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**PRODUCTION OF HIGH-ALUMINA SLAGS
IN THE BLAST FURNACE**

BY

T. L. JOSEPH, S. P. KINNEY, AND C. E. WOOD

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PRODUCTION OF HIGH-ALUMINA SLAGS IN THE BLAST FURNACE¹

T. L. JOSEPH, S. P. KINNEY, and C. E. WOOD

INTRODUCTION

The Bureau of Mines has been conducting a series of investigations relating to the smelting of iron ores for the past 10 years. Early investigations were prompted by the apparent need for more information regarding the physical properties of blast-furnace slags. As a result of systematic measurements the viscosity of blast-furnace slags was determined over a wide range of composition and temperature. One of the points covered in the slag-viscosity studies was the effect of varying percentages of alumina upon viscosity.

As the effect of alumina upon blast-furnace slag influences the efficient production of pig iron, the Bureau of Mines entered into a cooperative agreement with the Aluminum Co. of America and the University of Minnesota School of Mines Experiment Station to make an experiment for determining the practicability of smelting a charge of bauxite and iron ore mixed with enough limestone to produce a slag approaching the following composition: 47 to 48 per cent of Al_2O_3 , 41 to 42 per cent of CaO , 4 to 5 per cent of SiO_2 , 2 to 3 per cent of TiO_2 , 1 per cent of FeO , 1.8 per cent of MgO , and 1 per cent of S .

In addition to determining whether or not operating a blast furnace on slag approaching the composition given above was practicable, a quantity of slag was needed for a series of experiments to disclose the relative ease of extracting alumina from slag made in the blast furnace as compared with extracting it from raw bauxite. The value of the slag as a raw material for making aluminum as compared with the value of bauxite for the same purpose would depend upon the relative percentages of alumina available for extraction in the two materials and the cost of extraction. The practice of smelting high-iron bauxites in the blast furnace with a view to later extraction of the alumina from the slag produced would, if feasible, save the iron now wasted.

ACKNOWLEDGMENTS

The authors wish to acknowledge the active assistance of Francis C. Frary, director of research, Aluminum Co. of America. The practical operation of the 6-ton furnace used in the test described in

¹ Work on manuscript completed July, 1927.

this report was under the direction of Charles Ash and Eli Webb, two competent furnacemen. Chemical analyses of raw materials and products were made by F. W. Holbrook, of the Bureau of Mines, and E. B. Svenson, of the Aluminum Co. of America.

SCOPE OF REPORT

This report contains a general discussion of the function of blast-furnace slag and gives somewhat in detail the results of a two-week test with a 6-ton experimental blast furnace. A brief résumé is given of tests made in full-size furnaces on high-alumina slags. The furnace has been described in the Bureau of Mines Technical Paper 393² and Bulletin 12³ of the Minnesota School of Mines Experiment Station. A brief discussion of the economic possibilities of producing high-alumina slags in the blast furnace is given. Such a practice would be unique, inasmuch as the value of the slag would be much greater than in normal blast-furnace practice.

FUNCTIONS OF BLAST-FURNACE SLAG

In discussing blast-furnace slag, one should keep in mind the functions it performs. Iron ore, coke, and stone contain earthy materials that must be fused to be withdrawn from the furnace. The composition of the slag must also be regulated to eliminate the sulphur associated with the metal in the upper part of the furnace. The silicon in the metal is likewise related to slag composition. In general, the percentages of silica and sulphur are controlled by proper adjustment of hearth temperature and slag composition with respect to the ratio of bases to acids present. Furnace operators usually prefer slags that have low free-running temperatures and will permit control of silicon and sulphur. The most acid slag that will desulphurize the metal properly is usually employed.

IMPORTANCE OF REMOVAL OF COKE ASH BY SLAG

The results of early investigators⁴ indicated that combustion in the blast furnace is confined to a relatively small volume, and the more recent work of one of the authors⁵ has established this point beyond question. With combustion extending only 40 inches beyond the nose of the tuyère, the surfaces of the coke lumps in this area recede at a rapid rate, due to concentrated combustion. The exact shape of the combustion zone has not been determined thus far

² Joseph, T. L., Royster, P. H., and Kinney, S. P., Utilization of Manganiferous Iron Ores: Tech. Paper 393, Bureau of Mines, 1927, pp. 11-14.

³ Joseph, T. L., and Kinney, S. P., Minnesota Manganiferous Iron Ores in Relation to the Iron and Steel Industry: Bull. 12, Minnesota Sch. of Mines Exp. Sta., 1927, 101 pp.

⁴ Van Vloten, W., "Die Verbrennung in Gestell des Hochofens": Stahl u. Eisen, Jahrg. 13, 1893, pp. 26-30. The data of Bunsen and others are completely set forth in Wedding's Handbuch der Eisenhüttenkunde, Jahrg. 3, 1906, pp. 203-241.

⁵ Perrott, G. St. J., and Kinney, S. P., "Combustion of coke in blast-furnace hearth": Trans. Am. Inst. Min. and Met. Eng., vol. 69, 1923, p. 543.

by experiment, but if the shape is assumed to be approximately spherical the volume of the zone around each tuyère is about 20 cubic feet. If 4,000 cubic feet of air per minute enters each tuyère and the fixed carbon in the coke is 86 per cent and its density 1.0, about 2 cubic feet of coke will be burned per minute, or the coke in the combustion zone would be replaced every 10 minutes. Under these conditions the diameter of a 5-inch piece of coke would recede at a rate of $\frac{1}{2}$ inch per minute.

As combustion proceeds ash forms on the surface of the piece of coke. Unless this ash is removed and a clean coke surface provided, combustion is hampered. The blast enters at a temperature well below that of the lumps of coke, so that the pieces directly in front of the tuyère are chilled unless a carbon surface is available for combustion and for the simultaneous liberation of heat. If the coke ash has a low fusion temperature, some of it will drop from the lumps of coke before coming in contact with slag. However, one would expect the slag passing through the combustion zone to remove much of the ash.

AGITATION OF COKE IN COMBUSTION ZONE BY BLAST

Furnace operators find it necessary to adjust the size of tuyère to obtain the best-working furnace. The authors believe that one important object in having tuyères of proper size is to produce a desirable stirring or shifting of the coke in the combustion zone. The slag seems to be blown away from the nose of the tuyère, thus making it desirable to shift the coke from time to time, so that the individual lumps may reach the portion of the zone where there is greater contact with the slag.

Brassert,⁶ in discussing the combustibility of coke, refers to the tuyère action as follows:

The early coke produced in our by-product ovens, even from the same coals, burned too slowly and made our furnace operations exceedingly difficult by preventing rapid and continuous movement of the stock. Observing the action through the tuyère glasses would reveal each piece of such coke moving slowly and requiring considerable time before being entirely consumed, whereas coke of proper combustibility danced lively at the tuyères and quickly disappeared.

The authors believe that although tuyère action is important it is more closely related to the density of the coke, the velocity of blast through the tuyère, and the temperature-viscosity relations of the slag passing through the tuyère than to the combustibility of coke. Tuyères often become sluggish when the slag does not run freely at the temperature of the combustion zone. The combustion zones are the seat of furnace life, and one very important function of the slag is to remove the coke ash. To do this the slag should be fluid and

⁶ Brassert, Herman A., "Modern American blast-furnace practice": Yearbook, Am. Iron and Steel Inst., vol. 4, 1914, p. 28.

should drop readily through the combustion zone without adhering, except momentarily, to the coke lumps, so that the ash can be removed with the aid of the mechanical stirring produced by the blast.

TUYÈRE TEMPERATURES AND THEIR RELATION TO FREE-RUNNING TEMPERATURE OF SLAG

Unless the temperature maintained in the combustion zone of a furnace exceeds the free-running temperature of the slag the blast furnace can not be operated. In general, furnace operators prefer as wide a difference as possible between these two temperatures. Sulphur can be eliminated with a moderate amount of hot basic slag or with larger amounts of an acid slag at moderate temperatures. As a rule, operators prefer to work with acid rather than basic slags because acid slags have a lower free-running temperature and the margin between tuyère temperature and the free-running temperature of the slag is wider.

When hot blast was first used tuyère temperatures were increased, making it possible to maintain a proper margin between the free-running temperature of the slag and tuyère temperature after more burden had been charged. The latent heat of the fuel saved was far greater than the sensible heat brought in with the blast. This innovation emphasized the importance of temperature as well as heat units in blast-furnace practice. Johnson ⁷ states:

The introduction of the hot blast reduced the fuel consumption of soft-coal furnaces more than half, although the heat of the blast introduced was only about 18 per cent of the total produced. .

The hot blast offers a means of producing a quick change in tuyère temperature. It required hours for extra coke to reach the tuyères, while tuyère temperatures respond immediately to increased blast heats. In general, the ease of operating a blast furnace depends upon the spread between tuyère temperatures and the free-running temperature of the slag. Due to the fact that slags ranging from 45 to 50 per cent of Al_2O_3 , 40 to 45 per cent of CaO , and 6 to 10 per cent of SiO_2 had never been produced in a blast furnace, there was some question as to whether or not the temperature-viscosity relations of such slags would render it impossible to maintain enough spread between tuyère temperatures and the free-running temperature of the slag to permit smooth operation. A test with the experimental furnace seemed a logical method of answering this question, as the cost of such a test was only a fraction of the cost of making a similar test in even a small industrial furnace. Moreover, data from the experimental furnace would be a valuable guide in preliminary operations with full-size equipment. In addition to determining

⁷ Johnson, J. E., jr., *Principles, Operation, and Products of the Blast Furnace*: New York, 1918, p. 31.

whether or not such a slag could be produced, the authors also wished to find out how widely and in what manner operation on this slag differed from that on normal slag and to know the fuel economy, slag volume, and tonnages to be expected in operating an industrial furnace.

RESULTS OF PREVIOUS INVESTIGATIONS

When the question of operating a blast furnace on a burden that would produce a slag containing about 50 per cent of Al_2O_3 and 5 to 10 per cent of SiO_2 arose, three investigations offered a basis for forming an opinion. One of these investigations was conducted by Rankin and Wright⁸ on the ternary system $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$. A second investigation, referred to later, was conducted by Feild and Royster on temperature-viscosity relations. The third investigation was conducted by the Bethlehem Steel Co. on smelting Mayari ore.

MELTING-POINT DETERMINATIONS

The melting point of a slag does not reveal the whole story of its behavior in the blast furnace. In general, however, the melting temperatures indicate whether or not tuyère temperatures can be maintained at levels such that the slag will be fluid enough to function properly in the lower part of the furnace.

Commercial slags always contain more than the three components, CaO , Al_2O_3 , and SiO_2 . Such substances as MgO , CaS , MnS , MnO , and FeO are normally present and generally act to lower the melting point. Quantitative data on their effect are not available. However, as a result of the very thorough and comprehensive work of Rankin and Wright, melting temperatures covering a wide range in composition of the three-component system are available. Tables 1, 2, 3, and 4, taken from their results,⁹ contain the melting points of compositions grouped as follows: Range of blast-furnace slags, range of composition of slags made on Mayari ores, charcoal-furnace slags, and slags in the range of composition covered in the experimental blast-furnace test described in this paper.

TABLE 1.—*Melting points in approximate range of normal blast-furnace slags*

Slag	Melting point, °C.									
	1,500	1,400	1,415	1,335	1,310	1,316	1,402	1,477	1,345	1,265
CaOper cent.....	50	50	49.4	48.2	47.2	45.7	45	44.3	40.0	38.0
Al_2O_3do.....	15	10	14.4	11.9	11.8	13.2	10	20.0	15.0	20.0
SiO_2do.....	35	40	36.6	39.9	41.0	41.1	45	35.7	45.0	42.0

⁸ Rankin, G. A., and Wright, F. E., "Ternary system $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$ ": Am. Jour. Science, ser. 4, vol. 39, 1915, pp. 1-79.

⁹ Rankin, G. A., and Wright, F. E., work cited.

TABLE 2.—*Melting points in approximate range of slags produced from Mayari ore*

Slag	Melting point, °C.									
	1,590	1,570	1,535	1,545	1,540	1,490	1,495	1,490	1,564	1,548
CaO.....per cent..	51.3	50.9	50.0	49.6	49.0	48.8	47.6	47.0	46.6	46.3
Al ₂ O ₃do.....	29.7	30.9	32.8	23.7	30.0	35.6	38.0	39.4	28.3	33.7
SiO ₂do.....	19.0	18.2	17.2	26.7	21.0	15.6	14.4	13.6	25.1	20.0
Slag	Melting point, °C.									
	1,574	1,569	1,575	1,554	1,588	1,586	1,590	1,558	1,475	
CaO.....per cent..	45.8	45.0	45.0	45.0	42.3	41.0	40.8	40.0	40.0	-----
Al ₂ O ₃do.....	29.5	35.0	30.0	25.0	35.0	36.0	37.2	30.0	25.0	-----
SiO ₂do.....	24.7	20.0	25.0	30.0	22.7	23.0	22.0	30.0	35.0	-----

TABLE 3.—*Melting points in approximate range of charcoal-furnace slags*

Slag	Melting point, °C.								
	1,405	1,402	1,436	1,416	1,345	1,265	1,330	1,374	1,299
CaO.....per cent..	46.3	45.0	41.4	40.0	40.0	38.0	35.0	35.0	34.1
Al ₂ O ₃do.....	10.0	10.0	9.0	10.0	15.0	20.0	15.0	10.0	18.6
SiO ₂do.....	43.7	45.0	40.6	50.0	45.0	42.0	50.0	55.0	47.3

TABLE 4.—*Melting points in approximate range of slags made in experimental furnace*CaO HIGHER THAN Al₂O₃

Slag	Melting point, °C.							
	1,490	1,437	1,390	1,335	1,460	1,350	1,420	
CaO.....per cent..	60.0	55.0	52.5	52.0	52.0	51.3	50.0	
Al ₂ O ₃do.....	35.0	40.0	42.5	41.2	38.0	41.8	40.0	
SiO ₂do.....	5.0	5.0	5.0	6.8	10.0	6.9	10.0	
Slag	Melting point, °C.							
	1,375	1,335	1,432	1,390	1,430	1,361	1,380	
CaO.....per cent..	50.0	49.5	49.3	49.0	48.7	48.5	48.3	
Al ₂ O ₃do.....	42.0	43.7	47.7	42.0	39.3	45.0	42.0	
SiO ₂do.....	8.0	6.8	3.0	9.0	12.0	6.5	9.7	

TABLE 4.—*Melting points in approximate range of slags made in experimental furnace—Continued*Al₂O₃ HIGHER THAN CaO

Slag	Melting point, °C.							
	1,421	1,432	1,456	1,535	1,537	1,564	1,572	1,583
CaO.....per cent..	47.5	47.0	45.0	45.0	40.0	40.0	39.2	38.0
Al ₂ O ₃do....	49.5	49.0	47.0	50.0	50.0	45.0	46.0	44.0
SiO ₂do....	3.0	4.0	8.0	5.0	10.0	15.0	14.8	18.0
	Melting point, °C.							
	1,512	1,505	1,509	1,549	1,552	1,550	1,590	1,570
CaO.....per cent..	37.8	37.5	37.0	36.7	35.0	35.0	35.0	34.3
Al ₂ O ₃do....	52.9	53.25	54.0	58.1	50.8	50.0	55.0	52.7
SiO ₂do....	9.3	9.25	9.0	5.2	14.2	15.0	10.0	13.0

Tables 1 to 4 show that charcoal-furnace slags have the lowest melting point, blast-furnace slags from coke furnaces rank next, and slags composed largely of CaO and Al₂O₃ with greater quantities of the former (Table 4) have melting points that compare favorably with normal blast-furnace slags (Table 1). Melting points in the range of composition obtained in melting Mayari ores (Table 2) are in about the same order of magnitude as those of slags made in the experimental furnace, containing more Al₂O₃ than CaO (Table 4).

Johnson¹⁰ stresses the importance of free-running or critical temperatures and points out the important fact that the free-running temperatures are more useful than the melting points. However, for the wide range of compositions covered in Tables 1 to 4 the melting points generally vary with the free-running temperatures. For example, charcoal slags with the lowest melting points are known to have the lowest free-running temperatures; blast-furnace slags come next, followed by the slags in the first part of Table 4, then those in Table 2, and finally those in the last part of Table 4. In general, operation on the various types of slags would be more difficult as the melting points increased.

TEMPERATURE-VISCOSITY RELATIONS

Blast-furnace slags are not simple mixtures of lime, alumina, and silica but are composed of compounds formed from these three oxides. Temperature-viscosity relations, therefore, do not change directly with gradual changes of a single constituent. Feild and Royster's¹¹ viscosity determinations show that increasing the per-

¹⁰ Johnson, J. E., jr., *Principles, Operation, and Products of the Blast Furnace*: New York, 1918, p. 220.

¹¹ Feild, A. L., and Royster, P. H., *Temperature-Viscosity Relations in the Ternary System CaO-Al₂O₃-SiO₂*: Tech. Paper 189, Bureau of Mines, 1918, pp. 19-25.

centage of alumina in some ranges of composition increases slag viscosity while in other ranges it decreases viscosity. Four melts, two of which represent ternary eutectics, have particular interest. The composition of these melts follows:

Viscosity determinations

Point No.	CaO	Al ₂ O ₃	SiO ₂	Viscosity ¹ at 1,500° C.	Melting points, by Rankin and Wright
6 ¹ -----	47.2	11.8	41.0	5.2	1,310±5
8-----	49.0	14.4	36.6	13.6	1,415±5
14 ¹ -----	49.5	43.7	6.8	2.4	1,335±5
20-----	48.7	39.3	12.0	46.0	1,430±5

¹ Viscosities taken from Figure 13, Tech. Paper, 189, Bureau of Mines.

¹ Ternary eutectics.

It is interesting to note that point 14, a ternary eutectic containing 43.7 per cent of Al₂O₃, has the lowest viscosity of these four melts. The viscosity of three other melts representing quintuple points was measured by these investigators. Of seven such melts, point 14, the eutectic between β 2CaO.SiO₂, CaO.Al₂O₃, and 5CaO.3Al₂O₃, had the lowest viscosity. The viscosity of slag is generally determined by the relative amounts of various compounds present. One can not, therefore, generalize regarding the relation between viscosity and alumina content; however, Feild and Royster found the temperature coefficient of viscosity is usually greater for high-alumina content.

In studying the temperature-viscosity relations of blast-furnace slags Feild and Royster¹² found it convenient to compare the temperatures at which various slags had a viscosity of 10 and 4. The use of these particular values is explained as follows:

In this connection it may be stated that the slag is in intimate contact with the molten iron from the time when the slag is just fluid enough to entrap the molten iron globules until the time when the slag has such a low viscosity that the iron globules fall out of the slag to the bottom of the hearth. Both of these conditions should correspond to a more or less definite slag viscosity, which for lack of more definite information may be placed at a viscosity value of 10 in the first case and at 4 in the second case cited.

¹² Feild, A. L., and Royster, P. H., Slag-Viscosity Tables for Blast-Furnace Work: Tech. Paper 187, Bureau of Mines, 1918, p. 19.

TABLE 5.—*Temperatures at which slags containing 13.07 to 21 per cent of Al_2O_3 , with the ratio of bases to SiO_2 constant at 1.46, reach viscosities of 10 and 4*[The total percentage of MgO , CaS , and other minor oxides in each slag, 11.44]

Actual content of—			Content on basis of 100 per cent CaO , Al_2O_3 , and SiO_2			Temperature at which viscosity equals—		Difference
Al_2O_3	SiO_2	CaO	Al_2O_3	SiO_2	CaO	10	4	
<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>° C.</i>	<i>° C.</i>	<i>° C.</i>
13.07	35.32	40.17	14.76	39.88	45.36	1,352	1,456	104
14.00	34.96	39.60	15.81	39.48	44.71	1,383	1,487	104
15.00	34.55	39.01	16.94	39.01	44.05	1,432	1,541	109
16.00	34.15	38.41	18.06	38.56	43.38	1,470	1,594	124
17.00	33.74	37.82	19.19	38.10	42.71	1,503	1,633	130
18.00	33.33	37.23	20.32	37.64	42.04	1,509	² >1,640	² >131
19.00	32.93	36.63	21.45	37.18	41.37	1,513	² >1,640	² >127
20.00	32.52	36.04	22.58	36.72	40.70	1,526	² >1,640	² >114
21.00	32.11	35.45	23.71	36.26	40.03	1,519	² >1,640	² >121

¹ Represents the average slag.² The symbol > is used in its usual sense of "greater than."

Alumina has a marked effect upon the temperature-viscosity relations of slags approximating the composition of blast-furnace slags. Feild and Royster¹³ have also determined the temperature-viscosity relations of a slag approaching the average composition for American practice. In their experiments on this slag the Al_2O_3 was varied from 13.07 to 21 per cent and the ratio of bases to silica held constant at 1.46. Table 5, from their work, summarizes the temperature-viscosity relations for this range.

One will observe from the slags in Table 5 containing the minimum and maximum percentages of Al_2O_3 that an increase from 13.07 to 21 per cent of Al_2O_3 requires an increase in temperature from 1,352 to 1,519° C. to make the viscosities of the two slags equal 10, or a change from 1,456 to more than 1,640° C. to make the viscosities equal 4. Also, in the range of higher percentages of Al_2O_3 a greater rise in temperature is necessary to change the viscosity from 10 to 4.

A similar series of measurements was made over a wider range of Al_2O_3 content; in this case the bases were held constant at 51.61 per cent. The results are summarized in Table 6.¹⁴ Here, again, the marked effect of Al_2O_3 on slag viscosity is shown. With 6.2 per cent of Al_2O_3 the viscosity was 10 at 1,331° C., while with 21.25 per cent of Al_2O_3 the same viscosity was not attained until a temperature greater than 1,621° C. was reached. The slag that contained 8.86 per cent of Al_2O_3 showed a viscosity of 4 at 1,489° C., and the slag containing 13.07 per cent of Al_2O_3 showed the same viscosity at 1,456° C. An increase in Al_2O_3 in this range of composition decreased the viscosity, thus illustrating a point emphasized by Feild and Royster—that the temperature-viscosity relations of a slag do not

¹³ Feild, A. L., and Royster, P. H., Slag-Viscosity Tables for Blast-Furnace work: Tech. Paper 187, Bureau of Mines, 1918, p. 18.¹⁴ Feild, A. L., and Royster, P. H., work cited, p. 20.

change continuously in the same direction by gradual additions of a single constituent. From the results of the same investigation ¹⁵ profiles were prepared of the isothermal viscosity surfaces at 1,450° C. for mixtures containing 7, 10, 15, 18, and 21 per cent of Al₂O₃.

TABLE 6.—*Temperatures at which slags containing 6.20 to 21.25 per cent of Al₂O₃, with a constant amount of bases equal to 51.61 per cent, reach viscosities of 10 and 4*

[The percentage of lime, CaO, is constant at 40.17, while the total percentage of MgO, CaS, and other minor constituents is equal to 11.44]

Actual content of—			Content on basis of 100 per cent CaO, Al ₂ O ₃ , and SiO ₂			Temperature at which viscosity equals—		Difference
Al ₂ O ₃	SiO ₂	CaO	Al ₂ O ₃	SiO ₂	CaO	10	4	
<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>° C.</i>	<i>° C.</i>	<i>° C.</i>
6.20	42.19	40.17	7.00	47.64	45.36	1,331	1,404	73
7.08	41.31	40.17	8.00	46.64	45.36	1,334	1,429	95
7.97	40.42	40.17	9.00	45.64	45.36	1,350	1,460	110
8.86	39.53	40.17	10.00	44.64	45.36	1,365	1,489	124
9.74	38.65	40.17	11.00	43.64	45.36	1,357	1,480	123
10.63	37.76	40.17	12.00	42.64	45.36	1,348	1,467	119
11.51	36.88	40.17	13.00	41.64	45.36	1,337	1,447	110
12.40	35.99	40.17	14.00	40.64	45.36	1,350	1,448	98
¹ 13.07	35.32	40.17	14.76	39.88	45.36	1,352	1,456	104
13.28	35.11	40.17	15.00	39.64	45.36	1,339	1,460	121
14.17	34.22	40.17	16.00	38.64	45.36	1,383	1,498	115
15.06	33.33	40.17	17.00	37.64	45.36	1,437	1,545	108
15.94	32.45	40.17	18.00	36.64	45.36	1,464	1,589	125
16.83	31.56	40.17	19.00	35.64	45.36	1,467	1,596	129
17.71	30.68	40.17	20.00	34.64	45.36	1,480	1,596	116
18.60	29.79	40.17	21.00	33.64	45.36	1,484	1,604	120
19.48	28.91	40.17	22.00	32.64	45.36	1,491	1,590	99
20.37	28.02	40.17	23.00	31.64	45.36	1,494	1,588	97
21.25	27.14	40.17	24.00	30.64	45.36	1,504	² >1,621	² >117

¹ Represents the average slag.

² The symbol > is used in its usual sense of "greater than."

Although melting points and viscosities were useful in making a preliminary study of the problem, some sort of a practical demonstration seemed necessary to prove conclusively that a blast furnace can be operated on slags containing about 50 per cent of alumina.

INDUSTRIAL FURNACE EXPERIMENTS WITH HIGH-ALUMINA SLAGS

In 1904 the Pennsylvania Steel Co., at its Steelton plant, conducted experiments to determine the behavior of high-alumina slags in the blast furnace. McKay,¹⁶ in describing the experiment, states:

By means of Lake ore, chromite, brickbats, and bauxite, a furnace mixture was concocted approximating Mayari ore in chemical composition. The test run lasted 11 days, during which time the furnace averaged 102 tons on a 1 to 1 fuel ratio. This mixture worked with sufficient success as to the character of the slag and the general furnace conditions to warrant a small shipment of ore from the Mayari district. About 1,200 tons were transported on mule back from the deposit at El Perio to the seacoast and shipped to Steelton, where it was tried

¹⁵ Feild, A. L., and Royster, P. H., Temperature-Viscosity Relations in the Ternary System CaO-Al₂O₃-SiO₂: Tech. Paper 189, Bureau of Mines, 1918, pp. 28-29.

¹⁶ McKay, Richard V., "Modern American blast-furnace practice": Yearbook, Am. Iron and Steel Inst., vol. 4, 1914, pp. 85-101.

with more or less success on No. 1 furnace in February, 1906. This test was of six days' duration, the furnace averaging 59.5 tons of iron per day on a fuel ratio of 2.13. The flue dust was excessive, however, and as a result the actual yield of pig iron was but 29 per cent.

In 1914 a much more elaborate series of tests was made over a period of about three months in a furnace of the following dimensions: Hearth, 9 feet 6 inches; bosh diameter, 15 feet; stock-line diameter, 11 feet; and height, 65 feet. The results¹⁷ are briefly summarized as follows:

During the entire run the physical condition of the slag has been excellent. After flushes and casts the runners contained practically no cinder, all having drained clean. The slag was invariably hot and exceptionally fluid. With silica plus alumina about 52 per cent, composed of approximately 29 per cent alumina and 23 per cent silica, good results were obtained. In fact, it developed that variations in alumina from 27 per cent to 33 per cent and in silica from 20 per cent to 25 per cent had no apparent effect on the operation of the furnace. To me the temperature of the slag appeared far more important than its chemical composition. Our excellent coke gave an intensely hot hearth, and no difficulty resulted in handling the slag and obtaining good iron. A slag volume of approximately 1,740 pounds per ton of iron was maintained in the various tests. A small amount of mill cinder—6 per cent, running about 29 per cent SiO_2 —seemed to help the slag conditions by increasing the SiO_2 about 2 per cent in the slag.

In operating with slags of the composition specified above, McKay found 9 to 10 per cent of MgO very beneficial.

Although the previous information was of great assistance in determining the advisability of conducting a test on slags containing 50 per cent of alumina or more, an actual demonstration was necessary to prove that such slags may be used successfully.

OPERATION OF EXPERIMENTAL BLAST FURNACE

In 1919 the Bureau of Mines undertook to develop an experimental blast furnace at its North Central Experiment Station. After several years of experimentation with furnaces ranging in height from 20 inches to 20 feet the furnace shown in Figures 1, 2, 3, 4, 5, and 6 was erected. A description of the furnace and plant layout appears in a previous report.¹⁸ Figures 4 and 5 illustrate parts of the furnace in detail, and Figure 6 shows the furnace in operation.

¹⁷ McKay, Richard. V., work cited, p. 98.

¹⁸ Joseph, T. L., and Kinney, S. P., Minnesota Manganiferous Iron Ores in Relation to the Iron and Steel Industry: Bull. 12, Minnesota Sch. Mines Exp. Sta., 1927, 101 pp.

FIGURE 2.—General view of experimental blast furnace

FIGURE 3.—Top section of experimental blast furnace, showing sampling platforms

FIGURE 4.—Charging floor, bins, feed belts, and scale car

FIGURE 5.—Close view of hearth and bosh

FIGURE 6.—View of experimental furnace during casting

RAW MATERIALS USED

Bauxite.—About 60 tons of bauxite were used in the test. The analyses of two cars on a dry basis follow:

Analyses of car samples, per cent

Car No.	Al ₂ O ₃	SiO ₂	Fe	CaO	MnO	TiO ₂	Loss in ignition
1	57.62	2.75	16.77	0.78	0.48	2.64	13.72
2	57.06	2.78	16.32	-----	-----	3.08	13.41

The moisture in several samples taken after the bauxite had been unloaded frozen and stored in a heated building for about three weeks varied from 9.7 to 13.3 per cent. The structure of the bauxite was favorable for the test as there was only a small proportion of fine material after it was crushed to 2-inch and smaller pieces.

Limestone.—The limestone used in the test was of good quality, containing practically no fine material and no pieces larger than about 2 inches. It was not a sized product. Samples from two cars showed the following composition:

Analyses of car samples, per cent

Car No.	CaO	MgO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃
1	53.7	0.64	1.06	0.42	0.50
2	53.12	.60	1.00	.64	.48

Coke.—By-product coke, known on the domestic market as “nut coke,” was used in this test. This size was chosen to diminish the oxidizing area in the tuyère zone. Past experience has shown that with a hearth 36 inches in diameter coke of this size is more suitable than larger coke such as that used in industrial furnaces. One should not infer from this that small coke would be better suited for industrial furnaces. The analyses of respective cars follow:

Analyses of car samples, per cent

Car No.	Fixed carbon	Ash	Volatile matter	Sulphur	Moisture	Ash			
						SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO
1	90.67	8.38	0.95	0.53	10.1	40.32	21.86	21.86	3.06
2	92.30	7.37	.33	.55	9.25	-----	-----	-----	-----
3	91.93	7.59	.48	.42	10.75	35.24	27.20	28.22	6.12
4	91.37	7.81	.82	.57	8.20	35.72	29.60	28.83	3.12

The iron ore from the Vermillion range was dense in structure and high in iron, as shown by the following analysis: Fe, 63.5; SiO₂, 4.62; Al₂O₃, 1.16; CaO, 0.16; P, 0.085; Mn, trace; ignition loss, 1.83;

moisture, 4.85. It was essential to use high-grade iron ore to keep the silica in the slag within desired limits.

CAST TURNINGS

Several small lots of turnings were used to increase the production of metal without increasing the silica in the slag. The composition of the various lots was as follows:

Composition of turnings, per cent

Lot	S	C	P	Si
1.....	0.08	3.55	0.38	2.26
2.....	.08	2.99	.42	2.26
3.....	.09	3.84	.44	2.26
4.....	.07	4.52	.27	1.87
Average.....	.08	3.73	.38	2.16

The production of metal was in a sense incidental to the operation, as the primary object was to convert raw bauxite into a slag containing approximately 50 per cent of Al_2O_3 and 43 per cent of CaO , with the silica as low as possible. The 15 per cent of iron in the bauxite would be recovered, and the iron-bearing materials added to the charge would produce enough metal to offset a part of the operating expenses. Whether the iron can be most profitably obtained from high-grade iron ore or from borings is discussed later. The use of borings would permit the production of slag lower in silica and would also allow a larger burden of bauxite, thus increasing the production of slag. Contrary to normal practice, in which slag may or may not have enough value to pay for its disposal and in which large volumes of slag are generally opposed to economical practice, the volume of the slag would here be an important item.

FURNACE LINING

Inasmuch as the composition of the slag anticipated in this test differed markedly from normal blast-furnace slag, the lower part of the furnace—including about three-fourths of the bosh, tuyère breast, and crucible—was lined with special material composed of 40 parts of high-grade fire clay and 60 parts of a highly aluminous product (95 per cent Al_2O_3). A grog of this mixture was rammed in place, producing a lining of the thickness indicated in Figure 1. After several days of air-drying the temperature was gradually raised until the new section of lining had been thoroughly dried. Examination after the test showed that no appreciable wear had taken place above the zone of fusion, which was well defined at a position about 38 inches above the center line of the tuyères. From this position downward the thickness of the lining diminished from the original $4\frac{1}{2}$ inches

until the section above the tuyères was about $\frac{1}{4}$ to $\frac{1}{2}$ inch thick. On the whole, the condition was similar to that found after tests in which fire-brick linings were used. With external cooling only a thin section of lining can be maintained in the lower part of the bosh and tuyère breast. The lining above the fusion zone showed no signs of wear.

BLOWING IN

Enough wood to fill the furnace to the top of the bosh was charged, then four rounds of coke, 360 pounds to the round. As the coke blank was charged the distribution of stock on the bells was observed and minor adjustments were made. The coke was followed by charges or rounds consisting of 360 pounds of coke, 400 pounds of slag, and 15 pounds of stone. Periodic observations of stock distribution were continued as the blow-in burden was charged. After 27 rounds of the mixture indicated above were charged stock-line measurements showed that the stock line was about 50 inches from the top. The furnace was lighted and operated on about 300 cubic feet of air per minute for 24 hours. At the end of this time the blast was increased to 450 cubic feet per minute. To get the furnace to a high temperature before high-alumina slags were charged, the slag was recharged with enough stone to flux the coke ash. Operation was continued as a slagging-type gas producer for 60 hours from the time the furnace was lighted. At the end of this period the hot-blast stove was in operation, and the furnace had apparently reached the proper temperature.

OPERATION ON HIGH-ALUMINA SLAGS

Inasmuch as slags containing 40 to 50 per cent of alumina had never been produced in the blast furnace, the first burden high in alumina was carefully considered. Although melting points are not as indicative of the behavior of slags as temperature-viscosity measurements, it was necessary to rely on them because the latter information was not complete. According to the melting points determined by Rankin and Wright, slags containing more lime than alumina will have lower melting points than slags containing more alumina than lime in the range of compositions shown in Table 4. Therefore, the first attempts were made with a series of burdens that would produce a slag containing greater percentages of lime than alumina. The goal in the test was to produce a slag containing about 50 per cent of Al_2O_3 , but it seemed advisable to choose slag of the most favorable composition for the initial burden and gradually to change to the higher alumina composition.

PURPOSE OF TEST PERIODS

The chief purpose of the test was to determine if slag containing 50 per cent or more of Al_2O_3 could be produced in the blast furnace without difficulty. However, the authors also desired to obtain information on such factors as fuel consumption, slag volume, and the desirability of scrap as compared to iron ore in the burden. To get as much information as possible in the time available, the operators followed a schedule of tests as closely as conditions permitted.

TEST PERIOD 1

Operating data for the four test periods are given in Table 7. The raw materials and products are reported on a per-ton-of-metal basis. During test period 1 the burden, consisting of bauxite, limestone, and scrap, was gradually increased over a three-day interval. The burdens charged were as follows:

Burden, pounds per round

Burden letter	Coke	Bauxite	Limestone	Turnings
D	360	150	200	100
E	360	200	255	150
F	360	255	200	200
G	360	275	333	250
H	360	275	333	¹ 200

¹ Turnings decreased 50 pounds due to small stock pile.

Average analyses for slag and metal during the period are given in Table 7. The values recorded there are weighted averages of all the respective casts and flushes made during the test period. The lime in the slag is about 3 per cent higher than the alumina. Ten per cent of silica is several per cent more than is obtained in theoretical slag calculations, which do not take into consideration oxidation of silicon in the turnings. Silicon in the turnings charged ran 2.26, while the average silicon in the metal during this period was 1.12 per cent, a loss of over 1 per cent.

TABLE 7.—General operating data

Test period.....	1	2	3	4	Average
Bauxite.....pounds per ton..	2, 665	4, 551	4, 060	4, 241	3, 808
Ore.....do..		¹ 768	1, 353	771	¹ 1, 072
Limestone.....do..	3, 356	5, 567	4, 544	4, 241	4, 484
Borings.....do..	2, 145	1, 720	749	1, 542	1, 518
Coke.....do..	4, 572	5, 690	5, 013	5, 551	5, 127
Carbon.....do..	3, 786	4, 711	4, 151	4, 596	4, 245
Slag.....do..	3, 574	5, 490	4, 634	3, 480	4, 785
Metal.....tons per day..	3. 12	2. 57	3. 24	2. 78	2. 94
Metal analyses: ²					
Carbon.....per cent..	4. 55	4. 47	4. 57	4. 90	4. 60
Phosphorus.....do..	. 37	. 32	. 26	. 36	. 31
Silicon.....do..	1. 12	. 046	. 079	. 26	. 388
Sulphur.....do..	. 008	. 034	. 068	. 023	. 036
Slag analyses: ¹					
Lime.....do..	44. 37	45. 65	43. 94	39. 64	44. 11
Alumina.....do..	41. 36	42. 61	45. 79	47. 24	43. 44
Silica.....do..	10. 22	6. 98	6. 67	8. 46	7. 88
Ferrous oxide.....do..	. 93	1. 09	1. 23	1. 44	1. 17
Titanium oxide.....do..	1. 57	2. 20	2. 37	2. 12	2. 07
Sulphur.....do..	1. 10	. 52	. 56	. 70	. 72
Blast temperature.....° F.	920	865	870	870	885
Top temperature.....° F.	580	405	425	435	465
Tuyère temperature.....° C.	1, 785	1, 720	1, 640	1, 625	1, 705
Slag temperature.....° C.	1, 600	1, 550	1, 550	1, 570	1, 568
Metal temperature.....° C.	1, 485	1, 440	1, 430	1, 425	1, 450
Blast pressure.....inches of Hg.	4. 79	4. 74	5. 00	5. 18	4. 85
Blast pressure.....pounds per square inch..	2. 35	2. 33	2. 45	2. 54	2. 38
Air per minute.....cubic feet..	615	630	645	670	633

¹ Average for only that part of the period during which ore was charged.² Weight of flushes and casts considered in obtaining averages for various test periods.

Perhaps the most interesting phase of the experiment aside from knowing that high-alumina slags could be made without difficulty was the low sulphur in the metal produced. This factor is discussed in greater detail later; however, the sulphur in the turnings charged was reduced from 0.08 to 0.008 per cent in the metal produced. One-half of the first 26 casts were reported as containing no sulphur. All sulphur determinations were made by the gravimetric method. Change in the composition of the slag and metal may be followed in Tables 8 and 9, which give the analyses of individual casts and flushes made during the first test period. At the beginning of the period the furnace was hot, having been operated several days on a light burden of slag. The slag carried about 29 per cent of SiO₂, which was reduced during the test period to between 6 and 7 per cent. As the silica in the slag dropped the silicon in the metal also decreased. During the last half of the period silicon from the metal was removed either by the action of blast at the tuyère zone or by unreduced iron oxide reaching the crucible. The fact that the slag at cast was higher in silica than that withdrawn between casts indicates that some silica was being produced by oxidation of silicon in the metal. For examples of this see Table 9, which gives the analyses of slags at cast.

TABLE 8.—*Analyses of individual casts during test period 1, per cent*

Cast No.	C	P	Si	S	Cast No.	C	P	Si	S
2.....	3.01	0.37	6.96	Nil.	15.....	4.69	0.36	0.81	0.020
3.....	2.22	.40	7.05	Nil.	16.....	4.37	.37	.60	Nil.
4.....	3.47	.32	5.85	0.013	17.....	4.93	.42	1.12	.022
5.....	4.09	.42	4.13	.009	18.....	4.72	.38	.63	.005
6.....	3.42	.31	3.47	.005	19.....	4.99	.38	.51	Nil.
7.....	4.21	.31	3.61	Nil.	20.....	4.40	.34	.49	.003
8.....	3.93	.31	3.04	Nil.	21.....	4.75	.37	.39	.031
9.....	4.33	.34	2.12	Nil.	22.....	5.01	.37	.24	.015
10.....	4.44	.36	1.87	Nil.	23.....	4.95	.44	.16	.010
11.....	4.57	.35	1.81	Nil.	24.....	4.85	.40	.11	Nil.
12.....	4.64	.37	1.42	Nil.	25.....	4.58	.38	.43	.012
13.....	4.48	.39	1.13	Nil.	26.....	4.65	.35	.041	.033
14.....	4.71	.39	1.12	Nil.					

TABLE 9.—*Analyses of individual flushes during test period 1, per cent*

Flush No.	SiO ₂	FeO	Al ₂ O ₃	CaO	TiO ₂	Flush No.	SiO ₂	FeO	Al ₂ O ₃	CaO	TiO ₂
38 ¹	33.43	0.62	18.48	41.51	0.83	61 ²	11.42	0.59	40.50	45.21	1.78
41.....	33.50	1.45	18.92	39.16	.50	62.....	7.96	.27	43.05	48.55	.76
42.....	29.84	6.48	22.60	38.37	.94	63.....	7.25	.40	41.39	49.73	.88
42 ²	29.82	.76	23.20	41.50	.37	63 ²	11.69	.29	41.21	43.15	2.22
43.....	29.72	.51	24.40	44.15	.56	64.....	8.20	.35	42.00	47.75	.73
44.....	29.21	.62	23.97	45.18	.50	65.....	8.96	.54	42.01	46.60	.68
45.....	30.81	1.44	21.83	42.09	.48	65 ²	11.58	2.18	40.46	42.18	2.12
46.....	19.73	.75	34.72	39.32	2.40	66.....	7.69	1.38	48.50	38.90	1.86
47.....	16.62	.25	39.70	42.20	1.80	66 ²	10.33	1.03	41.76	39.90	2.52
48.....	11.83	1.00	40.00	47.40	.76	67.....	9.00	1.34	43.70	42.96	2.45
48 ²	13.05	1.43	35.32	45.09	.59	68.....	9.74	1.05	42.03	40.48	2.06
49.....	11.97	.01	41.68	46.40	.44	68 ²	10.25	1.30	39.85	43.02	2.00
50.....	11.92	.53	39.28	46.82	.39	69.....	9.35	.95	40.44	45.39	2.10
51.....	11.08	.78	44.70	42.53	.74	70.....	10.10	1.16	43.46	44.86	1.37
52.....	11.97	.56	38.06	46.99	1.09	71.....	6.92	.44	46.10	46.34	1.61
53.....	11.02	.56	41.48	45.48	1.81	72.....	8.72	.54	46.98	43.60	2.00
53 ²	7.75	.36	46.42	44.62	.34	73.....	9.10	1.35	42.09	45.54	1.97
56.....	7.69	.45	44.49	46.86	.78	74.....	8.76	.76	36.94	52.01	.98
56 ²	9.32	.40	40.29	49.81	.80	75.....	8.22	1.26	38.40	50.59	1.03
57.....	9.09	.35	41.90	46.50	1.00	76.....	9.05	1.92	41.17	42.67	2.36
58.....	8.40	.41	44.84	47.01	.44	77.....	8.81	1.86	41.30	43.55	1.97
58 ²	10.10	.29	41.85	43.15	.93	78.....	9.76	.82	41.64	42.93	2.16
59.....	8.58	.25	48.01	42.30	.68	79.....	13.77	.77	40.01	41.41	2.16
60.....	9.06	.20	45.00	43.82	2.05	80.....	7.12	1.66	44.72	43.01	2.32
61.....	8.69	.83	44.90	45.09	.74	81.....	6.59	1.20	43.50	42.99	2.20

¹ The MnO content dropped from about 3 per cent in flush 38 to a small trace in flush 48.² Slag at cast after flush number indicated.

TEST PERIOD 2

Before changing over to a slag that contained alumina in excess of lime the authors wished to determine how iron ore in the burden would affect the operation. During the second test period, which lasted about three and one-half days, a burden consisting of 325 pounds of bauxite, 394 pounds of stone, 50 pounds of iron ore, and 100 pounds of turnings was charged the greater part of the time. This burden was heavier than previous ones which contained no iron ore. One hundred pounds of turnings was taken off and 50 pounds of ore added. This change lowered the top temperature as well as that of slag, metal, and tuyère. (See Table 7.)

The decrease in hearth temperature is reflected in the composition of the metal; the sulphur increased from an average of 0.008 per cent for test period 1 to 0.034 per cent for test period 2. The addition of

iron ore to the burden apparently caused a further drop in silicon in the metal. Tables 10 and 11, which give the analyses of slag and metal for the second period, show that the metal contained very small percentages of silicon; the weighted average for the period was 0.046 per cent.

TABLE 10.—*Analyses of individual casts during test period 2, per cent*

Cast No.	C	P	Si	S	Cast No.	C	P	Si	S
27.....	4.78	0.37	0.050	0.026	38.....	3.25	0.037	0.040	0.130
28.....	4.88	.37	.080	.017	39.....	2.43	.09	.020	.051
29.....	4.77	.37	.030	.024	40.....	4.50	.23	.060	.060
30.....	4.35	.36	.010	.066	41.....	4.63	.27	.050	.040
31.....	4.25	.25	.067	.060	42.....	4.54	.30	.060	.020
32.....	4.27	.37	.157	.024	43.....	4.36	.32	.040	.040
33.....	4.19	.37	.006	.007	44.....	5.09	.29	.050	.040
34.....	5.03	.37	.011	.004	45.....	4.53	.17	.050	.040
35.....	4.59	.38	.013	.016	46.....	4.65	.20	.060	.054
36.....	4.32	.36	.013	.022	47.....	4.19	.21	.050	.051
37.....	4.95	.37	.050	.016					

TABLE 11.—*Analyses of individual flushes during test period 2, per cent*

Flush No.	SiO ₂	FeO	Al ₂ O ₃	CaO	TiO ₂	Flush No.	SiO ₂	FeO	Al ₂ O ₃	CaO	TiO ₂
82.....	6.75	1.35	43.46	39.40	2.15	102.....	6.29	1.13	48.04	43.88	2.31
83.....	6.90	.03	41.51	44.95	2.41	103.....	7.23	1.73	44.30	44.75	2.26
84.....	7.99	.41	40.80	45.86	2.26	113.....	8.12	1.71	43.00	45.91	2.10
85.....	7.15	.19	40.64	46.11	2.20	115.....	7.98	.90	44.70	45.08	2.25
86.....	6.81	.46	42.26	44.08	2.15	116.....	8.41	1.08	49.18	40.40	2.40
86 ¹	11.50	4.26	43.53	37.00	1.93	117.....	8.29	.74	42.80	47.71	2.46
89.....	6.53	1.77	46.60	40.92	2.31	118.....	7.55	.77	50.00	41.50	2.36
92.....	6.39	.50	42.22	49.35	2.15	119.....	7.19	.43	43.50	48.12	2.16
93.....	6.75	.28	42.40	49.30	1.91	120.....	6.76	.72	42.03	49.40	2.11
94.....	6.51	.28	40.50	50.90	1.86	121.....	7.19	.84	44.24	43.68	2.46
95.....	6.64	.33	42.18	48.40	2.10	122.....	6.40	1.59	41.52	46.28	2.11
96.....	6.35	.35	44.20	48.02	2.00	123.....	6.30	1.03	38.24	49.49	2.41
97.....	6.44	.19	40.31	49.39	1.96	124.....	6.43	.79	41.33	48.31	2.36
98.....	6.33	1.42	43.01	46.01	2.12	125.....	6.33	1.42	41.50	48.00	2.36
99.....	6.29	1.44	41.25	48.50	2.21	126.....	6.57	1.93	45.50	45.60	2.36
100.....	6.87	1.26	43.18	45.62	2.31	127.....	6.46	2.70	42.01	47.50	2.31
101.....	6.26	1.32	42.10	48.50	2.26						

¹ Slag at cast after flush number indicated.

With a few exceptions the percentages of ferrous oxide in the slag were not unusually high. Silicon in the metal was oxidized either by the blast or by ferrous oxide in the slag. Although there is no means of knowing how much oxidation the blast caused, the greater portion of the silicon seemed to be oxidized by ferrous oxide. Once oxidized the basic nature of the slag and the small amount of silica present provided conditions unfavorable to reentry of silicon into the metal by reduction of silica. Temperatures were high enough to reduce silica, but the small amount in the slag and the presence of iron oxide made this impossible. The average percentage of sulphur for the period was 0.034. This increase in sulphur was due largely to a decrease in the temperature of the hearth, slag, metal, and tuyères. The presence of ferrous oxide would also tend to retard desulphurization.

The unit charge during the greater part of this test period was as follows: Coke, 360 pounds; bauxite, 200 pounds; ore, 50 pounds;

stone, 394 pounds; turnings, 100 pounds. A lighter burden consisting of 200 pounds of bauxite, 255 pounds of stone, and 155 pounds of scrap to a coke unit of 360 pounds was charged during the latter part of this test period, after the furnace had been banked to repair the hot-blast stove. Reference to Table 7 shows that the operation resembled that of a slagging-type producer more closely than a blast furnace. However, as the primary object of the test was to study the production of high-alumina slags, the operation was not typical of either a slagging-type gas producer or a blast furnace. Approximately $2\frac{1}{2}$ tons of coke was used to make about the same quantity of high-alumina slag and 1 ton of pig iron. Most of the metal was obtained from the turnings in the charge.

TEST PERIOD 3

During the first two test periods the average percentage of lime in the slag was greater than the percentage of alumina. However, in the third test period the percentage of stone in the burden was decreased. The bauxite in the charge was held constant at 300 pounds and the iron ore at 100 pounds, the stone being decreased from 360 to 320 pounds. As a result of this decrease in stone the average slag for the period contained about 2 per cent more alumina than lime. This slag did not change operation of the furnace materially. There was, however, a large increase of sulphur in the metal, primarily because the hearth temperature decreased. The condition of the tuyères was not as satisfactory during this period as during the first two periods. A tuyère log covering the entire test shows a tendency for all tuyères to scull over. The drop in hearth temperature was due to the increase from 50 to 100 pounds of iron ore per round. If there had been more time, the changes in composition of slag and the amount of iron ore in the burden would have been made separately instead of simultaneously. However, the results of the next test period show that the change in composition of slag was not responsible for the higher percentages of sulphur in the metal. Analyses of individual casts and flushes are given in Tables 12 and 13.

TABLE 12.—Analyses of individual casts during test period 3, per cent

Cast No.	C	P	Si	S	Cast No.	C	P	Si	S
48-----	4.39	0.23	0.03	0.044	58-----	4.45	0.24	0.02	0.100
49-----	4.62	.21	.011	.036	59-----	4.62	.23	.02	.080
50-----	4.85	.24	.04	.036	60-----	4.38	.25	.04	.080
51-----	4.86	.20	.08	.035	61-----	4.61	.25	.04	.050
52-----	4.82	.26	.08	.055	62-----	4.61	.27	.06	.040
53-----	4.43	.24	.04	.052	63-----	3.96	.23	.03	.110
54-----	4.60	.26	.37	.038	64-----	4.45	.29	.014	.106
55-----	4.55	.26	.28	.071	65-----	4.81	.32	.03	.064
56-----	4.75	.25	.055	.071	66-----	4.73	.33	.09	.079
57-----	4.26	.25	.12	.075					

TABLE 13.—*Analyses of individual flushes during test period 3, per cent*

Flush No.	SiO ₂	FeO	Al ₂ O ₃	CaO	TiO ₂	Flush No.	SiO ₂	FeO	Al ₂ O ₃	CaO	TiO ₂
128	7.45	2.09	42.32	41.20	2.26	148	6.61	0.85	47.99	43.00	2.45
129	6.55	.88	41.20	49.70	2.25	149	6.55	1.38	47.88	43.01	2.46
130	6.28	1.44	43.95	43.54	2.35	152	6.94	2.72	49.20	40.27	2.27
131	6.08	.77	40.88	50.11	2.10	153	6.41	1.06	47.39	44.40	2.36
134	5.92	1.13	43.51	48.01	2.21	154	7.21	.89	49.61	41.70	2.45
135	6.12	1.61	44.00	46.68	2.30	155	7.08	.81	47.89	43.58	2.40
136	5.95	.92	43.88	46.10	2.40	156	7.45	.60	46.89	42.34	2.40
137	5.86	1.97	37.69	51.48	2.16	157	7.44	.94	44.82	45.30	2.35
138	6.25	1.18	44.30	46.74	2.41	158	7.11	.93	44.38	45.50	2.45
139	6.10	1.75	44.01	45.99	2.51	159	6.70	1.50	51.02	36.83	2.66
140	6.10	1.57	47.52	44.26	2.51	160	6.83	1.77	45.28	41.76	2.51
141	7.22	1.95	44.24	45.50	2.00	161	7.20	1.27	46.97	43.76	2.51
142	6.25	2.44	45.18	45.43	2.26	162	7.45	.60	46.58	45.17	2.40
143	6.15	1.74	44.39	45.51	2.31	164	7.25	.93	51.76	39.67	2.56
144	6.21	.69	48.70	43.39	2.46	164 ¹	7.04	.90	49.83	40.25	2.42
146	6.71	.45	46.59	44.70	2.15	166	7.45	.32	53.91	37.00	2.55
147	6.39	.51	44.51	45.76	2.40						

¹ Slag at cast after flush number indicated.

TEST PERIOD 4

One of the objects of test period 4 was to determine if a slag containing about 50 per cent of Al₂O₃ and 40 per cent of CaO could be produced in a blast furnace. During the last part of the test it was fully demonstrated that this is feasible and also that under proper conditions low-sulphur metal can be produced. The iron ore was reduced to 50 pounds per round and both the bauxite and stone to 275 pounds. Metal produced from this burden was considerably lower in sulphur than that produced from the previous burden, the last five casts ranging from 0.001 to 0.007 per cent. The average for the test period, considering the weight of the casts, was 0.023 per cent. Tables 14 and 15 show the range of composition of the individual flushes and the composition of individual casts. The increase of silica in the slag was due to an increase of ash in the coke.

TABLE 14.—*Analyses of individual casts during test period 4, per cent*

Cast No.	C	P	Si	S	Cast No.	C	P	Si	S
67	4.88	0.34	0.15	0.035	71	4.04	0.40	0.57	.002
68	4.81	.35	.11	.044	72	4.37	.39	.44	.007
69	4.98	.38	.47	.001	73	3.97	.34	.65	.001
70	4.94	.36	.39	.003					

TABLE 15.—*Analyses of individual flushes during test period 4, per cent*

Flush No.	SiO ₂	FeO	Al ₂ O ₃	CaO	TiO ₂	Flush No.	SiO ₂	FeO	Al ₂ O ₃	CaO	TiO ₂
167	7.18	1.84	51.61	36.45	2.45	175	10.05	3.60	42.60	41.88	1.92
171	7.68	.80	50.99	38.62	2.40	177	9.65	.80	47.96	38.62	2.15
173	8.67	1.28	46.64	40.24	1.87	178	10.02	.30	51.46	35.47	1.71

GENERAL OPERATION OF FURNACE

In general, the operation of the furnace was smooth and free from slips and hanging. The blast temperature was about constant throughout the test. Higher blast heats, although very desirable, were not possible with the iron-pipe stove employed in this connection. The top temperatures shown in Table 7 varied from 405 to 580° F., depending upon the burden on the furnace.

The blast pressure indicates much about the operation of a blast furnace. During the entire test the blast pressure was about 2.5 pounds. Periodic sculling of the tuyères occurred, but this condition could probably have been eliminated with higher blast heats. A total of about 70 tons of slag and 30 tons of metal was made during the test. The only difficulties were with tuyère leaks and the iron-pipe stove, neither of which was connected with the high-alumina slag. Table 17 gives analyses of top gas by test periods.

TABLE 16.—*Heat distribution in industrial and experimental blast furnaces*

Item	Average of 14 industrial American pig-iron furnaces ¹		Bureau of Mines experimental blast furnaces					
			Furnace A, ² pig iron		Furnace B, ³ manganese iron ore		Furnace B, ³ high-alumina slag	
	B. t. u. per long ton	Per cent of total	B. t. u. per long ton	Per cent of total	B. t. u. per long ton	Per cent of total	B. t. u. per long ton	Per cent of total
Heat generated								
Combustion of C to CO.....	5,209,980	34.12	8,434,060	41.63	9,598,914	45.91	17,094,870	64.3
Combustion of C to CO ₂	7,969,300	52.19	9,060,290	44.72	9,146,547	43.74	3,955,700	14.8
Heat in blast (including moisture).....	2,091,500	13.69	2,767,230	13.65	2,163,521	10.35	5,182,620	19.5
Oxidation of Si to SiO ₂							380,430	1.4
Total.....	15,270,780	100.00	20,261,580	100.00	20,908,982	100.00	26,613,620	100.0
Heat consumed								
Reduction of iron oxides.....	6,553,900	42.92	6,590,380	32.57	6,531,192	31.24	3,129,840	11.80
Reduction of Fe ₂ O ₃ and SiO ₂	526,100	3.44	400,060	1.97	205,712	.99	10,620	.04
Reduction of MnO.....			97,710	.48	1,038,410	4.96		
Calcination of carbonates.....	692,700	4.53	1,013,820	5.00	1,099,830	5.28	3,002,230	11.30
Dissociation of moisture.....	1,115,588	7.30	859,400	4.24	1,539,648	7.36	1,555,200	5.80
Carried off with the metal.....	1,143,100	7.50	1,093,820	5.40	1,056,994	5.08	1,136,130	4.30
Carried off with the slag.....	928,700	6.08	1,435,690	7.09	1,885,068	9.02	4,496,000	16.90
Carried off with the gases (dry).....	923,810	6.05	2,969,410	14.66	3,160,121	15.11	3,434,040	12.90
Carried off with moisture in top gases.....	634,200	4.15	874,240	4.31	1,687,576	8.07	1,228,390	4.60
Total heat accounted for.....	12,517,200	81.97	15,334,500	75.72	18,205,581	87.07	17,992,450	67.64
Heat unaccounted for.....	2,273,600	18.03	4,927,100	24.28	2,703,401	12.93	8,621,170	32.36

¹ Royster, P. H., Joseph, T. L., and Kinney, S. P., "Heat balance of Bureau of Mines experimental blast furnace": Blast Furnace and Steel Plant, April, 1924, p. 203.

² 20-inch hearth.

³ 36-inch hearth.

⁴ Reduction of phosphorus only.

HEAT BALANCE

To compare the distribution of heat in the experimental furnace during this test with that in previous experimental furnace tests and in industrial furnaces, a heat balance was calculated using the average operating data recorded in Table 7. Table 16 summarizes these calculations. Although the operation resembles gas-production practice as well as blast-furnace practice, the method of computing heat balances for the blast furnace has been followed. As a result of the small quantity of iron oxides in the charge, the top gases (Table 17) contained an average of 6.83 per cent of CO_2 by volume, or 10.47 per cent by weight. Under these conditions 64.3 per cent of the heat produced in the furnace was generated in the combustion of carbon to carbon monoxide. In normal blast-furnace practice about one-third of the heat is so generated. Approximately 5,000 B. t. u. was generated per pound of carbon consumed, compared with 7,500 B. t. u. in efficient blast-furnace practice. This difference in the heat generated per pound of carbon shows the importance for blast-furnace efficiency of attaining high percentages of CO_2 in the top gas. Although, as shown later, a full-size furnace would have greater thermal efficiency than the experimental furnace, the production of unusually large amounts of low-silica slag would limit the amount of iron ore that could be charged. Operation would resemble that of a gas producer, a large part of the potential heating value of the carbon leaving the furnace in the top gases as CO .

TABLE 17.—*Top-gas analyses during operation on high-alumina slag*

Test period No.	CO_2 , per cent—		CO , per cent—		H_2 , per cent—		N_2 , per cent—	
	By volume	By weight	By volume	By weight	By volume	By weight	By volume	By weight
1.....	5.02	7.70	32.40	31.60	1.30	0.091	61.30	59.79
2.....	7.55	11.58	29.63	28.90	1.55	.108	61.26	59.75
3.....	7.13	10.93	30.71	29.95	1.34	.093	60.83	59.33
4.....	6.05	9.28	30.15	29.41	1.16	.081	62.65	61.11
Average.....	6.83	10.47	30.32	29.57	1.40	.098	61.23	59.72

As shown in Table 16, a little over 5,000,000 B. t. u. was brought in by the blast used to produce 1 ton of metal, or about double the quantity used in previous experimental furnace tests and in industrial furnaces. Under the items giving the distribution of heat consumed the largest single item is the heat carried off in the slag. The calcination of stone consumed 11.3 per cent of the total heat generated. The authors could not account for over 32 per cent of the heat generated. A large part of this was carried off in the hearth and bosh cooling water. No data as to the actual amount lost in this manner were recorded. The large amount of coke per ton of metal

was due partly to the high heat loss; the poor fuel economy was due primarily to the small amount of iron ore in the charge, only a small part of the potential heat of the carbon being utilized in the furnace. The production of high-alumina slag, iron, and gas would be more economical if comprising only one unit in a plant requiring fuel gas low in sulphur. Such gas is needed in heating open-hearth furnaces and could also be used advantageously in reducing iron ore in direct steel processes.

EFFECT OF SLAG COMPOSITION ON HEARTH TEMPERATURES

The free-running temperature of slag determines its temperature upon reaching the crucible of the furnace. This idea, advanced by Johnson,¹⁹ is borne out by the temperature measurements made during this test. Table 18 lists tuyère, slag, and metal temperatures for various practices in commercial furnaces and includes similar results for experimental furnaces. Item 12 confirms the general observation that the hearth of the furnace was hotter than in previous experiments. The temperature of charcoal-furnace slags approaches the temperature of slag from ferro and spiegel furnaces. Charcoal slags are siliceous, and their composition is in the low melting range. Refractory slags pass through the lower section of the bosh more slowly, because of their high viscosity, and as a result are preheated to higher temperatures. The ratio of the coke to the total charge obviously affects the temperature of the furnace, including that of the hearth. The large quantity of fuel used in the test of high-alumina slags was no doubt partly responsible for attaining higher hearth temperatures than in previous experimental furnace tests. However, the effect of the more refractory slag was shown when the first burden of bauxite reached the hearth. Before this the furnace had been operating on a high burden of siliceous slag that contained several per cent of manganese.

TABLE 18.—*Hearth temperatures*¹ *with various practices*,² ° C.

Item	Furnace	Tuyère	Slag	Metal
1	Pig iron.....	1,711	1,509	1,466
2	do.....	1,708	1,526	1,472
3	Foundry iron.....	1,748	1,553	1,493
4	Bessemer iron.....	1,733	1,513	1,466
5	Basic iron.....	1,669	1,522	1,468
6	Charcoal.....	1,669	1,451	1,415
7	Manganese alloy.....	1,573	1,427	1,389
8	Spiegeleisen.....	1,597	1,427	1,392
9	Ferromanganese.....	1,550	1,426	1,386
10	Experimental furnace A, pig iron.....	1,647	1,529	1,396
11	Experimental furnace B, manganese.....	1,689	1,413	1,349
3 12	Experimental furnace B, high Al ₂ O ₃ slag.....	1,705	1,568	1,450

¹ Slag and metal temperatures corrected for emissivity, according to G. K. Burgess, *Temperature Measurements in Bessemer and Open-Hearth Practice*: Bureau of Standards Technol. Paper 91, 1917, pp. 8-9.

² Royster, P. H., Joseph, T. L., and Kinney, S. P., "Significance of hearth temperatures": *Blast Furnace and Steel Plant*, March, 1924, pp. 154-58.

³ This item not given in previous table.

¹⁹ Johnson, J. E., jr., *Principles, Operation, and Products of the Blast Furnace*: New York, 1918, pp. 39-41.

LOW-SULPHUR METAL

One important function of the lower part of the blast furnace is to remove sulphur absorbed by the metal in the upper part of the stack. In normal practice the coke contains about 95 per cent of the sulphur charged. Sulphur is transferred from the coke to the sponge iron in the upper part of the furnace. Metal reaching the region of the tuyères often contains twice as much sulphur as is permissible in the pig iron. Desulphurization is accomplished by the following reaction:

According to this reaction desulphurization of the metal is promoted by high lime concentrations and is inhibited by high iron oxide and sulphur concentrations in the slag. The iron oxide in the slag comes from (a) unreduced ore, (b) oxidation at the tuyères, (c) formation of FeO by reaction (1), (d) formation of FeO by reduction of SiO_2 with iron, and (e) formation of FeO by reduction of manganese from MnO. The iron oxide content of the slag is largely controlled by equilibrium conditions for the reaction $\text{FeO} + \text{C} \rightarrow \text{CO} + \text{Fe}$. This reaction is endothermic, and as the temperature is raised the FeO in the slag in equilibrium with carbon in the metal decreases. This accords with blast-furnace practice where hot furnaces give low iron oxide slags and cold furnaces give high iron oxide slags. The exact mechanism of the desulphurizing reaction is not known at present.

The effect of CaS in retarding reaction (1) depends upon how the sulphur is removed from the iron. There are now no data to show whether the greater part of the sulphur is removed as the globules of iron come in contact with slag in the tuyère region and later pass through the bath of slag or after the metal has collected at the bottom of the crucible and lies in contact with a layer of slag above it. Calcium sulphide formed at the slag-metal boundary would in the latter instance retard the reaction unless it diffused rapidly through the slag. The rate of diffusion of CaS through the slag would be controlled largely by slag viscosity (a function of temperature and composition) and the concentration of CaS at the reacting surface and at other positions in the slag bath. Increased solubility of CaS in the slag would facilitate absorption of this compound by the slag and would increase its rate of diffusion throughout the slag bath by making higher concentrations possible at the slag-metal boundary.

In desulphurization, which takes place as globules of iron pass through the layer of slag, diffusion of CaS would not be so important. The boundary plane between slag and metal would be changing constantly, and the tendency would be to equalize the percentages of

CaS in the slag. The area of contact under these conditions favors rapid desulphurization, but the time of contact is short.

EXPERIMENTS TO STUDY SULPHUR ELIMINATION IN THE BLAST FURNACE

Preliminary experiments were performed by one of the authors to study elimination of sulphur in the blast furnace. Two types of experiments were conducted. In the first type about 100 grams of molten metal, containing 0.13 per cent of S, was fed through a $\frac{1}{32}$ -inch opening and allowed to drop through a 10-inch layer (about 450 grams) of slag held in a graphite container at 1,500 to 1,525° C. From 10 to 15 minutes was required for the experiment. In the second type of experiment a sample of the same metal as that used in the first experiments was covered with a layer of slag and the contiguous layers of slag and metal were held for two hours at 1,500 to 1,525° C. The weight of metal in tests of the second type was approximately double the weight of slag.

Three slags of the following percentage composition were used:

Composition of slags, per cent

Slag No.	CaO	MgO	Al ₂ O ₃	SiO ₂	S	MnO	FeO
1	47.0	-----	44.6	9.3	0.32	-----	1.2
2	42.1	4.7	18.5	32.4	.01	-----	.76
3	10.44	-----	26.12	31.6	.57	27.0	3.0

When metal shot were dropped through slag 1 the sulphur was reduced from 0.13 to 0.01 per cent. The same reduction in sulphur occurred when molten layers of metal and slag were held in contact with each other at the temperatures named. Slag 2 reduced the sulphur from 0.13 to 0.029 per cent in the first type of experiment and to 0.022 in the second type. Slag 3 removed smaller amounts of sulphur. The metal from the first test contained 0.08 per cent of S, and that from the second 0.12 per cent.

DESULPHURIZING ACTION OF SLAG

These tests show that slag of the composition produced in the experimental blast furnace has a strong desulphurizing action. In the opinion of the authors, the desulphurizing action of this slag is due largely to its chemical constitution. Turner²⁰ and Schäfer²¹ advanced the theory that the spinels alone can react with the iron sulphide in the pig iron, the silicates being comparatively inert. The availability of CaO for reaction with FeS depends upon the stability of the various compounds making up the slag.

²⁰ Turner, Thomas, "The physical and chemical properties of slags": Jour. Soc. Chem. Ind., vol. 24, 1905, p. 1142; Stahl u. Eisen, Jahrg. 26, No. 1, 1906, p. 172; Metallurgie, 1906, p. 164.

²¹ Schäfer, Rudolf, "Das Entschwefelungsvermögen der Hochenschlacke": Ferrum, Jahrg. 10, Feb. 8, 1913, p. 129.

McCance²² found that when molten aluminum at about 850° C. was added to an equal quantity of FeS at about 1,250° C., a rapid reaction took place and a slag composed largely of Al_2S_3 and Al_2O_3 (the latter resulting from oxidation of the sulphide) was formed. If small amounts of aluminum became incorporated in the metal, some sulphur might be eliminated by the formation of Al_2S_3 , followed by its separation from the metal. The major part of the sulphur probably was not eliminated in such a manner, but the formation of Al_2S_3 may account for the complete removal of sulphur in some of the casts.

Blast-furnace slags are not mixtures of simple oxides but of more complex compounds. In writing equation (1) (p. 25) thermal dissociation of the lime compounds is assumed to take place. The major constituents of the slag produced in this test were $5\text{CaO} \cdot 3\text{Al}_2\text{O}_3$ and $\text{CaO} \cdot \text{Al}_2\text{O}_3$. Minor constituents were $2\text{CaO} \cdot \text{SiO}_2$, $2\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{SiO}_2$, and $3\text{CaO} \cdot 5\text{Al}_2\text{O}_3$. The desulphurizing power of a slag can not be expressed in terms of its percentage of CaO because the activity of the lime toward FeS will depend upon the thermal dissociation of the compounds making up the slag. Complete information showing the degree of thermal dissociation of the various compounds in blast-furnace slags is not available. Practice shows, however, that basic slags containing large amounts of the compounds listed above desulphurize more readily than acid slags in which a part of the lime is present as $\text{CaO} \cdot \text{SiO}_2$, $\text{CaO} \cdot \text{Al}_2\text{O}_3$, 2SiO_2 , and $3\text{CaO} \cdot 2\text{SiO}_2$.

FACTORS AFFECTING DESULPHURIZATION

McCaffery and Oesterle²³ have shown that alumina increases the solubility of slag for calcium sulphide. However, the increase in solubility is small. At 1,500° C. mixtures of CaO, Al_2O_3 , and SiO_2 in the range of blast-furnace slag were found to dissolve about 10 per cent of sulphur. Blast-furnace slag usually contains about 2 per cent of sulphur; that is, normal percentages of sulphur are about 20 per cent of the amount required for saturation. At the slag-metal surface concentrations higher than 2 per cent are probably attained. Exact information on this point is entirely lacking, however. Although the work of McCaffery and Oesterle indicates that the high-alumina slag produced in the experimental furnace would dissolve more CaS than ordinary slags, its unusual desulphurizing power was, in the opinion of the authors, due primarily to the fact that lime held as aluminates is more active toward FeS than the lime in compounds existing in the range of normal slag composition. The large volume of slag per ton of metal aided the production of low-sulphur metal.

²² McCance, Andrew, "Nonmetallic inclusions; their constitution and occurrence in steel": Jour. Iron and Steel Inst., vol. 97, 1918, p. 254.

²³ McCaffery, R. S., and Oesterle, J. F., "Desulphurizing power of blast-furnace slags": Trans. Am. Inst. Min. and Met. Eng., vol. 69, 1923, pp. 606-634.

However, test periods 1 and 4, with lower slag volumes, lower burdens, and higher slag temperatures than periods 2 and 3 (Table 7), show the effectiveness of temperature.

The authors believe that experimental data are needed to establish the relative importance of the factors affecting the velocity of the reactions involved in desulphurization. A continuation of the preliminary experiments described above is therefore being planned on a more comprehensive scale.

In the present test the high-alumina slag lost its strong desulphurizing power as the temperature dropped. The effect of temperature was probably twofold—it produced greater thermal dissociation of the compounds making up the slag and also increased the reaction rate.

OXIDATION OF SILICON FROM BORINGS CHARGED

On pages 17 and 19 reference has been made to the oxidation of silicon. Attention is again called to this point because it is important in considering the amount of silicon to be expected in full-size furnaces. The tuyère zone of the experimental furnace is more oxidizing than that of a larger furnace because the hearth of the former is smaller. Although the smaller coke (nut size) reduced the oxidizing area in the combustion zones, the large strongly reducing area present in the central part of industrial furnaces did not exist in the experimental furnace. In the experimental furnace the O_2 disappeared about 13 inches from the nose of the tuyère, and the CO_2 about 18 inches. In an industrial furnace with a 20-foot hearth the combustion zones extend about 30 to 40 inches beyond the tuyères, leaving a large strongly reducing area in the central part of the furnace. Although one can not determine what the exact silicon content of metal produced in a full-size industrial furnace would be, it should be higher than that of metal made in the experimental furnace.

ECONOMIC CONSIDERATIONS

In considering the cost of operating a blast furnace to produce high-alumina slags the geographical location of the furnace is important. Because of the advantage of obtaining cheap imported bauxite the authors have assumed in the following cost estimates that the furnace site is along the North Atlantic coast, the prices being those at which all raw materials would be available at such a location. The authors wish to point out at this time that the estimates are made primarily to indicate the amount of raw materials—particularly fuel—that would be required. Interested individuals or companies can readily make whatever changes they see fit in cost of materials.

The burdens that follow are based upon the experience and data obtained in operating the experimental furnace and upon the experience of the authors with blast-furnace practice in general. As operators might have their choice of using an all-scrap burden, burdens containing all iron ore and no scrap, or those containing both iron ore and scrap, three cost estimates have been made.

All-scrap burden

Material	Pounds per ton of iron	Ton per ton of iron	Cost per ton	Cost of material per ton of iron
Bauxite.....	2, 100	0.948	\$6.00	\$5.70
Stone.....	1, 850	.826	1.50	1.25
Borings.....	2, 100	.948	11.00	10.40
Coke.....	1, 900	.95	6.00	5.70
Cost above:				
Labor.....				1.00
Maintenance and repairs.....				.50
Steam.....				.35
Relinings and renewals.....				.30
Other costs.....				.75
				25.95
Products:				
Slag, 1 ton, at \$6.50.....				6.50
Metal, 1 ton.....				19.45

Information is not available as to the comparative cost of raw bauxite and high-alumina slag. The slag would probably be worth a little more than the raw bauxite, and a price of \$6.50 per ton has therefore been assumed.

All-ore burden

Material	Pounds per ton of iron	Tons per ton of iron	Cost per ton	Cost of material per ton of iron
Bauxite.....	3, 260	1.455	\$6.00	\$8.70
Limestone.....	2, 800	1.25	1.50	1.90
Ore.....	2, 800	1.25	6.00	7.50
Coke.....	3, 350	1.675	6.00	10.00
Cost above.....				2.90
				31.00
Products:				
Slag (3,600 pounds), 1.6 tons, at \$6.50.....				10.40
Metal (2,240 pounds), 1 ton.....				20.60

Ore-scrap burden

Material	Pounds per ton of iron	Tons per ton of iron	Cost per ton	Cost of material per ton of iron
Bauxite.....	2, 175	0.97	\$6.00	\$5.80
Limestone.....	1, 865	.83	1.50	1.25
Borings.....	1, 245	.56	11.00	6.15
Ore.....	1, 245	.56	6.00	3.35
Coke.....	2, 240	1.12	6.00	6.70
Cost above.....				2.90
				26.15
Products:				
Slag (2,450 pounds), 1.1 tons, at \$6.50.....				7.10
Metal (2,240 pounds), 1 ton.....				19.05

These estimates, which should be regarded as preliminary to more detailed cost studies, indicate that the profit in the operation, omitting the value of the surplus gas, will depend upon whether or not the actual value of the slag is more than \$6.50 per ton and whether or not more than \$20 per ton can be obtained for the low-sulphur metal. The amount of coke and its ash content limit the quantity of silica that can be derived from the raw products if a low-silica slag is desired. Slag made from an all-scrap charge would be lowest in silica, that from a scrap-ore charge would rank next, and that from an all-ore burden would be highest. This is true even when an exceptional grade of iron ore (4 to 5 per cent of SiO_2 and 60 per cent of Fe) is used.

ECONOMIC VALUE OF BLAST-FURNACE GAS

Brassert ²⁴ has recently pointed out the enormous heating value of blast-furnace gas. He states that in an annual production of 36,000,000 tons of iron, 473,760,000,000 B. t. u. of gas is produced, or the equivalent of 18,220,000 tons of coal. The operation of a blast furnace on high-alumina slag would resemble the operation of a slagging-type gas producer. More gas and a richer gas would be produced than in normal pig-iron practice. The heating value of blast-furnace gas is about 95 B. t. u. per cubic foot. The economic value of the gas made in producing pig iron and high-alumina slag would depend largely upon the furnace location and the local demand for gas. In modern steel plants, where the blast furnace is one unit, surplus blast-furnace gas is used in gas engines, coke ovens, and heating furnaces not requiring high temperatures.

METHODS OF ANALYSIS

The analysis of material containing large amounts of alumina requires care to obtain accurate results. Care should be taken in determining alumina mainly in the volume of precipitating solution, hydroxyl concentration of precipitating solution, double precipitation due to size of precipitate, washing of precipitate, and ignition of precipitate. Barrett and Schroeder ²⁵ have recommended igniting at a temperature of 1,150° C. Hillebrand ²⁶ recommends blasting for 5 or 10 minutes and points out that the full heat of an ordinary Bunsen burner is insufficient. Hillebrand ²⁷ has also discussed the volume and hydroxyl concentration necessary for the precipitation of alumina as the hydroxide and has recommended a bulk of 300 to 400 c. c. and a hydroxyl concentration indicated by the change of

²⁴ Brassert, H. A., "Possibilities of fuel economy": Abstracted in *Iron Age*, vol. 120, July 14, 1927, pp. 77-78.

²⁵ Barrett, E. P., and Schroeder, F. W., "Method for the analysis of aluminous-silicate refractories": *Jour. Am. Ceram. Soc.*, vol. 8, 1925, pp. 69-71.

²⁶ Hillebrand, W. F., *The Analysis of Silicate and Carbonate Rocks*: U. S. Geol. Survey Bull. 700, 1919, p. 107.

²⁷ See footnote 26.

methyl red. The washing solution of ammonium chloride will probably dissolve a little of the precipitate unless enough ammonium hydroxide is added to give an alkaline color to methyl red.

SUMMARY AND CONCLUSIONS

In the operation of a blast furnace the earthy materials or gangue of the charge are fused together to form slag. The furnace burden must be adjusted to produce a slag fluid enough to remove the ash from the coke in the combustion zone and to permit mechanical agitation of the coke by the blast. Silicon and sulphur specifications in the metal are met by proper adjustment of hearth temperature and basicity of the slag. In general, it is easier to operate furnaces when producing slags whose free-running temperatures are well below the tuyère temperatures. As the free-running temperature of the slag approaches the temperature attainable by burning coke with preheated air under blast-furnace conditions, operation becomes more difficult.

In the absence of experimental evidence that a blast furnace can be operated on a burden of iron ore, bauxite, limestone, and scrap, melting-point determinations were an invaluable guide in predicting the behavior of high-alumina slags. Melting-point determinations showed that a furnace could be operated on slags containing 47 to 48 per cent of Al_2O_3 , 41 to 42 per cent of CaO , 4 to 5 per cent of SiO_2 , and small percentages of TiO_2 , MgO , and S. Slags containing CaO and Al_2O_3 usually have the lowest melting points when the percentage of CaO exceeds the percentage of Al_2O_3 .

Viscosity determinations in the ternary system $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$ show that the ternary eutectic, composed of 49.5 per cent of CaO , 43.7 per cent of Al_2O_3 , and 6.8 per cent of SiO_2 , has a relatively low viscosity and that only a small change in viscosity takes place with changes in temperature above the melting point.

Industrial furnace tests have been made on slags containing 29 per cent of Al_2O_3 , 23 per cent of SiO_2 , 37 per cent of CaO , and 8 per cent of MgO . This composition differs widely from that of the slag made in the experimental furnace. Although there was evidence that a blast furnace could be operated on slags containing about equal percentages of lime and alumina with 6 to 10 per cent of silica, some sort of a practical demonstration was needed to obtain positive information. Furthermore, the Aluminum Co. of America wished to obtain a substantial quantity of slag to compare the ease of extracting alumina from high-alumina slag and from crude bauxite. Operating data from the experimental furnace were also needed to determine the economic possibilities of treating high-iron bauxite in the blast furnace to produce a calcium aluminate slag for the manufacture of aluminum.

During a two-week test experimental furnace slags were produced covering the following range of composition: 6 to 33 per cent of SiO_2 , 35 to 52 per cent of CaO , 18 to 53 per cent of Al_2O_3 , about 2 per cent of TiO_2 , about 1 per cent of FeO , and 0.5 per cent of S. No difficulty was encountered in operating the furnace on slag of this wide range of composition. Because of the temperature of the slag and its large volume and to the availability of the lime for reacting with iron sulphide, the metal produced was generally low in sulphur.

High-alumina slags lose their strong desulphurizing power at lower temperatures. Preliminary laboratory tests show that calcium aluminates desulphurize metal rapidly between 1,500 and 1,525° C. Although experimental evidence shows that CaS is more soluble in slags containing higher percentages of alumina, the marked capacity of such slags to desulphurize metal is attributed largely to the basicity of the slag or the amount of lime available to act as a driving force in the formation of CaS .

Silica was oxidized from the borings charged because of the oxidizing effect of the blast in the combustion zone; moreover, unreduced iron oxides reached the hearth. The oxidation of silicon from scrap charged in the experimental furnace would be much less pronounced in full-size furnaces.

Cost estimates for a burden of bauxite, limestone, and borings indicate that profits in operating a furnace at some site on the North Atlantic coast would depend upon the slag being worth more than \$6.50 per ton and the pig iron more than \$20 per ton. Iron ore can be used to increase the metallic content of the charge, but the silica from the coke ash places a limit upon the amount of silica that can be permitted in the other materials making up the charge. The lowest silica slags can be made on a burden of bauxite, limestone, and borings. A choice of raw materials would depend upon their price at the furnace site and upon the amount of silica permissible in the slag.