. The continuous three-phase, submerged-arc, electric furnace was usually operated by a three-man crew under the immediate supervision of a pilot-plant foreman. The pilot-plant, wet-magnetic separation tests were also conducted on a three-shift-per-day basis, but the laboratory beneficiation tests and the steelmaking tests were made on day shift only.

Electric pig iron smelting is well established in several European countries and in Japan, and electric-smelting techniques have been described by Collin[4] and others. Results of prior electric-smelting investigations have been published on the Wyoming titaniferous magnetite.[5] Back and coworkers

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[3] Rossi, Auguste J. Titaniferous Ores in the Blast Furnace. Trans. AIME, v. 21, 1892-1893, pp. 832-867.

United States Steel Corp. The Making, Shaping, and Treating of Steel. Pittsburgh, Pa., 1957, 7th ed., p. 253.

[4] Collin, F. C., and O. A. Grytting. A New Approach in Electric Pig Iron Smelting. J. Metals, v. 8, No. 10, October 1956, pp. 1464-1468.

[5] Back, A. E., C. J. Chindgren, and R. G. Peterson. Treatment of Titaniferous Magnetite From Iron Mountain, Wyo. BuMines Rept. of Inv. 4902, 1952, 15 pp.

Fuller, H. C., and V. E. Edlund. Electric Smelting Titaniferous Magnetite Ore, Iron Mountain, Wyo. BuMines Rept. of Inv. 5776, 1961, 11 pp.

roasted the ore with sodium carbonate to convert the vanadium to a water-soluble form. After leaching the vanadium from the calcine, the leached calcine was briquetted and smelted in an electric-arc furnace. About 90 percent of the iron was recovered as pig iron, and substantially all of the titanium was recovered in the slag, which contained about 60 percent TiO_2. The smelting tests were made in a batch-type furnace using a maximum charge of 100 pounds per test. The leached calcine charged to the furnace contained about 46 percent iron; approximately 4,100 kilowatt-hours of electrical energy was required per ton of pig iron produced. Fuller and Edlund conducted induction-furnace smelting tests and electric-arc furnace smelting tests on minus 3/4-inch plus 10-mesh ore. In one continuous-type smelting test, the ore was smelted at a rate of 35 pounds per hour; coal was used as the reductant, and limestone was used as flux. The electrical energy consumption was 4,628 kilowatt-hours per ton of pig iron produced; 90.5 percent of the iron was recovered. The authors concluded that in smelting titaniferous ore, over-reduction must be avoided, otherwise, a thick viscous slag would result.

The objective of the smelting tests on Wyoming titaniferous magnetite at the Albany Metallurgy Research Center was to produce pig iron and a high-titania slag suitable for chlorination. No flux was used in the furnace charge, and a mixture of wood chips and coke was used for the reductant. The tests were made on ore crushed to minus ½ inch, and the fines were not separated from the coarser ore prior to charging it to the furnace. The furnace was charged at the rate of about 700 pounds per hour. Tapping temperatures were slightly above 1,600° C. The slags contained from 65 to 67 percent TiO_2, and they were tapped from the furnace without difficulty. In one 88-hour test, the electrical energy consumption was 3,822 kilowatt-hours per ton of pig iron produced; 97.5 percent of the iron was recovered in the pig iron, and 98.5 percent of the TiO_2 was recovered in the slag.

Results of laboratory-scale beneficiation tests on samples of Choteau ore, containing 43.7 percent iron and 7.2 percent titania, were reported by Wimmler.[6] The ore was treated by a sink-float concentration method to yield a minus 100-mesh concentrate containing 60.6 percent iron and 6.6 percent titania with a recovery of 81.6 percent iron. Wet-magnetic separation of minus 100-mesh ore resulted in a concentrate containing 59.3 percent iron and 5.7 percent titania, with an iron recovery of 83.1 percent. Treatment of minus 100-mesh hydrogen-reduced material yielded a concentrate containing 59.4 percent iron and 6.4 percent titania, with an iron recovery of 88.5 percent.

Detailed laboratory-scale beneficiation studies on samples of Choteau ore at the Albany Metallurgy Research Center showed that treatment of 65-mesh ore rather than minus 100-mesh ore by wet-magnetic separation would yield a concentrate containing 60.2 percent iron with an iron recovery of 83.9 percent. A pilot-plant-scale test substantiated data obtained in the laboratory.

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[6] Wimmler, N. L. Exploration of Choteau Titaniferous Magnetite Deposit, Teton County, Mont. BuMines Rept. of Inv. 3981, 1946, 12 pp.

Thorne and Wells[7] investigated the amenability of the Klukwan and Snettisham ores to concentration. Their investigations showed that high-grade concentrates with good iron recoveries could be attained. However, an appreciable percentage of titania remained in the magnetic concentrate and the iron recoveries in the concentrates depended upon the grade of sample treated.

ACKNOWLEDGMENTS

Smelting studies on the Wyoming titaniferous magnetite were conducted under a working fund agreement with the General Services Administration to determine the amenability of domestic ilmenites and high-grade titaniferous iron ores for producing both pig iron and an enriched titania slag suitable for chlorination. The smelting studies on the Wyoming ore are included in this report, because it was the only sample of the several titaniferous samples smelted under the contract that might be of commercial value for its iron content only. The Bureau wishes to thank the General Services Administration for the financial assistance given and the Union Pacific Railway Co. for mining, loading, and shipping the sample to Portland, Oreg., without cost to the Government.

DESCRIPTION OF TITANIFEROUS SAMPLES

Five samples from the Klukwan, Alaska, deposit and one sample each from Snettisham, Alaska; Choteau, Mont., and Iron Mountain, Wyo., deposits were procured for this investigation. Samples from Alaska were in the form of wet- and dry-magnetic concentrates (wet and dry refer to production methods) and hand-picked lump ore; the samples of Montana and Wyoming were shipped as mined. Chemical analyses of the samples beneficiated at Albany are given in table 1, and chemical analyses of those smelted directly are given in the section on electric smelting tests.

Two shipments of Klukwan, Alaska, titaniferous material were received. Initially, a 15-ton sample of wet-magnetic concentrate that had been produced in a pilot mill run on several samples of material from the Klukwan iron deposit was obtained from the Bureau of Mines, Mineral Resource Office, at Juneau, Alaska. This concentrate had been prepared by a method described by Wells and Thorne.[8] Petrographic examination of the sample revealed that it was essentially magnetite with relatively small quantities of hornblende, augite, and epidote and very small to trace quantities of sphene, clinozosite, and apatite. The only discrete titanium mineral observed was sphene, a calcium silicate mineral containing approximately 41 percent TiO_2. Since this concentrate was consumed before the smelting investigation was completed, an additional shipment of the material was procured. It consisted of handpicked lump ore and crude concentrate. The lump ore was divided into two lots and contained pieces up to 3 inches in diameter. Lot 1 weighed 5.7 tons, and lot 2 weighed 1 ton. Some ore, taken from the alluvial fan of the deposit, was

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[7] Thorne, R. L., and R. R. Wells. Studies of the Snettisham Magnetite Deposit, Southeastern Alaska. BuMines Rept. of Inv. 5195, 1956, 41 pp.
Wells, R. R., and R. L. Thorne. Concentration of Klukwan, Alaska, Magnetite Ore. BuMines Rept. of Inv. 4984, 1953, 15 pp.

[8] Work cited in footnote 7.

beneficiated in the field using a permanent-magnet-pulley belt separator. The concentrate also was divided into two lots. One lot was designated crude concentrate A and weighed 3.2 tons; the other lot was designated crude concentrate B and weighed 10.9 tons.

TABLE 1. - Chemical analyses of titaniferous samples, percent

	Fe	Al_2O_3	SiO_2	CaO	MgO	TiO_2	Mn	V	S	P
Klukwan:										
Handpicked lump, lot 1..	40.1	9.80	18.8	2.55	5.43	3.16	0.34	0.14	0.03	0.11
Handpicked lump, lot 2..	36.6	5.70	23.2	6.40	6.95	2.88	.22	.14	.04	.10
Crude concentrate A.....	35.0	6.30	25.6	8.98	6.08	1.79	.10	.13	.03	.10
Crude concentrate B.....	29.0	6.90	30.5	8.93	6.45	1.84	.13	.11	.03	.10
Choteau:										
Crude lump ore..........	54.1	3.16	10.1	2.70	1.68	6.52	.42	.17	.01	.10

About 3.5 tons of Snettisham, Alaska, magnetic concentrate was received. This concentrate had been prepared at the Juneau station of the Bureau by a method which was described by Thorne and Wells.[9]

The 49-ton carload of Choteau, Mont., ore was procured from two trenches. One trench was located at N½NE¼NW¼ sec 13, T 25 N, R 6 W; the other trench was located at SE¼NE¼ sec 13, T 25 N, R 6 W. After the Choteau ore was received at the Albany Metallurgy Research Center, it was crushed to minus ½-inch and a sample for laboratory beneficiation tests was split from the bulk of the material by an automatic sampler. A petrographic examination revealed that the ore consisted of magnetite (titaniferous to a minor degree), some calcite, and quartz. Very small amounts of ferromagnesium minerals, ilmenite, chlorite, chromite, fluorite, zircon, and garnet also were present. The minor amount of ilmenite found in the sample was closely associated with the titaniferous magnetite.

The 40 tons of massive Iron Mountain ore was taken from trench 6 located at N½SE¼ sec 27, T 19 N, R 71 W in Albany County, Wyo. This ore was crushed to minus ½ inch for smelting. A petrographic examination of a representative sample revealed that the ore consisted of about 87 percent titaniferous magnetite and 10 percent ilmenite. Small amounts of spinel, limonite, chlorite, and ferromagnesium silicate minerals also were present in the ore.

BENEFICIATION STUDIES

Beneficiation studies were directed toward the production of a high-grade concentrate for electric-smelting tests. Because the principal iron-bearing mineral of the ores was titaniferous magnetite, beneficiation studies on the Kluhwan and Choteau materials were limited to wet-magnetic separation tests.

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[9] Work cited in footnote 7.

Laboratory Beneficiation Tests on Choteau Ore

Laboratory beneficiation tests were made to determine the effect of fineness of grind on iron recovery and grade of concentrate. A 72-pound sample was divided into eight equal fractions. These fractions were stage-ground in a small ball mill to pass 20-, 35-, 65-, 80-, 100-, 150-, 200-, and 325-mesh screens, respectively. Tyler standard screen-scale sieves were used. Concentration tests were then conducted on kilogram-size samples of all ground fractions. A sample was placed in a large Pyrex container, 2,000 milliliter of water was added, and the mixture was slurried by using a motor-driven stirrer. Then, a 250-milliliter beaker containing a permanent magnet was lowered into the slurry to collect the magnetite on its bottom surface. The beaker with the adhering magnetite was removed from the slurry, and the magnetite was deposited into another container by raising the magnet from the beaker bottom. The beaker was repeatedly immersed in the slurry until no material collected on the bottom surface of the beaker. The next step consisted of reconcentrating the magnetic fraction according to the same procedure to obtain a product similar to that which would be expected in a continuous operation. A summary of the data are given in table 2.

TABLE 2. - Results of laboratory beneficiation tests on Choteau ore

Mesh[1]	Concentrates											Fe recovery, percent
	Weight-percent	Analyses, percent[2]										
		Fe	Al_2O_3	SiO_2	CaO	MgO	TiO_2	Mn	V	S	P	
20	83.7	56.4	2.83	9.07	1.97	1.16	6.07	0.35	0.16	0.04	0.08	87.3
35	77.7	58.5	2.49	7.44	1.35	.91	6.13	-	-	-	-	84.1
65	75.4	60.2	2.09	6.00	1.09	.62	6.19	.29	.15	.04	.10	83.9
80	74.9	60.1	2.15	6.22	1.00	.70	6.26	-	-	-	-	83.2
100	73.7	60.6	1.99	5.71	.95	.49	6.30	-	-	-	-	82.5
150	73.2	60.6	2.05	5.53	1.00	.47	6.28	.28	.17	.04	.12	82.0
200	72.1	59.9	2.33	6.03	1.29	.66	6.11	-	-	-	-	79.8
325	71.6	59.7	2.41	6.15	1.07	.75	6.21	.31	.23	.02	.10	79.0

[1] Ore was stage-ground to pass the screen of the indicated mesh.

[2] A dash indicates no determination was made.

Test results showed that (1) the grade of concentrate improved with fineness of grind up to minus 100-mesh; (2) fine grinding did not completely liberate the titania from the iron; (3) there was little improvement in grade of concentrate by grinding finer than minus 65-mesh; and (4) iron recovery decreased with increase in fineness of grinding. Figure 1 shows the effects of fineness of grind on iron recovery and on the iron and titania content of the concentrates.

Pilot-Plant, Wet-Magnetic Separation Tests

To produce adequate quantities of concentrates for continuous smelting studies on the Klukwan lump ore lots 1 and 2, the Klukwan crude concentrates A and B, and the Choteau ore, each sample was ground in a ball mill and was magnetically concentrated.

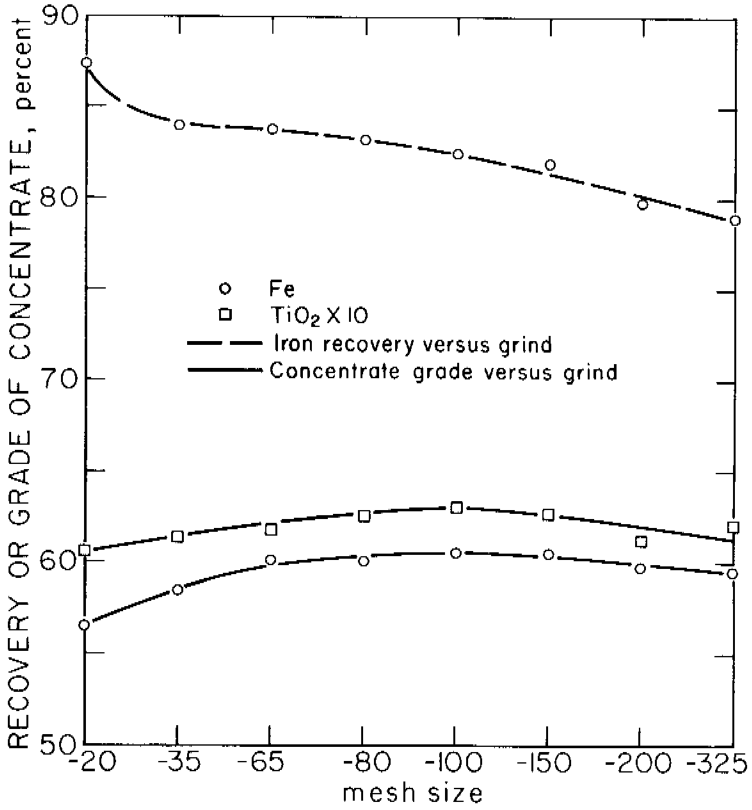

FIGURE 1. - Effects of the Fineness of Grind on the Iron and Titania Contents of Choteau Concentrates.

Klukwan Composite Concentrate

Concentrates were produced from lots 1 and 2 lump ore and from A and B crude concentrates by a technique similar to that described by Wells and Thorne.[10] The concentrates were composited for smelting; the composite sample contained 57.8 percent iron.

Choteau Pilot-Plant Concentrate

In this test the minus 1/2-inch ore was transferred from a bin by an automatic feeder to a 3- by 3-foot ball mill that was in closed circuit with a 12-inch spiral classifier. Overflow from the classifier was pumped to a 12-inch, belt-type, wet-magnetic separator. The concentrate was collected in barrels and the tailings were pumped to a waste pond. Figure 2 shows the pilot-plant flowsheet.

To determine flow rates, samples were taken of the crude starting material, the ball mill discharge, the classifier overflow, the final concentrate, and the tailing; at 30-minute intervals, the entire stream of each product was collected for 15 seconds. The samples of each product collected during each 8-hour period were composited. After each composite product was filtered, dried, and weighed, a portion was used for determining size distribution (table 3).

The pilot-plant test results are shown in table 4. The iron content of the concentrate and the iron recovery were 0.3 and 0.9 percent higher, respectively, than the iron content of the concentrate and iron recovery from the laboratory 65-mesh beneficiation test. The steel ball consumption was 11 pounds per net ton of ore ground. In grinding to 99 percent minus 65-mesh, 1.32 tons of crude ore was required to produce a net ton of concentrate containing 60.5 percent iron with an iron recovery of 84.8 percent.

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[10] Work cited in footnote 7.

TABLE 3. - Average size distribution of Choteau material

Sieve size, mesh	Weight, percent[1]			
	Material to ball mill	Classifier overflow	Concentrate	Tails
Plus 3	42.9	-	-	-
Minus 3 plus 4	12.3	-	-	-
Minus 4 plus 6	8.5	-	-	-
Minus 6 plus 10	9.8	-	-	-
Minus 10 plus 14	2.7	-	-	-
Minus 14 plus 20	2.0	-	-	-
Minus 20 plus 35	3.6	-	-	-
Minus 35 plus 65	3.1	1.0	0.1	0.9
Minus 65 plus 100	3.2	59.4	69.9	35.8
Minus 100 plus 150	3.3	15.4	13.8	15.9
Minus 150 plus 200	3.0	12.5	11.3	16.8
Minus 200 plus 325	3.2	9.4	4.1	12.1
Minus 325	2.4	2.3	.8	18.5

[1] A dash indicates none.

TABLE 4. - Choteau pilot-plant beneficiation test results

Feed:	
Quantity, net tons	30.1
Fe content, pct	54.1
TiO_2 content, pct	6.52
Feed rate, lb/hr	690-860
Ball mill:	
Ball load, lb	1,800
Discharge, sp gr	1.90-1.95
Ball consumption per net ton of ore ground, lb	11
Classifier overflow:	
Specific gravity	1.27-1.32
Minus 100-mesh, pct	39.6
Circulating load:	
Moisture, pct	15.5-17.2
Dry weight, lb/hr	995-1,290
Fe, dry basis, pct	57.1
Concentrate:	
Fe content, pct	60.5
TiO_2 content, pct	6.10
SiO_2 content, pct	6.28
Tailings:	
Fe content, pct	25.1
TiO_2 content, pct	7.71
Recovery:	
Fe, pct	84.4
TiO_2, pct	71.0

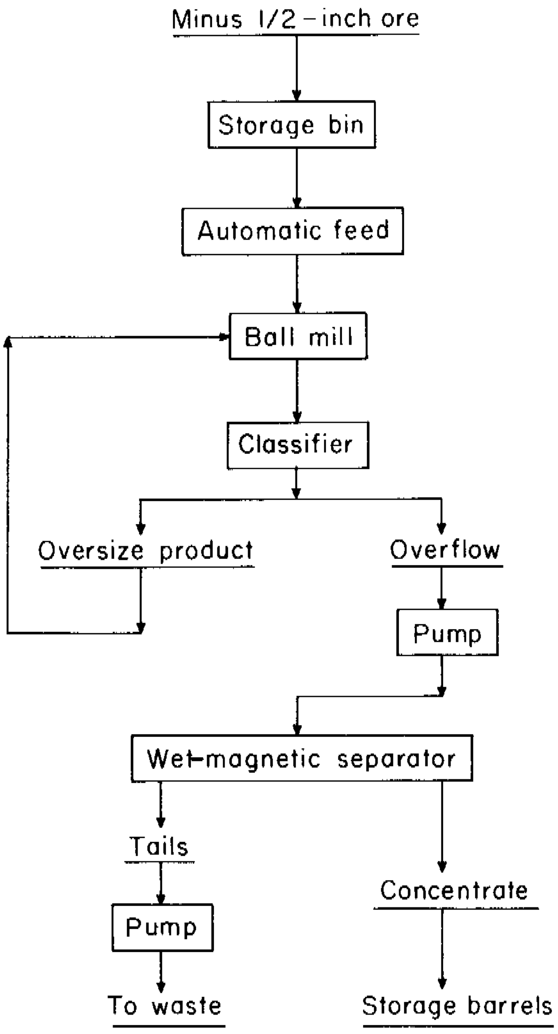

FIGURE 2. - Pilot-Plant Flowsheet.

ELECTRIC SMELTING TESTS

The objective of one smelting test each on Klukwan and Choteau concentrates and of two tests on massive Iron Mountain ore was to produce high-titania slag and pig iron. The objective of three smelting tests on Klukwan concentrates and of one test each on Snettisham concentrate, Choteau concentrate, and Choteau crude ore was to produce pig iron only. Potentially valuable slag was produced only in tests on Iron Mountain ore. Metal compositions were within specifications for foundry and low-phosphorus pig irons. Analyses of iron concentrates and ores used in the tests are given in table 5, and analyses of fluxes are given in table 6.

Experimental Techniques and Equipment

Two types of furnace charges were used, those without flux and those with flux. No flux was used in furnace charges in which attempts were made to produce high-titania slag. The ratio of carbon from wood chips or hogged fuel to that from coke was varied to control the tapping temperature. By increasing the proportion of wood chips in the furnace charge, a higher tapping temperature was obtained. Calculation of the reductant requirement for both types of charges was based on the iron oxide content of the starting materials and the fixed carbon content of the reductants. The stoichiometric proportion of carbon, as shown in the tables, is defined as the ratio of the actual weight of carbon used to the theoretical quantity required for the reduction of the iron oxides to metal with the formation of CO in the reduction reaction. Because some carbon entered the metal and some was consumed by air oxidation, more than the stoichiometric quantity was used in all tests.

Except for one test, limestone was used in all tests in which flux was added; in that one test silica was used. Slag basicities were calculated as the mole ratio of CaO plus MgO to SiO_2. In estimating flux requirements, liquidus data by Osborn and coworkers[11] and phase diagrams for ceramists by Lenin and coworkers[12] were used as a guide.

TABLE 5. - Chemical analyses of iron concentrates and ores used in smelting tests, percent

	Constituents[1]										
	Fe	Al_2O_3	SiO_2	CaO	MgO	TiO_2	Mn	Cr	V	S	P
Klukwan concentrate:											
Test 1 head sample....	62.7	2.00	5.21	2.16	1.88	1.52	-	-	0.27	0.02	0.06
Test 5 head sample....	62.3	2.00	5.05	2.32	1.30	.67	0.10	-	.24	-	-
Composite............	57.8	3.80	6.40	2.85	2.45	1.68	.20	-	.31	.05	.10
Snettisham concentrate..	61.6	3.20	7.10	1.55	.55	1.35	.36	-	.31	.02	.07
Choteau:											
Ore..................	54.1	3.16	10.1	2.70	1.68	6.52	.42	0.22	.17	.01	.10
Concentrate..........	60.5	1.87	6.28	.89	.47	6.10	.25	.11	.15	.02	.06
Iron Mountain ore.......	50.0	5.60	.70	.26	3.40	22.5	.19	-	.34	-	.02

[1] A dash indicates no determination was made.

TABLE 6. - Chemical analyses of fluxes and reductants used in smelting tests, percent

	Constituents[1]											
	Fe	Al_2O_3	SiO_2	CaO	MgO	TiO_2	Mn	Cr	V	S	P	Fixed carbon
Fluxes:												
Pebble lime....	0.26	0.88	0.88	94.0	0.29	0.01	0.05	-	-	-	-	-
Limestone......	1.66	.29	1.51	53.0	.61	.32	.03	-	-	-	-	-
Silica (quartz)	-	1.96	95.9	.32	1.14	-	-	-	-	0.01	-	-
Reductants:												
Coke...........	.40	3.15	3.20	3.08	.45	.06	-	-	-	.10	0.03	81.0
Coal, Utah.....	.74	1.05	4.65	1.80	.30	.02	-	-	-	.46	.03	49.5
Coal, Montana..	.65	2.88	3.29	1.72	.23	.08	-	-	-	.34	.01	55.0
Hogged fuel....	.33	.20	.40	.28	.09	.10	.05	-	0.01	.01	.01	[2] 13.0 [3] 15.3 [4] 16.3
Wood chips.....	.42	.23	.45	.41	.14	.23	.08	0.10	.01	.01	.01	[5] 13.5 [6] 19.7 [7] 22.0

[1] A dash indicates no determination was made.
[2] Fixed carbon content of hogged fuel used in tests 1 and 5.
[3] Fixed carbon content of hogged fuel used in tests 6 and 7.
[4] Fixed carbon content of hogged fuel used in test 8.
[5] Fixed carbon content of wood chips used in test 9.
[6] Fixed carbon content of wood chips used in tests 2 and 10.
[7] Fixed carbon content of wood chips used in tests 3 and 4.

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[11] Osborn, E. F., R. C. Devries, K. H. Gee, and H. M. Kramer. Optimum Composition of Blast Furnace Slag as Deducted From Liquidus Data for the Quaternary Systems $CaO-MgO-Al_2O_3-SiO_2$. Trans. AIME, v. 200, 1954, pp. 33-45.

[12] Lenin, E. M., H. F. McMurdie, and F. P. Hall. Phase Diagrams for Ceramists. Am. Ceram. Soc. Inc., 1956, pp. 152, 170-173, 180-181, and 186.

The tests were conducted in a three-phase, open-top, electric-arc smelting furnace. The steel shells of the furnace were lined with either magnesite or carbon key brick; for most of the tests, shells having diameters of 30 and 40 inches inside the lining were used. The bottoms were covered with four layers of 9-inch straight brick overlaid with 3 inches of the corresponding refractory material. The inside depth of the furnaces was 40 inches. The 4-inch graphite electrodes were held by cable-suspended, water-cooled, clamp-arm assemblies and were spaced in an equilateral triangle pattern. Each electrode was about 9 inches from the furnace center. The vertical movements of the electrodes were controlled automatically. The furnace was equipped with two tap holes; the higher one was used to withdraw slag, and the lower one was used to withdraw metal.

The general procedure for handling the materials was similar in all tests. Figure 3 is the flowsheet of the smelting operation. Charge components were weighed, were mixed in a 6-cubic-foot cement mixer, were hoisted to

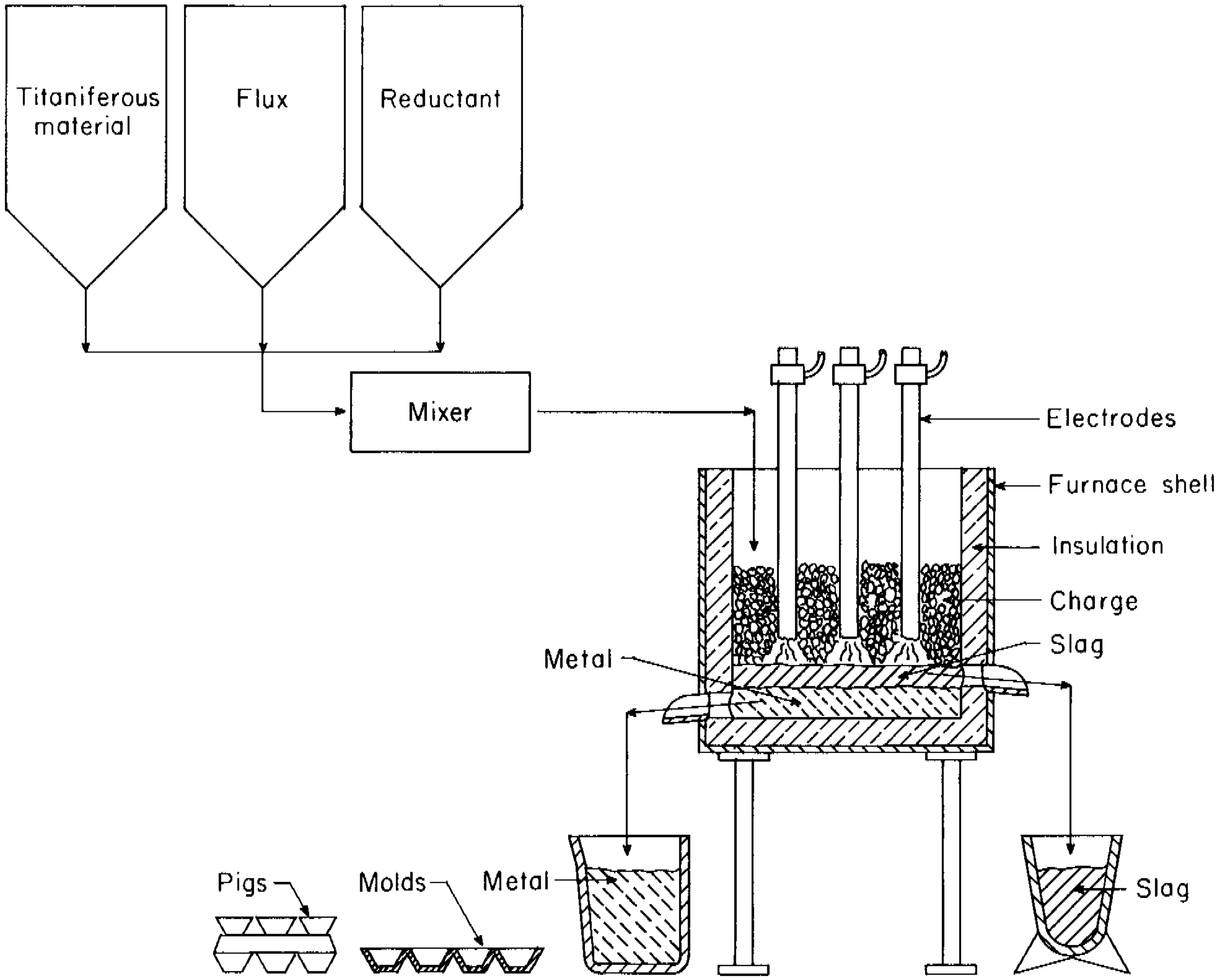

FIGURE 3. - Smelting Flowsheet.

the charging deck in a "tote" box by a 3-ton overhead crane, and then were dumped on shoveling plates located adjacent to either side of the furnace. Smelting was started on a preheated hearth; the charge was fed manually. A dry-top, submerged-arc smelting technique was used; that is, a layer of unfused charge was maintained over the molten pool at all times, and a high enough voltage was used to prevent the electrode from dipping into the slag. Slag and metal were tapped from the furnace at intervals of from 2 to 4 hours. Normally, the tapholes were opened with an iron rod; however, when necessary, an oxygen lance was used. Temperatures of the molten products were measured with an optical pyrometer as they were tapped from the furnace. After tapping, a mixture of crushed magnesite brick and periclase was used to close the tapholes. The slag was tapped into a cast-iron mold capable of holding approximately 1,000 pounds. Metal was drained from its taphole located approximately 3 inches below the slag taphole into a geared ladle. The molten metal was poured from the ladle into cast-iron pig molds.

Production of Titania Slag and Pig Iron

The smelting furnaces were lined with magnesite refractories for all tests. Data from smelting samples of Klukwan concentrate, Choteau concentrate, and Iron Mountain massive ore are given in table 7, and analyses of metal and slag test products are given in table 8.

Klukwan Concentrate

Part of the 15-ton concentrate sample from Juneau, Alaska, that had been produced in a pilot mill run on several samples of material from the Klukwan iron deposit was used in the initial smelting test. The assigned objective of the test was to produce a slag as rich in titania as practical and to produce pig iron. In an attempt to produce a slag of low SiO_2 content, a large excess of reductant consisting of hogged fuel only was added to the furnace charge. Satisfactory furnace operation was achieved; power was applied to the furnace almost 98 percent of the time during the test period. About midway through the test, however, the operators noted that the furnace bottom was receding. The high tapping temperature, about 1,670° C most of the time, contributed to the excessive corrosion of the magnesite refractories. Based on the analysis of the furnace charge, the slag should have contained 19 percent MgO; it contained 32 percent. The TiO_2 content of the slag was low--only 7.97 percent. Test results indicated that a valuable high-titania slag could not be produced from Klukwan concentrate; consequently, the objective of further tests on the concentrate was to produce pig iron only.

Choteau Concentrate

Because the ratio of TiO_2 to other slag-forming constituents of Choteau titaniferous concentrate was much higher than that of Klukwan, an attempt (test 2, table 7) was made to produce a potentially valuable slag. After 37 hours of furnace operation, the test was terminated because accretions had formed on the furnace hearth, and it was difficult to open the tap holes. Although the wood chip content of the furnace charge had been reduced below that used in the test on the Klukwan concentrate, the power input had been increased. These changes were not expected to effect as great a difference in tapping temperature as that which occurred--a decrease from 1,670° to 1,500° C. This large difference may be partly explained by the difference in the inside diameter of the furnaces used. A higher tapping temperature would be expected in the furnace having the smaller inside diameter. In the test on the Klukwan concentrate, the diameter inside the refractory lining was 30 inches, and in the test on the Choteau concentrate, it was 40 inches. Recent studies have indicated that the liquidus temperature of the slag produced in smelting the Choteau concentrate would be above 1,600° C. Attempting to operate the furnace with a tapping temperature below the liquidus temperature of the slag probably accounts for some of the difficulties experienced.

TABLE 7. - Summary of data on production of titania slag and pig iron[1]

	Material			
	Klukwan concentrate, test 1	Choteau concentrate, test 2	Iron Mountain ore	
			Test 3	Test 4
Net operating time, hr............	59	42.3	108.2	87.8
TiO_2 content of material, pct......	1.52	6.10	22.5	22.5
Charge additions per 100 pounds of concentrate, dry basis, lb:				
Coke...........................	-	-	7.0	8.5
Coal, Montana..................	-	7.5	-	-
Hogged fuel.....................	137	-	-	-
Wood chips......................	-	103	71.0	62.5
Moisture of hogged fuel or wood chips average, pct...............	36.4	23.5	56	60
Stoichiometric carbon, pct.........	143	139	147	143
Electrical conditions, average:				
Voltage, phase-to-phase..........	118	106	120	115
Power input, kw................	242	354	403	418
Tapping temperature, average ° C...	1,670	1,500	1,635	1,620
Products, lb:				
Slag...........................	1,548	2,423	13,789	12,250
Pig iron.......................	8,164	10,397	21,299	19,204
Kilowatt-hour consumption per net ton of pig iron.................	3,400	2,879	4,095	3,822
Electrode consumption per ton of pig iron, lb....................	48	39	46	45
TiO_2 content of slag, pct..........	7.97	40.4	64.5	67.4
Recovery, pct:				
TiO_2 in slag[2]..................	65.4	90.4	93.1	98.5
Fe in metal[3]..................	94.9	93.3	95.2	97.5

[1] A dash indicates none.

[2] Based on titania content in charge and in slag.

[3] Based on iron content in charge and metal.

TABLE 8. - Analyses of titania slags and pig iron, percent[1]

	Material			
	Klukwan, test 1	Choteau, test 2	Iron Mountain	
			Test 3	Test 4
Metal:				
Fe	90.6	93.1	95.8	94.5
C	4.7	3.01	3.25	3.73
Si	2.91	2.24	.23	.25
Ti	.49	.42	.12	.15
Mn	.18	.31	.04	.09
Cr	-	.19	-	-
V	.41	.13	.04	.42
S	.02	.03	.01	.01
P	.06	.04	.01	.01
Slag:				
TiO_2	7.97	40.4	65.2	67.4
Fe	4.8	4.10	4.1	2.4
Al_2O_3	9.8	14.9	15.3	16.4
SiO_2	26.0	25.2	2.89	2.91
CaO	20.0	9.3	.22	.23
MgO	32.0	4.2	10.7	9.70
Mn	-	.17	.10	.10
Cr	-	.17	-	-
V	-	.12	.18	.11

[1] A dash indicates no determination was made.

Iron Mountain Massive Ore

The production of a high-grade titania slag and low-phosphorus pig iron from massive iron ore was demonstrated in tests 3 and 4. The bulk of the carbon was supplied by wood chips, and the remainder was supplied by coke instead of coal as used in test 2. Furnace operation was excellent throughout these tests. Tapping temperatures exceeded 1,600° C. The electrical energy consumption was higher than in previous tests, and the metal products contained a lower percentage of silicon. The iron recovery (97.5 percent) in the fourth test was higher than in any previous test.

Evaluation of Titania Slags

Table 9 shows the actual chemical compositions of slags produced in the smelting tests and the slag compositions that would have resulted from the complete reduction of the iron oxide and 30 percent of the silica content. The slag-forming constituents of the reductants were added to those of the titaniferous material in calculating the theoretical slag composition. Only the slag produced from the Iron Mountain ore was comparable in titania content to those produced commercially.[13] The average TiO_2 contents of the slags from

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[13] Knoerr, A. W. World's Major Titanium Mine and Smelter Swing into Full-Scale Production. Eng. and Min. Jour., v. 153, No. 3, March 1952, pp. 72-79.
Miller, Jesse A. Titanium: A Materials Survey. BUMines Inf. Circ. 7791, 1957, p. 127.

tests 3 and 4 (table 7) were 64.5 and 67.4 percent, respectively. However, their alumina and magnesia contents were higher than the alumina and magnesia contents of commercial products. If high-titania Iron Mountain slag were to be produced commercially, its value for any particular use would need to be established.

Under present conditions, the possibility of producing a valuable slag from the Choteau ore is quite remote, and the low TiO_2 content of the theoretical Klukwan slag precludes producing a commercial slag product from that ore.

TABLE 9. - Actual and theoretical titania slag analyses, percent

	Constituents					
	Fe	Al_2O_3	SiO_2	CaO	MgO	TiO_2
Klukwan:						
Actual (test 1)..................	4.8	9.8	26.0	20.0	32.0	7.97
Theoretical[1]....................	-	17.8	32.5	19.3	16.8	13.6
Choteau:						
Actual (test 2)..................	4.1	14.9	25.2	9.3	4.2	40.4
Theoretical[1]....................	-	14.9	31.3	9.2	4.0	40.6
Iron Mountain:						
Actual (test 4)..................	2.4	16.4	2.9	.23	9.7	67.4
Theoretical[1]....................	-	17.8	2.6	2.3	10.4	66.9

[1] Assuming that all iron oxide and 30 percent of the silica content are reduced to the elemental state.

Production of Pig Iron

Since the results of previous tests indicated that a potentially valuable high-titania slag could not be produced from Klukwan or Choteau concentrates, the objective of the tests given in this section was to attain a low electrical energy consumption consistent with a high-iron recovery in the production of high-grade pig iron from titaniferous materials. The titania content of the titaniferous magnetites was treated as another gangue constituent that was to be rejected to the slag. Summary of test data and analyses of metal and slag products are given in tables 10 and 11.

Klukwan Concentrates

One smelting test was made on a sample of the high-grade concentrate obtained from the Juneau, Alaska, station, and the other two tests, tests 6 and 7, were conducted on the composite concentrate that was produced at the Albany Metallurgy Research Center. A magnesite-lined furnace was used in all tests.

TABLE 10. - Summary of data on production of pig iron[1]

	Material					
	Klukwan concentrates			Snettisham concentrate,	Choteau	
					Ore	Concentrate
	Test 5	Test 6	Test 7	test 8	Test 9	Test 10
Net operating time, hr.........	50.5	48.5	21.0	23.3	100	44
TiO_2 content of material, pct..	0.67	1.68	1.68	1.35	6.52	6.10
Charge additions per 100 pounds of material, dry basis, lb:						
Silica.......................	-	3.5	-	-	-	-
Pebble lime..................	-	-	-	-	-	1
Limestone....................	3.3	-	3	5	13	5
Coke.........................	11.2	-	-	-	-	-
Coal, Montana................	-	-	-	-	12.5	3.5
Coal, Utah...................	-	15.5	6	6.8	-	-
Hogged fuel..................	68	56	92	86	-	-
Wood chips...................	-	-	-	-	60	103
Moisture of hogged fuel or wood chips, average, pct...........	40.0	40.0	39.6	34.1	36.0	17.5
Stoichiometric carbon, pct.....	120	98.4	102.7	98.7	130	128
Electrical conditions, av:						
Voltage, phase-to-phase......	141	102	120	123	119	118
Power input, kw..............	242	240	214	229	329	340
Tapping temperature, av ° C....	1,450	1,450	1,525	1,395	1,545	1,625
Products, lb:						
Slag.........................	2,339	2,400	1,120	1,303	11,388	3,600
Pig iron.....................	10,517	7,184	3,997	4,330	17,683	10,450
Basicity of slag[2]..............	1.36	0.96	1.97	1.57	1.35	1.40
Kilowatt-hour consumption per ton of pig iron...............	2,460	3,196	2,240	2,750	3,721	2,858
Electrode consumption per net ton of pig iron, lb...........	27	63	52	61	21	36
Iron recovery, pct[3]...........	97.3	95.0	96.7	92.4	96.9	96.1

[1] A dash indicates none.

[2] The basicity was calculated as the mole ratio of $\frac{CaO + MgO}{SiO_2}$.

[3] Based on iron content in charge and in metal.

Enough limestone was used in the charge of the initial test (test 5) of the group to insure the production of a slag having a basicity of at least 1.0. About 36 percent of the carbon was obtained from coke, and the rest was obtained from hogged fuel. No operating difficulties were noted. About 97 percent of the iron charged to the furnace was recovered in the pig iron product.

In the sixth test, silica was added to the charge to yield a foundry pig iron and a slag having a basicity of 0.96. About 47 percent of the carbon was supplied by coal, and the remainder was supplied by hogged fuel. Forty-four hours after the test was started, accretions had formed on the furnace hearth; feeding of the charge was interrupted to smelt the crust of material from the delta zone and from the side wall of the furnace. After the material became molten, the furnace was tapped and the test was terminated. The iron recovery was lower than that of test 5, and the electrical energy consumption was higher. A higher proportion of slag to pig iron than in the previous test and the operating difficulties experienced were factors that added to the electrical energy consumption.

TABLE 11. - Analyses of products produced in pig iron smelting tests, percent[1]

	Material					
	Klukwan			Snettisham,	Choteau	
	Test 5	Test 6	Test 7	test 8	Test 9	Test 10
Metal:						
Fe	92.6	91.7	91.5	94.8	93.4	93.2
C	4.8	3.97	3.72	2.71	3.32	4.17
Si	3.51	3.13	2.23	.44	.88	.79
Ti	.10	.26	.43	.42	.59	.52
Mn	.18	.29	.61	.40	.67	.39
Cr	-	-	-	-	.34	.21
V	.32	.20	.60	.35	.26	.20
S	.02	.02	.02	.02	.03	.03
P	.06	.02	.01	.01	.03	.04
Slag:						
Fe	4.0	4.32	4.05	3.79	3.60	4.15
Al_2O_3	7.6	21.6	21.7	23.1	11.1	10.7
SiO_2	36.0	36.5	24.3	27.6	29.6	25.4
CaO	26.5	17.0	25.0	30.1	29.4	25.5
MgO	13.8	11.4	14.1	7.41	5.74	5.5
TiO_2	3.8	7.4	8.2	5.55	18.3	26.3
Mn	-	-	-	-	.44	.38
Cr	-	-	-	-	.21	.37
V	.46	.32	.63	.49	.06	.20

[1] A dash indicates no determination was made.

With some modification in operating procedure, test 7 followed test 6 without cooling off and cleaning out the furnace. Limestone was added to the charge instead of silica. More of the total carbon was obtained from hogged fuel than in the two previous tests. The test was characterized by excellent furnace operation, and a fluid slag was produced. The pig iron recovered was higher in manganese, titanium, and vanadium and 0.9 percent lower in silicon content than the metal produced in test 6 under acid conditions. Also, the electrical energy consumption was considerably lower.

Snettisham Concentrate

In the eighth test, limestone was used in the furnace charge to yield a low-phosphorus pig iron and a slag with a basicity of 1.57. A lower proportion of carbon was used than in previous tests. The percentage of total carbon obtained from coal was about the same as that of test 7. No operating difficulties were noted. About 92 percent of the iron was recovered in a premium-grade pig iron. Carbon and silicon contents of the metal were lower than in any of the tests on Klukwan concentrates. Electrode consumption was high; the low proportion of carbon in the charge was one of the factors that contributed to the high electrode consumption.

Choteau Materials

Smelting tests were made on both crude ore and concentrate. The furnace was lined with carbon refractories for the test on the crude ore and with magnesite refractories for the test on the magnetic concentrate.

Test 9 on Choteau crude ore was divided into four periods which varied from 22 to 31 hours each. After preheating the furnace, a mixture of crude ore, limestone, Montana coal, and wood chips was charged to the furnace. A satisfactory furnace operation was achieved. The metal and slag from the various periods were composited for sampling. Results of analyses, given in table 12, on the composited samples from the various periods show that neither the composition of the metal nor the slag varied greatly from one period to another.

TABLE 12. - Analyses of periodic samples of test 9 on Choteau crude ore

	Composite of taps			
	1-11	12-22	23-33	34-45
Period, hr	25	22	28	31
Metal, pct:				
C	3.05	3.41	3.45	3.38
Si	1.13	.69	.75	.71
Mn	.75	.56	.74	.69
Ti	.58	.62	.63	.53
Slag, pct:				
Fe	3.85	3.41	3.62	3.16
Al_2O_3	9.16	10.9	11.2	11.6
SiO_2	23.6	27.1	30.3	30.9
CaO	29.8	31.4	30.5	30.0
MgO	5.07	5.79	5.47	4.68
TiO_2	19.4	18.6	18.9	17.5

The test on concentrate to produce pig iron only was a continuation of the test conducted to produce a slag as high as possible in titania and pig iron. During test 2, accretions of slag had gradually formed in the furnace which caused termination of the test. Before starting this test, lime was added to the furnace and reacted with the accretions on the furnace side walls. The molten material which formed was tapped from the furnace. Only a small quantity of CaO was required in the charge of this test to produce a fluid slag; 5 pounds of limestone and 1 pound of CaO per 100 pounds of concentrate was sufficient. As in the test on the crude ore, the bulk of the carbon was supplied by wood chips; the remainder was supplied by 1/4-inch Montana coal. No operating difficulties were experienced. After 39 hours of continuous operation, however, corrosion of the furnace lining was observed. The accountability of the charged constituents in test products was satisfactory with the exception of MgO. A materials balance indicated that the slag contained 75 percent more MgO than was in the furnace charge. The MgO from the furnace lining, as well as the limestone added to the furnace charge, increased the slag basicity to 1.35 compared with a basicity of 0.64 of the slag from test 2 in which the concentrate was smelted without flux addition. Furthermore, the TiO_2 content of the slag was 26 percent compared with 40.4 percent for the slag of the previous test.

EVALUATION TESTS ON CHOTEAU PIG IRON

Laboratory tests were made to determine the feasibility of producing carbon steel from titaniferous pig iron. The pig iron chosen for these tests had been produced from choteau ore and concentrate. Before the steelmaking tests were initiated, the relationship between carbon content of the metal and its hardness was established in oxygen blowing tests; this relationship was used in adjusting the carbon content to the desired level in the steelmaking tests.

The single-phase, electric-arc furnace used in the oxygen-blowing and steelmaking tests was equipped with two manually regulated 3-inch graphite electrodes. The furnace shell was lined with magnesite; the inside diameter was 24 inches. Molten material was discharged from the furnace through its combination charging and decanting door by tilting the furnace with a gear-driven mechanism.

In each oxygen blowing test, 150 pounds of pig iron together with limestone and quartz was placed on the hearth of the preheated furnace. In melting, the fluxes formed a cover slag for the metal. The molten bath was heated until an immersion temperature reading of at least 1,680° C was attained, and then it was blown with oxygen in 1-pound increments at a manifold pressure of 40 psi until a total of 8 pounds was used. The oxygen lance was a magnesia-insulated 1/4-inch iron pipe. After each 1-pound addition of oxygen, a control sample was taken by dipping a cast-iron spoon into the bath; then the sample was deoxidized with aluminum before pouring it into an iron mold. The sample which weighed about 1 pound was allowed to cool for about one-half minute before quenching in water. The Brinell hardness of each sample was determined. Slag samples also were taken after each oxygen addition by dipping an iron rod into the bath. The test products were poured from the furnace with no attempt being made to produce carbon steel upon completion of the blowing.

Metal samples contained from 0.01 to 3.00 percent carbon. Test results indicated that 1 pound of oxygen removed about 0.64 pound of carbon, provided the initial carbon content of the bath exceeded 0.50 percent. Carbon analysis and hardness of metal samples are given in table 13. Figure 4 shows the relationship between Brinell hardness and carbon content of the samples from 0.01 to 2.0 percent carbon. Results of tests on samples of higher carbon content were not included on this graph because they were not of significance in the steelmaking tests.

TABLE 13. - Results of oxygen-blowing tests

	Test 1		Test 2		Test 3		Test 4	
	C, percent	Brinell hardness	C, percent	Brinell hardness	C, percent	Brinell hardness	C, percent	Brinell hardness
Pig iron, head sample	3.45	653	3.33	653	3.23	627	3.05	601
After O_2 addition of--								
1 lb	3.00	601	2.85	578	2.81	578	2.61	555
2 lb	2.49	534	2.40	514	2.37	514	2.21	495
3 lb	2.05	495	2.00	477	1.86	461	1.79	461
4 lb	1.60	444	1.54	444	1.44	429	1.35	429
5 lb	1.14	415	1.05	401	1.00	388	.92	388
6 lb	.63	341	.59	341	.57	331	.51	321
7 lb	.18	241	.14	223	.12	217	.06	197
8 lb	<.01	143	<.01	143	<.01	143	<.01	143

Three steelmaking tests were made. The Choteau pig iron had been remelted before its use in these tests in an attempt to produce a more uniform head sample; the remelting had altered its composition. In each test, 150 pounds of the pig iron was placed on the preheated hearth of the furnace together with lime and quartz. After melting the furnace charge and obtaining a temperature of at least 1,680° C, the bath was blown with oxygen until the

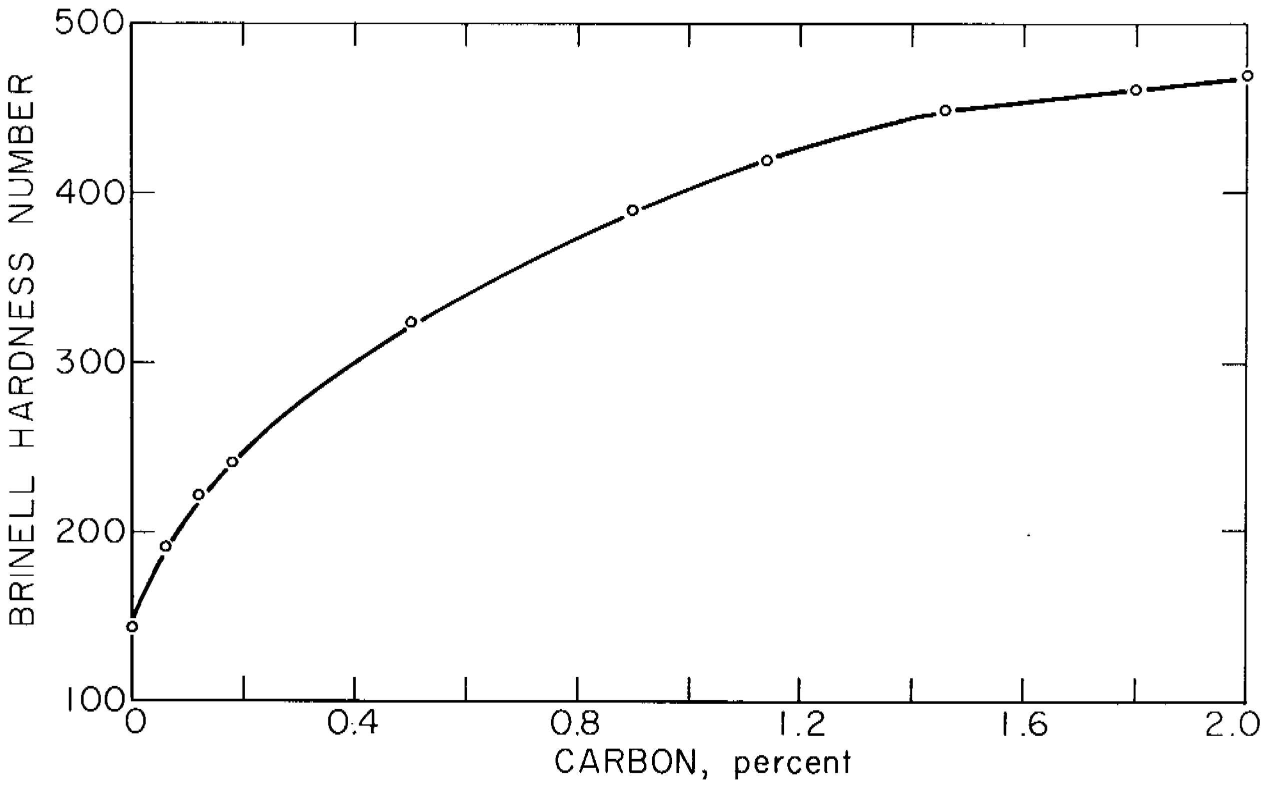

FIGURE 4. - Carbon-Brinell Hardness Curve.

carbon content of the metal was lowered to between 0.26 and 0.80 percent. Holding the molten products in the furnace after oxygen blowing resulted in further lowering the carbon content of the metal at the rate of 0.10 percent every 10 minutes. Silicomanganese was added to the bath to stop the oxidation reaction after the desired carbon content of the metal had been attained. The meltdown slag was then decanted from the furnace, and a new slag was formed by melting a mixture of lime and quartz. After attaining a temperature of 1,650° C, the bath was deoxidized with aluminum and the manganese content of the bath was adjusted by adding electrolytic manganese. The molten products were decanted from the furnace into a geared ladle, the slag was skimmed from the metal, and the steel was poured into a 200-pound ingot mold at temperatures of 1,600° C and higher. Test data are given in table 14; analyses of the pig iron charged to the furnace and of the steel produced are given in table 15.

TABLE 14. - Summary of data on Choteau steelmaking tests

	Test 1	Test 2	Test 3
Charge additions per 150 pounds pig iron:			
Limestone, lb	10	10	10
Pebble lime, lb	5	5	5
Quartz, lb	4	3.5	3.5
Silicomanganese, lb	1	1	1
Initial slag:			
Pouring temperature, ° C	1,690	1,650	1,640
Weight, lb	19	25	25
Cover slag prior to deoxidation:			
Pebble lime, lb	5	5	5
Quartz, lb	2	2	2
Aluminum, lb	1	1	1
Electrolytic manganese, lb	1	0.50	0.50
Pouring temperature, ° C	1,645	1,600	1,675
Final slag, lb	13.5	13	14
Metal, lb	136	133	134.5
Iron recovery, pct	91.3	90.8	92.7

TABLE 15. - Analyses of pig iron and carbon steel, percent

	Fe	C	C[1]	Si	Ti	Al	Mn	Cr	V	S	P
Pig iron:											
Test 1	97.5	1.66	0.26	0.34	0.08	-	0.12	-	0.15	0.02	0.04
Test 2	96.6	2.26	.63	.41	.05	-	.19	-	.13	.01	.05
Test 3	96.1	2.79	.66	.34	.09	-	.20	-	.16	.01	.03
Carbon steel:											
Test 1	98.3	.35	-	.10	.01	0.02	.68	0.09	.12	.01	.02
Test 2	99.0	.10	-	.10	.01	.01	.29	.08	.13	.01	.03
Test 3	99.4	.06	-	.10	.01	.01	.08	.07	.11	.01	.03

[1] After oxygen addition.

Ingots produced in the first and second tests were solid throughout, whereas the ingot produced in the third test contained blowholes. The high-magnesia content of the slag may be attributed to the dissolving of the magnesia insulating material around the lancing pipe and the magnesite lining while blowing the bath with oxygen.

Specimens for mechanical property evaluation were prepared from ingots of the first and third steelmaking tests. Each ingot, weighing about 134 pounds, was heated to 1,260° C in a preheated furnace and held for 20 minutes before hot-working. Then each ingot was forged to about 1-inch thickness. After conditioning the metal by either grinding or machining to remove folds and cracks, the slab was rolled into 1/4-inch sheet stock. The sheet stock was annealed by reheating to 900° C for 10 minutes, and then it was air-cooled. Next, the material was cleaned by grit blasting.

Six test specimens were prepared from each of the two sheets. Tensile strength, yield strength, elongation, and hardness of test specimens are shown in table 16. The tensile and yield strengths of test specimens were above average for carbon steels; the small vanadium and chromium contents of the specimens may have attributed to their strength.

TABLE 16. - Mechanical properties of carbon steel test specimens

	Tensile strength, psi	Yield strength, 0.2 percent offset, psi	Elongation, percent in 2 inches	Rockwell A hardness
	Test 1			
Specimen:				
1.............	113,000	75,500	23	58
2.............	113,000	76,000	23	59
3.............	115,500	77,000	24	59
4.............	119,000	82,500	22	60
5.............	119,500	81,500	22	59
6.............	119,000	82,500	23	59
Average......	116,500	79,000	23	59
	Test 3			
Specimen:				
1.............	74,000	47,000	30	50
2.............	75,000	47,000	30	50
3.............	79,500	50,000	28	52
4.............	83,000	60,000	25	50
5.............	74,500	47,500	30	49
6.............	74,500	51,000	30	50
Average......	76,500	50,500	29	50

CONCLUSIONS

Continuous electric smelting tests have shown that various types of high-grade pig iron can be produced without serious operating difficulties from Alaska, Montana, and Wyoming titaniferous magnetites which contain from 1.63 to 22.5 percent TiO_2. The test results indicated that fine-grained concentrate and crude ore can be smelted without flux, and a high-titania slag can be produced provided enough bulky reductant, such as wood chips, is used in the furnace charge and the furnace is operated at a high enough temperature. Probably the only titaniferous magnetite that would be of potential value for its TiO_2 content is the Wyoming material.

Results of wet-magnetic separation tests on Choteau material indicate that no significant increase in iron content or decrease in TiO_2 content of the concentrate could be attained by grinding finer than minus 65-mesh.

Steelmaking tests in a small electric furnace indicated that no unusual problems would be encountered in producing steel of high quality from titaniferous pig irons. The test results indicated that the tensile and yield strengths and the elongation of the test specimens were above average for carbon steels.