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COAL INJECTION IN AN EXPERIMENTAL BLAST FURNACE A COMPREHENSIVE REPORT

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CONTENTS

	<u>Page</u>
Abstract.....	8
Introduction.....	8
Acknowledgment.....	10
Coals selected for injection.....	10
Facilities.....	10
Experimental blast furnace.....	10
Coal injection system.....	13
Raw materials.....	16
Presentation of data.....	18
Tests and results.....	20
Discussion.....	31
Comparison of coal with oil.....	43
Conclusions.....	45
Appendix A.--Operating data for blast furnace tests with Pittsburgh seam coal injection.....	47
Appendix B.--Operating data for blast furnace tests with Pittsburgh seam coal injection with oxygen enrichment and tests with high sulfur coals.....	48
Appendix C.--Operating data for blast furnace tests with Wyoming coal injection with and without oxygen enrichment.....	49
Appendix D.--Operating data for blast furnace tests with various coals.....	50
Epilogue.....	51
Commercial experience 1960 to present.....	51
References.....	57

ILLUSTRATIONS

	<u>Page</u>
1. Cross-section of experimental blast furnace and pebble stove.....	12
2. Facilities for preparation and sizing coal for injection in experimental blast furnace.....	14
3. Lock-hopper system for injecting coal into tuyeres of experimental blast furnace.....	15
4. Calibration curves for coal injection rate, before and after modification.....	17
5. Effect of Pittsburgh seam coal injection on coke rates in the experimental blast furnace.....	33
6. Effect of Wyoming subbituminous coal injection on coke rates in the experimental blast furnace.....	36

TABLES

1. Typical screen analyses of sinter and ore.....	19
2. Typical chemical composition of burden materials (wt pct dry).....	19
3. Proximate and ultimate analyses of coke and injected coals (wt pct dry).....	19
4. Effect of coal injection on coke and production rates (Pittsburgh seam coal).....	22
5. Effect of coal injection with simultaneous oxygen enrichment of the blast on coke and production rates.....	24
6. Effect of injection of high-sulfur content coals on coke and production rates.....	26
7. Effect of subbituminous coal injection on coke and production rates.....	28

Tables (Continued)

	<u>Page</u>
8. Effect of various coal injection practices on coke and production rates.....	30
9. Effect of coal injection rate on coal/coke replacement ratios.....	40
10. Comparison of Pittsburgh seam coal and residual fuel injection in the blast furnace.....	44

LIST OF MEASURE ABBREVIATIONS USED IN THIS REPORT

in	inch
Btu	British thermal units
Btu/mole	British thermal units per mole
cfm	cubic feet per minute
°F	degree Fahrenheit
gr/ft ³	grains per cubic foot
h	hour
lb	pound
lb/h	pound per hour
lb/nt	pounds per net ton
MBtu	Thousand British thermal units
mole/nt	moles per net ton
nt/day	net tons per day
psi	pounds per square inch
psig	pounds per square inch, gauge
pct	percent
scfm	standard cubic foot per minute
scf	standard cubic foot
scf/nt	standard cubic foot per net ton
vol pct	percent by volume
wt pct	percent by weight

COAL INJECTION IN AN EXPERIMENTAL BLAST FURNACE

A COMPREHENSIVE REPORT

by P. L. Woolf¹

***** ABSTRACT**

Blast furnace coal injection tests conducted by the Bureau of Mines in cooperation with a consortium of 22 steel companies in 1963-1964 are described. These tests were part of a program of extensive investigation of auxiliary fuel injection in the Bureau's experimental blast furnace located at Bruceton, PA.

Seventeen coal tests are described on various coals ranging from anthracite to subbituminous. Factors affecting maximum rates of injection were studied. These included coal size, coal type, and oxygen enrichment. The effect of high sulfur content coal and the means to control metal sulfur were investigated. An epilogue briefly describing the commercial experience with coal injection from 1960 to the present has been included.

***** INTRODUCTION**

The Bureau of Mines has been credited for its pioneering research in the field of auxiliary fuel injection in the blast furnace. In 1959, after the first successful test program with natural gas injection, the Bureau completed a feasibility study of coal injection. Anthracite fines were injected intermittently into an experimental blast furnace using a portable double-bell pneumatic cement gun. Ostrowski reported that furnace operation was satisfactory and up to 20 pct of the coke had

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been replaced by anthracite (1).². Further tests with continuous coal

²Underlined numbers in parentheses refers to the references following the Epilogue.

injection were planned for the future.

The following two or three years the Bureau conducted cooperative programs of fuel injection research with individual steel companies, and also a three-party cooperative program with an oil and a steel company. The tests with fluid fuels were limited in scope although each made its own contribution to the technology.

In 1963, the Bureau entered into a cooperative research program with a consortium of 22 North American steel companies. The first phase of the multi-year program was devoted to a comprehensive study of fuel injection. Wide ranges of injection rates of gas, oil, and coal were studied, as well as the combination of fuels with oxygen enrichment. This report deals with the coal injection tests conducted in the program.

Unlike natural gas and residual fuel oil, coals can be very different, and the differences will significantly affect blast furnace performance.

The initial phase of the program for coal was to develop a suitable coal injection system. Then a program was adopted to study the effect of (a) coal rates, (b) simultaneous oxygen enrichment, (c) coal rank, (d) size, and (e) injection of high sulfur content coals. The means to control metal sulfur content also was investigated.

*** ACKNOWLEDGMENT

Many individuals from the cooperating steel companies served as committee members and observers and contributed to the success of the program. Personnel of the Morgantown Coal Research Center made the major contribution to the design, engineering, calibration, and modification of the coal injection system. The efforts of all the above are gratefully acknowledged.

*** COALS SELECTED FOR INJECTION

1. Pittsburgh seam, high volatile bituminous coal, 1.5 pct sulfur.
2. Pittsburgh seam, high volatile bituminous coal, 2.5 pct sulfur.
3. Illinois No. 6, high volatile bituminous coal, 3.4 pct sulfur.
4. Wyoming, high volatile subbituminous coal, 0.9 pct sulfur.
5. West Virginia, low volatile bituminous coal, 0.6 pct sulfur.
6. Anthracite, 0.9 pct sulfur.

*** FACILITIES

EXPERIMENTAL BLAST FURNACE

The experimental blast furnace conformed to the general lines of commercial size furnaces but was not an exactly scaled down model. Its height to hearth diameter ratio was about double that of modern large furnaces. The hearth dimensions were the minimum required to provide good blast furnace data. Shaft dimensions were designed so that the retention time for the solid stock or the gas velocities could be similar to industrial furnace experience by selection of appropriate wind rates. It was not possible to obtain similarity for both factors at the same time. To obtain a reasonable stockline diameter for the required height and hearth diameter, it was necessary to construct the furnace with smaller bosh angle and less inwall batter than the corresponding lines of a modern blast furnace.

The entire bosh of the furnace was lined with carbon brick to minimize sticking of the charge materials since carbon is neither wetted nor fluxed by the oxides of the burden. The hearth was lined with hard-burned super-duty firebrick. For ease of cleaning at the termination of a campaign, the hearth was detachable and was suspended above the floor by rods attached to the furnace shell. There were three water-cooled copper tuyeres spaced at 120° intervals around the lower bosh.

The shaft of the furnace was lined with hard-burned super-duty brick to within a foot or so of the stockline. Although the furnace was designed to minimize heat loss through the use of high quality insulation materials, its heat loss, per unit of production, was considerably higher than that of commercial furnaces. This required higher blast temperatures for the experimental furnace if fuel rates were to be comparable to standard blast furnace practice with similar burden materials. The higher blast temperature would offset the higher heat losses.

Two Royster pebble stoves were used to heat the blast air (2, 3). Conventional blast furnace stoves were not adequate to provide the blast temperatures frequently used in the experimental furnace. Figure 1 shows the cross-section of the furnace with one of the pebble stoves.

The furnace top consisted of a rotating small bell and hopper receiving the charge from the skip car, and a large bell and hopper. The top gas was cleaned by an orifice plate scrubber and then burned to CO_2 and H_2O through a flare stack.

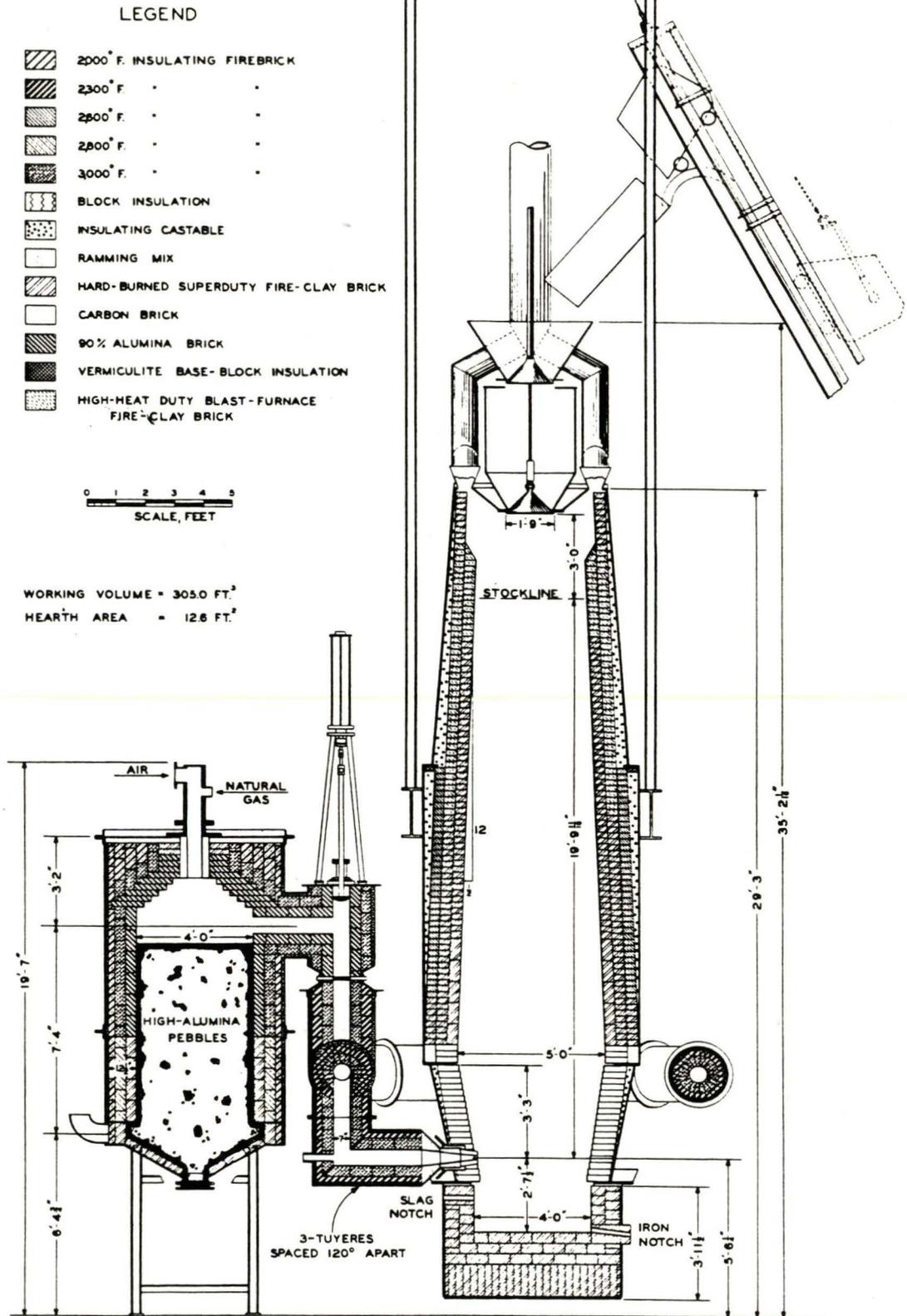


FIGURE 1. - Cross-section of experimental blast furnace and pebble stove.

COAL INJECTION SYSTEM

The coal system was in two parts, the first was the coal preparation system, and the second the injection system. Figure 2 shows the coal preparation system. Coal was brought in by truck. Most of the coals were 2 in x 1 1/4 in as received. The coal was fed by conveyor into a 15-ton receiving hopper. This hopper was equipped with a steam heated air dryer which reduced the surface moisture of the coal to below 3 pct. The dried coal was discharged by a vibratory feeder into a hammer mill and the crushed coal conveyed to a shaker screen and into the crushed coal storage bin. From the bin, the coal was transported pneumatically to a lock hopper system. Each receiving hopper was topped by a cyclone. A 3-way hopper selector was used to direct the coal to the appropriate hopper.

As may be seen in figure 3, which shows the injection system, there was a lock hopper pair for each tuyere. The upper hopper was designated the batch hopper and the lower one, the feed hopper. The hopper pair was pressurized except when the pressure in the batch hopper was released to receive coal. After coal was received, the hopper was closed and the pressure equalized with the feed hopper. Coal was dropped into the feed hopper by opening a 4 in ball valve.

Coal was fed into a carrier air stream by a rotary valve with a hydraulic drive. Different size rotors were available to cover a wide range of coal rates. Calibration curves were made of the RPM of the hydraulic drive versus rotor speed and the rotary feeder speed against the coal feed rate. Coal dropped out of the pocket at the bottom of the rotation of the feeder and was picked up at a tee by carrier air and conveyed to the tuyere. Each hopper pair was mounted with a load cell

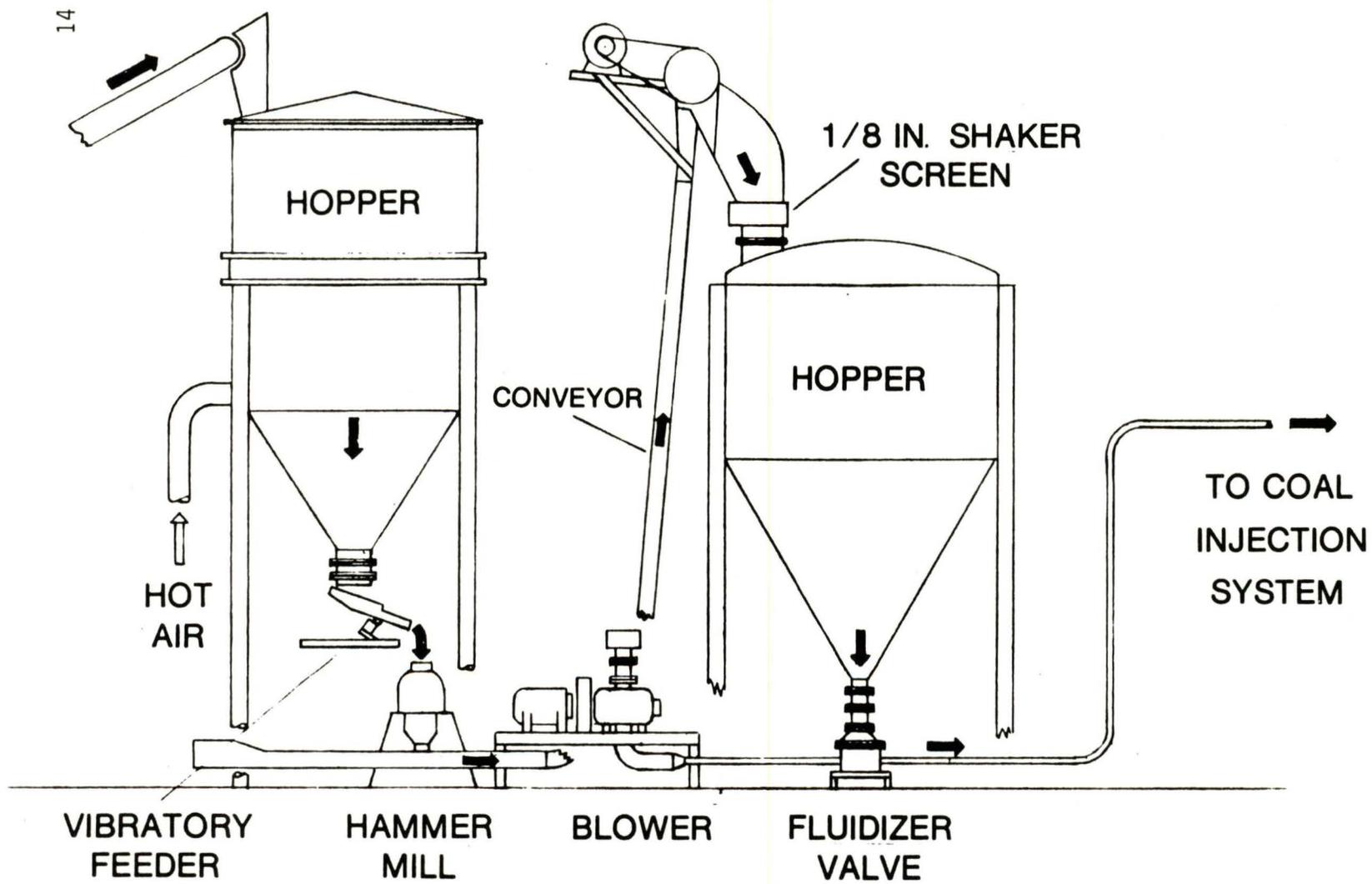


FIGURE 2. - Facilities for preparation and sizing coal for injection in experimental blast furnace.

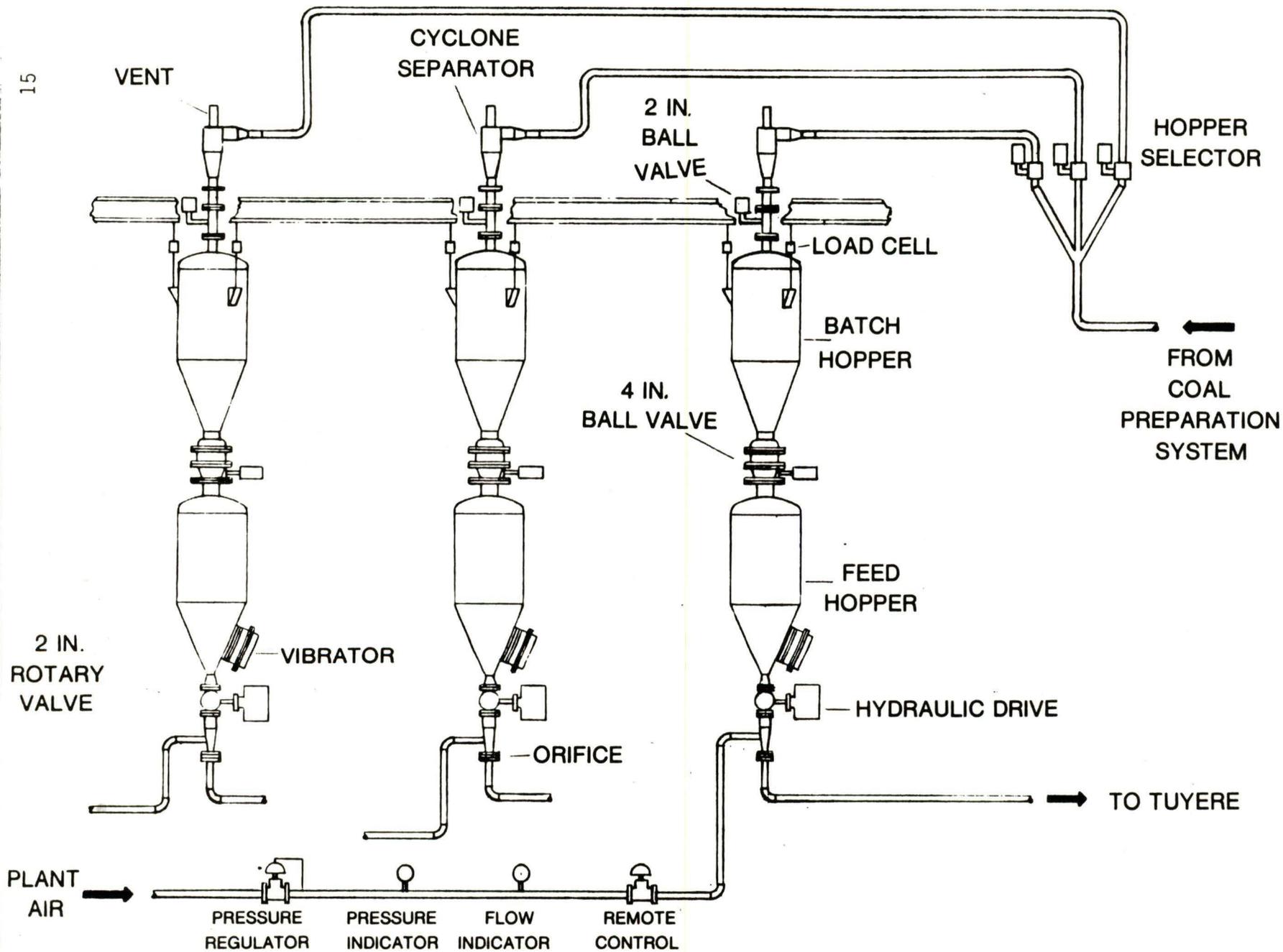


FIGURE 3. - Lock-hopper system for injecting coal into tuyeres of experimental blast furnace.

and thus, a periodic weight could be compared with the feed rate for a given time.

Coal tests were instituted in mid-March. The system worked quite well and a good test period was obtained. However, the coal feed rate was variable because of coal hanging up in the rotor pockets. To overcome the problem, the carrier air was brought up to the rotary valve just below the pockets. In addition, the pressure in the hopper was maintained about 1 psi above the carrier air pressure. This swept the pockets clean and provided uniform coal rates. The mixing tee was replaced by a large radius elbow. Figure 4 shows calibration curves before and after the modifications were made. The curve after the change was linear with no point off the line by more than 1 lb/h, whereas before the changes the confidence level was ± 5 lb/h.

The first test was conducted with straight stainless lances 1/2 in diameter inserted along the length of the blowpipes. The lances were changed for subsequent tests to 1/2 in diameter lances inside a 3/4 in pipe with cooling air in the annular space. This air was designated as shroud air. Later tests with the subbituminous coal and boiler-grind coals were conducted with water-cooled lances inserted through the side of the blowpipes about 18 in from the tuyeres.

*** RAW MATERIALS

The burden material for most of the coal tests was 70 pct sinter, with a bases to acids ratio of 1.20, and 30 pct Lake ore. Some of the later tests were conducted with a 100 pct pellet burden.

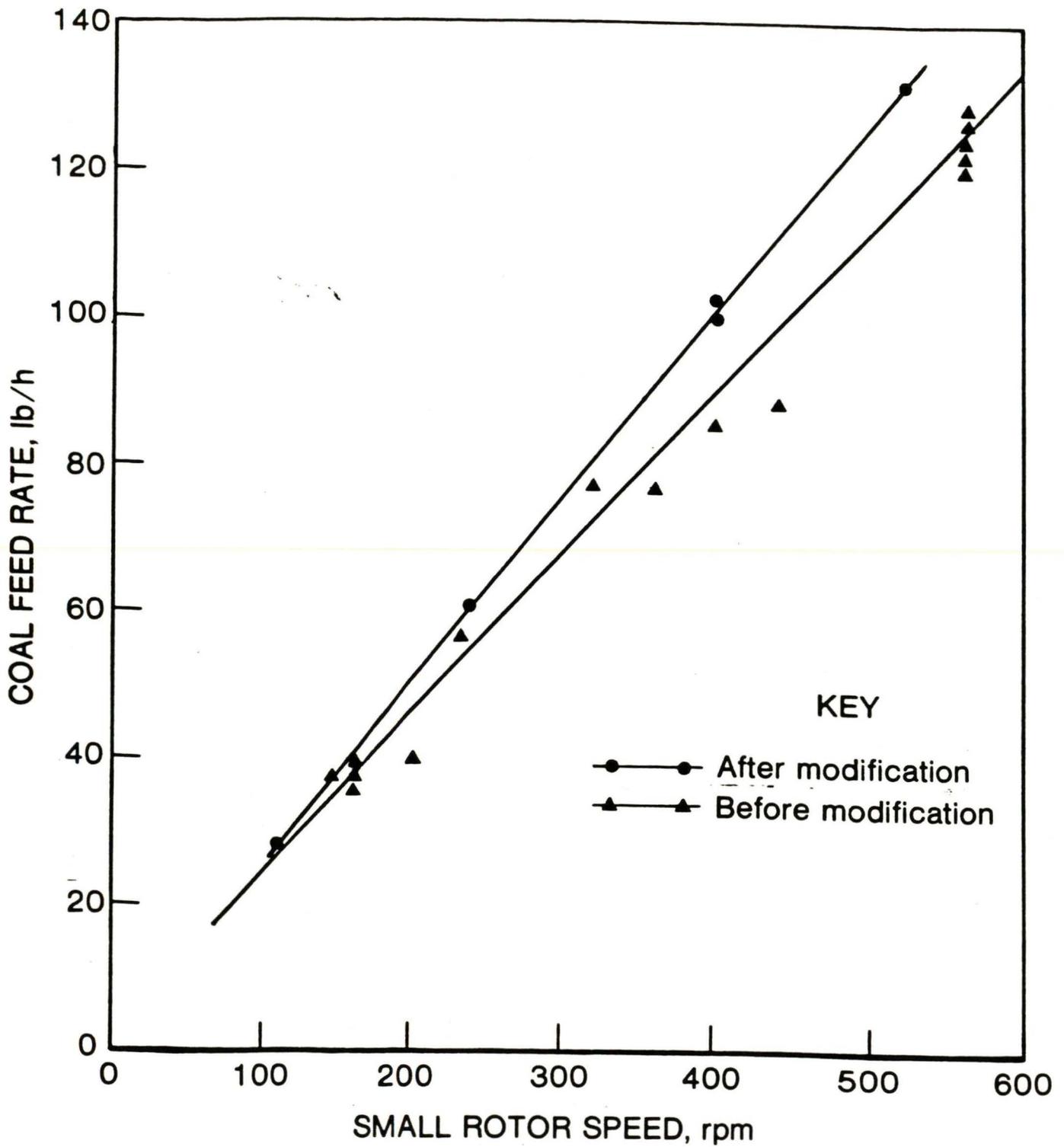


FIGURE 4. - Calibration curves for coal injection rate, before and after modification.

Sinter and ore were shipped at plus 3/8 in, coke was 1 1/2 in x 3/4 in and the fluxing stones were 1 7/8 in x 3/4 in. Sinter and ore were screened at minus 2 1/2 plus 1/8 in and the coke at plus 1/2 in prior to charging. The fluxes were charged as received. Coke dryers were used to maintain coke moisture below 1 pct.

Typical size analyses of the sinter and ore, as charged, are shown in table 1.

Chemical compositions of the burden materials are shown in table 2. The coke ash analysis is included in this table. For the sinter and ore the compositions must be considered typical rather than as representative of the test materials. They reflect the material as shipped in initially. However, over a period of several weeks of weathering, material handling and additional shipments of ore, the tabulated values cannot be considered to be truly representative. Composite samples were collected during test periods and the Fe and SiO₂ contents of the iron bearing burden are presented with the operating data.

Analyses for coke and the various coals utilized are given in table 3.

*** PRESENTATION OF DATA

Complete operating data for all coal injection tests are tabulated in the appendices. Appendix A lists the data for the Pittsburgh coal injection tests without oxygen enrichment and it includes an appropriate base period. Appendix B tabulates the data for the Pittsburgh coal tests with oxygen enrichment of the blast, as well as tests with high sulfur content coals. Appendix C shows the operating data for the tests with Wyoming subbituminous coal injection with and without oxygen enrichment and a base period which was conducted close to time of the

TABLE 1. - Typical screen analyses of sinter and ore

Screen size	Sinter		Ore	
	Retained on, pct	Cumulative, pct	Retained on, pct	Cumulative, pct
1 1/2 in	0.8	0.8	24.9	24.9
1 in	9.2	10.0	56.8	81.7
1/2 in	13.2	23.2	5.0	86.7
3 mesh	26.4	49.6	1.7	88.4
10 mesh	45.2	94.8	0.8	89.2
65 mesh	2.8	97.6	1.7	90.9
minus 65 mesh	2.4	100.0	9.1	100.0

TABLE 2. - Typical chemical composition of burden materials (wt pct dry)

Material	Fe	SiO ₂	Al ₂ O ₃	CaO	MgO	Mn	P
Sinter	56.00	7.67	2.28	9.87	2.20	0.51	0.12
Ore	61.00	5.90	0.89	0.34	0.13	1.04	0.07
Pellets	65.02	5.45	.47	0.53	0.54	0.15	0.01
Dolomite	0.40	0.64	.45	30.23	21.29		
Limestone	0.10	0.40	.40	55.01	0.31		
Gravel	3.17	71.00	5.47	7.12	2.22		
Coke ash	11.37	47.32	26.98	3.56	1.29		

TABLE 3. - Proximate and ultimate analyses of coke and injected coals (wt pct dry)

	Vol.								
	Matter	Fixed C	Ash	H ₂	C	N ₂	O ₂	S	Btu/lb
Coke	1.6	88.1	10.3	0.2	87.4	0.8	0.6	0.7	12,749
Pittsburgh seam	38.1	54.9	7.0	5.2	78.4	1.6	6.3	1.5	14,014
Pittsburgh Hi S	39.2	53.8	7.0	5.3	78.4	1.5	5.3	2.5	14,140
Illinois Hi S	48.8	44.5	6.7	5.4	74.9	1.4	8.2	3.4	13,640
Wyoming	44.2	53.8	2.0	5.3	75.1	1.3	15.4	0.9	13,060
West Virginia low vol	17.7	78.1	4.2	4.2	87.5	1.3	2.2	0.6	NA
Anthracite*	4.4	84.6	11.0	0.6	84.2	0.8	2.5	0.9	12,600
Pittsburgh B.G.**	38.1	55.3	6.6	5.2	78.7	1.6	6.4	1.5	14,073

*Analysis not run on particular coal used, but obtained from data supplied by the Anthracite Research Center, Bureau of Mines, Schuylkill Haven, PA.

**B.G. = Boiler-grind.

Wyoming coal tests. Finally, Appendix D shows data from tests with the pellet burden and Pittsburgh seam coal, minus 1/16 in and boiler-grind, and a test with low volatile coals, as well as the base for the pellet burden. The tests in Appendix D were all conducted at 1300 - 1400 cfm wind rates whereas all other tests were with wind rates between 700 and 800 cfm.

Production rates are presented as obtained and also expressed as nt/day/1000 cfm wind so that comparisons may be made between tests with different wind rates. The blast temperature has been corrected for the cold air used as carrier and shroud air and represents the equivalent blast temperature of the total wind. It was 2200 °F for all tests except for tests Nos. 14 and 17. As stated earlier the Fe and SiO₂ contents of the sinter and ore used in a test period are given. The values are for the combined burden of sinter and ore. The tests are numbered according to increasing coal rates within a series and not necessarily in the order they were conducted.

As the test results are presented, summary data of the more important parameters such as coke, coal, and production rates and blast conditions will be tabulated.

*** TESTS AND RESULTS

The first series of tests was conducted with Pittsburgh seam high volatile bituminous coal. It had been intended to operate with a wind rate of 800 cfm, however, an error in the air flow meter/controller resulted in the first two or three tests being conducted with about 10 pct less wind than planned. The objective was to determine the effect of coal injection on coke and production rates and to obtain the maximum coal rate at the given operating conditions. The straight lances were used with these tests.

Furnace operation was quite good with coal injection until the coal rate reached about 300 lb/nt. Attempts to operate in excess of this figure resulted in a rapid increase in tuyere pressure and erratic burden movement. Decreasing the coal rate restored the smooth furnace operation. Apparently as the coal rate increased above 300 lb/nt, unburned coal was being blown into the interstices of the burden causing the increased tuyere pressure and the tendency toward a hanging furnace.

There was an earlier indication of a combustion problem. When the coal rate exceeded about 200 lb/nt, a black streak appeared in the top gas flare. This phenomenon had also been experienced with residual fuel oil injection as injection rates approached 250 lb/nt. Since it is likely that particulate coal would have been filtered out by the burden (there was no evidence of channeling) it was believed that the carbon reaching the top gas originated in the volatile matter of the coal. The tests conditions may not have been conducive to complete combustion; firstly, the coal at minus 1/8 in may have been too large and secondly, the coal was carried in a dilute phase by carrier air and entered the furnace in a pocket of cool air.

The results of the tests with the Pittsburgh seam coal, without oxygen enrichment are summarized in table 4. The tests were conducted with 2200 °F blast temperature and wind rates were between 700 and 800 cfm. Test No. 1 was conducted before the coal program was scheduled and was the one with the variable coal feed rates.

The tests indicated that at the blast conditions used, the maximum coal rate was about 300 lb/nt.

TABLE 4. - Effect of coal injection on coke and production rates
(Pittsburgh seam coal)

Test No.	Base	1	2	3	4
Production rate:					
nt/day.....	17.0	19.3	19.0	17.6	17.7
nt/day/1000 scfm wind.....	24.2	24.0	25.2	24.4	24.3
Coke rate.....lb/nt.....	1268	982	986	901	876
Coal rate, dry.....lb/nt.....	-	184	206	288	319
Blast moisture.....gr/ft ³	16.1	5.6	6.5	6.7	6.0
Coal/coke replacement ratio...	-	0.64	0.73	0.78	0.81
Wind rate.....scfm.....	702	803	755	722	729

In a second series of tests with the Pittsburgh seam coal, the blast air was enriched with oxygen. The oxygen content of the dry blast air was 25 pct. It was expected that combustion of the coal might be improved and that more coal could be injected. However, once again increased tuyere pressure and erratic burden movement occurred at coal rates just above 300 lb/nt. During the test period with 288 lb coal/nt the flare was cleaner than without oxygen, but a thin black streak was still present. The use of oxygen did not permit an increase in the coal utilization rate. The results of two periods with oxygen enrichment are shown in table 5. Two period test Nos. 1 and 3 without oxygen are repeated in this table for comparison as they were at similar coal rates to periods 5 and 6.

The only benefit derived from the use of oxygen was the increased productivity. Periods 5 and 1, and 6 and 3 provide the opportunity to obtain the effect of oxygen on coke rate. In each case, the use of oxygen resulted in about 30 lb higher coke rates than for the same coal injection rate without the oxygen.

The third study was concerned with the utilization of coals containing high sulfur contents. Two tests were conducted with Pittsburgh seam coal containing 2.5 pct S. The tests were at the same coal injection rate. For the first test, slag basicity was increased to control the sulfur content of the hot metal. In the second test, gravel was added to the burden to increase the slag volume. The slag basicity was brought back to the base level. Thus a comparison was made of the two types of practice to control metal sulfur content. The results are displayed in table 6. Test No. 3 is also included as it was at the same coal rate but with the low sulfur coal and provides the opportunity

TABLE 5. - Effect of coal injection with simultaneous oxygen enrichment of the blast on coke and production rates

Test No.	5	6	1	3
Production rate:				
nt/day.....	22.4	21.0	19.3	17.6
nt/day/1000 scfm wind.....	31.6	29.5	24.0	24.4
Coke rate.....lb/nt.....	1,010	935	982	901
Coal rate, dry.....lb/nt.....	188	286	184	288
Oxygen, pct dry blast.....	25.1	25.0	21	21
Blast moisture.....gr/ft ³	7.2	6.5	5.6	6.7
Coal/coke replacement ratio...	0.73	0.86	0.64	0.78
Wind rate.....scfm.....	708	713	803	722

for quantifying the effect of increased sulfur coal on the furnace and the means of controlling the metal sulfur. A test period with Illinois high sulfur coal is also listed in table 6. It had been intended to run a short series with Illinois coal, however, a fire developed in the crushed coal storage hopper and the Illinois coal stock was destroyed with only one test completed. Fortunately, the test which was conducted was at the same rate of injection as the Pittsburgh high sulfur coal and can provide comparative information.

When slag basicity was increased to control metal sulfur content by increasing the fluxing stone, there was a coke rate increase of 50 lb and productivity was about the same as with the lower sulfur coal on the furnace. However, when both gravel and stone were added to increase the slag volume, the coke rate penalty was 100 lb/nt with a productivity loss of 5 pct. In changing from the Pittsburgh 1.5 pct S coal to the Pittsburgh 2.5 pct S coal the sulfur load on the furnace increased from 10.6 lb to 13.7 lb per ton of hot metal. The Illinois coal contained 3.4 pct S and the sulfur load was up to 17 lb/nt metal. Increasing the slag volume to 1,099 lb was not sufficient to bring metal sulfur under control. Over 95 pct of the casts were above 0.045 pct S, and even when metal silicon content was in the range of 1.1 to 1.2 pct, the metal sulfurs were running about 0.06 pct. The coke rate was 150 lb/nt above that for the Pittsburgh low sulfur coal.

The next phase of the program was devoted to Wyoming subbituminous coal injection. A new base period was established as the earlier base and Pittsburgh seam coal tests had been conducted at a lower wind rate than intended plus it was normal practice to repeat base tests periodically as furnace checks. Other changes made were to replace the

TABLE 6. - Effect of injection of high-sulfur content coals on coke and production rates

Test No.	7	8	9	3
Production rate:				
nt/day.....	19.4	18.0	18.1	17.6
nt/day/1000 scfm wind.....	24.6	23.1	22.9	24.4
Coke rate.....lb/nt...	951	1,000	1,043	901
Coal rate, dry.....lb/nt...	282	283	286	288
Type of coal.....	Pgh. Hi S	Pgh Hi S	Ill. Hi S	Pgh. Lo S
Blast moisture.....gr/ft ³ ..	5.4	7.0	5.0	6.0
Coal/coke replacement ratio.....	0.90	1.08	1.27	0.81
Wind rate.....scfm....	789	778	792	729
Slag volume.....lb/nt...	721	963	1,099	733
Slag basicity bases/acids.....	1.17	1.12	1.10	1.11
Slag sulfur content.....pct....	1.85	1.50	1.61	1.46
Metal sulfur content.....pct....	.042	.037	0.084	0.044

1/8 in shaker screen with a 1/16 in screen and to use water-cooled lances inserted through the side of the blow pipe. The results of the tests with the Wyoming coal are presented in table 7.

After an initial reduction of 112 lb of coke with the first 149 lb of coal, there was very little additional benefit for increased coal rates. Doubling the rate of coal injection saved only a further 48 lb of coke. The poor replacement was caused by the high inherent moisture content of the coal. The 149 lb of dry coal was combined with 40 lb of water. The endothermic reaction of the water with coke, as well as the heat of vaporization of the water caused a lowering of the combustion zone temperature. It appeared that a lower limit of high-temperature heat, or flame temperature may have been reached. If this were so, then the addition of oxygen could be expected to be effective by restoring the high temperature heat requirement. Test No. 13 does indeed confirm this. Raising the oxygen content of the blast to 24.7 pct permitted a further 92 lb of coal, beyond the initial 149 lb, with a saving of 69 lb of coke. Naturally, productivity was greatly increased with oxygen.

The remainder of the tests were conducted with a 100 pct pellet burden at higher wind rates than the work with the sinter/ore burden. Following an initial base period a test was run with Pittsburgh seam coal at 255 lb/nt. The operation was quite good, but metal sulfur was above specification. The pellets contained 65 pct Fe and 5.45 pct SiO₂ resulting in a slag volume below 500 lb. With limited time available it was decided to not spend the time establishing the specification practice but rather to investigate higher coal rates. Boiler-grind Pittsburgh seam coal was substituted for the minus 1/16 in coal and the rate increased to 300 lb/nt. The top gas flare became very dirty and

TABLE 7. - Effect of subbituminous coal injection on coke and production rates

Test No.	Base	10	11	12	13
Production rate:					
nt/day.....	20.42	19.0	18.5	17.9	23.2
nt/day/1000 scfm wind.....	26.0	24.3	23.5	22.7	29.6
Coke rate.....lb/nt...	1,231	1,119	1,114	1,071	1,050
Coal rate, dry.....lb/nt...	-	149	203	294	241
Oxygen, pct dry blast.....	21	21	21	21	24.7
Blast moisture.....gr/ft ³ ..	17.5	8.5	6.7	4.4	6.5
Coal/coke replacement ratio..	-	1.33	1.74	1.84	1.33
Wind rate.....scfm....	784	783	788	790	783

there was an excessive load on the gas washer system. The high volatile coal was taken off, and a low volatile West Virginia coal, also boiler-grind, was substituted. The change did not clean up the flare as had been expected. The coal rate was cut back to 260 lb/nt and the operation was stable. Another change was made in the coal to anthracite at minus 200 mesh. This resulted in the first clean flare stack at coal rates in excess of 250 lb/nt. Unfortunately, trouble was encountered with the injection system and less than a day of operation was completed. The data from the two short tests with the low volatile coal and anthracite were combined into a single test period, No. 15 in table 8. This was considered necessary because of large differences in the materials balance. One period was getting credit for production which probably resulted during the other.

After a short period during which the furnace was stabilized by injection of a combination of natural gas and oxygen, coal injection was resumed and gas injection was discontinued. The gas and oxygen were necessary as the furnace had been burdened for 260 lb coal when the problem developed with the injection system. Injection of boiler-grind Pittsburgh seam coal was resumed at 300 lb/nt and a test period obtained. Once again metal sulfurs were high. The last flurry with coal was to keep increasing the injection rate, and adjusting blast temperature and moisture to achieve a coal rate of 500 lb/nt. This was accomplished without furnace hanging, in fact the operation was good and despite the high sulfur load and low slag volume, the average sulfur content of the metal was only 0.041 pct versus the 0.069 pct with 300 lb coal per nt. However, the blast temperature had to be increased to over 2500 °F. The coke rate was only 684 lb/nt. Apparently to operate above 300 lb/nt coal injection pulverization of the coal to minus 200 or possibly minus 325 mesh is necessary.

TABLE 8. - Effect of various coal injection practices on coke and production rates

Test No.	Base	14	15	16	17
Production rate:					
nt/day.....	39.9	41.1	42.0	40.2	37.7
nt/day/1000 scfm wind.....	28.8	29.8	31.8	29.3	27.8
Coke rate.....lb/nt...	1,161	859	860	852	684
Coal rate, dry.....lb/nt...	-	255	261	295	503
Type of coal.....	-	Pgh.	L.V/Anth.	Pgh.	Pgh.
Size of coal	-	-1/16 in	-200 mesh	B.G.	B.G.
Blast moisture.....gr/ft ³ ..	25.5	7.4	9.1	15.8	12.4
Coal/coke replacement ratio.....	-	0.84	0.87	0.95	1.05
Wind rate.....scfm....	1,388	1,378	1,321	1,370	1,358
Metal sulfur content....pct.....	0.040	0.053	0.064	0.069	0.041

*** DISCUSSION

There are three limits of blast furnace operability which are relevant to the practice of fuel injection. First, there is an upper level of high-temperature heat input above which the burden movement becomes erratic and subsequently results in a hanging furnace; second, there is a lower level of high-temperature heat input below which metal specifications cannot be achieved; and third, there is a gas or reducing gas minimum which is necessary to heat and reduce the oxides in the stack in order to avoid a thermal requirement in the high-temperature zone that cannot be met by the heat input.

Without any blast modification, the first limit dictates the maximum blast temperature for a given burden. Blast temperature may be increased above this maximum by adding moisture to the blast air, which compensates for the increase in high-temperature heat input. It is expedient to operate at the maximum blast temperature available from the stoves. Before the advent of fuel injection, many furnaces were being operated with moisture additions to the blast. The base period for the current work represents high blast temperature/moisture operation. The high temperature heat limitations may be expressed in different ways, such as 1) heat available above 2800 °F (or some other selected temperature), 2) theoretical flame temperature, or 3) calculated raceway temperature or by any similar expression a technologist may conceive. The most commonly used is flame temperature.

Fuel injection, like moisture, has a cooling effect on the high temperature zone and thus, can be substituted for the blast moisture being used to permit the high blast temperature. However, fuels can also be substituted for an additional portion of the coke after blast

moisture has been returned to ambient. The fuel/coke replacement ratio will vary with the fuel.

In the tables presented in the results section of this report, an overall replacement ratio of coal/coke was calculated. However, there are two components to the replacement ratio, the first occurs when sufficient coal has been injected to permit the reduction of blast moisture back to ambient conditions. The second represents the direct replacement of coke by coal. The first part will be the optimum ratio and the second may be termed the incremental replacement ratio. The optimum replacement is always more favorable for injected fuels, because the coke saving achieved by removing blast moisture is combined with the coke replacement by the fuel. Incremental ratios are normally greater than unity since cold fuel is replacing preheated coke in the smelting zone, also the heat of formation of the fuel must be supplied.

The incremental replacement of coals will be a function of their quality. Moisture and ash will be detrimental. There have been many graphs, nomograms, and expressions for calculating flame temperature and the amount of fuel to maintain it published in the literature. However, a good approximation is that 2 lb of dry coal will replace 1 lb of blast moisture to maintain flame temperature.

Figure 5 shows the effect of injecting Pittsburgh seam coal on coke rates. The slope of the lines for sinter/ore burden indicates a coal/coke replacement ratio of 1.25. This slope represents the incremental replacement ratio. The optimum coke replacement reflects the operation with the lowest total fuel rate, not necessarily the most economic operation. The latter will depend on the cost of coal versus coke and other factors. The optimum coal quantity is that which will just replace the base moisture added above ambient levels using the 2 lb

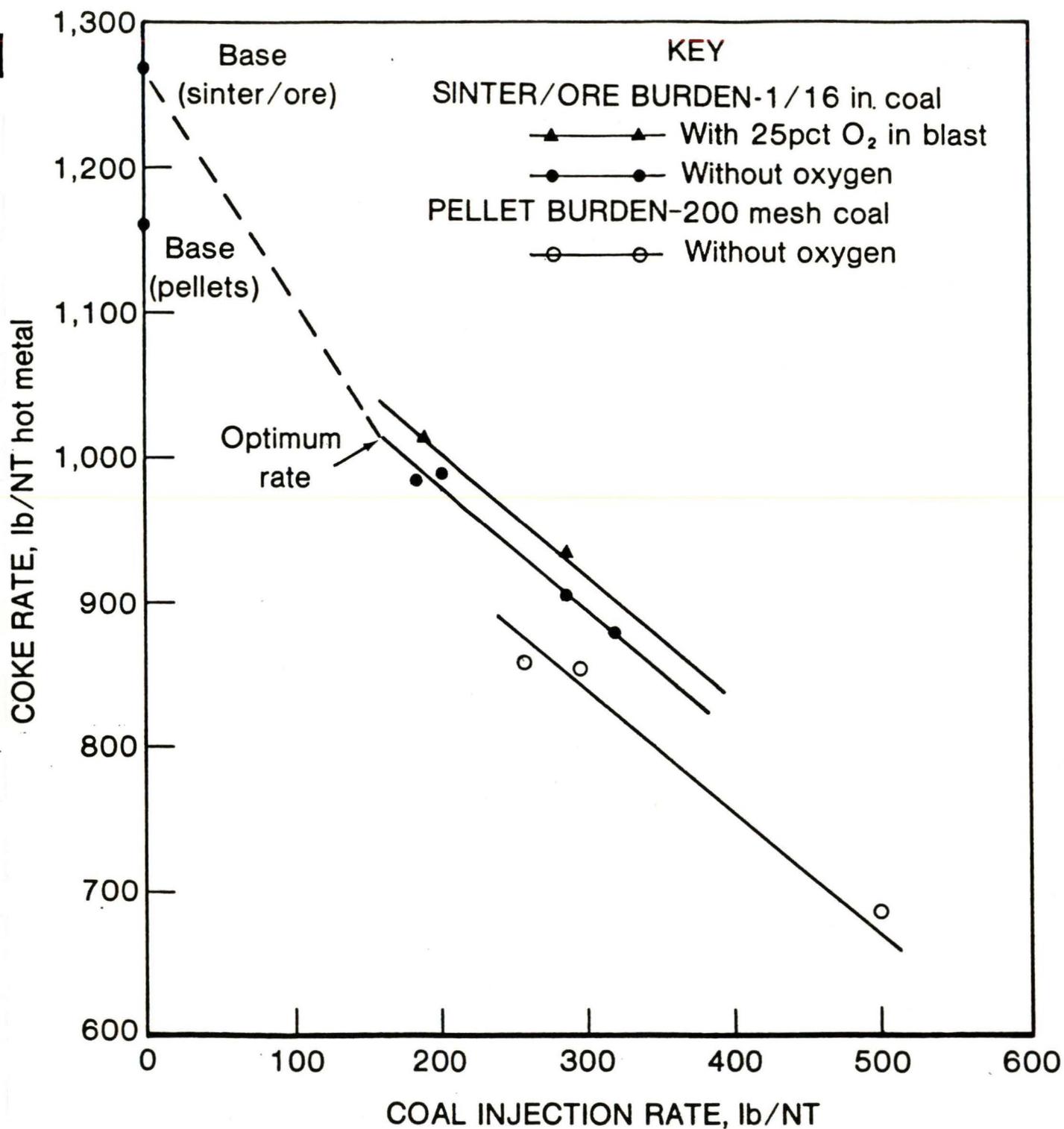


FIGURE 5.- Effect of Pittsburgh seam coal injection on coke rates in the experimental blast furnace.

dry coal to 1 lb blast moisture relationship to maintain flame temperature. The optimum coal may be calculated as follows:

$$\text{Base moisture lb/nt} = 59,682 \text{ ft}^3 \times 16.1 \text{ gr/ft}^3 / 7000 \text{ gr/lb} = 137 \text{ lb/nt}$$

$$\text{With coal injection and blast moisture at } 6 \text{ gr/ft}^3 \text{ blast moisture} =$$

$$59,682 \times 6 / 7000 = 51 \text{ lb/nt}$$

$$\text{Difference } 137 - 51 = 86 \text{ lb/nt}$$

Therefore, about 170 lb/nt of coal will be required, however the injected coal will contain ~5 lb moisture which reduces the moisture difference to 81 lb/nt (for coal with about 3 pct moisture). The removal of 81 lb/nt moisture will require 162 lb/nt coal to maintain flame temperature. This rate is considered the optimum for the Pittsburgh seam coal.

The above assumed no change in production rate with coal injection which was generally true, particularly at low coal rates. Optimum coal/coke replacement ratio for Pittsburgh seam coal without oxygen was 0.63. This was determined by the slope of the dotted line from the base to the optimum coal rate.

The use of oxygen with the coarsely crushed Pittsburgh seam coal did not permit an increase in coal rates. Actually it did permit more coal to be burned per unit of time but because production rate was increased about the same rate as the increase in coal burning rate, the coal per ton of metal was the same. Perhaps the coal/oxygen rate was limited for given coal size and burnability. The incremental replacement was similar to that without oxygen enrichment. Coke rates were about 30 lb/nt higher with oxygen than for the same coal injection rates without oxygen. Production rates increased about 31 pct and 21 pct over rates obtained without oxygen at comparable coal injection rates. The first value appears to be high for the oxygen added, although iron balances for both test No. 1 and test No. 5 were good.

Figure 6 shows the effect of injecting Wyoming subbituminous coal on coke rates. The incremental coal/coke replacement ratio was 2.0, that is, after the optimum was reached each additional point of coal saved only 1/2 lb coke. The optimum rate was 88 lb/nt for an initial coal/coke replacement ratio of 0.91 when calculated as shown earlier in this discussion. The moisture content of 21.5 pct in the surface dried Wyoming coal was the reason for the poor replacement ratios. Even these may be a little worse than given. The blast moisture was reduced in each of the tests without oxygen and if corrected by the experimental blast furnace moisture/coke rate factor of 9 lb/nt coke per gr/ft³ air, the coke rates for the three tests would be 1,109, 1,117, and 1,089 at 7 gr/ft³, thus, saving very little coke for coal rates above 150 lb/ton. Almost all the coal carbon was being utilized to supply the heat of vaporization of the coal moisture plus the heat required for the endothermic reaction of H₂O with C. In addition, the high-temperature heat input was probably close to the minimum. At the lower end of the operability range, the furnace is less efficient than near the maximum high-temperature heat input. Fuel rate increases and productivity drops. This was confirmed by the use of oxygen which increased flame temperature or high-temperature heat input and drastically improved performance. Test No. 13 with 24.7 pct oxygen in the blast resulted in the lowest coke rate with the subbituminous coal and greatly increased productivity. The coke rate was about 40 lb/nt less than the interpolated rate without oxygen for the same coal rate. Production was up about 28 pct over the estimated value without oxygen.

The injection of subbituminous coals with very high inherent moisture content will probably be limited to operations with oxygen enrichment.

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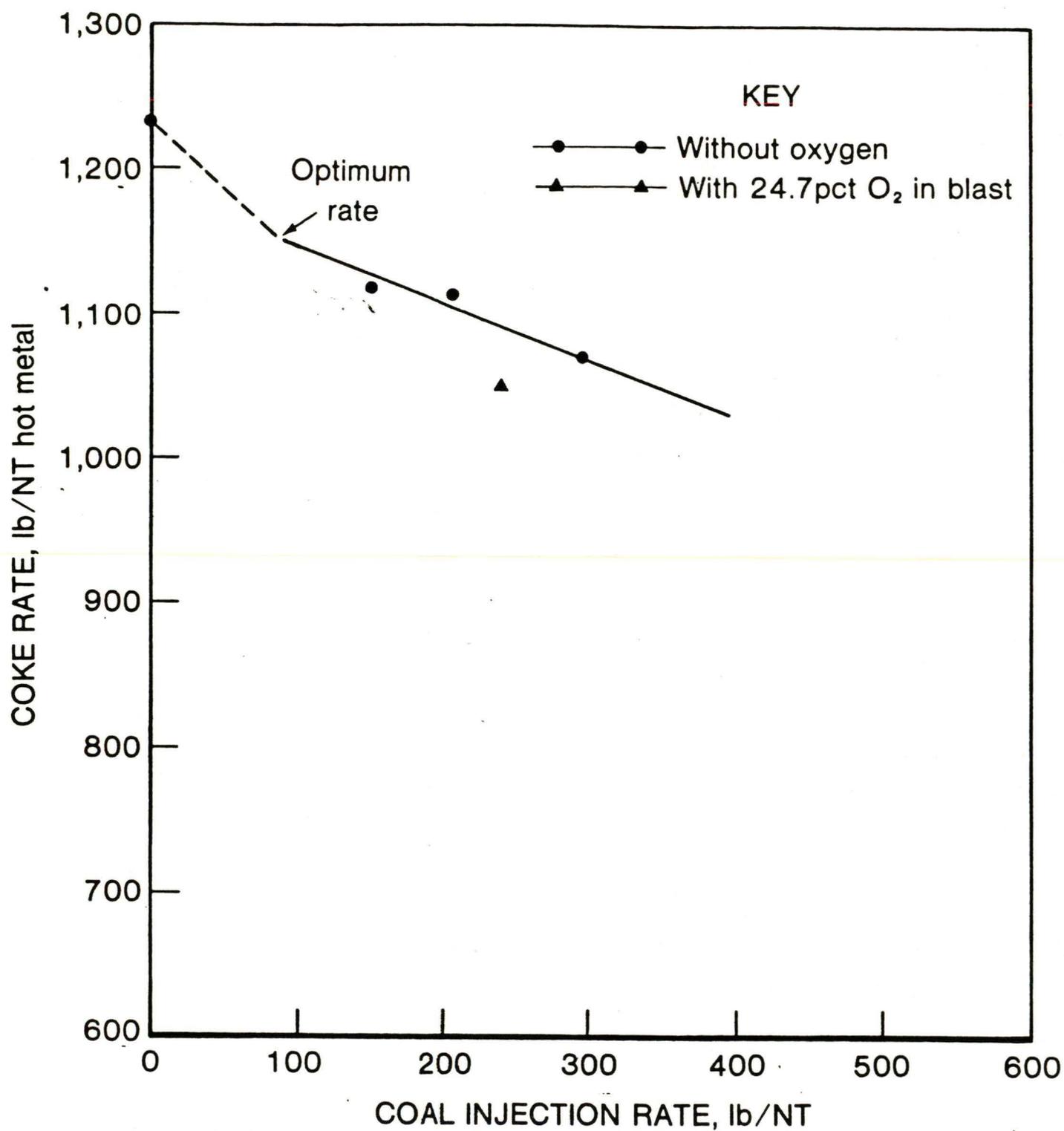


FIGURE 6. - Effect of Wyoming subbituminous coal injection on coke rates in the experimental blast furnace.

The small quantity that could be used effectively without oxygen would not result in sufficient coke saving to justify the expenditure and operation of a coal injection system. By the same token, little promise is held for the injection of coal-water slurries unless they are combined with oxygen and high blast temperatures.

The tests with the Pittsburgh high-sulfur coals indicated that slag basicity should be increased to the maximum, consistent with acceptable slag viscosity and liquidus temperature, before any slag forming additions be added to the burden to increase slag volume. The penalty for increased slag volume was higher than for increased basicity. Production rate was also better with the high basicity slag.

The Illinois high sulfur coal was simply too high in sulfur for the experimental blast furnace to produce specification metal during the time available. Even if metal sulfur content could have been controlled, the cost in terms of coke and production would probably have been enormous. It is suggested that if coals are to be used which will put a sulfur load on the furnace above that which could be handled by increased slag basicity, then external desulfurization be considered. The coal/coke replacement ratio presented with the results for Illinois coal is certainly lower than it would have been producing metal sulfurs of acceptable quality.

The apparent limitation of combustion of the coals was the focus of the tests with the pellet burden. Coal size and volatile matter were two of the parameters investigated. Initially Pittsburgh coal was injected at minus 1/16 in. As before a dark plume indicated carbon in the top gas when the coal rate exceeded 200 lb/nt. A test period was obtained with 255 lb/nt. The coal/coke replacement ratio was 0.84

compared with an estimated 0.76 for the equivalent coal rate with the sinter/ore burden, Interestingly at the same coal rate of 255 lb/nt, the coke saving was 26 pct for both burdens.

For the remainder of the tests, boiler-grind coals were used in an attempt to increase the coal rates above 300 lb/nt and to avoid carbon emissions in the top gas. Previous experience with high oil rates resulted in carbon being present in the gas that could not be cleaned by the gas cleaning system. It appeared to be colloidal in nature and resistant to cleaning. Lagoons had to be dug to avoid black water in the nearby streams.

A low volatile West Virginia coal resulted in the black plume with 250 lb/nt. The coal was changed to anthracite and for the first time there was a clean flare at 250 lb/nt. This would appear to confirm that the carbon in the top gas originated from the volatile matter of the coal. The two tests with these coals were short and the data given for test 15 represent the combination of these two coals. The performance was just about the same as for the Pittsburgh coal at an equivalent coal rate.

Smooth operation was realized with boiler-grind Pittsburgh coal at 300 lb/nt and as with the 200-lb/nt test, the replacement ratio was higher than the corresponding value for the sinter/ore burden. In this case 27 pct of the coke was replaced versus 30 pct of the coke with 300 lb/nt of coal and a sinter and ore charge.

The last test was simply to see how much coal could be injected, without oxygen, and how low a coke rate would result. Test condition restrictions were set aside. Blast temperature was increased as required to avoid a lower high-temperature heat limitation. With the

coal rate at 500 lb/nt, a test period was conducted. The blast temperature was 2560 °F and blast moisture was about 15 gr/ft³. Furnace operation was quite good with no interruption of smooth burden movement. Apparently, to achieve coal rates above 300 lb/nt the coal must be pulverized to a powder with most of the coal at minus 200 mesh.

Most of the problems relating to coal combustion occurred with coal rates approaching 250 lb/nt. It is quite likely that higher rates might be obtainable in big furnaces. There would be a little more time for combustion in the larger raceways, and the carrier air can probably be a smaller percentage of the hot blast air than was used in these experiments. In any case, it may be that the desired rate may not be above 200-250 lb/nt. As the rate of coal injection increases, the coal/coke replacement also increases. The best economic rate will depend on the local situation. Table 9 shows the way the coal/coke replacement changes from the optimum to the maximum injection rate for crushed Pittsburgh seam coal.

Although these numbers may look attractive, it must be considered that the Pittsburgh coal had only a 7.0 pct ash content versus the 10.3 pct ash of the coke. It also contained 5.2 pct H₂ against only 0.2 for the coke. A lower grade coal with higher ash would not appear so attractive with respect to replacement ratios, however, if its cost were low enough, it could be economical.

The three quality factors of coal for injection which will significantly affect blast furnace performance are ash, moisture, and sulfur contents. Since a suitable coal injection system is a multimillion dollar expense, a prospective user will need to be able to anticipate his return on investment before committing such an

TABLE 9. - Effect of coal injection rate on coal/coke replacement ratios

Coal rate, lb/nt	0	162	200	250	300
Coke rate, lb/nt	1,268	1,012	980	938	894
Replacement ratio	-	0.63	0.72	0.76	0.80

expenditure. Therefore, it would be advantageous to be able to quantify the detrimental quality factors of the coal. The author had used the Flint Decimal Effective Carbon approach and found it to be effective in predicting the effect of ash in injected coal on replacement ratio (4, 5). The references show that replacement ratios will be proportional to the Decimal Effective Carbon. A hypothetical calculation for a Pittsburgh coal with 15 pct ash is as follows:

	<u>Low ash coal</u>	<u>High ash coal</u>
Vol matter	38.1	38.1
Ash	7.0	15.0
Fixed carbon	54.9	46.9
Ultimate carbon	78.4	70.4
(Al ₂ O ₃ +SiO ₂)	5.9	12.6
(CaO+MgO)	.3	.7
Sulfur	1.5	1.5
DEC:		
Fixed C	54.9	46.9
0.6 (Al ₂ O ₃ +SiO ₂)	-3.54	-7.56
0.6 [(Al ₂ O ₃ +SiO ₂)-(CaO+MgO)]	-3.36	-7.14
Sulfur 1.5 x 5	-7.50	-7.50
	<u>40.5</u>	<u>24.7</u>
C+H ₂ in vol matter	28.7	28.7
	<u>69.2</u>	<u>53.4</u>

200 lb low ash coal saves (1,268-980) = 288 lb coke (see table 9).

200 lb high ash coal would save 53.4/69.2 x 288 = 222 lb coke.

High moisture content may be because of inherent moisture, as with the Wyoming coal, or high surface moisture. The latter could be high if a suitable injection system which could handle wet coal was utilized. The

effect on the blast furnace would be the same for inherent or surface moisture. To estimate the effect of moisture in injected coals, the best approach would appear to be thermal calculation combined with the DEC concept for the moisture-free coal. A calculation will be made and an estimate for the Wyoming coal compared with the determined coke rate. The period with oxygen enrichment was selected for the calculation because it was certainly in a good high-temperature heat range.

DEC	Wyoming coal
Fixed C	53.8
0.6 (Al ₂ O ₃ +SiO ₂)	-.7
0.6 [(Al ₂ O ₃ +SiO ₂)-(CaO+MgO)]	-.44
Sulfur 0.9 x 5	= -4.5
	<u>48.16</u>
C+H ₂ in vol matter	26.6
	<u>74.76</u>

If Wyoming coal had been dry, the coke saving for 241 lb would have been $74.76/69.2 \times 300 = 324$ lb/nt. However, this value must be reduced by the effect of the water in the coal. The coke factor for the experimental furnace was determined to be 9 lb/gr/ft³ of blast moisture which enters the furnace at blast temperature in the vapor phase. The heat content of the moisture at 2200 °F is 20,140 Btu/mole. The heat of reaction of $C+H_2O(g) = CO+H_2$ at 77°F is 56,490 Btu/mole. The net effect at 77°F is 36,350 Btu/mole. For water in coal the heat content is zero, but the heat of vaporization is 18,924 Btu/mole. Therefore, the net heat of reaction of $C+H_2O(l) = CO+H_2$ is at 77°F 75,414 Btu. If 36,350 Btu/mole corresponds to 9 lb/gr/ft³ then 75,414 Btu/mole would correspond to 19 lb/gr/ft³.

The injection of 241 lb/nt of Wyoming coal was associated with 66 lb of water. Since 241 lb of the Pittsburgh seam coal would contain 5 lb moisture, the moisture correction should be for 61 lb. The blast volume for the Wyoming coal test was 48,526 ft³ air plus 2,449 ft³ oxygen, or 51,075 ft³. The calculated gr/ft³ is 61 lb x 7,000 gr/lb/51,075 ft³ or 8.36 gr/ft³:

Calculated saving 324 - (8.36 x 19) = 324 - 159 = 165 lb

Actual saving 1,231 - 1050 = 181 lb

By comparison the injection of 241 lb Pittsburgh coal with oxygen enrichment would save 300 lb coke per net ton.

The effect of sulfur in injected coal may be included in the DEC calculation, or taken directly from the comparative results in this report.

*** COMPARISON OF COAL WITH OIL

Fuel oil has been the the most commonly used injected fuel so a comparison of coal with residual fuel oil would be in order. Although many tests had been conducted with oil injection with and without oxygen enrichment, many had been run with different burden materials or different blast conditions to those of the tests with coal. However, there were three tests, one with 27 pct oxygen and two without enrichment which can supply good comparative information. They were with the same sinter/ore burden, at the same wind rate and had identical base periods. Summary data for the three paired oil and coal tests which may provide good comparative information are shown in table 10.

The performance with coal was similar to that with oil injection. The coke replacement with oil was about 5 pct better than with coal and there was no significant difference in productivity with the two

TABLE 10. - Comparison of Pittsburgh seam coal and residual fuel oil injection in the blast furnace

Test No.	1	Oil 19A	3	Oil 18	6	Oil 15
Production rate:						
nt/day.....	19.3	19.1	17.6	18.1	21.0	24.2
nt/day/1000 cfm wind.....	24.0	23.8	24.4	23.3	29.5	32.8
Coke rate.....lb/nt...	982	993	901	917	935	910
Fuel	Coal	Oil	Coal	Oil	Coal	Oil
Fuel rate.....lb/nt...	184	165	288	266	286	291
Oxygen, pct dry air.....	21	21	21	21	25.0	27.0
Fuel/coke replacement ratio..	.64	.60	.78	.76	.86	.82

injectants allowing for the different oxygen enrichment for test 6 and and Oil 15.

*** CONCLUSIONS

Coal injection provides an effective means of reducing the coke rate in the blast furnace. When coal is injected with high blast temperature and moisture is removed from the blast air approximately 3 lb coke may be saved for each 2 lb of coal injected at moderate injection rates (150-200 lb/nt). After an optimum is reached, additional coal will replace coke incrementally at a coal/coke ratio of 1.25. However, the overall coal/coke may be less than unity.

Crushed coal, minus 1/8 in or minus 1/16 in, will probably be limited to a maximum rate in the order of 200-250 lb/nt. The use of oxygen will not permit an increase in the rate per ton. It will burn more coal per minute, but the proportionate increase in production will keep the lb/ton approximately constant.

Boiler-grind coal can be injected at very high rates, up to 500 lb/nt, as long as the minimum high-temperature heat limit is met. This will probably require a reserve in stove capacity to provide higher blast temperatures.

High sulfur content coal can be utilized and metal sulfur contents controlled by increasing slag basicity, with a small coke penalty. Adding slag forming materials to increase slag volume to control metal sulfur increases the coke penalty and decreases productivity. If the sulfur load is increased too much, it may be better to make high sulfur hot metal and desulfurize externally.

Subbituminous coals with high inherent moisture content do not appear to offer much promise unless they are combined with oxygen enrichment

and high blast temperature. This conclusion also extends to pipeline coal slurry which is usually 70/30 coal/water.

The effect of bituminous high volatile A coal was similar to oil in its effect on blast furnace performance. Oil replaced about 5 pct more coke than coal at the same injection rate with no significant difference in productivity. The advantage with oil is a simpler injection system and ease of handling. Because coal may be much less costly than oil, the investment in a coal injection system may be very worthwhile.

The coal injection system performed extremely well, with only one interruption of coal supply to the furnace for a matter of hours. Natural gas and oxygen were used to replace the unavailable coal and keep the furnace operating well. A backup system of gas or oil would be desirable if coal rates in excess of 200 lb/ton were used.

APPENDIX A.--OPERATING DATA FOR BLAST FURNACE TESTS WITH PITTSBURGH SEAM COAL INJECTION

Test	Base	1	2	3	4
Production rate:					
nt/day.....	17.0	19.3	19.0	17.6	17.7
nt/day/1000 cfm wind.....	24.2	24.0	25.2	24.4	24.3
Coke rate.....lb/nt..	1,268	982	986	901	876
Blast temperature.....°F.....	2,200	2,200	2,200	2,200	2,200
Blast moisture.....gr/ft3.	16.1	5.6	6.5	6.7	6.0
Blast pressure.....psig...	4.3	4.6	5.3	5.1	5.8
Wind (dry).....scf/nt.	59,682	59,695	57,208	59,436	59,304
Burden:					
Sinter.....lb/nt..	2,288	2,292	2,316	2,286	2,232
Ore.....lb/nt..	981	981	990	978	955
Dolomite.....lb/nt..	171	139	151	151	147
Coal rate (dry).....lb/nt..	-	184	206	288	319
Coal rate (wet).....lb/nt..	-	189	211	296	326
Oxygen pct-dry wind.....	21	21	21	21	21
Slag volume.....lb/nt..	764	710	725	733	701
Slag composition, wt pct:					
SiO ₂	36.78	36.47	35.40	35.61	36.67
Al ₂ O ₃	10.28	10.51	10.70	10.36	10.34
CaO.....	40.10	39.50	39.66	40.14	40.28
MgO.....	10.05	10.54	10.65	10.92	10.83
Fe.....	.27	.28	.30	.25	.32
S.....	1.17	1.27	1.44	1.46	1.55
Mn.....	.57	.68	.63	.54	.56
Metal composition, pct:					
Silicon.....	0.96	0.89	0.92	0.90	0.96
Sulfur.....	0.031	0.045	0.044	0.044	0.040
Top temperature.....°F.....	515	438	407	515	571
Top pressure in H ₂ O.....	16	16	20	15	15
Top gas composition, vol pct:					
CO.....	23.4	23.9	24.3	23.7	23.8
CO ₂	15.2	16.2	16.2	15.5	15.7
H ₂	4.1	2.6	3.2	3.5	3.8
N ₂	57.3	57.3	56.3	57.2	56.7
Flue dust.....lb/nt..	2	2	2	2	3
Wind rate.....scfm...	702	760	712	679	686
Shroud and carrier air..scfm...	-	43	43	43	43
Total wind rate.....scfm...	702	803	755	722	729

APPENDIX B.--OPERATING DATA FOR BLAST FURNACE TESTS WITH PITTSBURGH SEAM COAL INJECTION WITH OXYGEN ENRICHMENT AND TESTS WITH HIGH SULFUR COALS

Test	5	6	7	8	9
Production rate:					
nt/day.....	22.4	21.0	19.4	18.0	18.1
nt/day/1000 cfm wind.....	31.6	29.5	24.6	23.1	22.9
Coke rate.....lb/nt..	1,010	935	951	1,000	1,043
Blast temperature.....°F.....	2,200	2,200	2,200	2,200	2,239
Blast moisture.....gr/ft ³ ..	7.2	6.5	5.4	7.0	5.0
Blast pressure.....psig...	5.0	5.1	5.2	5.0	4.9
Wind (dry).....scf/nt.	45,331	49,320	58,732	62,153	62,900
Burden:					
Sinter.....lb/nt..	2,316	2,283	2,287	2,283	2,269
Ore.....lb/nt..	991	977	979	977	971
Gravel.....lb/nt..	-	-	-	132	177
Dolomite.....lb/nt..	167	169	185	351	428
Limestone.....lb/nt..	-	-	-	-	53
Coal type.....	Pittsburgh	Pittsburgh	Pgh. Hi S	Pgh. Hi S	Ill. Hi S
Coal rate (dry).....ln/nt..	188	286	282	283	286
Coal rate (wet).....lb/nt..	191	292	286	287	294
Oxygen pct-dry wind.....	25.1	25.0	21	21	21
Slag volume.....lb/nt..	760	739	721	963	1,099
Slag composition, wt pct:					
SiO ₂	35.44	35.05	34.52	36.76	37.57
Al ₂ O ₃	10.29	10.46	10.27	9.21	8.61
CaO.....	40.31	40.36	40.47	38.07	37.63
MgO.....	11.01	11.32	11.89	13.36	13.16
Fe.....	.29	.25	.27	.26	.27
S.....	1.45	1.53	1.85	1.50	1.61
Mn.....	.56	.49	.56	.54	.70
Metal composition, pct:					
Silicon.....	0.95	1.03	0.97	1.07	0.89
Sulfur.....	0.043	0.038	0.042	0.037	0.084
Top temperature.....°F.....	328	445	472	453	353
Top pressure in H ₂ O.....	16	15	22	15	20
Top gas composition, vol pct:					
CO.....	27.1	26.7	24.4	22.1	24.8
CO ₂	17.9	17.4	15.5	17.0	16.0
H ₂	3.2	3.8	3.6	3.6	3.7
N ₂	51.8	52.1	56.7	57.3	55.5
Flue dust.....lb/nt..	1	2	3	2	3
Wind rate.....scfm...	665	670	754	735	749
Shroud and carrier air..scfm...	43	43	35	43	43
Total wind rate.....scfm...	708	713	789	778	792

APPENDIX C.--OPERATING DATA FOR BLAST FURNACE TESTS WITH WYOMING COAL INJECTION WITH AND WITHOUT OXYGEN ENRICHMENT

Test	Base	10	11	12	13
Production rate:					
nt/day.....	20.42	19.0	18.5	17.9	23.2
nt/day/1000 cfm wind.....	26.00	24.3	23.5	22.7	29.6
Coke rate.....lb/nt..	1,231	1,119	1,114	1,071	1,050
Blast temperature.....°F.....	2,200	2,200	2,200	2,200	2,200
Blast moisture.....gr/ft ³ ..	17.5	8.5	6.7	4.4	6.5
Blast pressure.....psig...	4.7	4.6	4.7	4.9	5.4
Wind (dry).....scf/nt..	55,283	59,322	61,494	63,611	48,526
Burden:					
Sinter.....lb/nt..	2,265	2,325	2,330	2,286	2,311
Ore.....lb/nt..	971	993	997	978	989
Dolomite.....lb/nt..	159	130	160	147	129
Coal rate (dry).....lb/nt..	-	149	203	294	241
Coal rate (wet).....lb/nt..	-	189	259	376	307
Oxygen pct-dry wind.....	21	21	21	21	24.7
Slag volume.....lb/nt..	707	708	742	721	662
Slag composition, wt pct:					
SiO ₂	35.58	36.24	35.75	36.07	36.31
Al ₂ O ₃	11.25	11.09	10.84	10.68	11.12
CaO.....	39.78	39.30	39.70	39.74	38.99
MgO.....	11.04	10.22	11.22	10.73	10.39
Fe.....	.27	.28	.27	.26	.26
S.....	1.24	1.35	1.32	1.33	1.30
Mn.....	.56	.58	.56	.58	.66
Metal composition, pct:					
Silicon.....	1.00	1.01	0.93	0.83	0.087
Sulfur.....	0.032	0.039	0.036	0.034	0.047
Top temperature.....°F.....	424	361	369	443	316
Top pressure in H ₂ O.....	20	24	23	28	31
Top gas composition, vol pct:					
CO.....	26.0	25.7	25.0	25.8	29.4
CO ₂	15.7	15.5	15.3	14.2	17.1
H ₂	2.5	3.5	3.5	4.7	5.1
N ₂	55.8	55.3	56.2	55.3	48.4
Flue dust.....lb/nt..	1	2	3	4	2
Wind rate.....scfm...	784	740	745	747	740
Shroud and carrier air..scfm...	0	43	43	43	43
Total wind rate.....scfm...	784	783	788	790	783

APPENDIX D.--OPERATING DATA FOR BLAST FURNACE TESTS WITH VARIOUS COALS

Test	Base	14	15	16	17
Production rate:					
nt/day.....	39.9	41.1	42.0	40.2	37.7
nt/day/1000 cfm wind.....	28.7	29.8	31.8	29.3	27.8
Coke rate.....lb/nt..	1,161	859	860	852	684
Blast temperature.....°F.....	2,200	2,232	2,200	2,200	2,560
Blast moisture.....gr/ft3.	25.5	7.4	9.1	15.8	12.4
Blast pressure.....psig...	7.4	5.4	6.3	6.9	6.5
Wind (dry).....scf/nt.	50,060	47,532	46,449	49,080	51,896
Burden:					
Pellets.....lb/nt..	2,798	2,900	2,944	2,973	2,913
Gravel.....lb/nt..	-	15	-	11	24
Dolomite.....lb/nt..	326	331	96	108	198
Limestone.....lb/nt..	91	80	273	298	220
Coal type.....	-	Pgh. seam	Low vol	Pgh. seam	Pgh. seam
Coal size.....	-	-1/16 in	-200 mesh	- 200 mesh	- 200 mesh
Coal rate (dry).....ln/nt..	-	255	261	295	503
Coal rate (wet).....lb/nt..	-	260	261	301	509
Oxygen pct-dry wind.....	21	21	21	21	21
Slag volume.....lb/nt..	489	509	490	494	509
Slag composition, wt pct:					
SiO ₂	36.31	35.96	36.91	37.15	35.96
Al ₂ O ₃	9.80	9.04	10.09	9.38	9.04
CaO.....	34.51	34.69	41.43	42.35	34.69
MgO.....	17.20	17.16	8.92	8.96	17.16
Fe.....	.23	.27	.35	.30	.27
S.....	1.29	1.85	1.65	1.77	1.85
Mn.....	.24	.22	0.31	.27	.26
Metal composition, pct:					
Silicon.....	1.05	0.91	0.89	.84	1.20
Sulfur.....	0.040	0.053	0.064	0.069	0.041
Top temperature.....°F.....	489	333	323	373	400
Top pressure in H ₂ O.....	2.2	.69	1.65	.96	1.5
Top gas composition, vol pct:					
CO.....	(22.0)	20.8	23.3	N/A	23.6
CO ₂	(19.5)	20.5	17.8	N/A	18.5
H ₂	(2.5)	2.9	3.7	N/A	3.2
N ₂	(56.0)	55.8	55.2	N/A	54.7
Flue dust.....lb/nt..	1	1	3	3	2
Wind rate.....scfm...	1,388	1,360	1,300	1,349	1,336
Shroud and carrier air..scfm...	-	18	21	21	22
Total wind rate.....scfm...	1,388	1,378	1,321	1,370	1,358

*** EPILOGUE

COMMERCIAL EXPERIENCE 1960 TO PRESENT

During the early years when auxiliary fuel injection was being adopted as standard practice on many blast furnaces throughout the world, many, if not most, of the technologists writing on the subject proposed that coal had the potential of being the best injectant. Non metallurgical coals were relatively inexpensive and coal offered the possibility of replacing a larger portion of the coke than natural gas, oil, or coke oven gas. It was recognized, of course, that a coal injection system would be more costly than fluid injection systems. Further, operational problems were anticipated because of the erosive nature of crushed coal, the possibility of interrupted flow, and the danger of spontaneous ignition or even explosions with pulverized coal. However, these did not appear to be insurmountable difficulties and one might have expected to see widespread use of coal injection. This was particularly true in the years following 1973 with the rapidly escalating cost of oil.

A short description of the first few commercial experiences with coal injection, and the conclusions of the author follows. These are not in strict chronological order, but perhaps in a logical one.

Bethlehem Steel Company and National Steel Corporation cooperated in a joint research effort with coal injection in 1961. The work was conducted in the No. 2 blast furnace of the Hanna Furnace Corporation, Buffalo, NY, and described by Strassburger (6).

In December 1960, coal was injected into the furnace primarily to calibrate the system and make any necessary modifications. In July 1961 and continuing through January 1962, the testwork was conducted on a continuous basis.

The coal injection system was engineered by the Petrocarb Company and was similar to the twin lock hopper system described in this report. One principal difference was that the coal feed rate was controlled by the pressure differential between the feed hopper and the carrier air instead of by a rotary feeder as used in the Bureau's tests.

The coal size was initially $-1/8$ in and later $3/16$ in. The furnace operation was good and metal quality was as good as or better than the base at moderate injection rates. As the coal rates were increased to 22 to 30 pct of the fuel, neither the furnace operation nor the coal/coke replacement ratios were satisfactory. With coal rates of 264 and 284 lb/nt (about 17 pct) of the total fuel, the coal/coke replacement ratios were 1.13 and 1.06. The latter for coal with 4.4 pct ash and the former for coal with 7.6 pct ash.

The conclusions were that coal injection had been demonstrated to be both technically and economically feasible. Coal injection had led to a substantial reduction in coke rate and expensive coke had been replaced by a less expensive coal. Coal promised to share in the expanding auxiliary blast furnace-fuel market.

After the success at Buffalo, National Steel Corporation began coal injection at its Weirton Steel plant. A different coal injection system was used. Instead of the double hopper system which required that the coal be dried to a maximum of about 3 pct moisture, a system designed by Koppers Co was installed. A coal pump which could handle coal with up to 10 pct moisture was the heart of the Weirton system. Some operating problems were reported by Dietz (7). First, finely divided carbon showed up in the precipitation dust, perhaps a similar

occurrence to the black streak in the experimental furnace flare stack. This caused the precipitator to short out. A second problem was with ruptured blowpipes and the lost tuyeres. It was not known whether to attribute these difficulties to coal combustion. Both problems may have been caused by the position of the lances which extended through the peepsight along the length of the blowpipe. The initial position of the tip of the lance was 8 in from the tuyere nose. The lances were subsequently pulled back to 30 in from the nose of the tuyere. This improved the performance. The straight lances were then replaced by injection lances through the side of the blowpipe. Up to 15 pct of the fuel was coal which had replaced coke on a pound for pound basis. Additional work was planned.

Between the times of the two National Steel tests, other blast furnaces had been equipped for coal injection. These were in Europe. Summers described the coal injection work at Stanton and Stavely Ltd. in England (8). A Petrocarb system was used, a somewhat modified version of the system used in Buffalo. Although he described some of the problems associated with coal injection, the furnace operation was satisfactory. Coal injection had no obvious effect on metal quality. The percentage of casts outside the desired silicon range was of the same order for the base and coal injection period. Replacement ratios were 0.93 for a coal with 0.7 pct sulfur and 1.02 for coal with 1.47 pct sulfur. Summers' conclusions were that satisfactory techniques had been demonstrated; replacement values of 1:1 coal/coke or better can be obtained as long as theoretical flame temperature is maintained; a 10 pct increase in productivity was realized. Coal injection had been successfully demonstrated on a production basis at

up to 15 pct of the fuel requirements and it was felt that 20 pct could be achieved.

In December 1961 and January 1962 coal injection was practiced on a furnace at Chasse, France. The coal/coke replacement was very good on an as determined basis. However, Cordier (9) corrected the ratios for differences in blast operating conditions and calculated the ratios for two tests at 1.02 and 1.03.

However, despite this promise and potential replacement of expensive coke with coal by the beginning of 1965, there were no commercial furnaces known to be operating with coal injection on a continuous basis.

Armco Steel Corporation had shown as much interest in coal injection as any other organization. In the early 1960's a commitment had been made to build a new large blast furnace, Amanda, at the Ashland works. There was no coke plant at Ashland and coke was being purchased for Armco's Bellefonte furnace. Since coal offered the possibility of the largest replacement of coke, it was selected as the fuel to be injected over natural gas and oil. Further, because of the coke situation it was considered desirable to maximize the coal injection rate. To achieve this, pulverized coal at 78 pct minus 200 mesh was the selected size. The Bellefonte furnace was chosen for the initial work because it had experienced crews and some difficulties were anticipated.

A coal pulverization injection system was engineered by Babcock and Wilcox and two short trials were conducted in December 1964 and January 1965. Both ended with fires. Modifications were made to the system and inert gas was used to convey the coal to the furnace.

Coal injection was resumed in January 1966 and was on the furnace continuously for 20 months when the work was published (10). The average coal/coke replacement was 1.1. Coal injection has been a continuous feature of Armco's operations both in the Bellefonte and now in the newer Amanda furnace. These are the only established practices with coal injection in the USA. The coal injection rate is about 200 lb/nt. Several reports of the operations have been published (11, 12, 13).

In June 1981, Nippon Steel Company began using the Armco technology to inject coal in a large high top pressure furnace (14). There has been no serious trouble in operations and the corrected replacement is on a 1:1 basis.

In March and May 1983, Kobe Steel Ltd. began coal injection into the Kakogawa No.2 and Kobe No. 3 blast furnaces, respectively. The Petrocarb system is being used. Furnace operation is reported to be stable and increased coal rates are planned (15).

Just about the same time as Armco Steel Corporation began its resumption of coal injection after the early problems with fires and "puffs," powdered coal injection was begun in a blast furnace of Shoudu Iron and Steel Company, Peoples Republic of China. Injection was begun in 1966 and continues to present. Very low coke rates are being achieved. Bocong (16) claims that in 1981 Shoudu's coke rate was less than the average for Japanese ironmakers, although he conceded that total fuel rate was a little higher. He points out that coal is less than half the cost of coke and that the operation is very economical.

There are other instances of coal injection taking place during the 1970's. Koster (17) described operation with lignite and steam coal injection at ARBED Belval Works in Luxembourg. Excellent operation with both coals was experienced. The lignite contained 11 pct moisture and the steam coal was a high volatile bituminous coal with 13.5 pct ash. Favorable economics were claimed with coal/coke replacement ratios of 1.85 for lignite and 1.23 for the steam coal.

Yarmal (18) described coal-dust injection at the Donets Works in the USSR. The work was over the four year period 1972-1975. Good operations was experienced and the replacement ratio of 0.88 coal/coke was considered economically justified. However, it is not known whether coal injection has been practiced since the four year period.

The forgoing has been described in the literature through early 1984. It is expected that by 1985, approximately 10 Japanese blast furnaces will be operated with coal injection as well as a blast furnace in Scunthorpe, England.

Obviously, coal injection can be conducted successfully and if the economics are as they seem to be, a renewed effort by U.S. steel companies would appear to be in order.

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