PREPRINT

OPERATION OF THE BUREAU OF MINES EXPERIMENTAL BLAST FURNACE WITH FUEL-OIL INJECTION

by

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Because one of the major components in the cost of raw materials for producing pig iron in the blast furnace is the cost of the coke, practical means for reducing the amount of this fuel required to produce a ton of pig iron are desirable. During the last decade, many improved operating practices, such as the use of higher blast temperatures and beneficiated burdens, have helped reduce blast-furnace coke rates. Recently, another new operating technique has been developed for reduction of the coke required in the blast furnace, namely, the injection of natural gas through the tuyères. Several full-scale furnaces currently are operating with natural-gas injection. A year ago, the Esso Research and Engineering Company and the U. S. Steel Corporation joined with the Bureau of Mines, U.S. Department of the Interior, in a cooperative test program, using the Bureau's experimental furnace to determine whether liquid petroleum fuels might also prove to be a partial substitute for coke. It was believed that heavy Bunker C fuel oil would react similarly to natural gas and could possibly have some technical and economical advantages over those of natural-gas injection. The experimental program was set up to determine the empirical relationships among fuel-injection rate, coke savings, production rate, and hot-blast temperature.

Over the last several years, the Bureau of Mines furnace has been operated on a number of different blast-furnace burden materials with several new operating techniques and has demonstrated its ability to predict full-scale blast-furnace performance. The furnace was designed to conform with the general lines of a full-scale blast furnace. It has a hearth diameter of 4 feet, a working volume of 305 cubic feet, and a working height of 19 feet 10 inches (that is, from the center line of the tuyères to the stockline). Three water-cooled copper tuyères are equally spaced around the bottom of the bosh. The blast air is heated by two large pebble stoves fired with high-velocity natural-gas burners. These stoves are capable of heating the blast air to approximately 2300 F at a wind rate of 1400 cfm. Figure 1 is a cross-section of the furnace and one of the pebble stoves.

Fuel-Oil Injection System

During the test program oil was injected into the combustion zone of the furnace through each of three tuyères by means of a ¼-inch-diameter stainless-steel injector fitted inside a concentric shroud inserted through the blowpipe and extending to within a few inches of the nose of the tuyère.

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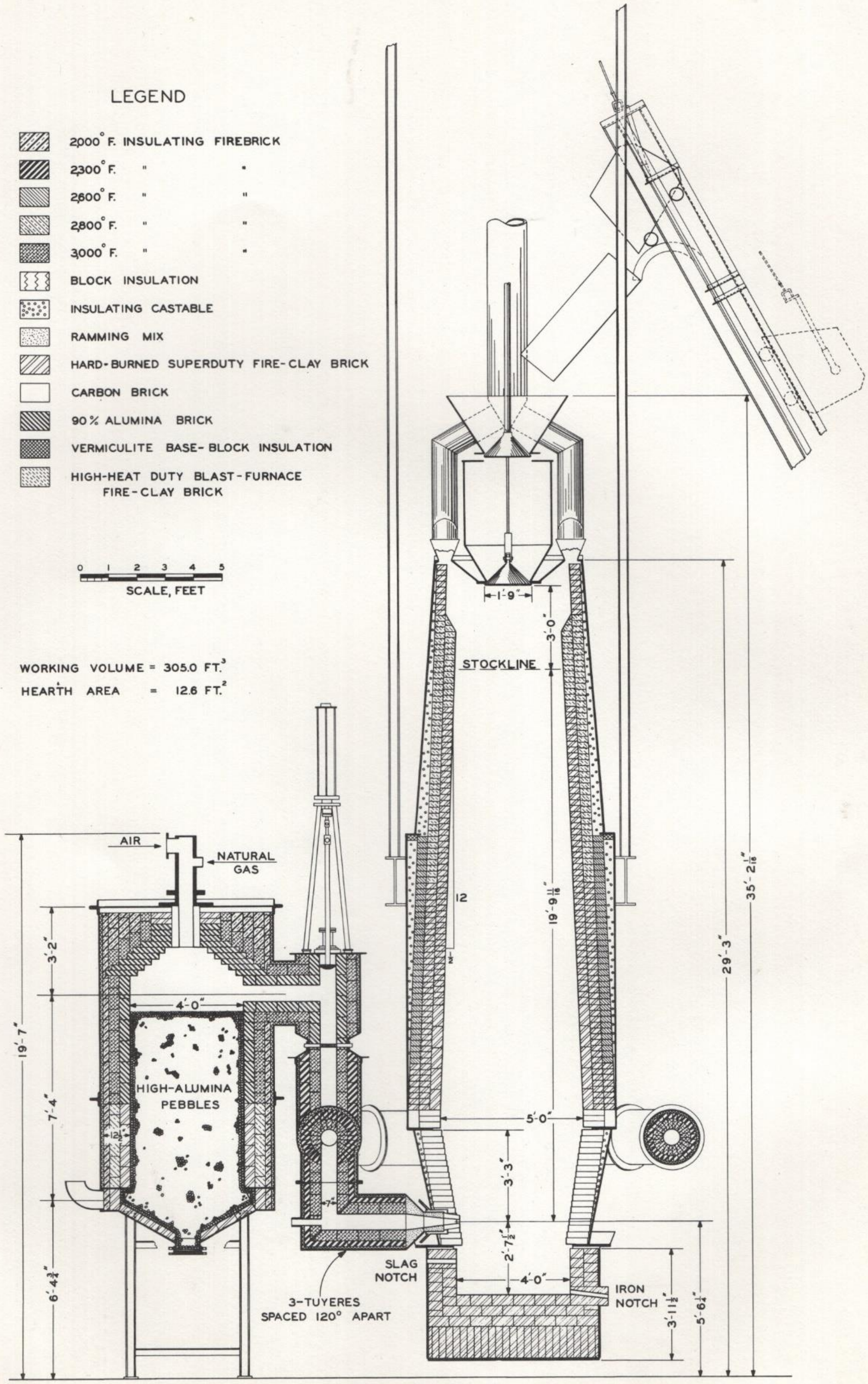


Figure 1

Cross-Section View of Experimental Blast Furnace

Figure 2 shows the construction of the entire oil-injection system. The oil was brought in by tank truck, and two tank-trailers with a total capacity of approximately 9000 gallons were permanently parked at the Bureau to be used as storage tanks. Because of the high viscosity of the oil at room temperatures, steam coils were installed in the tanks to heat the oil to about 120 F, so that it would be fluid enough to pump easily. The oil was pumped from the storage tank by a master pump, and circulated through a closed loop containing a heat exchanger to heat the oil to injection temperature. Connected to the loop were the supply lines for each of the three tuyères. Each of these lines fed a positive displacement pump that pumped the oil to the individual tuyère-injection tubes. The tuyère pump motors were equipped with speed controls so that the oil flow to each tuyère could be regulated. The pumps were also equipped with remote flow-rate-indicating tachometers located on a panel in the control room. The oil from the tuyère pumps passed through a positive displacement flow meter. To maintain preheat temperature, the lines from the pumps to the tuyères were steam-traced and insulated. The flow rate of shroud air to each tuyère was measured by a rotameter. The oil-injection tubes were equipped with quick-disconnect fittings to facilitate changing of the tubes. A shut-off valve was located before each injection tube so that the oil flow to any tuyère could be stopped whenever it was necessary to replace one of the injection tubes. A pressure-recorder sensing element was installed in the oil line just before the injection tubes, and pressure variations due to flow restrictions were recorded on the panel board in the control room. Pressure gauges, thermometers, strainers, and valves were installed where needed.

The initial installation was designed so that oil flow to the tuyères was automatically stopped whenever wind rate was reduced to permit closing the iron notch after casting. However, because of the extremely low oil flow rates required in the pilot plant, considerable difficulty was encountered with injection tube coking after such oil shut downs. The problem was eliminated by allowing oil to continue to flow during brief periods of reduced wind rate.

Cooling air flow through the annular space between tubes was required throughout the test to prevent coking at the high blast temperatures employed. The amount of low-pressure cooling air necessary was only about 1 per cent of the total wind rate. The higher oil flow rates employed in commercial practice may provide sufficient injector cooling to eliminate any need for cooling air.

When the furnace was operating smoothly, the oil injectors coked up infrequently. However, when the tuyères "fringed" (when slag would build up around the nose of the tuyère) because the furnace was cold, the tubes tended to coke. Occasionally, the tuyères would fringe because of the position of the tip of oil injector. To correct this, the furnace operators would slide the injector forward or backward as required. Changing an injector was a simple operation consisting of loosening a bushing on the faceplate and pulling the injector from the blowpipe. A new injector would then be connected to the oil supply line and reinserted into the blowpipe. Plugged injectors were cleaned by drilling out the coked materials. The injectors held up very well throughout the test, even under hot-blast temperatures as high as 2300 F. Some distortion occurred at the higher hot-blast temperatures; however, oil flow through

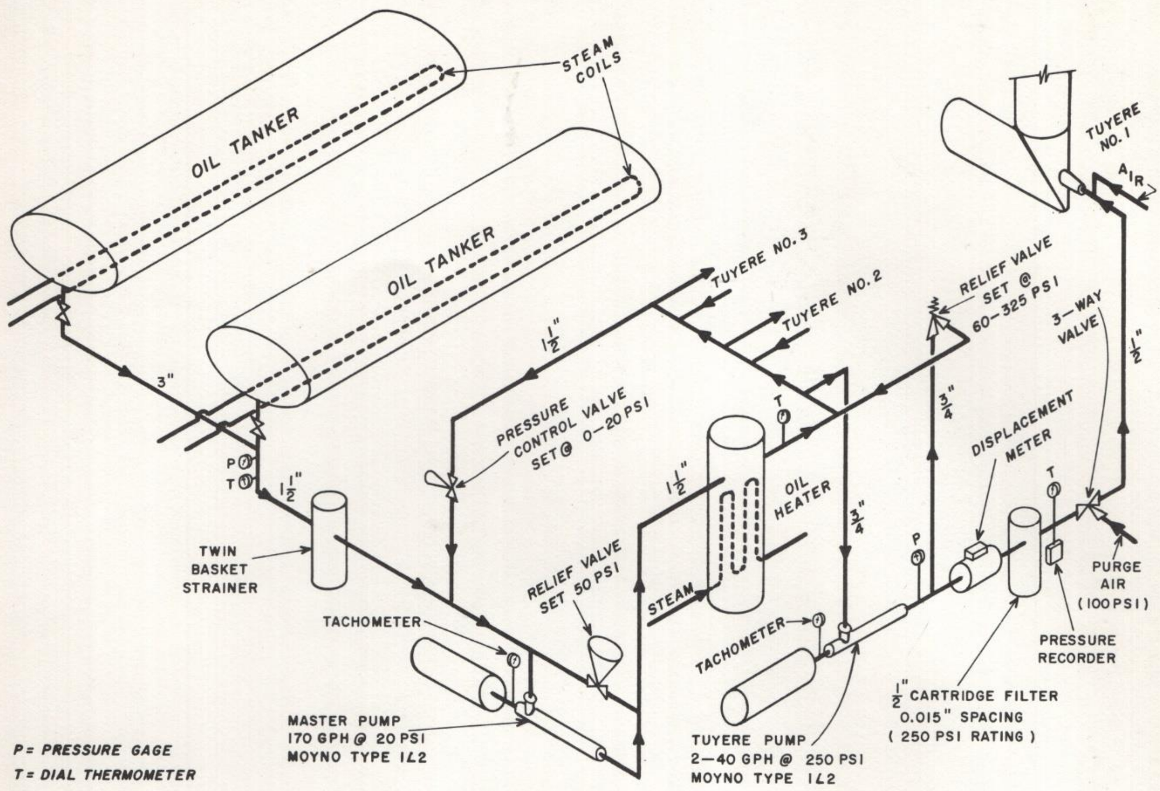
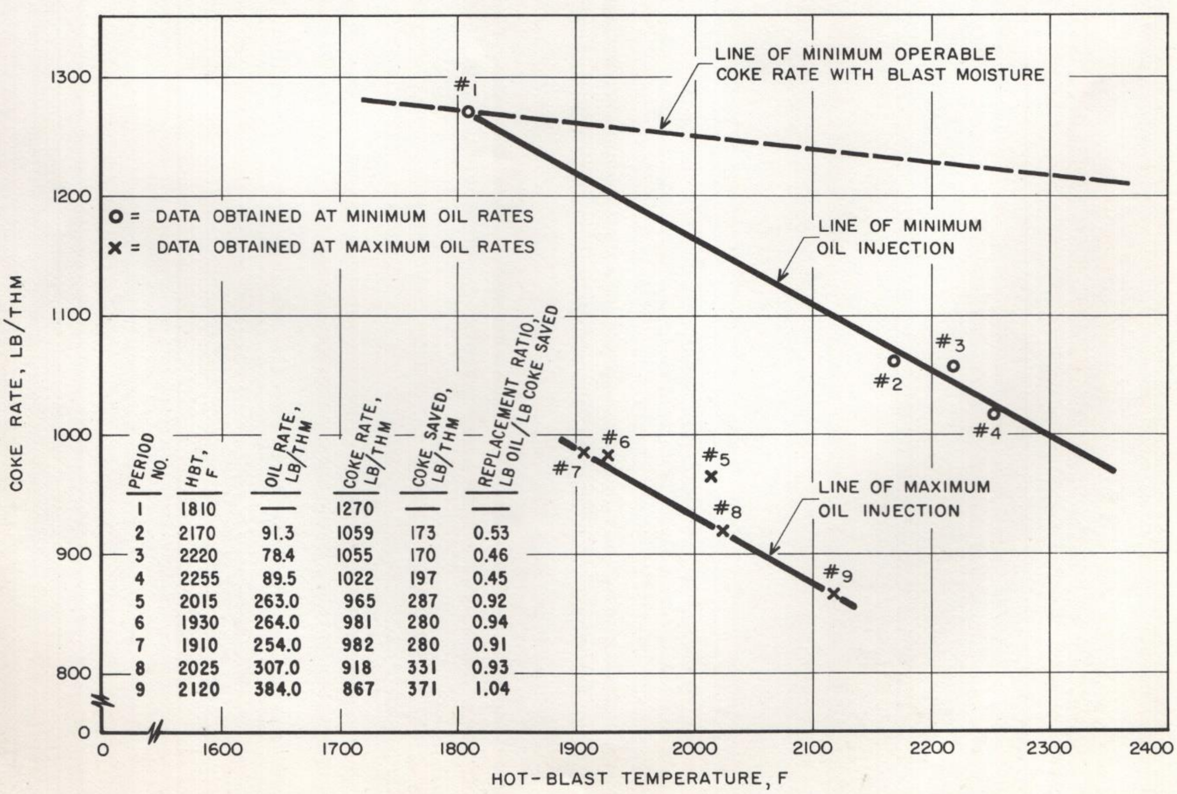


FIGURE NO. 2, SCHEMATIC DRAWING OF THE OIL-INJECTION SYSTEM AT THE BRUCETON XBF



PERIOD NO.	HBT, F	OIL RATE, LB/THM	COKE RATE, LB/THM	COKE SAVED, LB/THM	REPLACEMENT RATIO, LB OIL/LB COKE SAVED
1	1810	—	1270	—	—
2	2170	91.3	1059	173	0.53
3	2220	78.4	1055	170	0.46
4	2255	89.5	1022	197	0.45
5	2015	263.0	965	287	0.92
6	1930	264.0	981	280	0.94
7	1910	254.0	982	280	0.91
8	2025	307.0	918	331	0.93
9	2120	384.0	867	371	1.04

FIGURE NO. 3, COKE RATE VERSUS HOT-BLAST TEMPERATURE

the injector was never restricted because of a physical failure of the injectors. Aside from the above-mentioned minor problems, the oil-injection system performed satisfactorily throughout the test.

General Observations on Effect of Oil Addition

The appearance of the combustion zone, as observed through the tuyères, changed when oil was injected. The tuyères appeared cloudy and did not look as bright or as hot as normal.

The top gas from the furnace during operation with high oil rates contained traces of carbon black, most of which was removed by gas-washing facilities. Carbon black, if present in commercial practice, could present a waste water disposal problem. In this test, the effluent water was satisfactorily cleaned by use of a double-compartment settling basin. Subsequent reports from a commercial furnace indicate no signs of carbon black formation in normal operation with oil injection at low rates.

Raw Materials

The No. 6 fuel oil used in the test was supplied by Humble Oil and Refining Company and was typical in all respects of fuel widely available in the Eastern United States. Table I gives the chemical and physical properties of the oil.

The furnace was operated on a burden of 100 per cent self-fluxing sinter prepared from Mesabi ore. The sinter was screened at the experimental furnace to remove the minus 1/8-inch material. Coke sized at 2 inches by 3/4 inch was used. For control of slag basicity and volume, dolomite sized at 1-7/8 by 3/4 inches and gravel were used. Chemical analyses of these raw materials are given in Table II.

Operating Procedures

The entire program was run at a 1400-scfm wind rate with 7 grains of moisture per scf of blast air. The 1400-scfm wind rate was chosen because at this wind rate the average superficial velocity of the gases in the pilot furnace most closely approximates that in a 28-foot-diameter furnace blowing wind at rates up to 100,000 scfm. Seven grains of blast moisture were used to approximate the average atmospheric moisture of steel plants located in the northern district of the United States.

All of the process data periods were obtained while holding hot metal silicon content constant at a nominal value of 1.0 per cent. This requirement was established to eliminate product quality as a major factor affecting the variability of test results.

Another criterion for valid data was smooth stable equilibrium furnace operation. In the step approach employed in changing conditions, final adjustments were always made in coke rate and/or blast temperature to bring the furnace to stable conditions before data collection was begun.

After operability of the injection system had been established, the fuel-oil-injection program was divided into three parts, as follows:

1. Determination of the minimum amount of oil required to operate at the maximum hot-blast temperature available. The procedure for this part of the program was to set the oil rate and then to lower the coke rate and increase the hot-blast temperature until furnace operation became irregular. The oil rate was then increased, and again the coke rate was lowered and the hot-blast temperature raised until operation once more became irregular. (During these manipulations of oil and coke rates, the hot-blast temperature was varied to maintain 1 per cent silicon in the metal.) This procedure was repeated until the maximum available hot-blast-temperature level was reached. At that point, the minimum coke rate corresponding to the minimum oil-injection rate had been established. Two other minimum oil rate data points were obtained at approximately the same temperature level.

2. Determination of the maximum amount of coke that can be replaced with oil at a constant hot-blast-temperature level. The method here was to increase oil rate and decrease coke rate in such a way as to maintain 1 per cent silicon while holding blast temperature at the desired level. This procedure was followed until operation became erratic as characterized by frequent hanging and inability to maintain 1 per cent silicon.

3. Study of sulfur control. This program was designed to determine the effect on hot metal sulfur content of operation at combinations of two levels of slag volume, two levels of slag basicity, and two sulfur loadings. All of this study was done at a high oil-injection rate (260 lb/THM).

Operating Results

Table III presents a summary of the average operating data for each of the selected steady-state periods. Data are only included for those periods in which the furnace behaved normally and was producing consistently good quality hot metal. A base period with 7 grains moisture injection is included so that the operation with oil injection can be compared with the operation with moisture injection.

For evaluating the effect of oil injection, we have calculated an oil-to-coke replacement ratio. This replacement ratio is determined by dividing the amount of oil injected by the difference between the coke rate obtainable with moisture injection and that obtainable with fuel-oil injection at the same blast temperature. Based on previous experiments with the experimental furnace, it has been shown that the blast temperatures used in this furnace are 300 to 400 F higher than commercial furnace blast temperatures. Because of the higher blast temperatures and hence higher flame temperatures in the tuyère zone, the oil-to-coke replacement ratio that can be achieved in a commercial furnace may be somewhat different.

1. Determination of minimum oil rate. At coke rates below that of the base period, it was necessary to add oil to operate the furnace satisfactorily. For each oil rate, there was a minimum operable coke rate which coincided with a maximum operable hot-blast temperature. Figure 3 shows a plot of coke rate

versus hot-blast temperature. The line of minimum oil injection shows the effect on coke rate when the minimum amount of oil required to maintain good furnace operation is used. For comparison, the line of minimum operable coke rate with moisture injection is shown on the same graph. This line was established by using the base period obtained during the oil-injection test, and the slope of the line as determined by a previous moisture-injection test. During oil injection, an injection rate of about 90 lb per THM was required to utilize the maximum available hot-blast temperature (2255 F). At this hot-blast temperature the coke rate was reduced to 1022 lb per THM or 197 lb per THM less than that obtained by using blast moisture to utilize the same blast temperature. At hot-blast temperatures, between 2170 and 2260 F, with the minimum amount of oil required to maintain good furnace operations, the oil-to-coke replacement ratio ranged from 0.45 to 0.53 lb of oil per lb of coke with an average value of 0.48.

A lower coke rate was obtained by injecting oil than by injecting moisture because the oil contains carbon that can replace some of the coke carbon and because moisture addition actually consumes some of the coke carbon.

Figure 4, a plot of reducing gas volume at the tuyères, moles/THM versus hot-blast temperature for the minimum-oil-rate run, shows that as the hot-blast temperature increases, the total moles required decrease. This decrease was the result of the additional hot-blast temperature that could be used when oil was injected, and of the improved over-all fuel utilization.

Figure 5 is a plot of production rate versus oil-injection rate. Along the line of minimum oil injection, production rate increased from 33 lb hot metal per Mscf air to 39 lb per Mscf as the oil rate and blast temperature were increased. This production-rate increase was principally the result of a decrease in the total amount of carbon required per THM. Reduction in carbon requirement was a function of increased blast temperature and increase in hydrogen input.

2. Determination of maximum coke savings. The plot of coke rate versus hot-blast temperature at high oil injection rates in figure 3 shows that at a hot-blast temperature of approximately 2100 F, the coke rate was reduced to 867 lb by injecting 384 lb of oil per THM. The lower line in this plot is believed to represent the lowest operable coke rate possible with oil injection. We believe that this coke rate of 867 is the lowest coke rate ever attained on an operating blast furnace.

As the oil rate was increased from the minimum oil line at 2100 F to 384 lb per THM at the same temperature, the oil-to-coke replacement ratio increased from 0.5 to 1.0 lb of oil per lb of coke.

The major part of this increase in replacement ratio is due to the fact that when increasing oil above the minimum, we are no longer removing moisture and do not obtain credit for its removal. When proceeding from operation with moisture injection to operation with minimum oil, moisture can be removed and oil substituted for it. When proceeding from minimum oil rate to maximum oil rate at constant blast temperature, however, there is no more moisture that can be replaced (moisture level has been reduced to approximate ambient conditions),

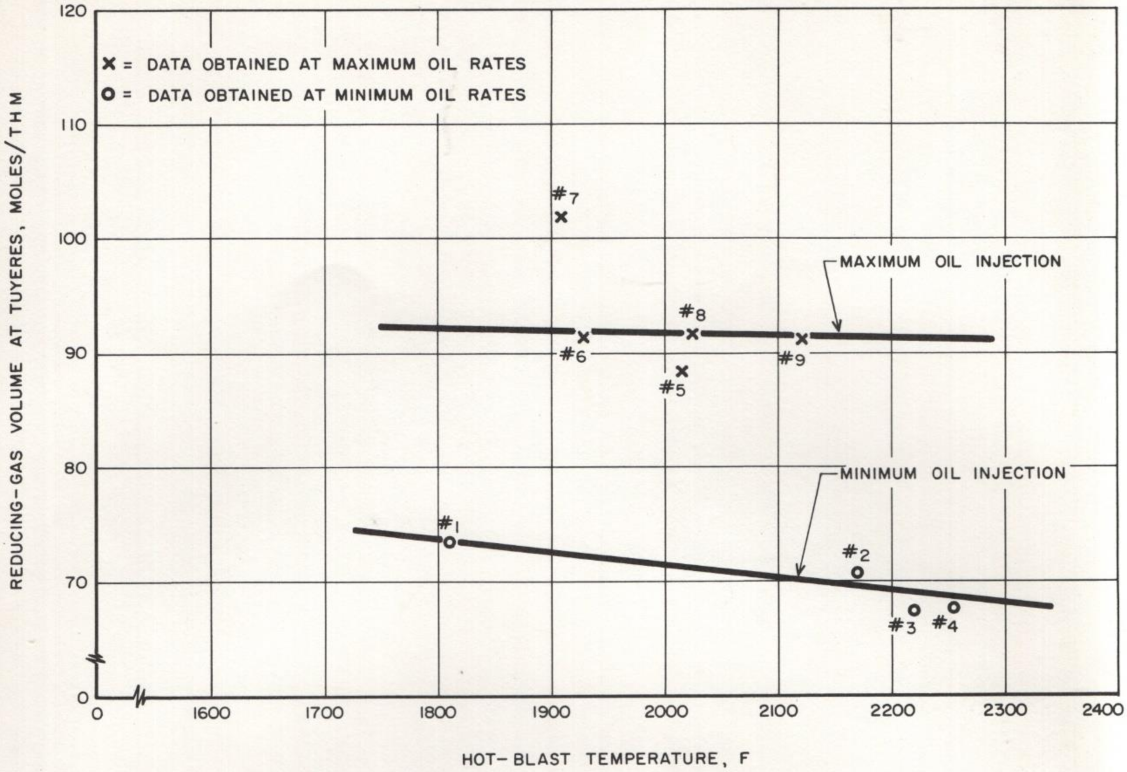


FIGURE NO. 4, REDUCING-GAS VOLUME AT TUYERES VERSUS HOT-BLAST TEMPERATURE

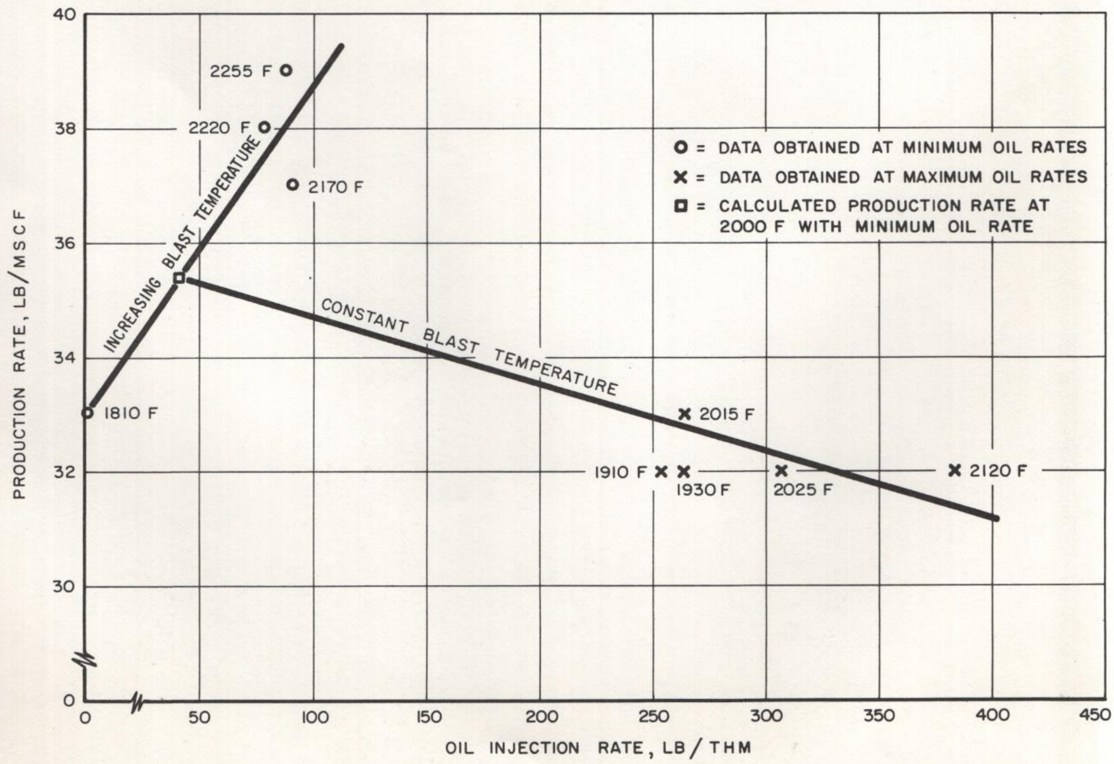


FIGURE NO. 5, PRODUCTION RATE VERSUS OIL INJECTION RATE and thus, the additional oil serves as a flame coolant and the raceway adiabatic flame temperature (RAFT) decreases. When this happens there is a decrease in furnace efficiency as defined by top-gas temperature, CO/CO_2 ratio, and production rate. This represents a heat deficiency, not present at minimum oil rate, which must be supplied by an increased total fuel rate and thus an increased (poorer) replacement ratio.

As Figure 5 indicates, at a constant hot-blast temperature, an increase in oil rate resulted in a decrease in production rate. This is the result of having to burn more carbon per ton of hot metal. As more carbon must be burned per ton of hot metal, the furnace is slowed down; the production rate therefore decreased because the wind rate was constant. Thus, at maximum oil rate conditions, the production rate was approximately 8 per cent lower than could be obtained by using a minimum amount of oil at the same hot-blast temperature. Production rate was about the same, however, as in the base coke operation at 7 gr/scf moisture.

3. Sulfur-control study. Because fuel oil normally contains 2 to 4 per cent sulfur, and blast-furnace coke contains only 0.6 to 1.2 per cent sulfur, sulfur control in the furnace was considered a potentially serious problem. However, the results show that during operation with the 2.5 per cent sulfur No. 6 fuel oil, there was no difficulty in controlling the sulfur content of the hot metal. Table IV shows that as the sulfur load to the furnace was increased from 6.3 lb per THM to 11.6 lb per THM, no increase in slag volume or basicity was required to handle the additional sulfur load. To study the effect of an even higher-sulfur-content oil, four additional tests were conducted with a 3.5 per cent sulfur oil. The results of these tests are also shown in Table IV. At approximately the same slag volumes (647 and 623 lb per THM) and the same basicity (approximately 1.44), the sulfur in the hot metal increased from 0.032 to 0.043 per cent when 3.5 per cent sulfur oil was used. The sulfur-partition ratio (per cent S in slag divided by per cent S in metal) remained constant at about 52. However, at the higher sulfur load it was possible to lower the sulfur in the metal to 0.033 per cent by increasing the slag volume from 623 lb per THM to 760 lb per THM at a 1.44 bases-to-silica ratio. The sulfur in the hot metal was further reduced by increasing the slag basicity from 1.44 to 1.57, where the sulfur-partition ratio increased to 83 and sulfur in the hot metal was reduced from 0.043 to 0.023 per cent.

These results indicate that at high sulfur inputs (14 lb S per THM), desulfurization can be controlled either by increasing the slag volume or by increasing the basicity. The apportionment of sulfur between the slag and the hot metal obtained in this test is similar to that obtained in full-size furnaces, where slag normally holds a maximum of 2 per cent sulfur, and where, for a slag of 1.5 basicity ratio, the normal partition ratio is between 75 and 85.

Therefore, if the sulfur input to the furnace were raised by using fuel-oil injection, and if the slag already contained about 2 per cent sulfur, it would be necessary to increase the slag volume to maintain the hot-metal sulfur content at acceptable levels.

It had been suggested that some of the sulfur from the fuel oil might leave the furnace in the top gas. However, careful analyses of top-gas composition throughout the test program showed no traces of sulfur compounds. In addition, sulfur material balances (see Table V for an example) showed reasonable closure throughout the test using only slag and hot metal as output sources.

Summary

These oil-injection tests demonstrated that oil can be injected into the combustion zone of a blast furnace safely and with a minimum of difficulty. When the furnace was operated with the minimum amount of oil (90 lb/THM) required to utilize the maximum hot-blast temperature, the coke rate was decreased 197 lb/THM. Under these conditions the production rate increased over the base period by approximately 19 per cent. For this type of operation, the oil-to-coke replacement ratio was approximately 0.5 lb oil per lb coke. With some sacrifice in production rate, even greater reductions in the coke rate were obtained by injecting increased quantities of oil. At an oil-injection rate of 384 lb/THM, the coke rate was reduced by more than 370 lb/THM. This type of operation results in a maximum coke savings, but the oil-to-coke replacement ratio increases to 1.0 lb oil per lb coke. Although this type of operation is not the most efficient, it may be economically attractive where the price of coke greatly exceeds the price of oil. In determining the value of oil injection as compared to injection of natural gas or other fuels, an economic study must be made with the local fuel costs and particular operating costs involved. Because of this, no general economic picture can be presented on the relative merits of these types of injection.

Table I

Properties of Bunker C Fuel Oil

Physical Properties	Low-Sulfur Fuel	High-Sulfur Fuel
Specific Gravity, 60 F	0.9779	0.9679
API Gravity, degrees	13.2	14.7
Viscosity, SSF/122 F*	167	117
SSU/210 F**	164	---
Pour Point, F	+ 25	---
Heat of Combustion, Btu/lb		
Gross	18,373	18,535
Net	17,529	17,646
Approximate Chemical Formula	$CH_{1.5}$	$CH_{1.5}$
Chemical Composition, % by weight		
Carbon	85.09	84.54
Hydrogen	11.01	11.28
Sulfur	2.52	3.53
Ash	0.08	0.05

* Saybolt seconds, furol
** Saybolt seconds, universal

Table II

Chemical Analysis of Raw Materials, Per Cent

	Fe	SiO_2	Al_2O_3	CaO	MgO	TiO_2	Mn	S	P	FeO	Fe_2O_3
Sinter	56.89	7.12	2.13	7.37	2.20	0.19	0.30	0.03	0.07	12.16	68.15
Coke Ash	8.1	46.0	30.7	5.5	2.2	1.6					
Dolomite	1.02	0.70	0.86	30.15	20.85						
Gravel	4.32	72.16	4.42	5.25	1.14						

	Volatile Matter	Ultimate Carbon	Ash	Sulfur	H_2
Coke	1.04	92.0	6.0	0.52	0.3

Table III

Furnace Operating Data

		Base Period	Minimum Oil-Rate Study			Maximum Oil-Rate Study				
		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9
1.	Dry Blast Air*, scfm	1314	1350	1356	1329	1367	1401	1413	1424	1392
2.	Blast Temperature**, F	1810	2170	2220	2255	2015	1930	1910	2025	2120
3.	Blast Moisture Content, gr/scf	7	7	7	7	7	7	7	7	11
4.	Production Rate, THM/day	31.5	35.7	37.5	37.2	32.1	31.9	32.5	32.7	31.4
5.	Production Rate, lb/Mscf	33	37	38	39	33	32	32	32	32
6.	Coke Rate, lb/THM	1270	1059	1055	1022	965	981	982	918	867
7.	Oil-Injection Rate, lb/THM	0	91.3	78.4	89.5	263	264	254	307	384
8.	Slag Volume, lb/THM	697	654	694	653	661	646	661	646	642
9.	Dust Rate, lb/THM	7.7	25.9	16.2	22.0	21.0	25.9	25.9	54.4	25.9
10.	Metal Analysis									
	Si, wt %	0.99	1.10	0.88	0.99	0.97	1.10	1.02	1.07	1.05
	S, wt %	0.020	0.020	0.020	0.024	0.020	0.032	0.038	0.039	0.053
11.	Top-Gas Analysis									
	CO, vol %	27.6	27.9	26.9	27.1	26.2	25.9	26.2	26.1	25.1
	CO_2, vol %	13.2	13.3	14.2	14.0	12.2	12.0	12.1	11.8	11.6
	H_2, vol %	1.4	2.9	2.6	2.9	5.0	5.1	5.0	5.9	6.7
	N_2, vol %	57.7	55.8	56.4	56.0	57.6	56.9	56.7	56.2	56.5
12.	Top-Gas Temperature, F	557	502	469	470	559	656	658	703	683
13.	Sulfur in Slag, wt %	0.86	1.12	1.09	1.04	1.64	1.60	1.92	1.62	1.95
14.	Slag Basicity, $\frac{\%\ CaO + \%\ MgO}{\%\ SiO_2}$	1.52	1.54	1.48	1.48	1.55	1.43	1.49	1.39	1.41
15.	Slag Basicity, $\frac{\%\ CaO + \%\ MgO}{\%\ SiO_2 + \%\ Al_2O_3}$	0.97	0.98	0.95	0.96	1.07	1.00	1.04	0.98	0.98
16.	Oil-to-Coke Replacement Ratio, lb oil/lb coke	0	0.53	0.46	0.45	0.92	0.94	0.91	0.93	1.04
17.	Reducing Gas Volume at Tuyères, moles/THM	73.6	70.9	67.5	67.4	88.1	91.2	102	91.7	91.0
18.	Raceway Adiabatic Flame Temperature, F	3770	3853	3908	3910	3523	3426	3426	3412	3319
19.	Hydrogen Utilization***, %	42	40	44	41	43	41	41	39	44

* Includes 13 scfm shroud air for periods 2 through 4, and 19 scfm for periods 5 through 9.

** Corrected for cooling effect of shroud air as follows:
- 15 F for periods 2 through 4
- 22 F to - 31 F for periods 5 through 9

*** Per cent of the hydrogen input (excluding the hydrogen in burden moisture) converted to H_2O in the furnace.

Table IV

Effect of Sulfur Load, Slag Volume, and Basicity on Sulfur-Partition Ratios

	Base Period (6.3 lb/THM Sulfur Load)	2.5% S Oil (11.6 lb/THM Sulfur Load)		3.5% S Oil (14.1 lb/THM Sulfur Load)			
Slag Volume, lb/THM	697	647	662	623	760	712	733
Basicity							
Bases/SiO_2	1.50	1.43	1.56	1.44	1.44	1.57	1.56
Bases/Acid	0.96	1.01	1.06	1.00	1.06	1.11	1.13
Si in Hot Metal, %	0.98	1.10	0.97	1.15	1.06	1.00	1.01
S in Hot Metal, %	0.020	0.032	0.020	0.043	0.033	0.023	0.025
S in Slag, %	0.86	1.70	1.70	2.12	1.75	1.91	1.85
Partition Ratio							
$\frac{\text{\% S in Slag}}{\text{\% S in Hot Metal}}$	43	53	85	52	53	83	74

Table V

Sulfur Balance for 72 Hours Operation with High-Sulfur Oil

Sulfur In:

982 lb coke/THM x .005 lb S/lb coke	=	4.91 lb/THM
245 lb oil/THM x .035 lb S/lb oil	=	8.94 lb/THM
Total Sulfur In		13.85 lb/THM

Sulfur Out:

2000 lb HM/THM x .00038 lb S/THM	=	0.76 lb/THM
661 lb slag/THM x .0193 lb S/lb Slag	=	12.76 lb/THM
Total Sulfur Out		13.52 lb/THM
Sulfur Unaccounted for		2.4%