Coinjection of Natural Gas and Pulverized Coal in the Blast Furnace at High Levels: Field Test Results at USS/Gary

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INTRODUCTION

Supplemental fuels are injected at the tuyere level of blast furnaces to reduce coke consumption and increase productivity. These fuels include natural gas, coke oven gas, oil, tar, and coal. The economic benefits derived from supplemental fuel injection are of two types: 1) the reduction in costs of hot metal production arising primarily from decreased coke consumption, and 2) the value of the increased production of hot metal — and steel — that can be sold. All blast furnaces in North America inject supplemental fuel. Approximately one half of the hot metal produced in North America is from blast furnaces that inject coal at levels between 150 lb and 350 lb/ton of hot metal. Most of the rest of the hot metal is produced on blast furnaces injecting up to 310 lb of natural gas per ton hot metal.[1] The balance is produced by blast furnaces injecting oil or coke oven gas.

Ten years ago, about half of the furnaces in North America were injecting natural gas, but the average injection level was below 50 lb/THM. The prevailing belief at the time was that it would be necessary to maintain a constant value of the raceway adiabatic flame temperature (RAFT) at high-injection levels, so that very high blast enrichments would be required.[2] Also, the extent of productivity improvement that could be obtained at higher gas injection levels had not been demonstrated. To address these technical and economic concerns, the Gas Research Institute has sponsored a number of tests with injection levels of

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[1] *Results of Ultra High Rates of Natural Gas into Blast Furnace at ACME Steel Co.*, Iron Making Conference Proceedings, Iron & Steel Society, 1997.

[2] *The Use of Natural Gas in the Blast Furnace Area – A White Paper*, Gas Research Institute, February, 1988.

gas as high as 310 lb/THM in operating blast furnaces.[3] [4] [5] [6]

The productivity at the natural gas injection level of 310 lb/THM was increased by 40% (to 8.8 TPD/CCF) while the coke rate was reduced to 641 lb/THM, and valuable insights were gained as to the requirements for practice changes appropriate for differing burden permeabilities and for the designs of lances and tuyeres over a wide range of injection levels. Specific oxygen consumption in these tests was typically in the range of 0.9 – 1.1 lb/THM gas.

Increasing productivity was a goal in all of these tests, and was achieved by increasing blast enrichment as the level of natural gas injection was increased. In a subsequent experiment carried out at WCI Steel, natural gas injection levels were increased from 120 to 250 lb/THM at constant productivity.[7] These tests showed that when productivity increases are not required natural gas can be injected at high levels without a corresponding increase in blast enrichment: specific oxygen consumptions below 0.7 lb/lb natural gas were obtained with stable furnace operation and a coke replacement ratio of about 1.1 at the highest injection levels.

Of the 16 blast furnaces currently injecting coal, only two consistently inject over 50 lb of natural gas/THM but the quantity of coal injected is limited because of limitations in the coal preparation facilities. Very little data have been published on this practice. Thus, there is a need to develop and document high-level coinjection practice.

OPERATING HISTORY AND TEST OBJECTIVES AT USS/GARY

This paper presents the results of a series of field tests sponsored by the Gas Research Institute and managed by Charles River Associates on a commercial blast furnace, the No. 4 furnace at USS/Gary, at gas coinjection levels up to 125 lb/THM, or 2,800 scf/THM. The objective of the test program was to develop the process technology for high levels of coinjection to increase productivity and reduce coke consumption. A test plan for the experimental work was developed to define the aim values and expected furnace performance at a baseline coal injection condition and for natural gas coinjection levels ranging from 25 lb/THM to 150 lb/THM. Throughout the tests USS/Gary operated the furnace primarily to meet commercial requirements for hot metal and secondarily as a vehicle to obtain test data. A full description of the planning of the tests is presented elsewhere.[8]

United States Steel operates four blast furnaces at its Gary works. The largest (No. 13) is baseloaded and operates at constant conditions to the extent possible. The three South Side furnaces (Nos. 4, 6, and 8) are used to manage swings in hot metal demand.

All furnaces are served by a common coal preparation system, and all are equipped with blowpipes that would accommodate coinjection of oil. No. 13 is also equipped with a delivery system for natural gas to atomize coinjected oil. A number of operating issues in the coal preparation system and in the furnaces, however, limit the types of coal that can be used and the maximum delivery rates to the furnaces, however. The blast furnace area has access to both high- and low-purity oxygen, but

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[3] *Injection of Natural Gas in the Blast Furnace of High Rates: Field Experiments at Amico Steel Company*, Gas Research Institute (GRI-93/0353), 1993.

[4] *Injection of Natural Gas with Blast Furnace at High Rates: Field Test Results at National Steel – Granite City*, Gas Research Institute (GRI-95/0359), October 1995.

[5] *Injection of Natural Gas in the Blast Furnace at High Rates: Field Test Results at Acme Steel Company*, Gas Research Institute (GRI-95/0358), October 1995.

[6] *Injection of Natural Gas in the Blast Furnace at Very High Levels: Field Test Results at Acme Steel Company*, Gas Research Institute (GRI-97/0211), July 1997 and Iron Making Conference Proceedings 1998.

[7] *Injection of Natural Gas at High Levels in the Blast Furnace with Low Oxygen Consumption: Field Test Results at WCI Steel*, Gas Research Institute (GRI-98/0317), November 1998.

[8] *Coinjection Of Natural Gas and Pulverized Coal in the Blast Furnace at High Levels: Field Test Results at USS/Gary*, Gas Research Institute, GRI 98/0318, November 1998.

piping constraints limit the operator's flexibility to obtain unlimited supplies of one type or the other.

On-site coke production is insufficient to meet the total demand at Gary, so external coke is acquired from a variety of sources. Coke for No. 13 is screened, but there is no blending facility and the coke supply to the other furnaces can change on a day-to-day basis. The burden on No. 13 is carefully controlled, with the other furnaces taking up swings in the supply of plant reverts, blended scrap, etc. As a result, the operators of the South Side furnaces are forced to react continuously to changes in production requirements, burden quality, and injectant rate and composition while trying to maintain hot metal chemistry within acceptable ranges.

Number 4 furnace operated at the baseline conditions of approximately 340 lb/THM of coal and less than 10 lb/THM of natural gas injection in September and October 1997, and ramp-up to higher gas injection levels was initiated in November after necessary upgrades had been completed. The coinjection levels had reached 60 lb/THM gas and 325 lb/THM coal in mid-December when a hot furnace condition forced the operators to reduce gas injection levels to restore the proper thermal balance. Levels of gas and coal injection and the scrap charge on the burden varied over the rest of the winter and spring in reaction to changes in production requirements and maintenance problems, with aim values set in response to the operators' perceptions of the requirements of the new practice. In early May 1998, productivity improvement became the key operating objective because of the reline of No. 6; this objective remained in place through the end of the data acquisition period in August. The natural gas and coal injection levels were held at about 100 and 180 lb/THM respectively over this time frame, except for brief periods when the coal supply was lost. A maximum gas coinjection level of natural gas of about 125 lb/THM was reached when the coal injection level had been reduced to about 175 lb/THM.

TEST SITE DESCRIPTION AND OPERATING PRACTICES

This section describes the equipment in the blast furnace area, USS's standard operating procedures, and the data collection procedures used in the tests.

Furnace Description

USS/Gary No. 4 furnace is located in the Gary, Indiana, plant and has a two bell top type with a two skip loading system. There is a single tap hole with outlets for two torpedo cars via a tilting spout. Hot metal is weighed at the furnace and delivered by rail car to the BOF on site. The furnace details are listed below.

Furnace details

Furnace Name:	No. 4
Hearth Diameter:	28 ft 10 in
Working Height:	82 ft
Number of Tuyeres:	20
Normal Top Pressure:	6.5 PSIG
Top Type:	Two Bell System
Pressurizing Gas:	Nitrogen
Top Gas Analyzer:	ABB Extrel Mass Spectrometer
Working Volume:	52,818 ft^3
Tap Hole	Single
Trough Design:	Tilting Spout
Bosh Cooling:	Channel
Type of Burden Distribution:	Moveable Armor
Date of Last Blow-in:	September 1996

Tuyere design - Eighteen of the tuyeres are 6.5 inches in diameter, and #1 and #20 tuyeres adjacent to the tap-hole are 6 inches in diameter and ported for addition of natural gas, since no coal is injected over the tap-hole.

Natural gas delivery and injection systems - Natural gas is delivered to the US Steel Gary plant at 200 PSIG in a 12-inch high-pressure supply line. The pressure is reduced at a metering station for delivery to the blast furnace at 130 PSIG in a 6-inch feed line. A 6-inch Vortex Shedding meter is used as the primary measuring element for the natural gas flow control system. The 6-inch feed line is connected to an 8-inch circle pipe that is fitted with twenty 1 ¼-inch drop-down pipes that are fitted with quarter-turn shut-off valves. Ten-foot runs of flexible hose connect the shut-off valves to check valves on stainless steel lances.

The lances are 54 inches long (except for #2 and #19, which are 43 inches long) and enter the side of each blowpipe in a horizontal position opposite to the point of insertion of the coal lances. The angle of entry is 27 degrees from the tuyere center line. The tip of the lance is normally positioned 2 inches back from the tuyere/blowpipe joint where the blowpipe butts to the tuyere. Table I shows the lance and flexible hose diameters used during the test, along with the range of flows and circle pipe pressures.

Table I. Natural Gas Injection System Configurations

Lance Diameter (in.)	Flexible Hose Diameter (in.)	NG Flow Rate Range (MSCFM)	Circle Pipe Pressure Range (PSIG)
½	1 ¼	1,500-6,500	32-110
¾	1 ¼	4,000-9,000	45-95

Source: Charles River Associates, 1998.

Since the coal lance assemblies had been located on the sides of the blowpipes with the most access, positioning of the natural gas injection lances was constrained by the furnace support columns. As a result, the lances could only be moved axially within a few inches of their nominal insertion length.

Fire detection/suppression system - Two flame detection thermocouples were placed in the receiving hopper above the small bell, one in the centerline next to the cables and one next to the hopper wall. When either of these thermocouples detects a temperature above 125°F, nitrogen is automatically introduced between the bells. The N_2 purge has been activated about once per month during the tests.

Top gas analysis - The top gas sample is taken after the demister before the clean gas goes to the stoves. A $^{3}/_{8}$-inch sample line runs about 100 feet to the sample conditioning cabinet, which dries and filters the gas down to 5 um. Then a pump boosts pressure to deliver the gas another 200 feet to the ABB Extrel Mass Spectrometer. The top gas analyzer is tested daily against five calibration gases and is recalibrated as needed.

Auxiliaries description - US Steel's Gary plant has an on-site sinter plant that has the capacity to prepare about 15% of the metallic content of the charge. An on-site coke plant provides most of the coke used at Gary although coke from two external sources was used during the trial. PCI operates a facility on-site to prepare and deliver coal to all four furnaces. The rate of coal injection for each furnace is set at its control room.

Raw coal was fed to the coal preparation system as it became available from the in-plant storage area. Since storage capacity for any particular type of coal was limited, and since the coals were not blended prior to preparation, the type of coal injected to the furnace could change fairly frequently and abruptly.

Oxygen supply - Both high- and low-purity oxygen are available from on-site Praxair plants. The oxygen content of the low-purity oxygen is about 89-92% and 5,000 SCFM is available for BF No. 4, but only when No. 13 furnace is operating and taking low-purity oxygen. About 10,000 SCFM of high-purity oxygen is available at all times.

Stockhouse - Gary's charging equipment is a two-skip system fed by an automated stockhouse. The hoppers are filled automatically by a burden-charging program. Coke is the only material screened at the blast furnace. An on-line measurement of coke moisture (MOLA) gauge is used to measure coke moisture and track the amount of coke charged on a dry basis. Each skip has a volume of 330 ft^3 and maximum weight of 34,000 lb

Wind delivery system - Automatic controllers are used to set the wind at a constant volume. The snort valve is used for wind rate changes under upset conditions and for off blast conditions. The blast moisture system has a feedback controller that manipulates steam addition to achieve the target gr/SCF.

Data acquisition system - An extensive real-time data system collects and stores all of the data related to the blast furnace operation. An Excel spreadsheet was used to average the data by day and save the data into files by month.

Charging practice - The charging sequence used throughout the tests was:

CC/CC/PPP/PPS\C/CC/CC/PPP/PPPS\C/

C = Coke, P = Pellets, S = Sinter,

/ = Large Bell Dump

Contaminated sinter, buckwheat coke, blended scrap, and Auburn ore were added to the pellet skips and trim was added to the sinter skip loads.

The coke-to-ore ratio was changed by changing the amount of iron-bearing material per charge; the amount of coke charged per skip was held constant.

Reported burden analyses are shown in Table II, while Tables III and IV show typical natural gas and reported coal assays. The elemental assays of the burden constituents and coal are reported on a dry basis. When the compositions do not sum to 100%, the assays have been adjusted up or down on a pro ratio basis to bring the sum to 100% for use in furnace material balance calculations. The coal assays were performed before the onset of these tests and were not repeated. The prepared coal delivered to the furnace contains 1% or less moisture. Pellet and sinter compositions did not change materially over the course of these tests, but blended scrap and contaminated sinter compositions were variable. The scrap originated from a variety of sources with greatly different iron contents and degrees of metallization.

Table II. Reported Burden Analyses

Material	Percent by Weight										
	H_2O	C	S	P	Mn	SiO_2	Al_2O_3	Fe	MgO	CaO	Others(1)	Total(2)
White Tag Coke	3.5	92.18	0.53	0.08	0.03	4.20	2.32	0.52	0.08	0.15	1.56	101.64
Wheeling Pitt Coke	N.R.	91.66	0.6	0.01	0	4.23	2.37	0.55	0.07	0.28	1.81	102.47
Acme Coke	N.R.	92.24	0.76	0.24	0.01	4.52	2.41	0.62	0.24	0.09	N.R.	102.0
Minntac Flux Pellet	3.5	0	0.11	0.01	0.12	4.26	0.17	63.04	1.10	3.52	0.04	98.15
Sinter	0.5	0.06	0.04	0.13	1.58	7.65	1.97	45.47	3.85	18.38	0.36	98.46
Auburn Ore	11.2	0.18	0.01	0.05	1.24	6.52	1.35	60.50	0.36	0.15	0.04	95.63
Contaminated Sinter	N.R.	0.03	0.64	0.11	1.37	5.65	1.47	49.32	3.59	15.88	0.18	99.91
Trim	7.0	0	0.06	0.03	0.56	48.6	0.24	25.8	2.47	2.29	0.08	89.67
Blended Scrap	0.5	0	0.18	0.10	1.31	6.53	1.63	74.74	2.88	12.60	0.02	105.34

(1) Others include Ti, Zn, K_2O, Na_2O, H_2 and N_2.
(2) Total includes oxygen not reported, dry basis.
Source: USS/Gary

Table III. Typical Natural Gas Analysis

Constituent	Percent by Volume							
	CO_2	N_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	H_2
	0.96	1.58	93.73	2.91	0.51	0.18	0.12	0

HHV = 1,020 Btu/cf at 14.65 PSIG, 60°F, and dry.
Source: USS/Gary

Table IV. Reported Coal Analyses

	Percent by Weight								
Coal	C	H_2	O_2	N_2	S	Ash(1)	Total(2)	H_2O	HHV(3)
Corbin	79.16	3.27	5.98	1.61	0.98	7.71	98.71	7.0	14,140
Premier Elkhorn	74.06	5.83	10.17	1.36	0.78	7.66	99.86	6.9	13,720
Buckeye	79.04	5.40	6.43	1.59	0.90	6.40	99.76	5.5	14,350
Pinnacle	86.60	4.22	1.75	1.22	0.83	5.10	99.72	6.5	14,950

(1) Ash includes SiO_2, Al_2O_S, CaO, MgO, P, Mn, Ti, K_2O, Na_2O, Cl_2, Fe and their oxides.
(2) Total on a dry basis.
(3) BTU/lb
Source: USS/Gary

Natural gas, pulverized coal, and oxygen flow rate control - Natural gas and oxygen flow rates are controlled by constant set-point feedback controllers. The furnace injection rate for coal is specified in the control room, with delivery to the furnace surge hoppers controlled at the preparation facility. If the blast pressure falls below 18 PSIG, the flows are automatically shut off to prevent a highly enriched blast if the blowers shut down.

Test Plan Outline — Aim Values and Data Acquisition

Prior to these trials, No. 4 furnace had operated with gas injection through the nose of the tuyeres adjacent to the tap hole (at an overall average injection level of about 400–500 SCFM, 5-10 lb/THM) and coal injection through lances on all other tuyeres. The test plan for these trials was designed to develop and evaluate practices for natural gas coinjection at levels up to 150 lb/THM. There were four major issues that needed to be resolved through execution of these trials:

- What would the required marginal oxygen consumption be as the natural gas injection level increased? Would it be necessary to maintain a constant, high value for RAFT?
- What would the effect of increasing natural gas injection levels on burden permeability be, especially if RAFT were allowed to drop?
- Would the extent of the decrease in the solution loss reaction with increasing levels of natural gas injection be as high as with all gas injection practice, or would it be lower as is the case with all coal injection practice?
- Would the details of the design of the gas injection lances (e.g., lance diameter) affect natural gas and coal combustion, and thereby affect furnace performance? Could the same lance design be used over the entire range of injection rates?

Because coinjection of large amounts of natural gas at high coal injection levels (> 250 lb/THM) was a new practice, a test plan was developed that increased gas injection levels in increments of 25 lb/THM, with a data collection plan that minimized the risk of extrapolating to conditions in which the issues described above could result in operability problems.

A key question was the amount of oxygen that would be required to combust the natural gas and burn out the coal sufficiently to prevent soot formation or char build-up that would decrease permeability. Therefore, a sequence of aim values was prepared for the trials that would let the operators initially “overshoot” the amount of oxygen required, and then increase the natural gas injection level up to the point where any adverse effects could be observed.

As will be discussed later, the test plan and data collection plan were altered, and data were obtained at different coal injection rates and burden compositions than were contemplated.

DATA ANALYSIS PROCEDURES AND DATA ACQUISITION ISSUES

This section describes the data analysis procedures used to analyze the information collected from the No. 4 furnace at Gary. A description of the blast furnace computational procedures used has been presented elsewhere (see reference 8).

Data sets that have met the described criteria are considered “rationalized” and, unless otherwise noted, are the results of a series of good days at the furnace and are reported here.

Data Acquisition Issues

The operating data rationalization procedures used for these tests produced a total of seven data points covering 35 days of operation in the two-month “base case” period with coal-only injection on the furnace. Initial attempts to rationalize the data according to CRA’s usual procedures were not successful: no periods could be found that met *all* of the necessary criteria for satisfactory rationalization. This led to a comprehensive and ongoing review of the data acquisition system and procedures used in these tests. Key results of this review and their impact on data rationalization procedures are discussed below.

Natural Gas Metering

With CRA's usual procedures, no correction factor is applied to the values reported for furnace natural gas consumption. The natural gas flow to the tuyeres adjacent to the tap hole, normally at a rate of about 400-600 SCFM, was added to the flow to the lances in the remaining tuyeres to obtain the total flow reported here.

Problems with the coal preparation system during the reline period resulted in a brief period of operation during which natural gas was the only fuel injected at the tuyeres. The ordered injection level was about 150 lb/THM, well within the range practiced by many other furnaces where performance had been evaluated carefully. Review of the data from No. 4 at these conditions suggested that a scaling error had been introduced into the vortex meter transmitter, and that natural gas flows were being underreported by about 20%. The rationale for this conclusion is discussed in detail elsewhere (see reference 8).

Coke Moisture

USS/Gary uses a Texas Instruments nuclear gauge for an on-line measurement of coke moisture (MOLA), and the output of this instrument is used in the data acquisition system to calculate the dry weight of coke in the charge. It was determined early in the tests that the calibrations of the instrument tended to drift. Therefore, the coke moisture values reported by the MOLA were adjusted based on the moisture values reported from the lab assays performed on grab samples twice per week.

Other Stockhouse Measurements

The scrap was obtained from a number of sources, each with different total iron content and degree of metallization. About 25% of the estimated composite scrap iron content is purchased.

In house "scraps" are retrieved from a variety of locations around the mill. Some are screened and blended, and the materials are transported to the scrap bins in the stockhouse. The average scrap composition shown in Table II is more in the nature of an allowance for a "typical" mix than an accurate assay of the scrap actually charged at any time, as is the estimate of 75% metallization of the iron content. Visual inspection of some of the materials in the scrap bins suggests that they are far below average in iron content and metallization at certain times.

The uncertainty in the iron content and its metallization is significant because misestimation of the assay affects the oxygen and carbon balances as well as the iron balance.

Coal Injection

Raw coals are received, dried, and ground in a central facility at Gary. In-plant stockpiles of raw coal from any individual source are relatively small and there is limited capability for coal blending, so that the origin (and composition) of the coal fed to the furnace could change abruptly, as frequently as every two or three days.

The prepared coal is discharged to lockhoppers from which it is withdrawn at the required rate and transferred to the furnace. Furnace operators stipulate the rate, but the actual control is effected at the central coal preparation facility. USS/Gary can track the total amount of coal delivered, which can be balanced against the sum of all coals delivered to the operating furnaces as a check on overall coal metering accuracy. While the accuracy of the metering system for a single furnace cannot be checked in this manner, overall consumption balance checks have been performed to the satisfaction of USS/Gary personnel. Checks are made by estimating changes to the in-plant inventory, which can be estimated to within ± 10%.

The coal compositions shown in Table IV were obtained before these tests were initiated. Some variability is to be expected from shipment to shipment and over time but no data are available to quantify the variability during the test period. Uncertainty in the coal carbon, oxygen, and hydrogen composition or in the coal delivery rate introduces uncertainty into the furnace material balances, especially in the carbon and hydrogen balances. Where the amounts of carbon and hydrogen in the coal are understated, for example, rationalization of the furnace balances will result in abnormally low CO:CO_2 ratios and hydrogen utilization efficiencies. Where these parameters are far from their expected values, and where other correction factors are also unusually large, they would suggest that errors may have occurred in the coal assay or that the coal injection rate had been misestimated.

These circumstances occurred, and were identified and evaluated in the description of the experimental results that follows. The most significant adjustment required was to the reported coal injection rate during periods of low-coal injection. The logic behind the necessity to correct the reported coal rate under these circumstances is the same as described above for the correction to the natural gas rate. The evaluations of furnace performance suggested that the coal injection rate was being underreported by about 10% at injection rates below about 16 tons/hour.

Top Gas Assay

For the first part of these tests, there were two analyzers available to measure top gas composition: an ABB Extrel and a P&E mass spectrometer. Both instruments were standardized with the same calibration gases, but reported different assays. The P&E instrument typically reported about 1.5% more CO_2 and 1.2% less CO than did the Extrel. Because of this difference, CRA rationalized furnace performance with both sets of assays as long as both instruments were in service. We found that the choice of analyzer made essentially no difference in the estimated values of key furnace operating parameters. While the correction factors required to normalize the data differed, the corrected top gas assays were typically brought to within about 0.3% of each other.

Summary of Data Acquisition Issues

The effects of uncertainties in the scrap and coal compositions and in the calibration of the natural gas and coal injection meters are difficult to quantify. *Therefore, the following discussions of the evaluation of rationalized data are based on the results obtained by forcing closure of the furnace elemental balances based on the information obtained from the data retrieval system and on CRA's judgment to adjust for errors or biases believed to be incorporated in the raw data.* In addition, summaries of furnace performance based on normalized "as reported" data are presented for reference purposes.

EVALUATION OF RATIONALIZED DATA

The operating data obtained from USS/Gary's data acquisition system were reviewed and checked for consistency. Data were rejected when the furnace experienced transient conditions due to scheduled or unscheduled maintenance requirements and other upsets in operating conditions unrelated to the tests. As a result, steady state data representing about 31 weeks of operation over the year that data were acquired were used to evaluate furnace performance. The rationalized data were used to estimate key furnace operating parameters, which are summarized below. The values of Table V are based on rationalizing data that have been adjusted according to CRA's judgment of the extents of natural gas and coal rate metering errors as described above. The values in Table VI are based on the data as reported.

Table V. Summary of Coinjection Tests at USS/Gary No. 4

Process Parameters	Units	Period				
		Baseline	**High Supplemental Fuels**	**Reline**	**Intermediate Gas and Coal**	**High Gas, Low Coal**
Blast						
Temperature	°F	1,895	1,884	1,897	1,894	1,892
Moisture	gr/SCF	8.9	6.0	7.9	6.2	6.7
Delivered Wind	MCF/THM	30.3	31.0	29.1	28.6	29.3
Supplemented O_2	lb/THM	188	206	205	230	218
AISI RAFT	°F	3,836	3,675	3,559	3,597	3,461
Injectants						
Natural Gas	lb/THM	6	49	99	97	125
Coal	lb/THM	339	326	189	219	177
Tuyere O_2:C	mole/mole	1.10	1.06	1.39	1.25	1.36
Burden						
Pellets	lb/THM	2,105	2,267	2,358	2,357	2,333
Sinter, Ore, Others	lb/THM	763	742	509	552	534
Scrap	lb/THM	294	184	274	285	290
Coke	lb/THM	6.7	608	647	616	632
Permeability	m^2/sec^2	6.16	6.44	7.84	7.16	6.78
Production						
Hot Metal	TPD	3,724	3,757	4,184	4,027	4,045
Productivity	TPD/CCF	7.05	7.12	7.92	7.63	7.66
H.M. Temp/SD	°F	2,677/31	2678/27	2,665/31	2,676/27	2,657/32
H.M. Si/SD	%	0.74/0.17	0.74/0.13	0.58/0.16	0.64/0.16	0.60/0.16
H.M. S/SD	%	0.049/0015	0.039/0.009	0.049/0.015	0.037/0.009	0.039/0.011
Operating Parameters						
TCE	MMBtu/THM	0.70	0.76	0.72	0.72	0.71
Solution Loss	mole/THM	9.35	8.41	7.39	6.72	6.10
Bosh H_2	mole/THM	11.1	17.2	18.8	18.8	21.3
H_2Utilization	%	41.8	49.2	46.5	51.6	47.8

Table VI. Summary of Coinjection Tests at USS/Gary No. 4 Based on "As Reported" Data

Process Parameters	Units	Period				
		Baseline	**High Supplemental Fuels**	**Reline**	**Intermediate Gas and Coal**	**High Gas, Low Coal**
Blast						
Temperature	°F	1,895	1,884	1,897	1,894	1,892
Moisture	gr/SCF	8.9	6.0	7.9	6.2	6.7
Delivered Wind	MCF/THM	30.3	30.9	28.0	28.2	27.8
Supplemented O_2	lb/THM	188	207	207	231	219
AISI RAFT	°F	3,836	3,723	3,684	3,693	3,604
Injectants						
Natural Gas	lb/THM	6	43	85	83	106
Coal	lb/THM	339	327	173	221	161
Tuyere O_2:C	mole/mole	1.10	1.07	1.51	1.28	1.47
Burden						
Pellets	lb/THM	2,105	2,267	2,358	2,357	2,333
Sinter, Ore, Others	lb/THM	763	742	509	552	534
Scrap	lb/THM	294	184	274	285	290
Coke	lb/THM	6.7	615	653	624	634
Permeability	m^2/sec^2	6.16	6.40	7.28	6.91	6.19
Production						
Hot Metal	TPD	3,724	3,746	4,155	3,992	4,043
Productivity	TPD/CCF	7.05	7.09	7.87	7.56	7.64
H.M. Temp/SD	°F	2,677/31	2678/27	2,665/31	2,676/27	2,657/32
H.M. Si/SD	%	0.74/0.17	0.74/0.13	0.58/0.16	0.64/0.16	0.60/0.16
H.M. S/SD	%	0.049/0015	0.039/0.009	0.049/0.015	0.037/0.009	0.039/0.011
Operating Parameters						
TCE	MMBtu/THM	0.70	0.74	0.74	0.75	0.73
Solution Loss	mole/THM	9.35	8.94	7.35	7.05	6.08
Bosh H_2	mole/THM	11.1	15.4	16.6	17.2	18.6
H_2Utilization	%	41.8	47.0	41.3	47.6	42.8

Effect of Uncertainties in Coal and Scrap Compositions

The hydrogen utilization efficiency during the baseline period was in the expected range when Elkhorn coal was being injected, but was low when the average mix was two-thirds Corbin, one-third Buckeye. The calculated hydrogen utilization efficiency for the hydrogen content assumed for Corbin coal suggests that the assay in Table IV underestimates the hydrogen content of this coal. More reasonable utilization efficiencies are obtained with a coal hydrogen content of about 5.5%. This is also consistent with the observations that, at 3.27%, the hydrogen content is rather low for a coal of this volatility and the total elemental and ash compositions do not sum to 100%.

The sensitivity of the calculated furnace performance to the hydrogen content of the coal would be lower at lower injection levels and the effect would tend to be masked at higher natural gas injection levels. However, *knowledge of the coal chemistry is important because it affects not only the hydrogen utilization efficiency calculations but bosh gas hydrogen content (which is an important correlating parameter), the extent of the solution loss reaction, the calculated thermal profile in the high-temperature zones, and therefore the proper aim values to set and the expected replacement ratios for the coal and coinjected gas*.

Lance Design Issues

Previous work on high rate gas injection had shown that improper lance design could lead to operating problems (see reference 6). There were two major concerns with respect to lance designs for these tests:

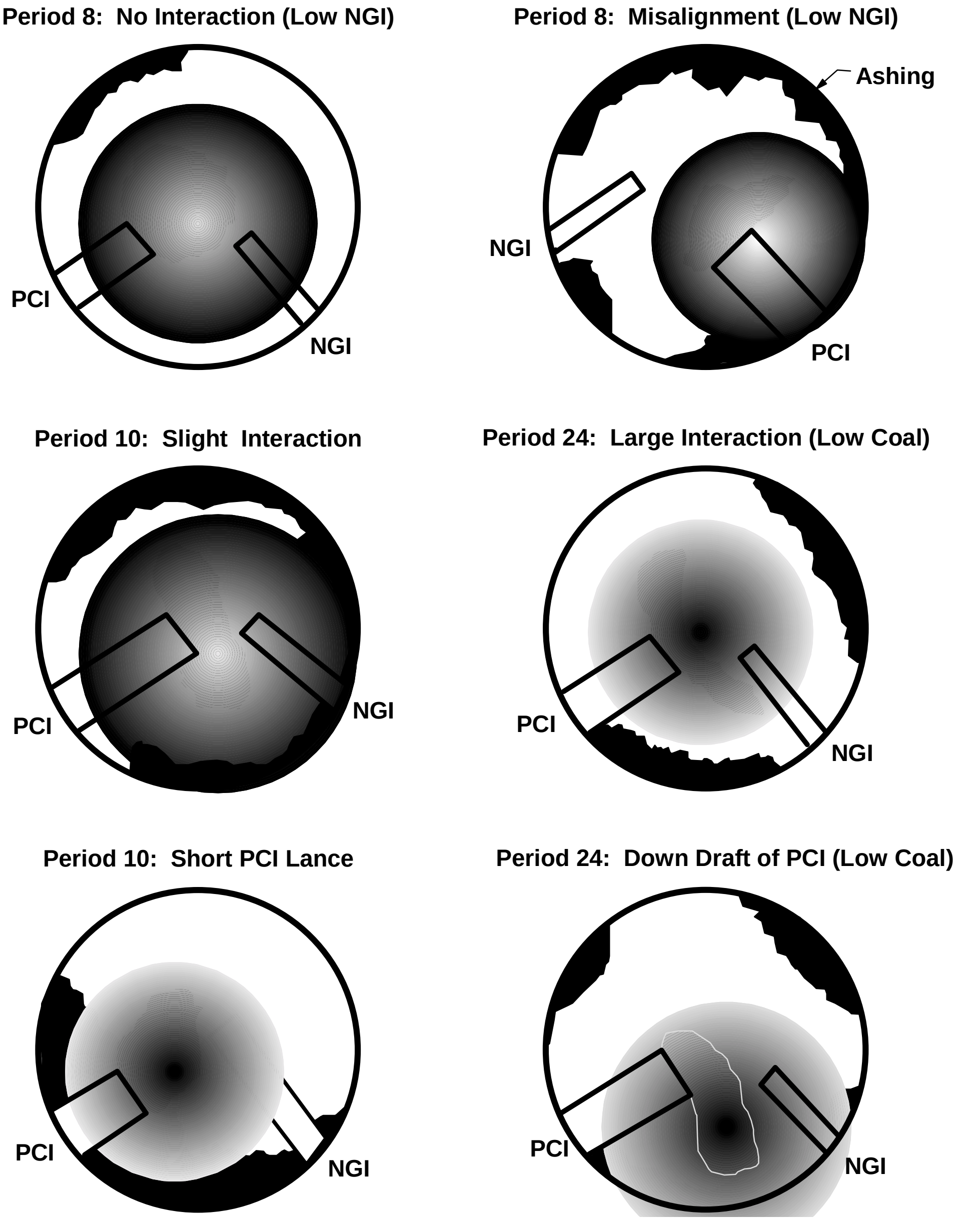
- The high turndown in projected gas flow rate (7 times) could make achieving stable operations over the entire range difficult.
- The extent of the interaction, if any, between the issuing gas and coal plumes, and the subsequent effect on furnace operation was unknown.

The potential turndown problem was addressed by using lances with different diameters: ½-inch IPS Sc 40 lances were to be used at flow rates below about 4,000 SCFM, and ¾-inch IPS Sc 40 lances were to be used at higher rates. Initial operation was with the smaller lances, at gas flow rates of about 5,500 SCFM. The larger-diameter lances were in use when the estimated actual gas flow through the lances was about 10,400 SCFM. At this flow rate the calculated pressure drop from the circle pipe to the blast is about 52 PSIG, while average measured pressure drop ranged from 54 to 61 PSIG. The agreement between calculated and measured pressure drops is additional evidence of the appropriateness of the application of the 20% correction factor to the indicated natural gas flow.

The gas lances were designed to penetrate the blowpipe essentially the same distance as the coal lances and to have the axes of the two lances intersect. Thus, in the absence of the aerodynamic effects of the blast, the gas and coal plumes would interact with each other some distance into the tuyeres. The flow of the blast would tend to separate the two plumes, however. Observation of the ashing patterns in the various tuyeres before the initiation of coinjection showed clearly that a simple description of the coal plume flow patterns was not possible. The coal lance positions and orientations were obviously not uniform and ashing could occur on any quadrant of the tuyere nose. When the gas lances were installed it was obvious that their orientations and positions were nonuniform as well.

During the initiation of coinjection testing with gas flows through the lances below 2,000 SCFM, there was very little indication of any interaction between the gas and coal plumes, although the operators claimed that there seemed to be a reduction in the extent of ashing on some tuyeres. As the gas flow rate was increased, however, interaction could be observed on some tuyeres and by the time the gas flow rate exceeded 3,000 SCFM several different types of interactions became obvious. Minimal interaction was observed at the lower flow rates and when "misalignment" of the lances directed the gas plume over or under the coal plume. In these cases one could observe the gas plume appearing to gently redirect the coal plume up, down, or toward the center line, depending on the relative orientations of the flows. At higher gas flows, say 5,000 SCFM, the natural gas plume would show a much more pronounced tendency to redirect the coal plume, or even to “punch” right through the coal plume in some cases. Some types of interaction that were observed are shown in the sketches in Figure 1.

Figure 1. Some Types of Plume Interactions Observed During Coinjection Testing


Period 8: No Interaction (Low NGI)

Period 8: Misalignment (Low NGI)

Period 10: Slight Interaction

Period 24: Large Interaction (Low Coal)

Period 10: Short PCI Lance

Period 24: Down Draft of PCI (Low Coal)

It was always observed that the gas plume influenced the behavior of the coal plume, and not the reverse. The reason for this is shown in the data in Table VII, which compare the momentum of the blast and the gas and coal plumes issuing from the lances at a variety of test conditions. During the ramp-up period the momentum of the blast exceeded both the coal and gas plume, which would retard mixing of the plumes. At a gas flow of about 2,750 SCFM in the high-coal/low-gas period, however, the gas momentum exceeded that of the blast and therefore could penetrate the blast axially more effectively and begin to influence the coal plume. The estimated average velocities of the blast, gas, and coal for this period are about 435, 400, and 55 ft/sec while their average densities are about 0.052, 0.14, and 2.6 lb/ft^3, respectively.

Table VII Estimated Momentums of the Blast and Gas and Coal Plumes for Various Test Conditions

Coal and Gas(1) Flows, Lb/THM	Blast Momentum $\rho V^2/2g_c$, PSI	Gas Momentum(2) $\rho V^2/2g_c$, PSI	Coal Momentum(3) $\rho V^2/2g_c$, PSI	Comments
307, 28	1.3	0.8	0.7	Ramp-up
333, 47	1.1	2.3	0.8	High coal, low gas
166, 88	1.3	8.1	0.3	Low coal, intermediate gas
218, 83	1.3	7.5	0.5	½" lance
225, 74	1.3	2.4	0.5	¾" lance
175, 116	1.3	4.7	0.3	Low coal, high gas
—, 164	1.4	9.0	—	No coal, highest gas

(1) Gas flow through lances only.
(2) Estimated at the lance tip prior to expansion.
(3) Assumes homogeneous flow of coal and carrier gas.

Clearly, the gas plume had sufficient momentum to influence the coal plume at gas injection levels above 50 lb/THM with the ½" lances, or 75 lb/THM with the ¾" lances if the positioning of the lances provided trajectories that would favor it. However, it is possible that the presence of the gas in the tuyere/raceway could influence the behavior of the coal even if the plumes did not physically interact. For example, rapid combustion of the gas could lead to preferential consumption of oxygen that would, in turn, retard coal combustion and lead to incomplete char burnout and a decrease in furnace permeability or increased soot formation in the top gas.

Previous modeling studies of gas combustion[9] and the results of tests of gas injection with lances of different diameters suggest that the extent of partial combustion of the gas within the tuyeres can and should be controlled. Regions of stable furnace operation were defined based on the mole ratio of oxygen to gas in the blast and the ratio of the gas-to-blast momentum. Higher values of either parameter promote combustion and prevent the occurrence of “twinkling” and partial closure of the tuyere that can be caused by the cooling effect of high rates of flow of cold gas.

It is not clear how to develop such a simple map for coinjection of coal and natural gas because the combustion rates and mechanisms are so different.

Coal devolatilizes as it is heated, and the complex hydrocarbons released are less stable than natural gas and so could be ignited at lower temperatures. Turbulent mixing of the blast with the gas and coal plumes determines the rates of both heat and mass transfer and therefore the rates of combustion of the gas and of devolatilization and then combustion of the coal.

EFFECT OF NATURAL GAS INJECTION LEVEL ON FURNACE PERFORMANCE

This section presents an analysis of the performance of No. 4 furnace at Gary with coal only, gas only, and coinjected gas and coal. As discussed earlier, there were a number of concerns prior to the test regarding the most appropriate ways to set aim values and the effects of high-level gas injection on furnace performance. Key issues to be resolved included:

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[9] *Direct Injection of Natural Gas in Blast Furnaces at High Rates — Tuyere/Lance Design*, Gas Research Institute (GRI–90/0159), September 1992.

- The appropriate level for RAFT at various injection levels;
- The extent to which increasing levels of hydrogen would decrease the solution loss reaction;
- The effects that differing levels of fuel injection would have on permeability;
- The productivity gains that might be obtained at various levels of fuel injection;
- The replacement ratios that could be achieved with natural gas; and
- The effects of coinjection on furnace stability, availability, and hot metal chemistry.

In the previous analyses of furnace performance with high levels of natural gas injection, it has been possible to correlate changes in furnace performance with changes in either the level of gas injection or the bosh gas hydrogen content, since these were the parameters that were varied independently in the tests. Such a simple scheme is not possible here, however, because the coal injection level and scrap charge to the burden also varied significantly throughout the tests. Changes in the coal injection level and scrap charge can affect furnace performance to a greater extent than the relatively small changes in gas injection level effected in these tests, and this complicates the analysis significantly.

Therefore, we have used the bosh gas hydrogen content, in moles/THM, rather than the individual or total level of supplemental fuel injection, as a correlating parameter wherever appropriate. This parameter does reflect the effects of changes in fuel mix and injection level qualitatively since natural gas contains 25% hydrogen (or 2 moles/mole C) while the coals used here contain only 3-6% H_2 (or about 0.4 mole/mole C). In addition, the data are displayed as part of either all-coal, all-gas, or high-, intermediate- or low-coal injection level groups. Periods with coal injection levels below 200 lb/THM are in the low group, while periods with coal injection levels above 300 lb/THM are in the high group. The effects of changes in scrap charge or natural gas or coal injection level within each group are then addressed as required.

Tuyere and Hearth Level Energy Control

Practice with high-level coal injection called for changing the supplemental oxygen rate by 300 SCFM for each 1.5 TPH change in coal injection rate, which is equivalent to a marginal oxygen consumption of about 0.5 lb/lb coal. The change in RAFT, then, would be determined largely by the marginal amount of oxygen injected as the level of gas injection was changed. As shown in Figure 2 it proved possible to decrease the AISI RAFT by some 450°F during the tests, with the energy balance RAFT (CRA RAFT) decreasing by about 350°F.

While there is considerable overlap in the groupings, the CRA RAFTs decreased with decreasing coal injection levels (as shown by H_2 content) in Figure 3. The decrease in RAFT within a group results from increasing levels of gas injection, however. The RAFTs within the intermediate coal injection group drop by more than 150°F, for example, as bosh hydrogen contents increase by about 6 mole/THM. The best line fit through these data gives a slope with a decrease of about 25°F RAFT per mole/THM increase in the hydrogen content, which is more than 20% greater than the drop in RAFT for all gas injection (see reference 6). The lowest RAFTs, around 3,460°F, were obtained at injection levels of about 177 lb/THM coal and 125 lb/THM natural gas, and RAFTs were actually 40-60°F higher during the all-gas 170 lb/THM injection condition. Furnace performance was quite satisfactory under these low RAFT conditions, although the operators believed that the RAFT was actually about 3,600°F based on the indicated coal and natural gas injection levels.

With the furnace properly balanced thermally, RAFT can be allowed to drop as increasing levels of coinjection increase the hydrogen content without compromising hot metal temperature aim values as shown in Figure 4. With all-gas injection it has been shown that the necessary furnace thermal balance can be obtained by maintaining roughly constant values for the thermal-plus-chemical energy contents of the hearth gases. This appears to be the case with coinjected coal and gas as well, as shown in Figure 5.

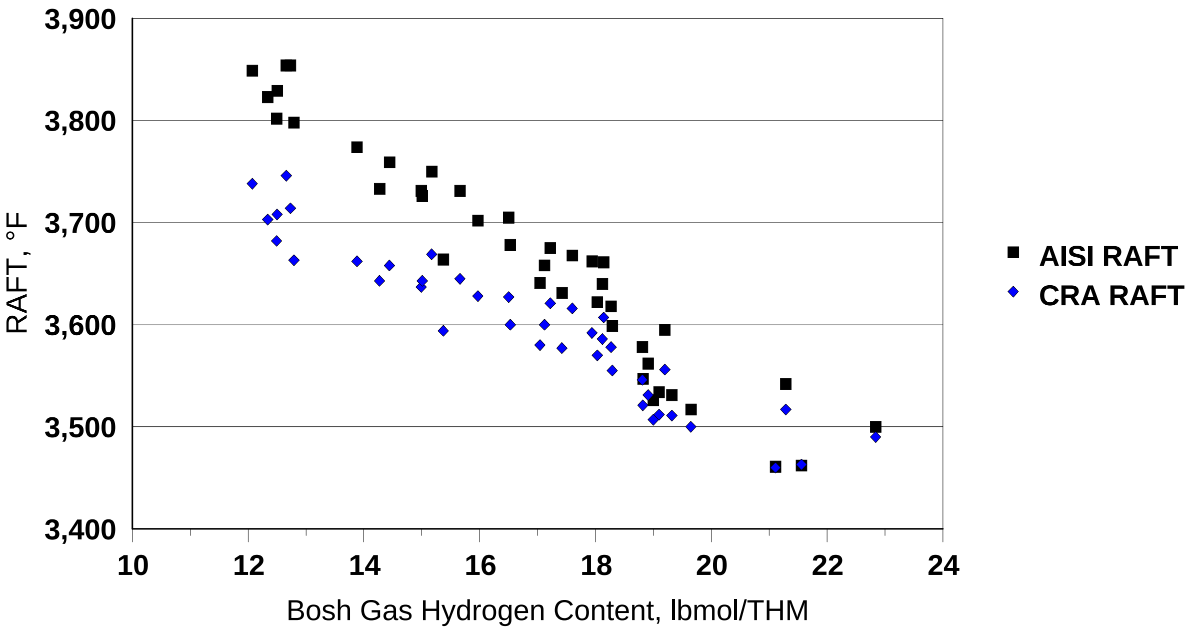
Most of the data fall within range of 0.7-0.8 MMBtu/THM for the thermal-plus-chemical energy, a range that is narrower than often found in furnaces practicing high-level gas injection. There does not appear to be any trend in the values with coal or gas injection levels, but the two highest points are for gas-only injection. The furnace was simply being run “hotter” in the gas-only period than it had been in the coinjection period immediately preceding it.

The fundamental reason why it is appropriate to maintain the thermal-plus-chemical energy level constant and allow the RAFT to decrease as bosh hydrogen contents increase is that changing hydrogen contents change the reduction mechanisms in the furnace. Overall, the hydrogen utilization efficiency does not decrease as hydrogen contents increase, as shown in Figure 6. As discussed earlier, the calculated utilization efficiencies are sensitive to the coal compositions and injection rate and natural gas injection rate assumed, and the biases in the top gas hydrogen analysis. The scatter in the data in Figure 6 are typical of the scatter obtained for gas-only injecting furnaces where there is no uncertainty in the rate or composition of the injected fuel.

Since the hydrogen content is increasing and its utilization efficiency is constant, the extent of indirect reduction in the bosh and stack must be increasing as well. With a burden of constant composition, an increase in indirect reduction must be accompanied by a decrease in the energy intensive direct reduction reaction. That this does indeed occur is shown in Figure 7, and it is the decrease in the high temperature energy required that permits the RAFT and physical hearth gas temperature to be decreased with increasing bosh hydrogen contents.

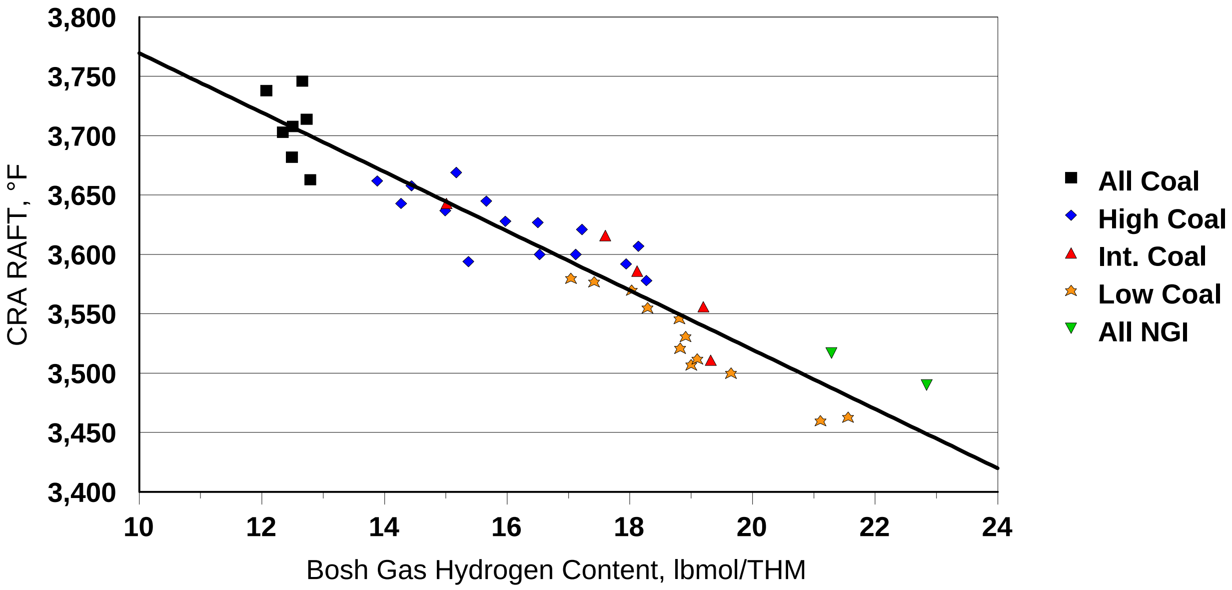
The best fit of the change in the solution loss reaction with changes in hydrogen content gives a slope of about 0.4 mole/mole, which is about 0.125 mole/mole higher than for an all-pellet burden with all-gas injection. The combined extent of direct plus indirect reduction, obtained by summing the best fit slopes for each, show an apparent decrease of about 0.1 mole/mole in the total amount of oxygen removed, but this is not related to the changes in the levels of fuels injected. Rather, it is a consequence of changes in the amount of scrap charged to the burden. While changes in the scrap charge occurred under all injection conditions, most of the practice was with scrap charges between about 200 and 300 lb/THM. At the average scrap composition assumed, a change of 100 lb/THM in the scrap charge would change the total reduction by about 1.5 mole/THM and, on average, there was more scrap on the burden when hydrogen contents were higher than when they were lower.

Figure 2. AISI RAFT and CRA RAFT vs. Bosh Gas Hydrogen Content



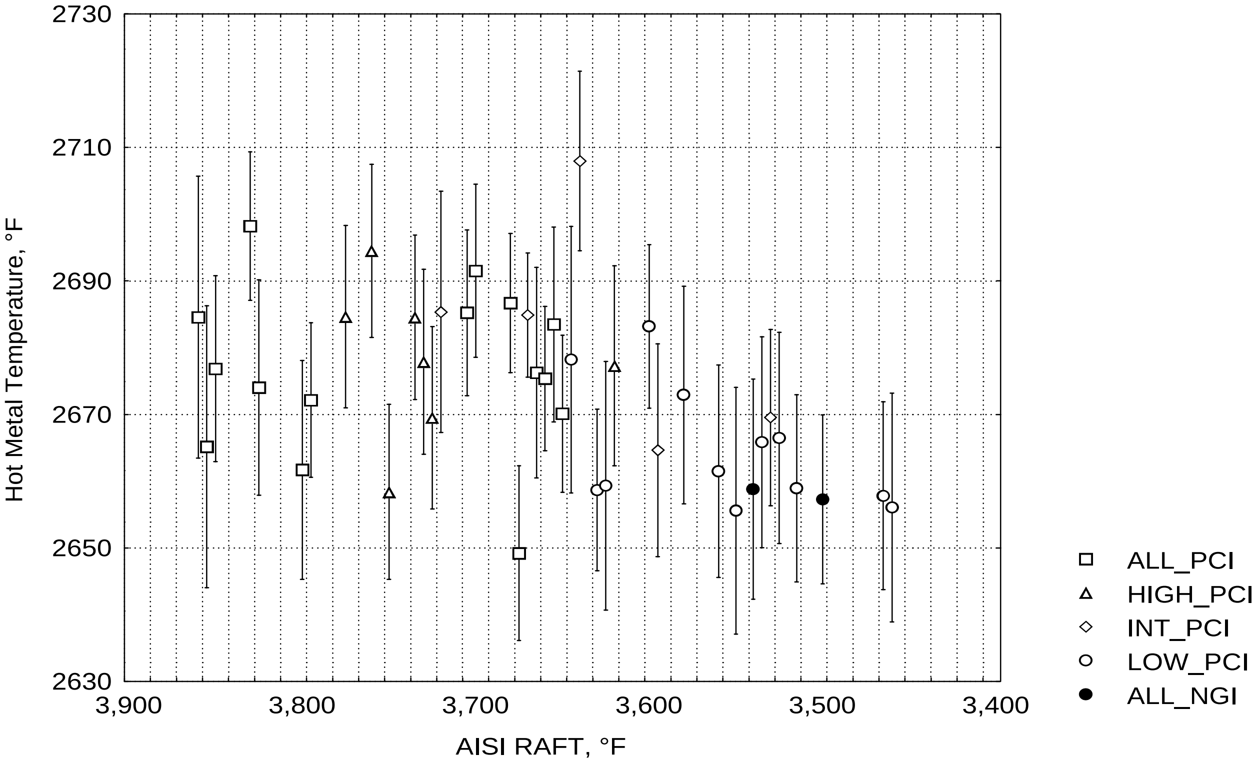
Source: Charles River Associates, 1998

Figure 3. CRA RAFT vs. Bosh Gas Hydrogen Content



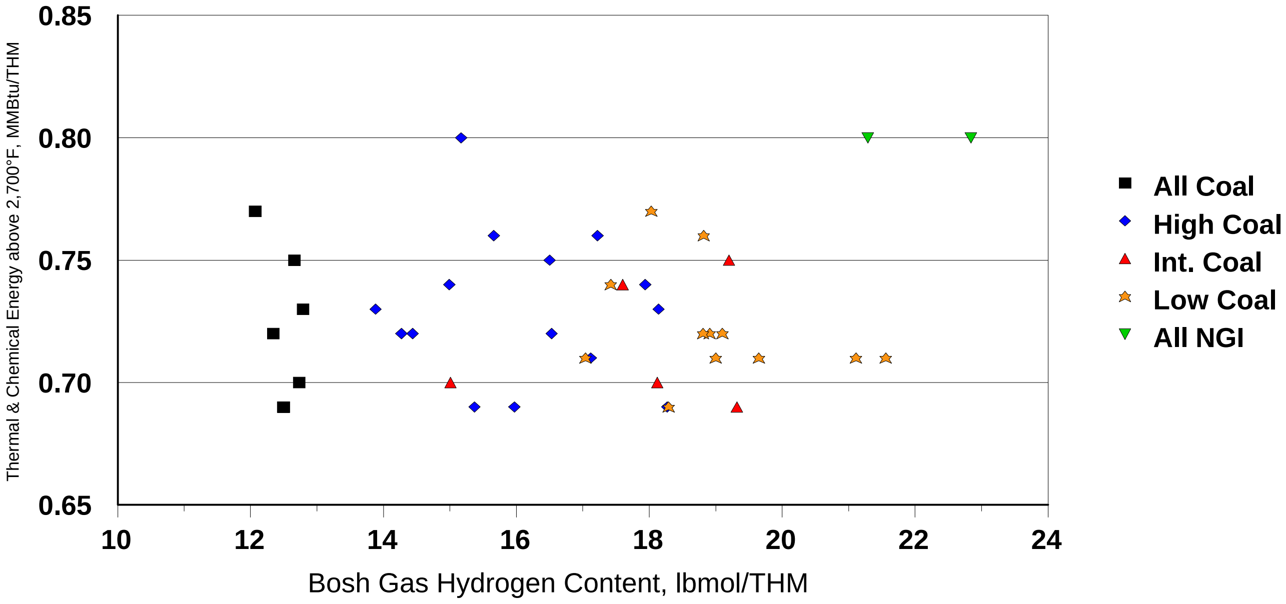
Source: Charles River Associates, 1998

Figure 4. Hot Metal Temperature vs. AISI RAFT



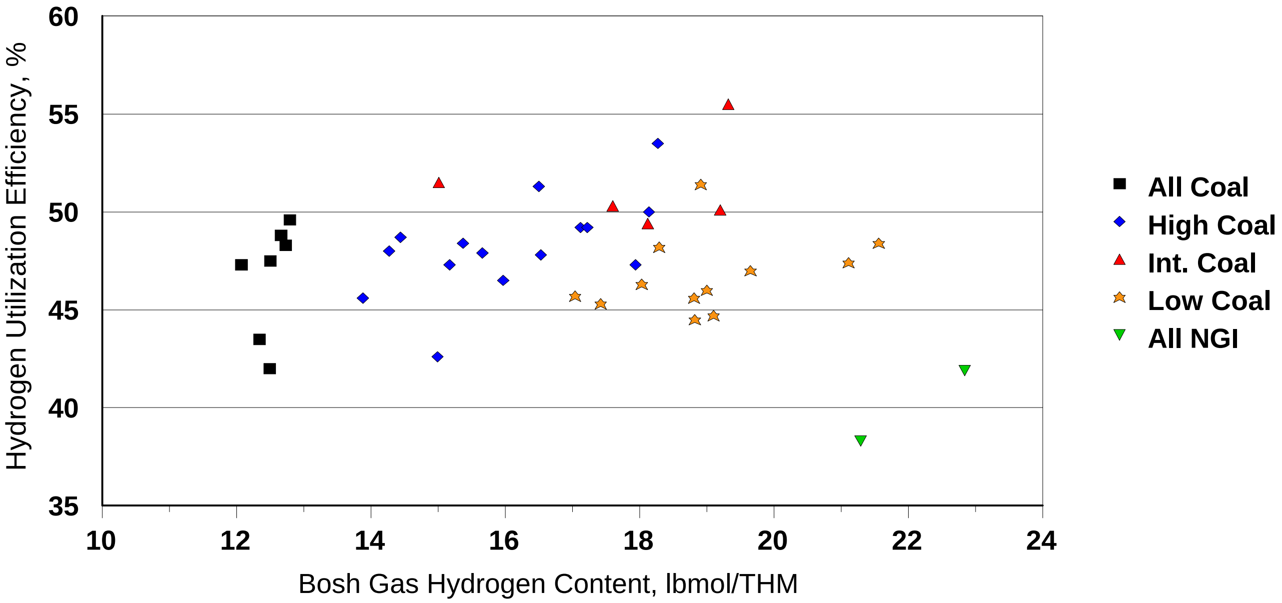
Source: Charles River Associates, 1998

Figure 5. Thermal Condition vs. Bosh Gas Hydrogen Content



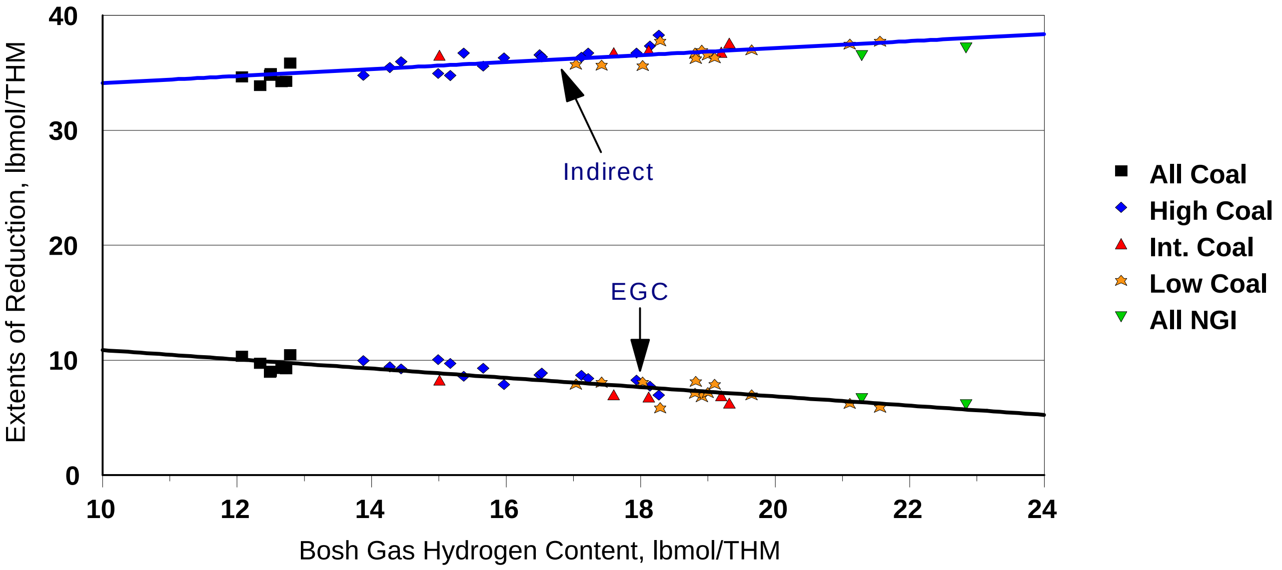
Source: Charles River Associates, 1998

Figure 6. Overall Hydrogen Utilization Efficiency vs. Bosh Gas Hydrogen Content



Source: Charles River Associates, 1998

Figure 7. Extents of Direct and Indirect Reduction vs. Bosh Gas Hydrogen Content at USS-Gary BF No. 4



Source: Charles River Associates, 1998

These analyses show that the aim values and thermal control for a furnace coinjecting natural gas and coal should be altered from values used with all coal injection.

- The RAFT should be allowed to drop with increasing levels of gas injection and bosh hydrogen contents. The rate of decrease is at least as high as for gas-only injection, at about 25°F/mole/THM H_2.
- This decrease is appropriate because the extent of the highly endothermic solution loss reaction decreases with increased bosh

hydrogen content. The rate of decrease in these tests was higher than for gas-only injection, at about 0.4 mole/mole H_2, but that may have been influenced somewhat by the changes in scrap charge made during the tests.

- Maintaining an essentially constant value for the thermal-plus-chemical energy will provide proper thermal balance for the furnace as the levels of coinjection change, even though RAFT is decreasing.

Furnace Productivity and Permeability

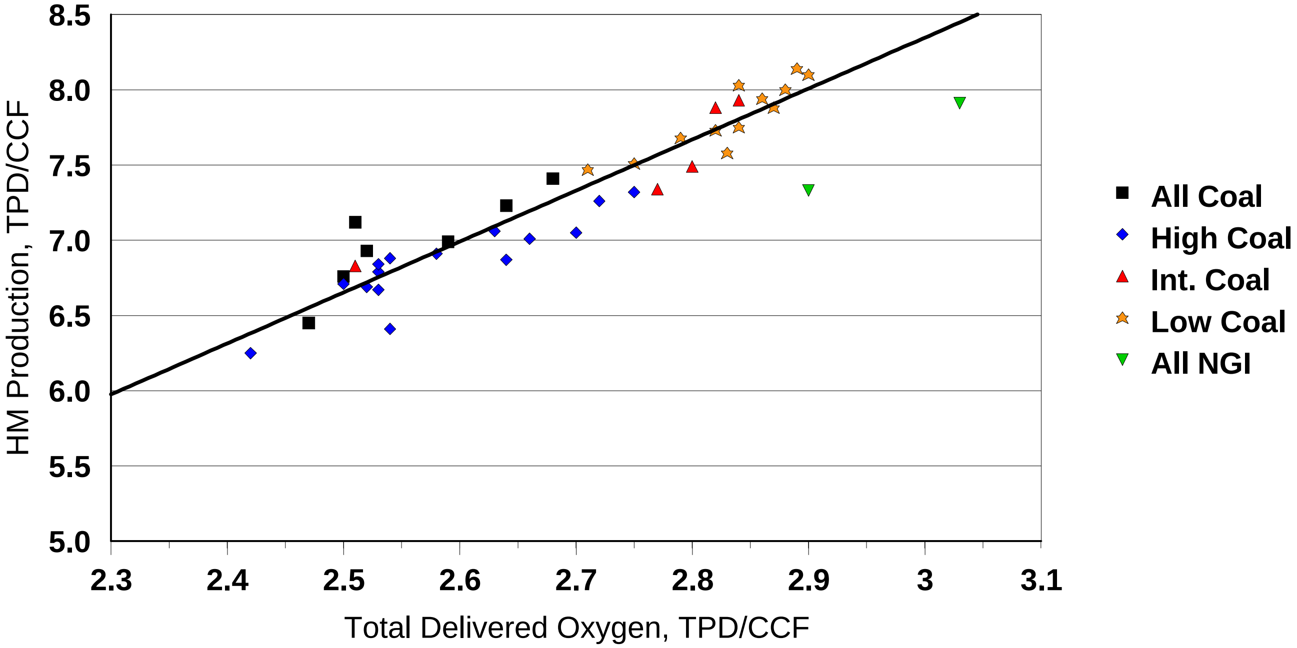
Increases in furnace productivity can be obtained by driving the furnace harder, i.e., supplying more oxygen to it, or by reducing the specific furnace energy requirements by putting metallics on the burden, or both. As discussed above, the scrap charge on the burden was mostly between about 200 and 300 lb/THM through the tests, and its composition was variable. Furnace productivity data are shown in Figure 8 as a function of the total amount of oxygen delivered to the furnace. As expected, these productivities are higher than for all-pellet burdens at the same oxygen consumption because of high scrap charge. The slope of the best fit through the data shows a marginal productivity of about 3.4 TPD hot metal/TPD oxygen supplied, which is quite high. In absolute terms, there was an increase of 460 TPD in productivity, or 12%, with coinjection of natural gas. While there is some overlap in the groupings, it is clear that the furnace took more oxygen with low coal injection levels than at intermediate levels, and more at intermediate than at high levels or all coal practice. As will be shown, there was some improvement in furnace permeability as the level of coal injection decreased and the level of gas coinjection increased. However, increasing the level of coinjection also decreased the *actual* volume of the bosh gases, because it was accompanied by higher enrichment and the temperature of the gases was lower at the lower RAFTs. This would have allowed the furnace to accept more total oxygen even at a constant level of permeability.

Different levels of scrap charge would have affected both the absolute productivity and the slope of the productivity–oxygen curve. Evaluation of data from gas injecting furnaces using well characterized scraps on the burden showed that the contribution to productivity was about 0.54 TPD/CCF/100 lb/THM Fe in the scrap. Using this correction factor, and normalizing to a blast temperature of 1,850°F using a correction factor of 0.3 TPD/CCF/100°F change in temperature, shifts the slope and location of the productivity curve as shown in Figure 9.

Here the slope has been reduced to about 2.65 TPD production/TPD oxygen, but this is still significantly higher than the average of about 2.0 TPD/TPD obtained from furnaces injecting gas only. However, the data on gas injection furnaces extend normalized productivity to 9 TPD/CCF and oxygen consumption to 3.8 TPD/CCF, far higher than obtained here. In fact, the high range of the data for coinjection in Figure 9 (7 and 2.9 TPD/CCF, respectively) are right in the middle of the low range of data for gas injecting furnaces and they are lower at the low end of productivity and oxygen consumption. Data at higher levels of coinjection and oxygen consumption would be required to determine if the high slope shown here persists to even higher levels of productivity.

There is reason to believe that the slope would decrease, however, because the relative contributions of supplemental oxygen and wind to the total oxygen supply would change at high productivity. The sources of oxygen consumed by the furnace during the tests are shown in Figure 10.

Figure 8. HM Production vs. Total Delivered Oxygen



Source: Charles River Associates, 1998

Figure 9. Normalized HM Production vs. Total Delivered Oxygen

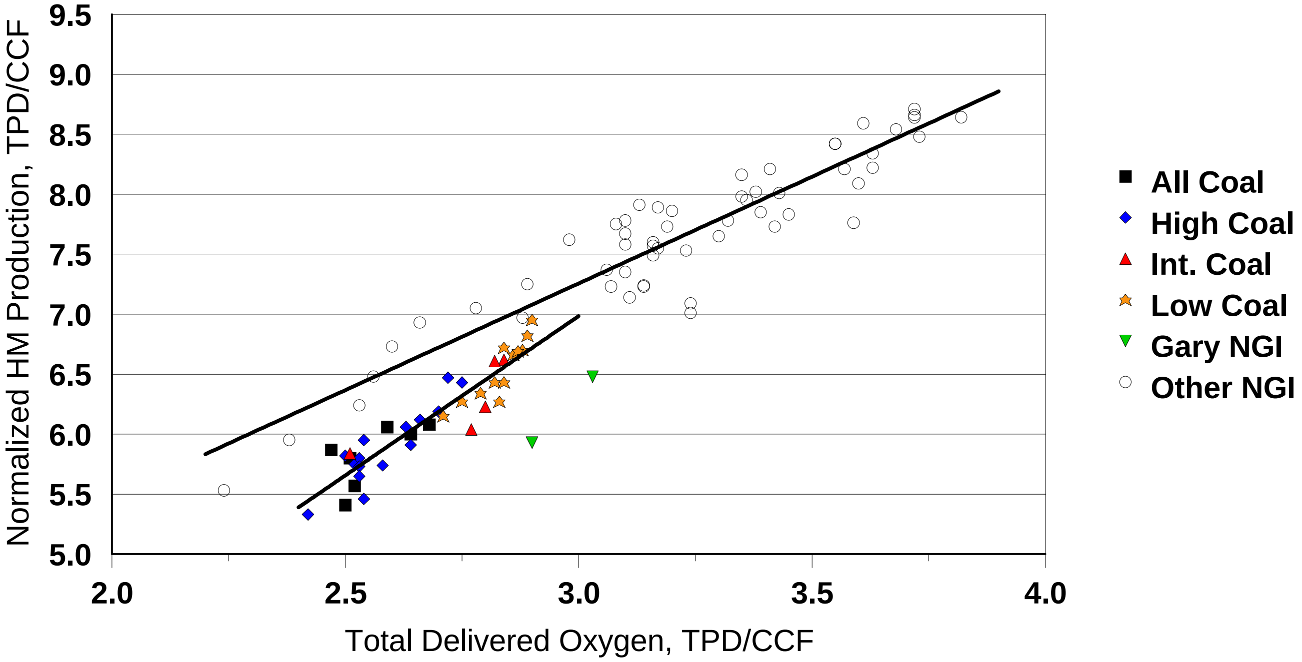
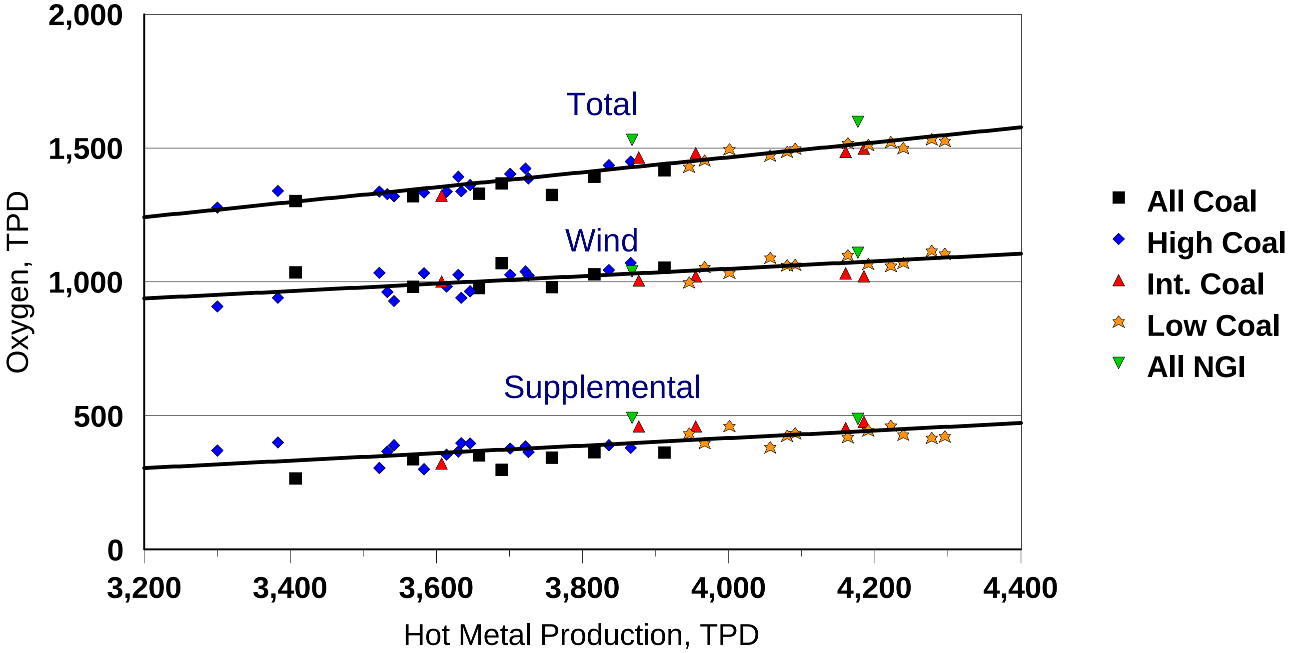


Figure 10. Wind and Oxygen vs. HM Production



Source: Charles River Associates, 1998

Higher productivity was achieved by providing the furnace with both more supplemental oxygen *and* more wind, and the slopes of each were almost exactly the same. This is in sharp contrast to the situation with injection of gas only where increased productivity is obtained with less wind and much more supplemental oxygen. When gas injecting furnaces are not being pushed for production, supplemental oxygen consumption at high injection levels can be as low as 0.67 lb/lb gas (see reference 7). When productivity is required, however, the supplemental oxygen consumption is typically in the range of 1 lb/lb, or about 8 lb of oxygen per mole of contained hydrogen. The consumption of supplemental oxygen in these tests is shown in Figure 11 normalized to the bosh gas hydrogen content, most of which is derived from the coinjected coal and gas. While there is considerable scatter in the data, the best fit gives a marginal consumption of oxygen of about 5.9 lb/mole H_2.. The low coal injection data on average lie below the best fit while the intermediate and high coal data lie above it. These data show that *total* supplemental oxygen consumption was driven by coal injection, not gas injection, and the *marginal* consumption of oxygen for gas was only of the order of 0.6 lb/lb gas. On a weight basis this is slightly higher than the amount of oxygen provided for coal combustion. However, this is only about 0.3 mole O_2/mole CH_4, which is far below the amount required for complete combustion. During the gas-only injection periods supplemental oxygen consumption was very high, at more than 1.4 lb/lb, which contributed to the high thermal-plus-chemical energies and high hearth gas temperatures produced at that time.

The balance of supplemental oxygen and wind that is “optimum” for any mix of coinjected fuels may be constrained by the furnace production requirements and furnace permeability, and both varied significantly over the course of these tests.

The values of the furnace pressure drop per unit height divided by the average burden density are shown in Figure 12, and the scatter in the data are typical of furnaces with all-pellet burdens injecting natural gas only. There does not appear to be any dependence of pressure drop on either coal injection level or coinjection level as measured by the bosh hydrogen content. This is probably because operators would react to increasing blast pressures by reducing the coal and oxygen injection rates, or by reducing the wind rate.

The permeability is lower than for all-pellet gas injecting furnaces, however, by as much as a factor of two. Of the variables examined, the total level of injection of supplemental fuels was the best predictor of furnace permeability as shown in Figure 13.

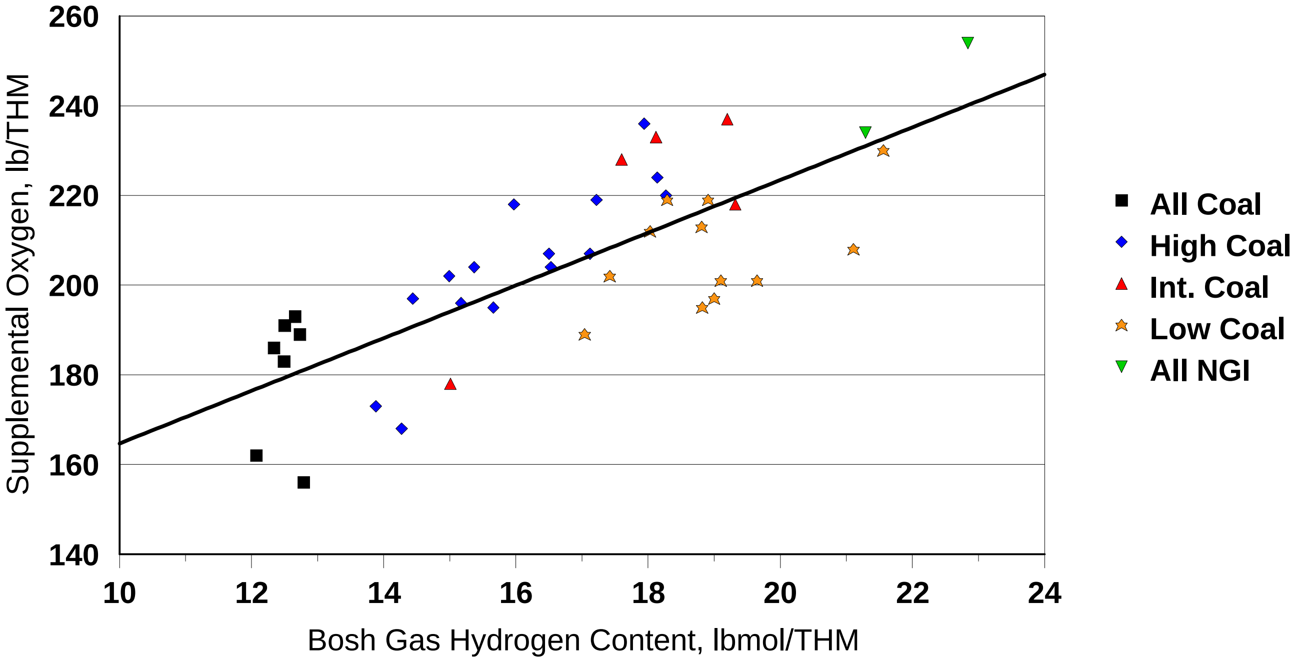
As is the case with other correlations shown in this chapter, the data can be grouped by coal injection level. Permeabilities for all coal injection practice lie below the best fit through all of the data, and the slope of the permeability-injection relationship is high with about a 30% loss in permeability per 100 lb/THM increase in coal injection level. The high and intermediate coal rate coinjection data straddle the best fit, and show permeability losses of more than 15%/100 lb/THM increase in injection level. These relationships between increasing permeability loss and increasing coal injection level are consistent with the operator’s previous experience with all coal injection practice.

Some of the scatter in the data, and the generally low permeability values, is due to the presence of the large amounts of scrap of variable quality and ore, burdening practice, and the effects of the injected coals. The general increase in permeability with increasing bosh gas hydrogen contents appears to be related to increases in the level of coinjected natural gas, however, which is consistent with the observation that operators often make of smoother burden descent upon introduction of natural gas.

Furnace Fuel Consumption

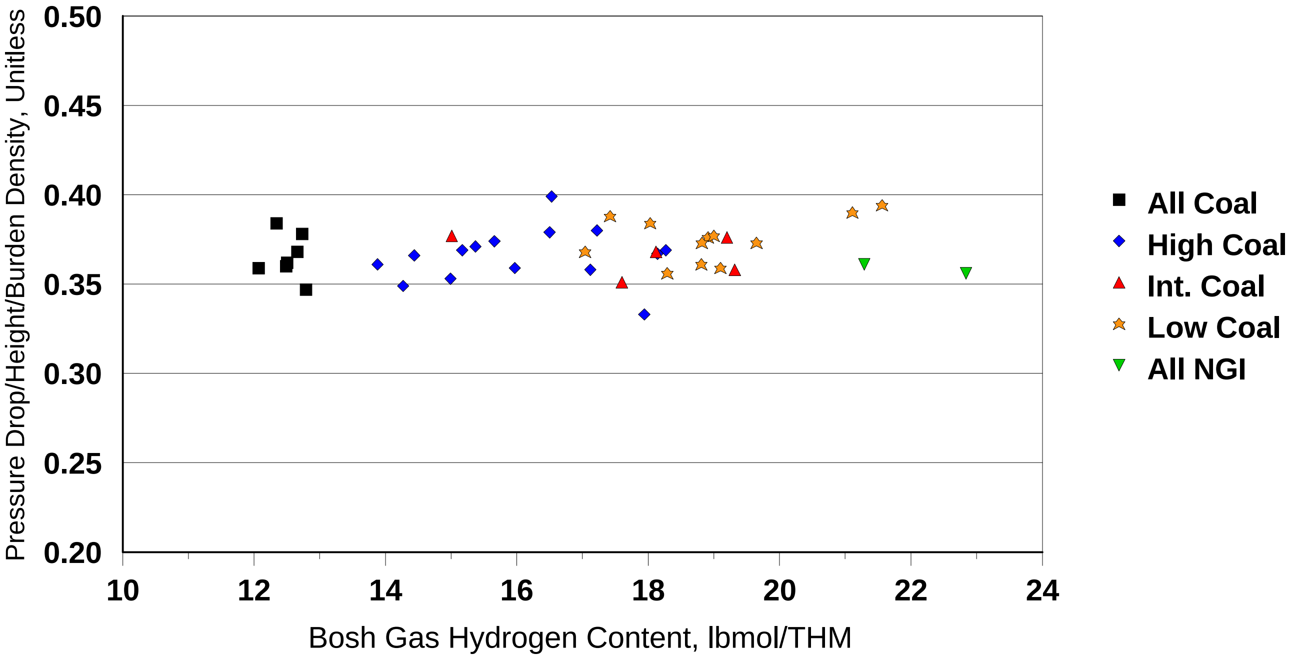
Changing the amount and mix of fuels coinjected would change the furnace fuel rate because coal and natural gas have different replacement rates for coke. The fuel rate would also change as the scrap charge to the burden, blast moisture and blast temperature, and hot metal silicon contents changed. The furnace coke and fuel rates obtained in these tests are shown as a function of the bosh gas hydrogen content in Figure 14.

Figure 11. Supplemental Oxygen Use



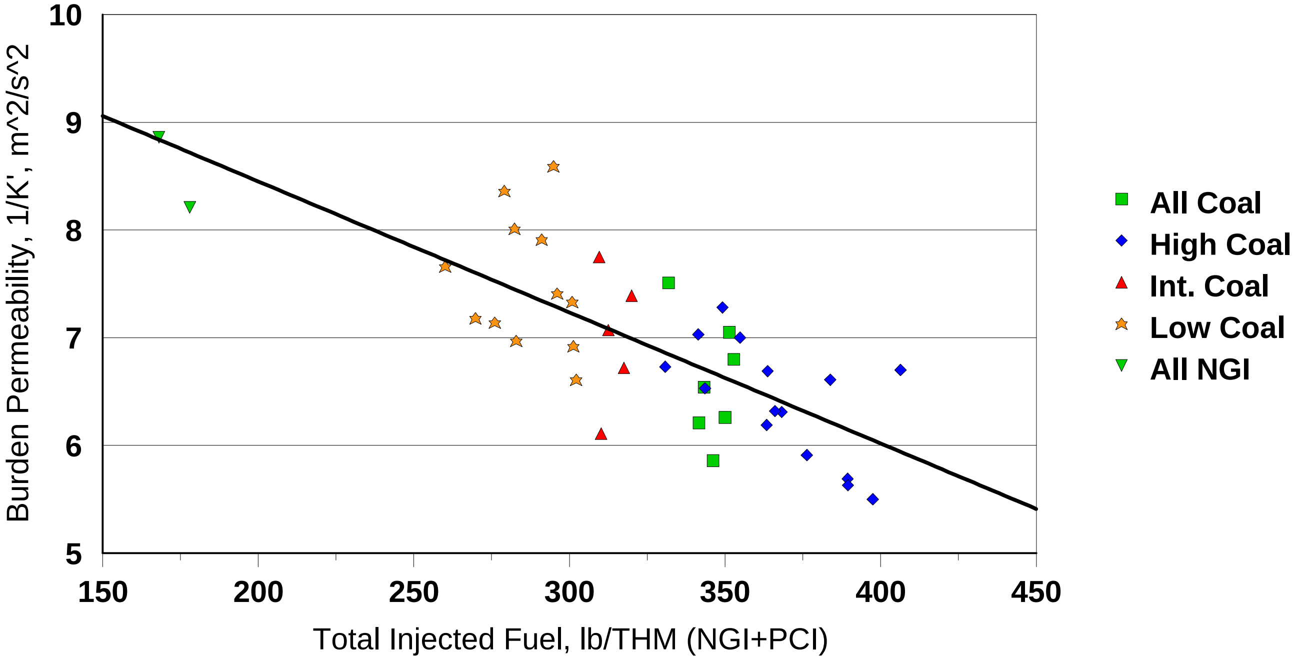
Source: Charles River Associates, 1998

Figure 12. Pressure Drop per Unit Height Divided by Burden Density



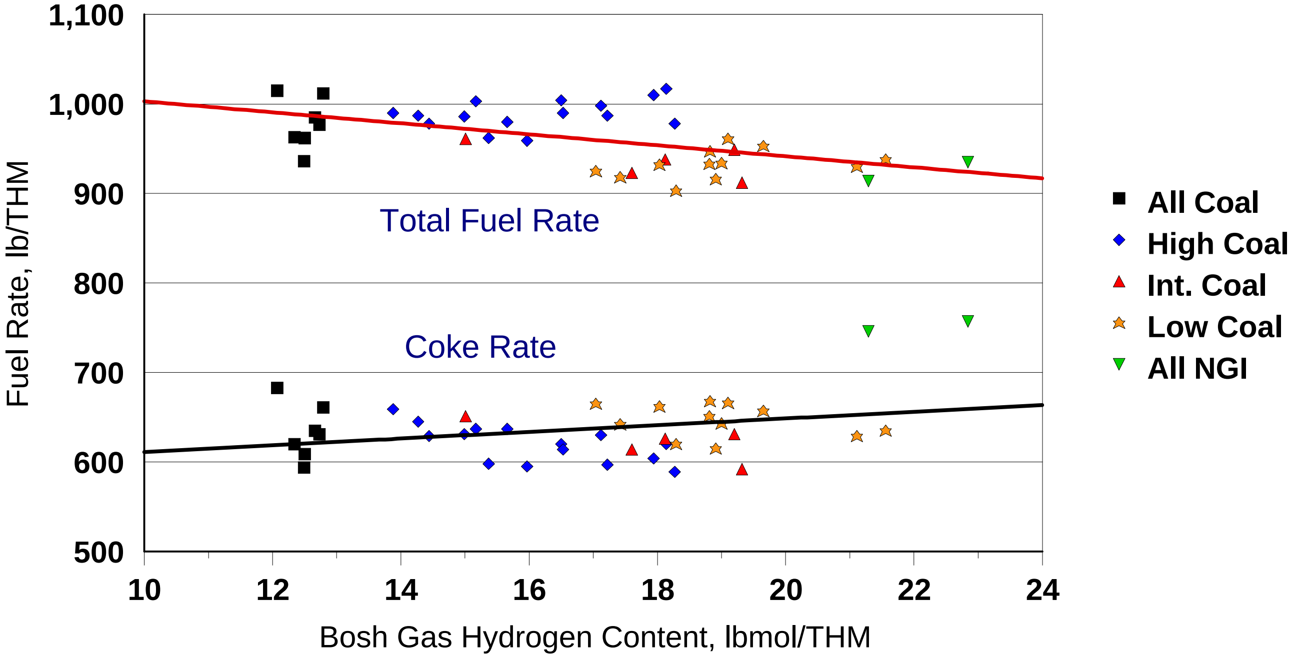
Source: Charles River Associates, 1998

Figure 13. Burden Permeability vs. Total Injectant Level



Source: Charles River Associates, 1998

Figure 14. Unadjusted Coke and Fuel Rate vs. Bosh Gas Hydrogen Content



Source: Charles River Associates, 1998

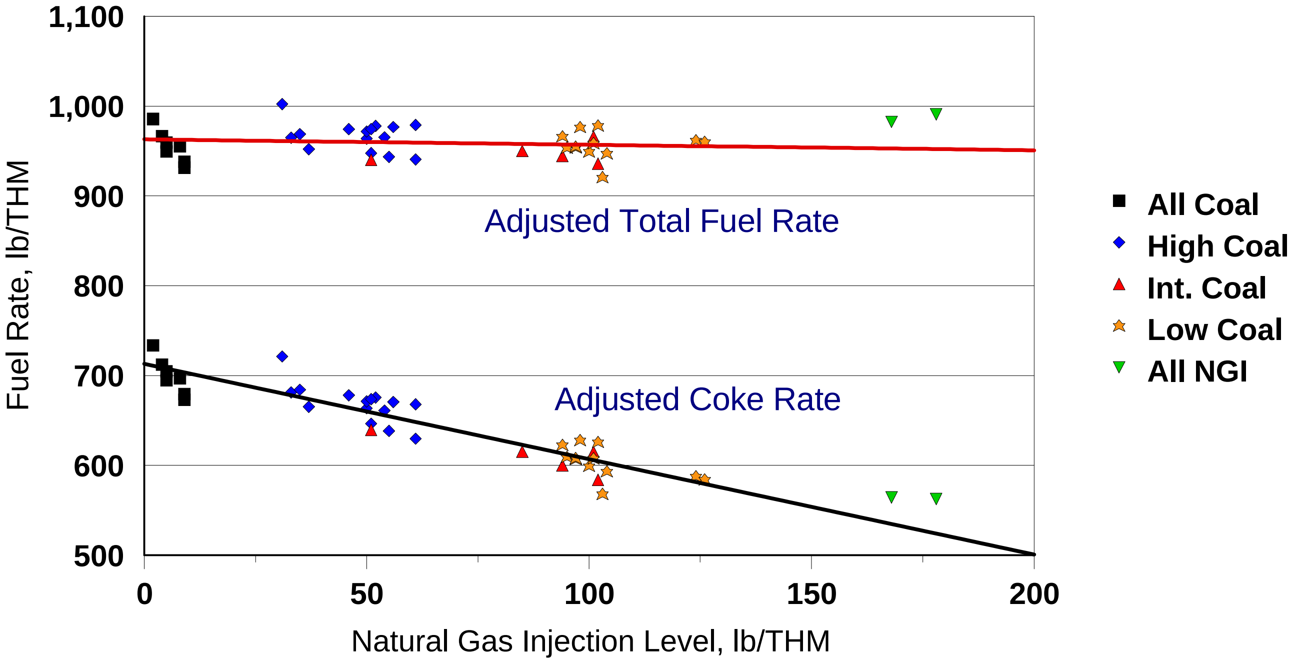
Once again there is considerable scatter in the data, with R^2 values for the best fits to the fuel and coke rates of only 0.28 and 0.12. The data are grouped, however, with the low coal periods showing lower and the high coal periods showing higher than tread line fuel rates. This behavior is generally reversed on the coke rate trend line. The coke rate increased slightly as bosh hydrogen content increased because of amount and mix of injected fuels changed. The total injection levels decreased from 330-400 lb/THM for the high-level coal periods to 310-340 lb/THM for the intermediate and 270-300 lb/THM for the low coal periods. The total fuel rate decreased, however, because lower replacement ratio coal was being displaced in the supplemental fuels mix by higher replacement ratio natural gas. The natural gas injection levels increased from 40-60 lb/THM in the high coal periods to 50-90 lb/THM and then to 100-120 lb/THM in the intermediate and low coal periods.

The data in Figure 14 cannot be used to determine the replacement ratio obtained with the coinjected gas because of the changes in burdening and coal injection levels that occurred at the same time. To "back out" the effects of the injected gas it is necessary to account for the effects that other changes in practice had on the coke rate. Based on analysis of the performance of other furnaces, the coke correction factors in Table VIII were applied to the furnace parameters presented in Table VI to normalize them to a common basis. The coke and fuel rates obtained by normalizing performance in this way are shown as a function of the natural gas injection level in Figure 15.

Table VIII. Coke Correction Factors used to Normalize Furnace Fuel and Coke Rates

Factor	Reference Value	Adjustment Factor
Coal	250 lb/THM	0.85 lb coke/lb coal
Scrap	250 lb/THM	0.20 lb coke/lb Metallic Iron
Blast Moisture	7 gr/scf	4 lb coke/gr/scf
HM Silicon	0.7%	10 lb coke/0.1% Si.

Figure 15. Adjusted Coke and Fuel Rate vs. Natural Gas Injection Level



Note: Coke Rate Adjusted to 250 lb/THM PCI (0.85 lb Coke/lb Coal), 250 lb/THM Blended Scrap (20 lb Coke/100 lb Fe Met.)
7 gr/SCF blast moisture (4 lb coke/gr), and 0.70% HM Si (10 lb coke/0.1% Si)
Source: Charles River Associates, 1998

The normalization procedure decreases the amount of scatter in the unnormalized data shown in Figure 15 and results in the expected trend of slightly decreasing fuel rate and strongly decreasing coke rate with increasing levels of natural gas injection. The replacement ratio for coinjection of natural gas, the slope of the coke rate curve, is almost 1.1 pound of coke displaced per pound of gas injected, with an R^2 value of the fit of 0.86. This value is somewhat sensitive to the magnitude of the coke correction factors chosen. If the scrap quality is lower than assumed, its coke correction factor will be lower, but decreasing the correction factor to 0.1 lb coke/lb Fe only increases the estimated replacement ratio for gas by 0.04 lb/lb The estimated replacement ratio for gas is more sensitive to the replacement ratio assumed for the coal: a change in coal's replacement ratio by ±0.05 lb/lb would result in a change in the ratio calculated for gas of ± 0.08 lb/lb These conclusions do not depend on the reference point chosen to normalize the data.

The data in Figure 15 represent the normalized estimates of coal, coke, and natural gas rates after applying the correction factors to coal and gas rates as discussed earlier. These data, in our judgment, best represent furnace performance, satisfying material and energy balances with the least correction to "as-reported" data to give reasonable results. Since the natural gas rates have been corrected systematically by 20% and the coal injection rates have been corrected upward by 10% at the lower range of rates, use of the "as-reported" data would have resulted in the calculation of higher replacement ratios for gas. Using all as-reported data and the coke correction factors in Table VIII gives a replacement ratio for gas of about 1.25 lb/lb

Given the limited span of injection rates covered and the uncertainty in the coke and scrap correction factor used, the sense of the data is that the replacement ratio obtained for gas in these tests was at least 1.1 lb/lb

Hot Metal Quality

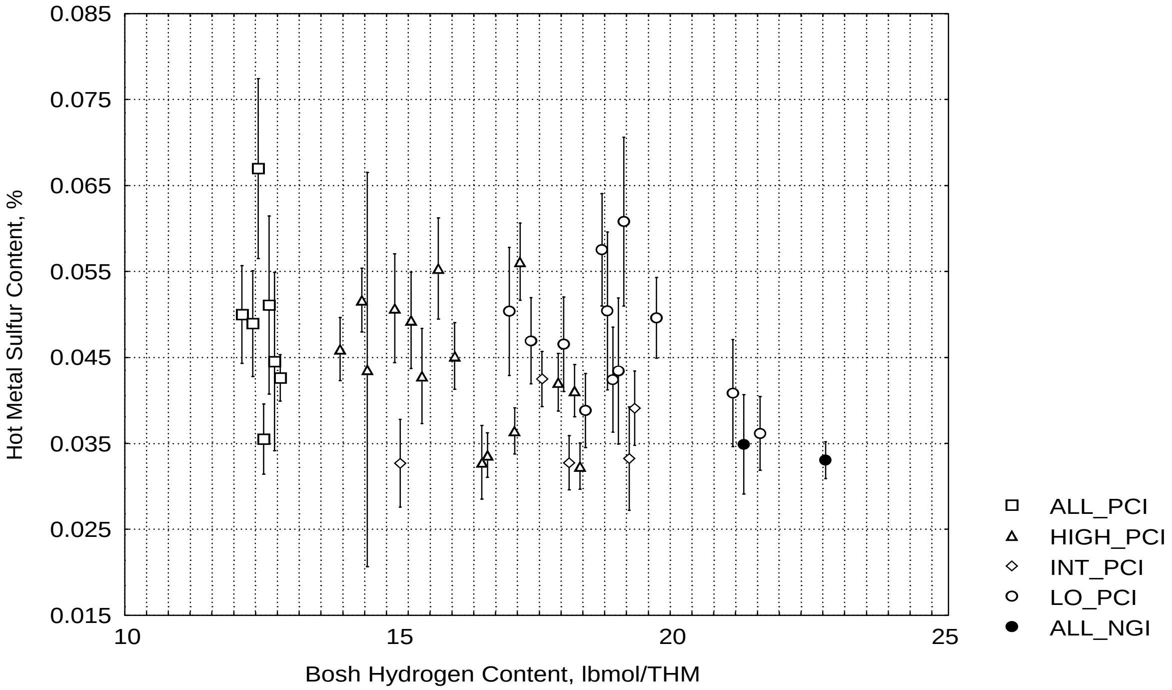
In Figure 4 it has been shown that the hot metal temperature did not change significantly as the level of gas coinjection increased and the RAFT decreased. The standard deviations in the hot metal temperatures were also unaffected by the coinjection level, so by these measures hot metal quality was not affected by this practice.

With average coal sulfur contents in the range of 0.8-0.9%, a replacement ratio for coal of less than 1.0, and coke sulfur contents of about 0.6%, decreasing the level of coal injection and increasing the level of gas injection would decrease the sulfur load to the furnace. During these tests the sulfur level decreased from about 7.5 to about 5.5 lb/THM as the bosh hydrogen content increased from about 12 to about 22 mole/THM.

The operators did not readjust the aim value for slag basicity during the tests and it remained in the vicinity of 1.1. As a result of these changes, the hot metal sulfur content decreased, as expected, from about 0.05% in the base case periods to less than 0.04% in the low or no coal high gas injection periods, as shown in Figure 16. The decrease is significant with respect to the magnitude of the standard deviation in the averages, which were typically about 0.011%.

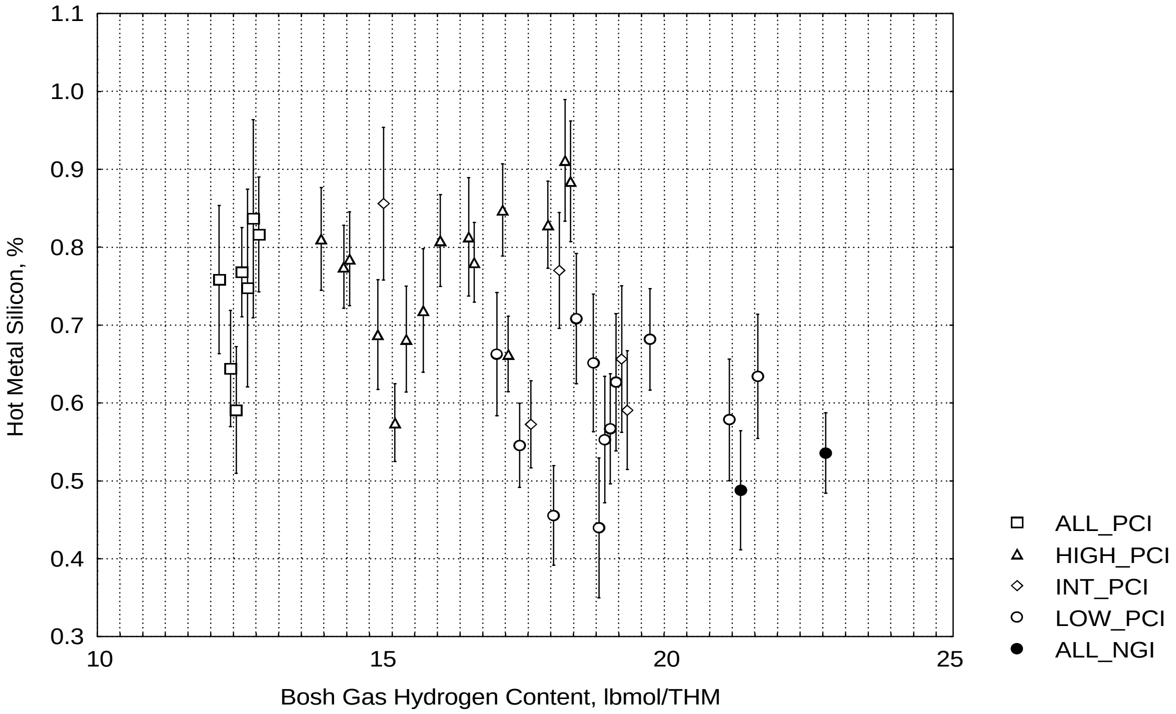
The reduction behavior of silica under injection or coinjection conditions is not well understood. Overfueling the furnace increased the silicon content in these tests even in the absence of significant increases in hot metal temperature. The data in Figure 17 suggest that the hot metal silicon content decreased somewhat as the level of coal injection decreased and the coinjected gas level increased, independent of changes in hot metal temperature as shown in Figure 4. While there is considerable scatter in the data, the slope of the decrease is large with respect to the standard deviations of the averages, which are about 0.15%.

Figure 16. Hot Metal Sulfur Content vs. Bosh Gas Hydrogen Content



Source: Charles River Associates, 1998

Figure 17. Hot Metal Silicon Content vs. Bosh Gas Hydrogen Content



Source: Charles River Associates, 1998

In addition to the usual statistical measures of hot metal quality, the standard deviation in hot metal silicon and sulfur contents and temperature, CRA calculates the cast-to-cast variability in the thermal state of the hearth as measured by the change in energy required to produce the amount and composition of the hot metal in each cast (see reference 4 for an extended description of this parameter). A furnace that could produce hot metal with identical compositions and temperatures on successive casts would show a cast-to-cast variability, dQ/dt, of zero MMBtu/hr. The greater the changes in temperature and composition, the greater the variability. The values of the cast-to-cast variability for the range of bosh hydrogen contents in these tests are shown in Figure 18, together with some data from the high-level injection tests at ACME.

The bosh hydrogen contents in these tests ranged from about 11 to 22 mole/THM, whereas the range in the tests at ACME was from about 4 to 37 mole/THM because the practice there varied from no injection to an injection level of more than 300 lb/THM gas. For injection levels where the bosh hydrogen contents were the same, there is no difference between the cast-to-cast variability for the two operations. The implication of this finding is that bosh hydrogen contents above 10 mole/THM or so are sufficient to reduce cast-to-cast variability to the same level regardless of burdening practice or the level or composition of the injectants. This is somewhat surprising given the well known deleterious effects that high-level coal injection and poor quality scrap have on permeability and burden movement.

ECONOMIC IMPLICATIONS OF COINJECTION PRACTICE

Under circumstances in which the economics of scale inherent in large coal preparation systems can be utilized, injection of granular or pulverized coal at levels of 250–350 lb/THM can provide substantial economic benefits in terms of coke savings, so long as burdening practice can be adjusted to prevent productivity losses and limit the consumption of supplemental oxygen. The lowest costs will probably be obtained when the coal preparation and injection systems are operated near their capacity limits, the proper coal has been selected, and coke savings are maximized.

The coke replacement ratios that can be achieved by injected coals depends on furnace operating conditions, injection practice, and especially on the composition of the coal. However, available data on medium to large sized furnaces suggest that replacement ratios are normally below one pound coke displaced per pound coal injected, and that increasing the injection level of coal typically results in decreases in burden permeability that will either constrain production or require high levels of blast enrichment.[10] These tests have shown that coinjection of natural gas at levels up to 125 lb/THM can provide additional coke savings with a high replacement ratio as well as increased productivity with relatively low marginal consumption of supplemental oxygen when additional hot metal is required.

The economic impacts of coinjection practice under typical North American conditions are illustrated by the examples shown in Tables IX through XII.

The enrichment necessary in these examples is higher than was required in the tests at Gary because the coal injection rate is constant and permeability must be expected to decrease as the total amount of fuel injected increases. The decrease shown in coal injection level results from the increase in furnace productivity, not from a decrease in injection rate.

The decreases in coke rate resulted both from reductions in the extent of the solution loss reaction and in the blast moisture level that are made possible by the hydrogen content of the injected gas. The amount of top gas generated decreases as the gas injection level increases, but its energy content increases because of its higher hydrogen content.

When coinjecting gas at relatively low levels, costs are reduced in the furnace area because the replacement ratio is high and relatively little additional enrichment is required. When coinjecting at high levels to obtain productivity increases, the incremental costs of oxygen and gas exceed the savings due to decreased coke

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[10] *The Impacts of High Rates of Fuel Injection on Coke Reduction and Productivity Improvement in the Blast Furnace*, Gas Research Institute (GRI-96/0226), June 1996.

consumption, but that is more than offset by the value of the incremental hot metal produced. Also,

Figure 18. Averages and Standard Deviations for Cast-to-Cast Variability

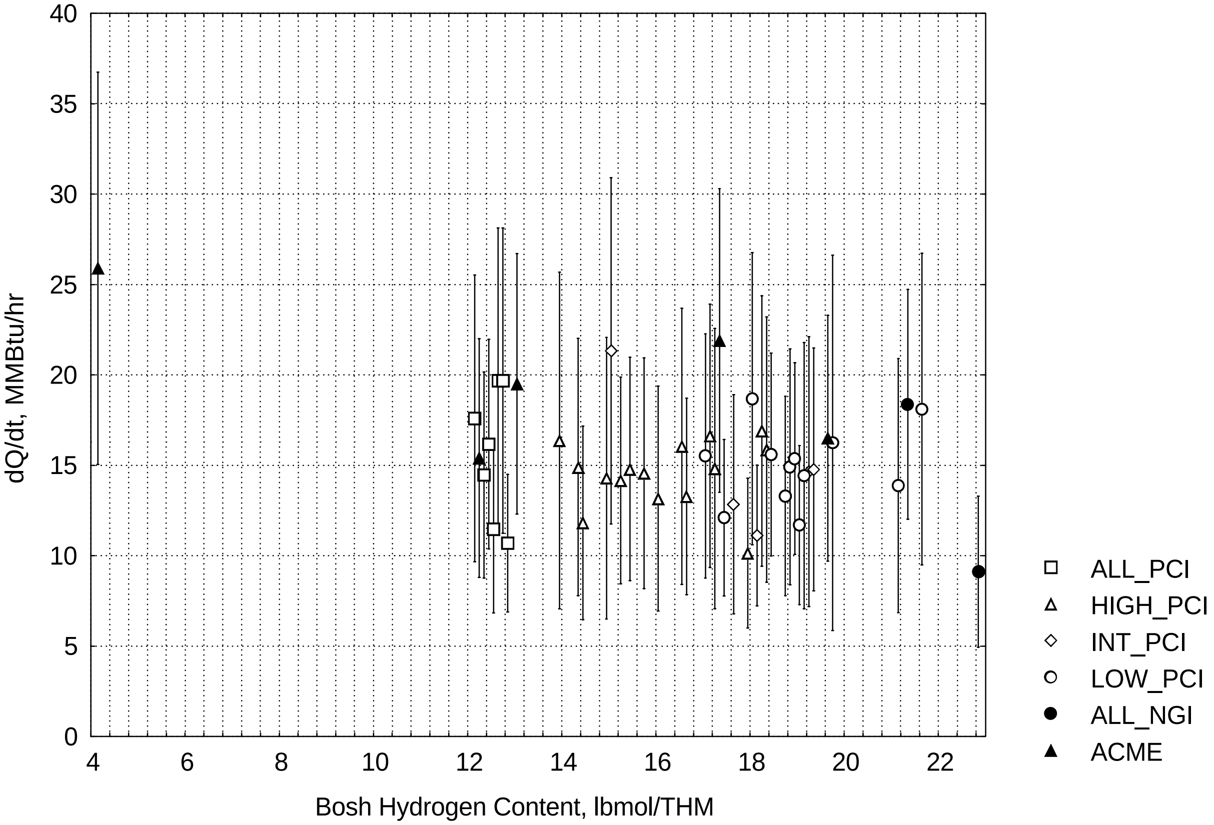

Table IX. Compositions Assumed for Economic Analysis of Coinjection Practice

Material	**Composition, %**							
	H_2O	**Fe**	**C**	**S**	**SiO_2 Al_2O_3**	**CaO+MgO**	**H_2**	**O_2**
Pellets(1)	5.0	63.1	-	0.01	3.59	0.66	-	27.2
Sinter(1)	3.0	55.2	0.03	0.03	6.14	12.97	-	22.0
Coke	3.7	0.7	91.9	0.53	6.50	0.23	-	-
Coal	1.0	-(2)	86.8	0.83	-(2)	-(2)	4.23	1.76

(1) Burden is 60% pellets, 40% sinter.
(2) Ash content 5.1%.

Table X. Furnace Parameters for Coinjection Economic Analysis

Case		Base Case	Coke Rate Reduction	Productivity Increase
Parameter	**Units**			
Production	TPD	7,000	7,000	7,400
Productivity	TPD/CCF	7.77	7.78	8.22
Wind	MCF/THM	32.8	31.6	29.3
Supplemental O_2	lb/THM	136	165	233
	TPD	475	577	861
Blast Moisture	Gr/SCF	12	5	5
Blast Temperature	ºF	2,075	2,075	2,075
Coal Injection	lb/THM	250	250	236
Gas Injection	lb/THM	0	50	125
RAFT(1)	ºF	3,880	3,796	3,547
TCE(2)	MMBtu/THM	0.90	0.89	0.84
Coke Rate	lb/THM	729	658	600
Fuel Rate	lb/THM	979	958	961
Hot Metal S	%	0.0415	0.0395	0.0369
Hot Metal Si	%	0.50	0.50	0.45
Hot Metal Temperature	ºF	2,700	2,700	2,700
Top Gas Temperature	ºF	310	333	358
Top Gas CO/CO_2	-	1.11	1.07	1.12
Top Gas HHV	BTU/SCF	89.7	92.2	104.7
Top Gas Energy	MMBtu/THM	4.66	4.69	5.28
Stove Heat	MMBtu/THM	2.09	2.04	1.95
Blast Compression	MMBtu/THM	1.55	1.51	1.44

(1) By energy balance with coke at 2900ºF; AISI RAFTs are higher.
(2) Thermal plus chemical energy content of the hearth gases.

Table XI. Unit Costs for Economic Analysis of Coinjection Practice

Component	Unit/Cost	Component	Unit Cost
Coke	\$120/ton	Hot Metal Desulfurization	\$0.05/0.001%
Coal(1)	\$60/ton	Hot Metal Value(2)	\$30/ton
Natural Gas	\$3.0/MMBtu	Top Gas Value	\$2.25/MMBtu
Supplemental O_2	\$26/ton	Blast Moisture	\$4/Mlb

(1) Incremental cost of purchased coal plus preparation.
(2) Incremental value.

Table XII. Cost Savings for Coinjection Practice

	Cost Savings from Base Case, $/THM	
Coinjection Case	**Coke Rate Reduction**	**Productivity Increase**
Cost Component		
Furnace Area		
Coal	-	0.45
Gas	(3.34)	(8.34)
Coke	4.26	7.74
O_2	(0.39)	(1.30)
Total Area	**0.53**	**(1.45)**
Utilities and Other		
Hot Metal Value	-	1.62
Desulfurization	0.03	0.16
Blast Moisture	0.38	0.39
Stove Enrichment(1)	0.21	1.12
Total Utilities & Other	**0.62**	**3.29**
Net Top Gas Value	**0.15**	**0.69**
Total Savings and Credits(2)	**1.15 – 1.30**	**1.84 – 2.53**

(1) Reductions in gas consumption to fire stoves at 105 Btu/SCF.
(2) Savings plus credits without and with value attributed to additional net top gas energy generated.

the total amount of coke consumed per day is lowest for this case at about 2,200 TPD versus about 2,550 TPD in the base case.

The coinjection practice described here results in additional cost savings and credits outside of the furnace area due to reductions in desulfurization costs and in the energy requirements for blast steam generation and stove fuel enrichment. The latter savings result from the increase in the heating value of the top gas and are recovered even if there is excess top gas available. Additional credits are available if the increased energy content of the top gas can be used elsewhere in the mill.

The extent to which coinjection of natural gas with coal can reduce coke consumption and increase furnace productivity will depend on the specific operating practices and constraints on a given furnace. The economic benefits will depend on local unit costs and the amount of performance improvements that can be obtained. The savings projected in Table XII are very significant, however, and show that coinjected gas can be a valuable tool to optimize the performance of furnaces injecting coal.

Summary and Conclusions

Baseline and coinjection testing carried out on No. 4 furnace at Gary over a year's time showed that:

- Increasing the level of coinjected gas while decreasing coal injection levels can increase productivity by more than 12%.
- Improvements in permeability allow the furnace to take more wind so that supplemental oxygen injection levels only have to be increased modestly.
- A coke replacement ratio for coinjected gas of up to at least 1.1 lb/lb can be obtained, so that low furnace coke and fuel rates can be obtained at high productivity.

- RAFTs can be allowed to decrease substantially from the levels practiced for all coal injection without compromising furnace stability or hot metal chemistry.
- Furnace SOPs appropriate for coal injection may have to be modified for successful coinjection practice.
- It is important to verify burden and fuel assays and all furnace measuring instrumentation to obtain valid data and evaluate properly the effects of changes in practice.
- Coal chemistry is very important and has a large impact on the blast furnace performance.