Results of Ultra High Rates of Natural Gas Injection Into the Blast Furnace at Acme Steel Company

By J.C. Agarwal, F.C. Brown, D.L. Chin (Charles River Associates, Boston, MA), F.C. Gambol (Acme Steel), and D.M. Smith (GTI)

March 22, 1998

The article can be found in Volume 57 of the 1998 ICSTI / Ironmaking Conference Proceedings at Toronto, Canada, 1998, a publication of the Iron and Steel Society

Table of Contents

Results of Ultra High Rates of Natural Gas Injection Into the Blast Furnace at Acme Steel Company (300 lb/THM Level)

1. Executive Summary

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 two-thirds currently inject or coinject natural gas in the range from 30 to 200 pounds per ton of hot metal (lb/THM) or from 1,800 to 4,500 standard cubic feet per ton of hot metal (scf/THM). Currently, natural gas injection levels average about 100 lb/THM or 2,200 scf/THM. The total amount of natural gas consumed in North American blast furnaces is now about 100 billion cubic feet per year (bcfy).

Natural gas use in blast furnace injection has increased substantially in recent years as operators became aware of its operating and economic benefits. Results of a number of blast furnace tests have been published describing natural gas injection practices at higher-than-average levels, up to 260 lb/THM. However, there are still significant differences among operators in the way aim values are set for high natural gas injection levels — particularly values for the raceway adiabatic flame temperature (RAFT). These differences in aim values cause significant differences in the amount of coke savings and productivity gains that can be achieved and hence affect the economic benefits that can be realized.

This report presents the results of a series of tests on a commercial blast furnace, the A furnace at Acme Steel Company (Acme) in Chicago, at gas injection levels up to 310 lb/THM, or 6,900 scf/THM. The objective of the test program was to develop the process technology for very high levels of injection to substantially increase productivity and reduce coke rate without using metallics on the burden, and to provide the steel industry with a base-line operating manual for this

practice. A test plan for the experimental work was developed to define the aim values and expected furnace performance at a baseline condition that duplicated previous operations at Acme at an injection level of 250 lb/THM, and for operation at injection levels of 275 and 300 lb/THM. Throughout the tests, Acme operated the furnace primarily to meet commercial requirements for hot metal and secondarily as a vehicle to obtain test data.

The furnace operated in the baseline condition, initiating Phase E test work, during July and August 1996, after necessary upgrades had been completed. An increase in hot metal demand coincided with the move to the intermediate injection level of 275 lb/THM in September, which was followed by a move to the targeted injection level of 300 lb/THM in October. Evaluation of operating data obtained during the early part of these tests suggested that burden properties differed from those found in Phases A and C, so the test plan was amended to gather data at lower injection levels and lower production rates through November and December 1996.

Operating data obtained from Acme's data acquisition system were reviewed and checked for consistency. Data were rejected when the furnace experienced transient conditions due to scheduled and unscheduled maintenance requirements and other upsets in operating conditions unrelated to the tests. As a result, steady-state data, representing about six weeks of operation, were used to evaluate furnace performance at the high levels of injection and an additional five weeks of data were evaluated at the 100 lb/THM injection level. The results of the furnace performance are summarized in Table S-1.

For the Acme A furnace, these descriptions of furnace performance show:

- A productivity increase of 40% (1,036 TPD, to 8.8 TPD/CCF) without metallics additions when production is normalized to a scrap-free burden. When compared to the baseline condition in which scrap was charged to the furnace, the productivity increase is 22% (663 TPD).

- Supplemental oxygen consumption of about 1.15-1.2 pound oxygen per pound of natural gas at the highest injection levels. This is slightly higher than in previous tests at high injection levels because of a decrease in burden permeability from previous phases unrelated to injection of natural gas.

Table S-1. Summary of Tests at Acme A Furnace, Phase E

Process Parameter	Units	Period				
		No Scrap Baseline	**100 lb/THM**	**250 lb/THM**	**275 lb/THM**	**300 lb/THM**
Natural Gas Injection	lb/THM	0	99	248	283	306
Blast						
Temperature	°F	1,875	1,892	1,903	1,877	1,908
Moisture	gr/SCF	11.2	2.7	9.3	6.6	4.2
Delivered Wind	MCF/THM	45.5	43.9	32.2	30.9	26.8
Supplemental O_2	lb/THM	0	0	274	329	360
AISI RAFT	°F	3,960	3,661	3,100	3,041	2,911
Pressure Drop	psi	16.2	20.8	21.8	21.9	17.4
Burden						
Pellets	Lb/THM	2,993	3,080	3,078	3,089	3,080
BOF Slag + Dolomite	lb/THM	164	172	98	91	91
Dry Coke	lb/THM	1,032	872	730	712	641
Production						
Hot Metal	TPD	2,597	2,586	3,163	3,424	3,633
Productivity	TPD/CCF	6.3	6.3	7.7	8.3	8.8
H.M. Temperature/SD	°F	2,642/48	2,690/31	2,638/25	2,646/26	2,642/30
H.M. % Si/SD	%	0.62/0.25	0.70/0.16	0.49/0.11	0.42/0.09	0.34/0.07
H.M. % S/SD	%	0.050/0.016	0.061/0.014	0.061/0.011	0.066/0.009	0.062/0.010
Operating Parameters						
Thermal + Chemical Energy Above 2,700°F	MMBtu/THM	0.88	0.76	0.77	0.81	0.80
Solution Loss	lb mole/THM	14.1	12.6	6.0	5.6	5.1
Hydrogen Utilization	%	41.2	48.2	44.3	44.9	49.1

(1) Phase A conditions, 6/94.

- Stable furnace operations over the range of natural gas injection levels tested, even though the AISI RAFT was decreased to 2,910°F at the highest injection level. The variability in hot metal chemistry improved, and burden descent became smoother; the only significant change in chemistry was a progressive decrease in the hot metal silicon content.

- A coke consumption decrease of 391 lb/THM from the no-scrap baseline condition to a level of 641 lb/THM. The burdening practice was changed to reduce the coke slit by almost 30% from the no-injection condition as the ore-to-coke ratio increased. A replacement ratio of about 1.0 lb coke/lb gas was achieved over the range of injection levels between 150 and 300 lb/THM, although some of the benefits of coke reduction must be attributed to changes in the blast conditions and hot metal chemistry.

- When productivity increases were not being sought, coke consumption was decreased by more than 200 TPD from a no-scrap baseline condition through injection of natural gas at levels of about 100 lb/THM. The total coke consumption was held at about 1,200 TPD, 176 TPD, and 242 TPD below the no-scrap and scrap baseline levels, respectively, as productivity gains were achieved by injection of natural gas at levels above about 200 lb/THM.

Acme made a number of changes to the tuyeres and natural gas injection lances used throughout these tests. Evaluation of the data obtained with these changes shows:

- It is possible to design injection lances that will provide sufficient mixing of the natural gas with the blast to promote partial combustion within the tuyere and stable operation over a very wide range of injection levels and blast rates. Improper designs may lead to a “twinkling” condition and partial tuyere blockage or excessive pressure drop, however.

- Use of tuyeres with different areas will shift blast flows to accentuate differences in the RAFTs in front of various tuyeres, but will not adversely affect furnace operation. The data suggest that moderate amounts of CO_2 and H_2O persist at significant distances beyond the raceway at high levels of natural gas injection, effectively increasing gas temperatures and providing a margin of safety during upset conditions.

These tests confirm that high productivities and replacement ratios can be obtained with good hot metal chemistry and relatively low oxygen consumptions at natural gas injection levels in excess of 300 lb/THM without elaborate burdening practices or the need to charge metallics. Obtaining these favorable results requires only that aim values be set in such a way that the characteristics of natural gas as an injectant are recognized properly. The trends observed in the data suggest that additional benefits can be obtained at even higher levels of injection.

2. Introduction

A. PROJECT HISTORY AND OBJECTIVES

North American blast furnaces have injected small amounts of natural gas (about 50 lb or 1,100 scf/THM) since the early 1950s. In 1987, the Gas Research Institute (GRI) reviewed the technology of fuel injection in North America and issued a white paper entitled “The Use of Natural Gas in the Blast Furnace Area.” [1] Although there were references in the foreign literature (primarily Russian) to blast furnaces operating at natural gas injection levels up to 250 lb/THM, there was no information on which reliable operating and economic practices could be developed for domestic blast furnace operations. Therefore, GRI began a multi-pronged approach to develop the operating practices and disseminate the required information. The major elements of the approach were to:

1. Analyze existing domestic natural gas injection practices.

2. Develop a technical and economic model for comparison of natural gas, oil, and coal injection in the blast furnace.

3. Run controlled sets of field experiments on well-instrumented commercial blast furnaces to obtain reliable experimental information on natural gas injection levels of up to 250 lb/THM.

Under this approach, GRI analyzed the operating information available at Warren Consolidated Industries (WCI)[2] and issued a report to show the evaluation of operating data and practices for natural gas injection at 160 lb/THM over extended periods and natural gas injection levels up to 183 lb/THM for shorter periods. The Iron & Steel Society also published a detailed description of the operating behavior of the WCI blast furnace, and used the analysis of the WCI work to provide valuable insights on the effectiveness of natural gas as a control

---

[1] “The Use of Natural Gas in the Blast Furnace Area.” J.C. Agarwal and F.C. Brown, Gas Research Institute, February 1988.
[2] *Direct Injection of Natural Gas in Blast Furnaces at High Rates: An Analysis of Historical Operating Data at Warren Consolidated Industries*. Gas Research Institute (GRI 89/0239), 1989.

tool in blast furnace operation.[3] The WCI report was used to design the subsequent field test of gas injection performed at Armco's #3 blast furnace in Middletown, Ohio.

In 1991, LTV Steel (LTV) reported the results of natural gas injection tests of up to 230 lb/THM on the Cleveland C-6 blast furnace.[4] LTV's primary interest was to increase productivity of the blast furnace while another blast furnace was relined. These operating results were also useful in formulating other field tests.

To further develop economic operating practices for gas injection, GRI developed a thermochemical model of the blast furnace to project the comparative economics of injecting various fuels into the blast furnace.[5] The analysis took into account various operating parameters and capital costs of injection systems and the assigned value of increased hot metal productivity. These analyses have proved to be extremely valuable in planning field tests, in evaluating the results of these field tests, and in analyzing the comparative economic benefits of natural gas and coal injection in those blast furnaces where such options were available.

In 1992, GRI sponsored a field experiment at Armco Steel (now A-K Steel) to inject natural gas at levels up to 250 lb/THM on their #3 blast furnace at Middletown. This blast furnace is well instrumented, has a 29.5-foot diameter, is capable of reaching a 2,000°F hot blast temperature, and had adequate oxygen available to experiment with the high rates of natural gas injection up to 250 lb/THM. The objective of this field test was to develop the process technology necessary to inject high rates of natural gas and to analyze the performance of the blast furnace under relatively stable conditions. Excellent results were obtained from this field experiment. The results were published[6] and showed that for natural gas injection levels of up to 200 lb/THM, the coke consumption decreased 25% and the productivity increased by 10% over baseline production. The oxygen consumption was approximately one pound of oxygen

[3] "Natural Gas Injection at W-1 Blast Furnace." W.G. Sherwood, Warren Consolidated Industries, Inc. *Ironmaking Conference Proceedings*. AIME, 1991.
[4] "Blast Furnace Operation with High Oxygen & Fuel Injection Rates." R.F. Hall Jr., D.E. Heinz and K.S. Nanavati, LTV Steel Company. *Iron & Steel Maker*, August 1991.
[5] *A Model for Economic Comparison of Natural Gas, Oil, and Coal Injection into the Blast Furnace*. Gas Research Institute (GRI 92-0352), September 1992.
[6] *Injection of Natural Gas in the Blast Furnace at High Rates: Field Experiments at Armco Steel Company*. Gas Research Institute (GRI-92/0353), April 1993.

per pound of natural gas. Furthermore, the prevailing concept of maintaining a high raceway adiabatic flame temperature (RAFT) for high rates of gas injection practice was shown to be in error — during the tests, RAFT was lowered by about 700°F with no adverse effect on the blast furnace. For gas injection levels between 200 and 250 lb/THM, the results were inconclusive because the injection period was too short to make any meaningful quantitative analysis. Even so, the blast furnace operated smoothly at the 250 lb/THM gas injection level. Armco decided to end the field experiment program in response to a lower demand for hot metal.

Subsequent to the field trials, A-K Steel has reported very high productivity on its #3 Middletown furnace by injecting over 180 lb/THM of natural gas and by charging over 250 lb/THM of metallic iron as hot briquetted iron.[7]

As a result of the increased confidence of blast operators that high rates of natural gas injection can indeed be used in the blast furnaces, more than ten blast furnaces were injecting natural gas at levels over 150 lb/THM by the end of 1993. However, many important operating questions still remained. In 1994, GRI decided to conduct a series of field tests to meet the following objectives for injection levels of 250 lb/THM or more:

1. Optimize the results obtained at A-K Steel by injecting high rates of natural gas with lesser or no quantities of metallic iron. The objective is to obtain high hot metal production without using excessive amounts of expensive briquetted iron or scrap in the charge.

2. Maximize blast furnace productivity for optimal operating flexibility so swings in hot metal demand can be accommodated both technically and commercially.

3. Decrease coke consumption and obtain more definite information on replacement ratios at high rates of gas injection when high productivity is not required.

[7] "Sustained Production in Excess of 9 tons per day/100 ft^3 WV at Middletown's No. 3 Blast Furnace." D.A. Kercsmar, Y. Yamauchi, W. Dilbert, and J. Kleather, A-K Steel Corporation. *Iron & Steel Maker*, July 1994.

4. Minimize oxygen use based on technical and operating support for lower RAFT practices.

5. Co-inject natural gas with coal and oil to maximize the economic benefits from dual-injection practices.

In 1994 GRI entered into agreements with National Steel and Acme Steel to conduct high injection level field experiments at their Granite City and Chicago plants, respectively. The major test objective at both sites was to increase furnace productivity, but with different burdening practices: an all-pellet burden was to be used at Acme, while burden metallics were to be added at National Steel/GCD. Natural gas injection levels were increased from about 150 lb/THM to about 220 lb/THM at Granite City and productivity increased by almost 21% while the coke rate was reduced to 723 lb/THM and hot metal sulfur contents as low as 0.017% were obtained.[8] Natural gas injection practice was initiated at Acme and levels of 260 lb/THM were obtained with a 32% increase in furnace productivity and a coke rate of 717 lb/THM.[9] In both tests stable furnace operation was obtained by allowing the RAFT to drop by about 300°F/100 lb/THM increase in injection level, and the trends in process parameters appeared to be linear suggesting that additional benefits could be obtained at higher levels of natural gas injection.

The general approach used to arrange these field tests consists of the following steps:

- Visit targeted host sites and discuss the overall objectives of the field tests.

- Obtain an expression of the host site's operating management's interest in running the selected field test.

- Obtain an estimate of the cost of required equipment upgrades to the ironmaking facilities to run the test. In many instances, the host sites needed larger equipment to deliver and measure greater amounts of natural gas and oxygen.

---

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

- Enter into a subcontract for performing the field test, to supply the necessary funds to upgrade the facilities, and to obtain a co-funding commitment from the host steel company.

- Obtain base-line operating data necessary to develop a test plan for the host steel company.

- Provide a test plan to blast furnace operating management detailing the test objectives, duration, aim values for various parameters, and contingency plans.

- Perform the field test at several levels of natural gas injection using aim values developed for the field test to achieve the desired objective (productivity increase, coke consumption decrease, etc.).

- Monitor the test work with the host site and provide real-time, in-process technical support.

- Collect operating data for several steady-state conditions for subsequent analysis and interpretation.

B. OPERATING HISTORY AND TEST OBJECTIVES AT ACME

Acme Steel Company has two blast furnaces (A and B) at its Chicago plant. Only the A furnace has operated in recent years, supplying hot metal to the BOF shop located at Riverdale and hot metal for production of pig iron at Chicago. Before the field test, the A furnace was only equipped to inject natural gas at relatively low levels, up to about 150 lb/THM.

Acme also operates a coke plant in Chicago that has sufficient capacity to supply the furnace coke necessary for recent hot metal demands. The furnace was burdened with a mixture of self-fluxing and acid pellets and BOF slag, and was run without fuel injection or blast enrichment to meet normal hot metal production requirements before the field test. Steam was added to the blast to

[9] *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.

control RAFT, and normal productivity was in the range of 6 to 6.5 tons per day per hundred cubic feet of working volume (TPD/CCF). Productivities up to about 7 TPD/CCF were achieved by adding up to about 150 lb/THM of B scrap containing less than 50% metallic iron to the burden, again without fuel injection or blast enrichment.

Acme recognized that achieving further increases in production would require the use of fuel injection, both as a means to drive the furnace with additional oxygen and to obtain reductions in coke consumption so that the capacity of the coke plant would not be exceeded. In addition, further cost savings could be realized if productivity targets could be met without using scrap. Consequently, Acme decided to conduct a series of field tests on its A furnace in the fall of 1994 to demonstrate the advantages of natural gas injection to achieve productivity gains, to decrease coke consumption, and to decrease burden metallics in the charge. The results of the test work are presented in technical reports and organized into technical data packages that will be provided to the steel industry as a baseline manual for this practice.

The natural gas injection tests at Acme have been carried out in five phases:

Phase A: Injection tests at rates up to 150 lb/THM NGI
Phase B: Upgrade of facilities
Phase C: Injection tests at rates above 150 lb/THM NGI, up to 250 lb/THM NGI
Phase D: Additional upgrades of facilities
Phase E: Injection tests at rates above 250 lb/THM NGI, up to 300 lb/THM NGI

The first three phases of the tests were completed in 1994 and 1995, and the results have been reported (see reference 9). The upgrades in Phase D and testing in Phase E were carried out in 1996, and are reported here.

3. Test Site Description and Operating Practices

This chapter describes the equipment in the blast furnace area, Acme's standard operating procedures, and the data collection procedures used in the tests. First, the blast furnace itself is described, followed by description of the auxiliary systems that support the blast furnace operations. Then, a description of the upgrades and changes made in conjunction with the test is presented, and the normal operational procedures and the changes implemented with the test plan are described.

A. FURNACE DESCRIPTION

Acme's 'A' furnace is located in the Chicago 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. Hot metal is weighed at the furnace and at the basic oxygen furnace. The hot metal is either delivered by rail car to the BOF 11 miles away in Riverdale, Illinois, to other consumers of hot metal, or is cast into pig iron on site. The furnace details are listed below.

Furnace Details

Furnace Name:	'A'
Hearth Diameter:	25 ft
Working Height:	80 ft
Number of Tuyeres:	14
Normal Top Pressure:	8 psig
Top Type:	Two Bell System
Pressurizing Gas:	Dirty BF Gas
Top Gas Analyzer:	PE Mass Spectrometer
Working Volume:	41,132 ft^3
Trough Design:	Fixed
Bosh Cooling:	Plates
Type of Burden Distribution:	Fixed Armor
Date of Last Blow-in:	April 1990

3. Test Site Description and Operating Practices

Tuyere Size

The diameters of some tuyeres were increased during Phase E to decrease pressure drop and allow more wind to flow at the blast pressure limit of 30 psig. In the previous tests all tuyeres were 6.5″ diameter except for #1 and #14, which were 5.5″. Table 3–1 below shows the tuyere size change schedule; by mid-October velocities would have been decreased by 6.2% on average at a given blast condition, but the changes in area were 7.3% on the four 6.75″ diameter tuyeres and 28.4% on #1 and #14 adjacent to the taphole.

Table 3–1. Tuyere Size Changes

Tuyere Number	New Size	Date of Change
1	6.5″	August 14, 1996
6 and 9	6.75″	September 15, 1996
3 and 12	6.75″	September 25, 1996
14	6.5″	October 13, 1996

Source: Charles River Associates, 1996.

Natural Gas Delivery and Injection Systems

Natural gas is delivered to the Acme Chicago Plant at 275 psig in a 4-inch high-pressure supply line. The pressure is reduced at a metering station for delivery to the blast furnace at 155 psig in an 8-inch feed line. A vortex meter is used as the primary measuring element for the natural gas flow control system. The 8″ feed line is connected to a 6″ circle pipe that is fitted with seven 2″ drop-down pipes that are teed to two quarter-turn shut-off valves. Ten-foot runs of flexible hose connect the shut-off valves to check valves on Inconel lances.

The lances are 69 inches long and enter the side of each blowpipe in a horizontal position. The angle of entry is 15 degrees from the tuyere center line. The tip of the lance is normally positioned at the tuyere/blowpipe centerline where the blow pipe joins the tuyere. Different combinations of flexible hoses and lance sizes were used in an attempt to achieve even gas flow through each lance within the pressure rating of the fittings. Table 3–2 shows the combinations of lance and flexible hose diameters used throughout these tests.

3. Test Site Description and Operating Practices

Table 3–2. Natural Gas Injection System Configurations

Lance Diameter (in.)	Flexible Hose Diameter (in.)	NG Flow Rate Range (MSCFM)	Maximum Circle Pipe Pressure (psig)	Test Phase
½″	1″	3.9–7.4	125	A
1″	1″	3.5–13.5	150	B, C
1½″	1½″	11.1–14	50	E
1″	1″	11.1–15.9	160	E
1″	1½″	15.9–17.0	110	E
1″	1″	3.7–6.5	45	E

Source: Charles River Associates, 1996.

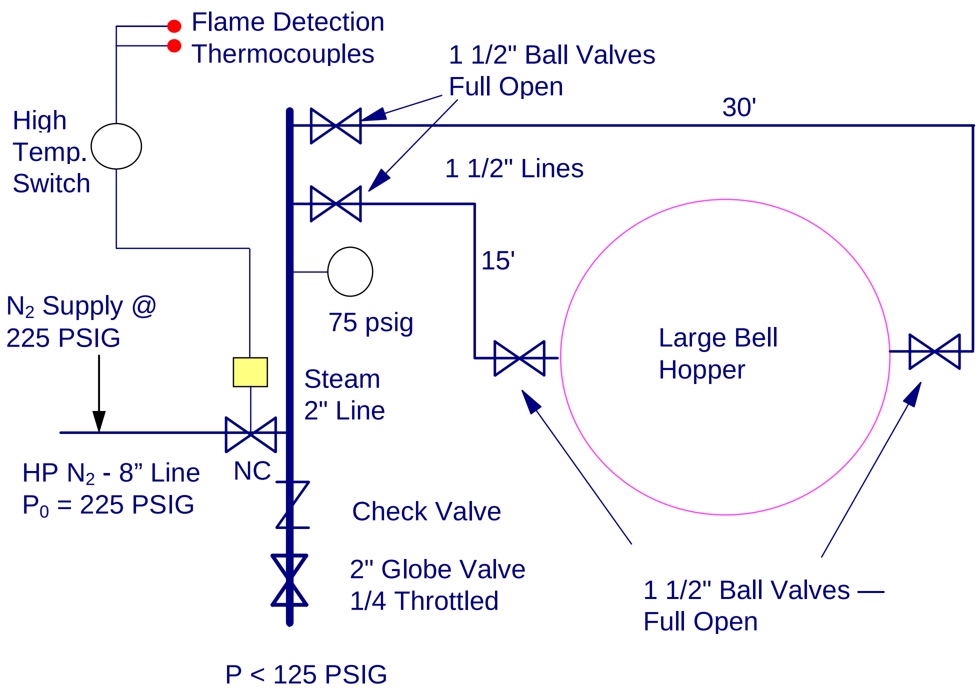
Fire Detection/Suppression System

Prior to these tests, Acme did not inject steam between the bells and did not experience problems with top fires. As gas injection levels exceeded about 125 lb/THM (top gas hydrogen exceeded about 7%), top fires occurred occasionally, and intermediate pressure (IP) steam was injected between the bells through two lances.

Upon testing at higher gas injection rates, top fires occurred more frequently even though steam was injected between the bells continuously. Consequently, Acme installed an automated fire detection and suppression system, which controlled the fires to the operators' satisfaction. The steam/N_2 purge system used in Phase C is shown schematically in Figure 3-1.

3. Test Site Description and Operating Practices

Figure 3–1. Top Fire Suppression System at Acme for Phase C



A second 1½-inch line was installed to increase the flow of steam to the bells. In addition, a supply of high-pressure nitrogen was connected to the steam line and was normally isolated by a quick-opening valve. Two thermocouples were placed above the small bell hopper, one at the wall of the hopper and one near the center line at the cable. Their output was connected to a high-temperature switch. A top fire alarm was tripped if either thermocouple detected a temperature above 150°F. Operators were notified and the quick-opening valve on the nitrogen line was opened to provide a rapid flow of additional inert gas to snuff the fire. The alarm was shut off when both temperatures had decreased to less than 150°F.

Top Gas Analysis

The top gas is sampled after the off-gases are cleaned in the dust catcher/scrubber system. A ½-inch pipe penetrates the cleaned gas main for sample collection. A ½-inch traced tube conveys the sample to a drip leg in the instrument room, a distance of about 20 feet. After passing over the drip leg, the gas is further cleaned through a filter sequence — a 40μ coarse filter, a 5μ Extractor/Dryer filter, and then a 0.9μ fine filter. The gas flow rate is controlled with a manual rotameter and is normally 1 cfh. The filtered top gas is analyzed continuously by a Perkin-Elmer 1200 Mass Spectrometer. Transit time from sample extraction to analysis is on the order of two minutes.

The instrument is recalibrated by the vendor once per month, or by the operators more frequently if required. The data are automatically collected and stored by the data acquisition system. No changes to the system or the data acquisition procedures were made during the course of these tests.

B. AUXILIARIES DESCRIPTION

Acme operates a coke plant adjacent to the blast furnace area and is self-sufficient in coke. A boiler house produces the steam required for the turbo blowers, cooling water pumps, and other plant uses. Coke oven gas, cleaned blast furnace gas, and natural gas fuel the burners in the boiler house and the stoves. Oxygen is delivered by Praxair, Inc. via pipeline, while natural gas is supplied by Peoples Gas Light & Coke Company. The oxygen delivery system, stoves, stock house, data collection system, and wind delivery system are described below.

Oxygen Supply

High-purity, high-pressure oxygen is delivered via a 10-inch main, and passed through a 4-inch metering station, and then to a 10-inch line, which connects into the cold blast main. A low-pressure trip set at 100 psig is installed downstream of the metering station. The metering is done through a vortex meter that serves as the primary measuring element for the oxygen flow control system.

3. Test Site Description and Operating Practices

Stoves

A description of Acme's blast heating stoves is presented below.

Number:	4
Total Heating Surface:	557,292 ft^2
Stove Burner Capacity:	40,000 cfm
Burner Stove Isolation:	Manual valve
Hot Blast Valve Type:	36-inch mushroom and 36-inch gate
Stove Gas:	Clean blast furnace gas enriched with natural gas and coke oven gas
Target HHV for combustion gas:	105 Btu/SCF

The stoves were automated in Phase B, decreasing changeover time to 7 minutes and increasing hot blast temperature to 1910°F. No natural gas or coke oven gas was required for enrichment at injection levels above 200 lb/THM since the top gas HHV exceeded 105 Btu/SCF.

Stock House

Acme's charging equipment is a two-skip system fed by one scale car and two coke hoppers. The coke hoppers are filled automatically by a burden-charging program. The scale-car operator manually fills ore, scrap, make-up coke, and flux to target weights specified by the loading program. No mixing or screening of the burden materials is done prior to charging. A burden charging program tracks over/under draws and sets future targets accordingly. A nuclear moisture gauge is used to measure coke moisture and track the amount of coke charged on a dry basis. Make-up coke equivalent to the amount of water in the previous coke charge is added to the next ore skip.

Each skip has a volume of 270 ft^3 and ascends to the top of the blast furnace at a maximum speed of 400 ft/min. The skip motor can lift a maximum weight of 22,000 lb. The normal number of charges per hour is 8 to 10, with 12 being the maximum sustainable charging practice for long periods of time.

3. Test Site Description and Operating Practices

Wind Delivery System

Through Phase C of these tests two turbo blowers were used with a third on stand-by. The flow of wind was controlled manually by cold blast main valves located downstream of each turbo compressor. The ordered wind rate is recorded in the furnace control room, and the set point is expressed in terms of the required pressure at the blower discharge. The blast moisture system has a feedback controller than manipulates steam addition to achieve the target gr/SCF.

Data Acquisition System

An automated data acquisition system allows on-line, real-time information to be gathered on charging, stoves, wall and trough temperatures, hot blast data, and top gas analysis and temperature. The data system also tracked burden inventory and burden recipes, and allowed more elaborate charging sequences to be used. Two above-burden probes were installed as part of the Phase B upgrade.

All meters read automatically and store data each minute. Wind, natural gas, oxygen, top gas assay, top gas temperature, hot blast temperature, top pressure, hot blast pressure, blast moisture, and top temperature probes were read into five-minute block averages. The five-minute averages were averaged for hourly data. The hourly averages were then averaged for the daily average. The hourly and daily averages were reported on the daily logs.

C. UPGRADES

Several upgrades were required to provide the capability to inject 300 lb/THM of natural gas and to produce data for evaluation of the tests. The major upgrades to Acme’s A furnace carried out in Phase D are described below. The upgrades made prior to the tests and during Phase B summarized above have been described fully in the previous report (see reference 9).

3. Test Site Description and Operating Practices

Large Bell Skirt

The large bell was skirted to minimize blast furnace gas leakage and decrease top fire occurrences. A 14-day bank was required for the skirting and was completed on June 14, 1996.

Turbo Blower Automation

Prior to Phase D, the turbos were controlled by a manual cold blast valve and oil-jet controlled relief valves were used to prevent surging. Operators manipulated a 42″ gate valve manually and estimated wind flow by a calibration of the readings of mercury manometers.

New automatic controls were installed to hold the wind at a constant flow, and the relief valve operators were switched to air-operated controllers which, however, greatly increased their response time. The controllers can run in any of three modes: constant flow, constant pressure, or blower optimization. In the constant flow or pressure modes, the intake flow rate is controlled by modulating the steam rate into the turbo and the relief valves open at a set pressure. In the blower optimization mode, the wind rate is increased or decreased depending on whether or not the relief valves are open or closed.

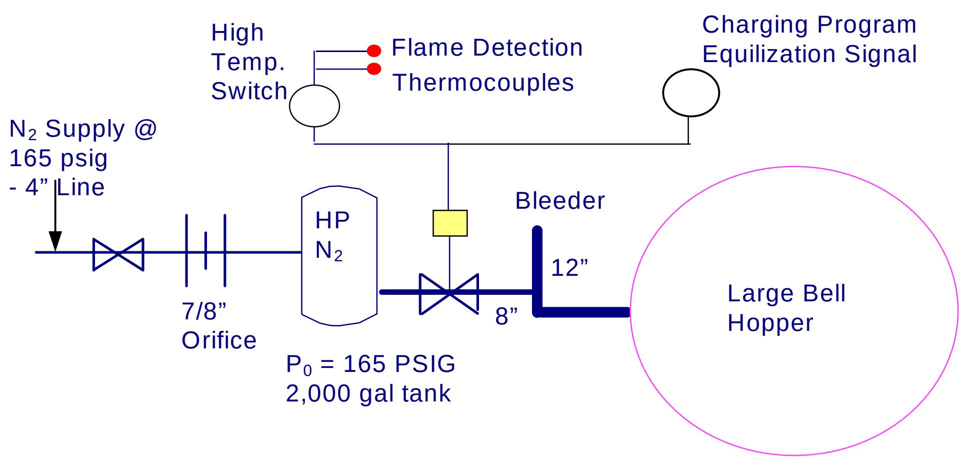
Coke Hopper Redesign

Prior to Phase D, the coke weight hoppers took 27 seconds to empty into the skip cars. By increasing the hopper opening and increasing the pitch of the chute, the discharge time was decreased to 9 seconds. This allowed the maximum sustainable charges per hour to go from 12 to 14 which gave operators greater ability to catch the furnace stockline instead of pulling wind for minor stock house delays.

Nitrogen Top Fire Suppression and Pressure Equalization System

During Phase D a nitrogen delivery system was installed that would equalize the bell pressure after large bell dumps as well as deliver bursts of N_2 that would snuff out top fires. A 2,000-gallon tank was installed on the top platform next to the large bell hopper and the nitrogen feed pressure was reset to 165 psig. Steam was kept on between the bells using the piping arrangement shown in Figure 3–1, but the nitrogen line was moved to connect into the 12″ bleeder line. Nitrogen flow to the bells is initiated by opening the normally closed valve in response to either a high temperature or differential pressure signal. The equipment arrangement used during Phase D is shown in Figure 3–2.

Figure 3–2. N_2 Fire Suppression Equalization System at Acme — Phase E



Source: Charles River Associates, 1996.

D. ACME OPERATING PRACTICES

The operating practices at Acme have evolved significantly since the beginning of the natural gas injection tests. Before September 1994, no supplemental fuel was injected and B-scrap was used to boost productivity from an all-coke practice at a production rate of 2,550 TPD. The most significant changes in operating procedures involve injection of oxygen and natural gas at high rates with an all-pellet burden to increase productivity, and using the flow rates of natural gas and oxygen as trim control for hot metal temperature. Furnace charging practices and other operating practices used during the 300 lb/THM NGI test at Acme are described below.

3. Test Site Description and Operating Practices

Charging Practice

The charging sequence used throughout the tests was OOCC/, with each ore skip containing 22,000 lb (14.5 THM/charge). BOF slag, at 800 to 1,800 lb/charge, and small amounts of dolomite were added to the ore skips to adjust slag volume and basicity. Make-up coke, used to correct for water or misfilling in the previous coke skips, was also charged with the ore skips. The distributor rotates the small bell charges at 0, 60, 120, 180, 240, and 300 degrees in that order.

Typical burden analyses are shown in Table 3-3, while Table 3-4 shows a typical natural gas assay. Pellet compositions did not change materially over the course of these tests, but coke and BOF slag compositions were somewhat variable.

Table 3-3. Typical Burden Analyses for Phase E

Material	Percent Natural Basis									
	H_2O	C	S	P	Mn	SiO_2	Al_2O_3	Fe	MgO	CaO
Coke	4.8	90.8	0.76	0.24	0.01	4.52	2.41	0.9	0.09	0.24
Tilden, Fluxed	4.4	NR	0.01	0.03	0.16	4.49	0.42	59.1	1.68	4.33
Wabush, 1% Mn	5.0	NR	NR	0.01	1.11	3.30	0.26	62.7	0.10	0.55
BOF Slag	2.3	–	0.17	0.31	3.42	13.0	3.72	22.5	7.81	40.4
Dolomite	0.3	NR	0.31	0	0.01	5.69	0.25	1.2	18.8(1)	72.8(1)

(1) Reported percentages as carbonates.

Table 3-4. Typical Natural Gas Analysis for Phase E

Constituent	Percent by Volume							
	CO_2	N_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	H_2
Calumet NG(1)	0.77	1.54	93.58	3.53	0.40	0.11	0.06	0.00

(1) HHV = 1,020 Btu/cf at 14.65 psig, 60 °F, and dry.
Source: Peoples Gas Light & Coke Company, Oct. 1996.

The amounts of Wabush and Tilden pellets charged remained relatively constant throughout this Phase at about 34% and 66%, respectively, with the production rate being dictated by the number of charges per hour. When testing in this Phase was initiated at an injection level of about 250 lb/THM, the coke weight per charge was about 10,500 lb, the same as at the conclusion of testing in Phase C. (Note: the operators thought that the weight was about 11,200 lb because of a miscalibrated load cell, as discussed in Chapter 5.) Coke rate aim values were reduced by decreasing the amount of coke per charge because the amount of ore per skip could not be increased. At the highest injection levels the coke weight per charge had been reduced to about 9,300 lb. Thus, the coke slit was decreased by about 11% during this Phase of the test, and by about 28% from the initiation of natural gas injection.

Top Fire Suppression

The above between bell pressure was maintained at 20″ H_2O above top pressure to ensure proper purging. Top fires usually occurred when the coke skips were being dumped into the small bell hopper, and some cokes were more prone to initiate them than others.

Two above-bell thermocouples are located on top of the receiving hopper, one near the wall and the other located at the center next to the bell rods. A program senses the temperature and when the above-bell temperature reaches 120°F, a nitrogen burst is fired. Thirty seconds later, another N_2 burst is fired if the temperatures are still rising. If the temperature goes above 150°F, an alarm alerts the operator, who may shut off NG and O_2 flow and manually set off N_2 bursts until the fire is suppressed as indicated by falling temperatures. The cessation of natural gas and oxygen flows for the duration of top fires decreases the top gas hydrogen content and its HHV very quickly, thereby making the gas less combustible and accelerating fire suppression. Fires were normally extinguished within one to two minutes of detection, temperatures returned to normal, and gas and oxygen flows resumed within five minutes of the initial detection.

Nitrogen is also used for pressure equalization before a large bell dump. The system is disabled during shutdowns to prevent accidental firing.

Natural Gas and Oxygen Flow Rate Control

Natural gas and oxygen are controlled by constant set-point feedback controllers. To maintain more constant injection rates with respect to hot metal production, the constant volume flow rate set points were adjusted based on how many charges were delivered in the previous four hours. This prevents the furnace from having an excess or a shortage of fuel if the charging rate changed for other reasons. Table 3–5 shows a typical set point sheet for 310 lb/THM NGI and 350 lb/THM O_2.

Table 3–5. Typical Set Point Sheet for High-Rate Gas Injection

Charges per Hour	HM Production, TPD	Natural Gas Set Point, SCFM	Supp. Oxygen Set Point, SCFM
10.00	3,410	16,200	10,000
10.25	3,490	16,600	10,300
10.50	3,580	17,000	10,500
10.75	3,660	17,400	10,800
11.00	3,750	17,800	11,000

Source: Charles River Associates, 1996.

If the blast pressure falls below 20 psig, the flows are automatically shut off to prevent a highly enriched blast if the turbos shut down.

Scheduled Shutdown

For an eight-hour shutdown, two extra coke skips are added 7, 6, 5, and 4 hours before the scheduled outage, which is equivalent to 10,000 lb of Coke an hour for four hours. The wind is then decreased to zero flow, with natural gas and oxygen flow rates stopped when blast pressure drops to 20 psig. The shutdown takes approximately five minutes from full wind to zero wind. The natural gas lances are cooled with approximately 30 psig of N_2, until they can be removed. The peep sites are opened and the tuyeres are plugged with clay to seal the furnace. The furnace is back-drafted through a stove as there is no back-draft stack.

For a 20-hour shutdown, the procedure is the same except two extra coke skips are added from hours 7 through 2 before the scheduled outage. The extra coke is added to drive off the moisture from any grout used in the stack and the additional water absorbed during the shutdown from the condensate from the furnace and gas system steam purge.

3. Test Site Description and Operating Practices

Start-up

Wind is brought on line as fast as steam generation allows. When the blast rate reaches 50,000 SCFM, natural gas and oxygen flow rates are turned on at half their previous set points. When turbos reach full wind, natural gas and oxygen are set at their set points plus an additional 1,000 SCFM natural gas and 500 SCFM oxygen. The extra natural gas and oxygen are kept on until the first hot cast.

Wind Rate Control

Hot blast volume is maintained at a target rate or is maximized, depending on production requirements. Fluctuations in volume occur with changes in pressure drop (during a bell dump), permeability (burdening practice change), or with stove changes. Because the revised wind rate control system did not respond as rapidly to pressure fluctuations on stove changing, constructions were installed to reduce the rate of flow during repressurization and to reduce the disturbance.

Casting

Acme “A” furnace is a single tap hole, fixed runner system that feeds two ladle cars and has an air-cooled slag pit. The number of casts per day varies with production, with 150 to 200 tons of hot metal per cast as the target. Casting practice is summarized below.

Table 3–6. Casting Schedule at Various Hot Metal Production Rates

Hot Metal Production, TPD	Number of Casts, Casts/Day
< 2,600	12
2,600–3,000	14
3,000–3,400	16
< 3,400	18

Source: Charles River Associates, 1996.

3. Test Site Description and Operating Practices

Hot Metal Temperature Control

Hot metal temperature is controlled to 2,650°F ±25°F by adjusting natural gas and oxygen flow rates. If hot metal temperature is cold for two casts, the natural gas flow rate is increased by 500 SCFM and oxygen by 500 SCFM. The opposite move is made for a hot furnace condition. This replaces a manipulation of the hot blast moisture that was the practice before high rates of natural gas injection were achieved at Acme.

The use of natural gas and oxygen flow rates as agents to control hot metal temperature is effective because both the heat level in the hearth and the extent of the solution loss reaction can be altered rapidly as the hydrogen content of the gases is changed.

Other Procedures

Other moves (changes to operating set points) made for various furnace conditions at Acme are shown in Table 3–7.

In general, Acme's current control philosophy is to have operators intervene as little as possible with the operation of the furnace. Changes in set point are authorized only under the conditions shown in Table 3–6.

Table 3–7. Current Standard Operating Procedures

Condition	Move
High/Low Hot Metal Temperature (First Cast)	No moves.
Low Hot Metal Temperature (Second Cast)	Increase O_2 and NG by 500 SCFM each above aim value.
Low Hot Metal Temperature (Third or Later Cast)	Increase O_2 and NG by 500 SCFM each. Reduce wind 5,000 SCFM. Increase coke by 50 lb/charge.
High Hot Metal Temperature	Increase NG by 500 SCFM above aim value. Decrease coke by 50 lb/charge.
Top Fire (above-bell temperature exceeds 150°F)	Shut off NG and O_2. Return NG and O_2 when temperature < 150°F.
Fanning	Reduce wind to 3 psig blast pressure and shut NG and O_2 off.
Slipping or Hanging	Reduce wind by 10,000 SCFM.
Unscheduled Shutdown	Turn off NG and O_2 and pull wind.
Start-up	Increase NG and O_2 1,000 SCFM above aim value for one cast after start-up, then reset to aim value if hot metal temperature is normal.

Source: Charles River Associates, 1996.

E. TEST PLAN OUTLINE — AIM VALUES AND DATA ACQUISITION

Test Plan

The test plan was designed to evaluate a base period of 250 lb/THM in order to verify the furnace was operating close to the same condition as at the end of Phase C during the 1995 natural gas test at Acme. Ramp-up in 25 lb/THM NGI increments was programmed since no domestic furnace had operated at these high rates of injection. After the furnace operation had stabilized at 275 lb/THM NGI for an extended period (at least two weeks), then the move up to 300 lb/THM NGI would be made.

3. Test Site Description and Operating Practices

Aim Values

Aim values were provided as guidance in setting desired operating conditions and test lengths for each injection period. The aim values were determined by the predictive model using the most recent "A" furnace data that could be rationalized by the analytical blast furnace model.

Phase E aim values, shown in Table 3-8, were estimated based on a period in July 1996 before Phase E began. This period was the first period analyzed after Acme had completed the upgrades. The hot metal production targets and specific desired natural gas flow rates were set by Acme.

Table 3-8. Phase E Aim Values

Process Parameters	Units	Phase C Practice	250 lb/THM	275 lb/THM	300 lb/THM
Test Duration	Days	—	30	30	30
Hot Metal Production	TPD	3,430	3,300	3,400	3,500
Natural Gas Injection	Lb/THM	258	250	286	306
Supplemental Oxygen	Lb/THM	278	273	310	329
Blast Moisture	Gr/SCF	6.1	6.0	6.0	6.0
Blast Temperature	°F	1,901	1,910	1,910	1,910
Delivered Wind	Scfm	75,740	72,500	72,500	71,850
AISI RAFT	°F	3,157	3,180	3,000	2,910
Thermal and Chemical Energy above 2,700 °F	MMBtu/hr	0.81	0.79	0.77	0.76
Dry Coke Rate	lb/THM	717	721	685	665

RAFT is a derived parameter, not an input parameter in setting these aim values. The wind and supplemental oxygen rates are chosen to maintain the desired thermal plus chemical energy in the hearth zone, while limiting the flow of bosh gases to control the pressure drop at the desired value. As in the case with RAFT, the coke rate is a derived parameter. Charging a different amount of coke will change the hot metal temperature, the top gas temperature and composition, or both.

3. Test Site Description and Operating Practices

Data Acquisition

Ramp-up schedules were set up assuming ten-day periods would be necessary for increasing natural gas injection levels in increments of 25 lb/THM. This amount of time was set in consideration of the experience during the previous natural gas tests in 1994 and 1995. Thirty-day periods were allowed for the base period (250 lb/THM) and at the target natural gas injection level (300 lb/THM). Table 3–9 shows the planned data collection sequence for Phase E.

Table 3-9. Data Collection Plan for Phase E

Natural Gas (lb/THM)	Production (TPD)	Number of Days
250	3,300	30
Ramp-Up	3,350	10
275	3,400	30
Ramp-Up	3,450	10
300	3,500	30
Ramp-Down	T.B.D.	10

Source: Charles River Associates, 1996.

The actual ramp-up takes a day or two to achieve, but longer periods were allotted to allow the furnace to balance out at the new set point. Once a change is made, the furnace may go hot due to operators setting conservative coke rates (i.e., higher than needed). After the furnace production rate increases a cooling effect may occur, and operators need to adjust coke and gas rates depending on the furnace heat level.

As will be discussed in Chapter 5, the data collection plan was altered, and an additional 50 days of data were evaluated with production at 2,700 TPD and a nominal injection rate of 100 lb/THM.

4. Data Analysis Procedures

This chapter describes the data analysis procedures used to analyze the information collected from the A furnace at Acme. First, a summary description of the blast furnace computational procedures is given. Then, a summary of the data-screening rationale is shown with a description of what is a good operating day at the blast furnace.

A. DESCRIPTION OF COMPUTATIONAL PROCEDURES

These blast furnace computational procedures provide a tool to analyze and predict blast furnace performance in support of operational and economic decision making. The main features of the procedures have been described previously (see reference 6) and are only summarized here.

The blast furnace model operates in two modes: an analysis mode that evaluates real-time furnace operating data, and a predictive mode that projects furnace performance under new conditions. In the analysis mode, at least four consecutive days of "steady-state" furnace operation are required for the model to perform material and energy balances under conditions in which the statistical uncertainties in the rationalized results are reduced to acceptable levels. Three component material balances are made around the blast furnace (on iron, carbon, and oxygen) to initiate the procedure, with the hydrogen balance closed by calculating reaction water production "by difference." Errors are closed to zero by correcting burden material charge rates, composition, and blast volume.

There are sufficient degrees of freedom in this procedure that many different solutions are possible that satisfy the three balances. Burden material change and blast rate adjustments are constrained so that the corrections required are within the likely ranges of measuring errors at the furnace. The hierarchy of choosing the best values for the corrections is to adjust the iron-bearing constituents first, then the coke, and then the wind. After these corrections are made, the slag rate is fixed by forced closure of the acid constituents (SiO_2 + Al_2O_3) and closure is sought on the alkali (CaO + MgO) constituents. The alkali balance may be closed in two ways: the first option is to adjust the flux rate within the allowed correction limit, and if this does not produce closure, the acidic and alkali compositions of the major iron-bearing constituent (pellets or sinter) are adjusted in equal but opposite amounts to achieve closure.

Once the overall material balances are closed, an overall energy balance is performed to obtain the overall furnace heat loss. The calculated overall loss is assigned to five zones in the furnace (hearth, bosh, lower, middle, and upper stack), and material and energy balances are performed for each zone. As mentioned above, no unique solution to the overall balances can be obtained, and such factors as analytical errors, reporting errors, unknown operating problems (e.g., stave leakage), or unsteady state conditions may produce an unacceptable result even though the overall material balances close.

Unacceptable results include heat losses that are physically unreasonable, the calculation of thermodynamically infeasible conditions in the zonal balances (e.g., gas temperatures below burden temperatures or compositions beyond their equilibrium limits), or correction factors for the burden that exceed the likely errors in measurement. If any of these conditions are found to occur, they can be removed (within limits) by adjusting the top gas composition. Changes of up to ±1% in N_2, CO, and CO_2 are allowed (the reported H_2 content is retained) with the hierarchy of changes being to adjust the N_2 content first at a constant CO:CO_2 ratio, and then to adjust the CO:CO_2 ratio only if closure cannot be obtained on the carbon balance.

Closure of the furnace balance is acceptable if the following criteria are met:

- Iron, carbon, and acid/alkali balances are closed with correction factors or assay changes that are within the likely range of measuring errors.

- The correction factor applied to the wind rate is consistent from period to period.

- Changes in top gas composition are within ±1% of the reported value.

- The zonal balances do not show pinches (gas temperature minus burden temperature) of less than 20°F.

- The calculated furnace heat loss is within about ±50% of the value estimated from wall heat flux measurements.

The latter constraint is actually a rather stringent test of the data quality because furnace heat loss is calculated as the difference between very large input and output enthalpy flows. For example, a typical mid-sized furnace would have blast plus burden enthalpies of about (minus) 1,100 million Btu per hour (MMBtu/hr) and hot metal, slag, plus top gas enthalpies of about (minus) 1,180 MMBtu/hr, so that the furnace heat loss is about 80 MMBtu/hr. Changes of 40 MMBtu/hr or more can be induced by very small changes in burden assays or moisture contents or top gas assays — particularly CO_2 content.

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

B. DATA SCREENING PROCEDURE AND RATIONALE

Previous analyses of the errors in material balance closure have shown that a period of about 100 hours (four days) of continuous, steady-state operation is required to reduce the errors to acceptable limits given the capability of typical data acquisition systems. As a practical matter, a minimum of three consecutive delay-free days or a run of four consecutive days with delays less than one hour are needed as the minimum periods required to obtain reliable closure. A day with excessive down or delay time “breaks” the continuity, and requires re-indexing the period of time that can be included for analysis at a given level of gas injection. Also, events such as recalibration of the top gas analyzer or a significant shift in the composition of the burden also would require re-indexing of the period.

5. Experimental Results

This chapter presents the results of the natural gas injection tests at Acme. The first section of the chapter describes the chronology of events during the tests and the results of the screening of the operating data obtained in Phase E. The second section presents the evaluation of the rationalized data for each data point selected at the various injection levels in Phase E. A discussion of the impacts of some mechanical and process changes that occurred between Phases C and E is presented in the next chapter, and the implications of operation at very high rates of gas injection on furnace performance are presented in the final chapter.

A. CHRONOLOGY OF TESTS

The chronology of tests and results of data rationalization for Phases A and C have already been presented in detail and are only summarized here (see reference 9).

Phase A

Several upgrades were made prior to Phase A such as installing natural gas injection lances and upgrading the data acquisition system. Test work began on September 22, 1994 with natural gas turned on and the B-scrap taken off the burden. Natural gas injection rates were then increased to 150 lb/THM in several 50 and 25 lb/THM increments in order to establish a base period at 150 lb/THM. Approximately one month was required for this ramp-up period, and production was increased from about 2,600 TPD (with no scrap) to 3,100 TPD at an injection level of 154 lb/THM natural gas. The natural gas injection rate was held at about 7,400 SCFM for a period of about three weeks, with the supplemental oxygen rate at about 3,700 SCFM.

Phase B

Five months were required to complete the necessary upgrades in Phase B. The upgrades included improving the natural gas and oxygen delivery systems, a stove automation program, improved wind measurement, further upgrading and debugging of the data acquisition system, and installation of two above-burden temperature probes.

Phase C

When Phase B was completed, testing in Phase C was initiated at an injection level of 150 lb/THM to "bridge" to the results of Phase A. Testing began on April 17, 1995 and this condition was held for a week before initiating ramp-ups to higher injection rates. Periods of approximately one month each were run at nominal injection rates of 200 and 250 lb/THM (10,300 and 13,400 SCFM of natural gas, respectively). The oxygen enrichment rate during these periods was increased to about 6,000 and 7,800 SCFM, and hot metal production increased to about 3,270 and 3,430 TPD, respectively.

High-rate gas injection testing was terminated when the oxygen supply was curtailed and order book requirements decreased.

Phase D

Evaluation of the results of the testing of injection rates of up to 250 lb/THM indicated that further benefits in productivity increases and coke rate reductions could be expected at still higher natural gas injection rates. To operate consistently at production rates above 3,400 TPD required additional upgrades in the stock house (coke discharge), to the charging system (reskirting the bell), and to the wind delivery system (blower controls). These and other minor upgrades were installed in early 1996, with bell skirting completed in mid-June 1996. The natural gas injection rate was ramped up to about 200 lb/THM within two weeks after restart.

Phase E

Phase E began July 5, 1996 after the furnace had been operating satisfactorily at an injection level of about 200 lb/THM. The objective of initial operation was to establish a baseline period at an injection level of 250 lb/THM (13,000 SCFM) to "bridge" to the results of Phase C. However, the oxygen supply was limited from early August until early September. Thereafter, high hot metal production became a priority as an outlet became available for additional hot metal as well as for pig iron and the regular consumption at the BOF in Riverdale. Ramp-up to the 275 lb/THM setpoint was initiated on September 9, and this condition was held for about two weeks. Then, the injection rate was increased to 17,000 SCFM to achieve the target rate of 300 lb/THM. This condition was held throughout the month of October 1996, when decreased hot metal demand led to elimination of oxygen enrichment and decreased injection of natural gas. Monitoring of furnace operations at low gas injection levels continued through the months of November and December for data acquisition to permit “bridging” of the results to the Phase A tests.

Table 5–1 shows the data points selected for analysis and other major events that took place during Phase E.

Table 5-1. Acme Gas Test Data Selection for Phases D and E

Period Description	Dates	Natural Gas Consumption (SCFM)	Notes
End Phase D	6/01/96-6/16/96		Upgrade of Facilities — Skirt large bell
Restart Furnace	6/17/96-7/04/96	1,000-9,000	Ramp up from 25 lb/THM NGI rate to 190 lb/THM
Begin Phase E–Base Period	7/05/96	11,400	Target 250 lb/THM NGI rate
	7/06/96-7/08/96	11,400	Wind pulled due to ladle problems
Data Point 1	**7/09/96-7/12/96**	**11,230**	**232 lb/THM NGI**
	7/13/96	11,700	Data Collection System Down
	7/14/96	11,900	Data Collection System Down
Increase NG	7/15/96	12,200	2 hr. Downtime
Data Point 2	**7/16/96-7/20/96**	**13,000**	**267 lb/THM NGI**
	7/21/96-7/23/96	13,200	Data Collection System Down
	7/24/96	13,200	10-hr. Scheduled Shutdown
	7/25/96	13,200	Start-up Day
	7/26/96	13,200	Good Day
	7/27/96	13,200	Good Day
	7/28/96-7/31/96	13,200	Problems with Data Acquisition System
Data Point 3	**8/01/96-8/04/96**	**12,400**	**242 lb/THM NGI**
Decrease NG	8/05/96-8/08/96	7,200	Limited oxygen supply
Decrease NG	8/09/96-8/10/96	5,400	Limited oxygen supply
	8/11/96	5,400	5-hr. downtime to repair trough gate
	8/12/96	5,400	3-hr. downtime due to blower power loss
	8/13/96	5,400	Limited oxygen supply
	8/14/96	5,400	8-hr. scheduled outage

5. Experimental Results

Table 5-1 (continued)

Period Description	Dates	Natural Gas Consumption (SCFM)	Notes
Increase NG	8/15/96-8/19/96	7,400	Limited oxygen supply
Increase NG	8/20/96-8/21/96	8,200	Limited oxygen supply
	8/22/96	8,200	Coke weigh hopper miscalibration fixed
Increase NG	8/23/96-8/26/96	9,000	Limited oxygen supply
	8/27/96	8,000	3½-hr. downtime — BOF slowdown
Increase NG	8/28/96	8,400	More oxygen available — 250 lb/THM NGI rate target
Data Point 4	**8/29/96-9/01/96**	**11,300**	**245 lb/THM NGI**
	9/02/96	11,300	Data acquisition system failed
	9/04/96	11,300	10-hr. scheduled outage
	9/05/96	11,300	Start-up day
	9/06/96	11,300	HBT reduced to 1,800°F due to crack in stove shell
	9/07/96	11,900	3-hr. downtime — lost #2 tuyere twice
Phase E — Ramp-up Period	9/08/96	13,400	3-hr. downtime 275 lb/THM NGI rate target
Data Point 5	**9/09/96-9/12/96**	**14,000**	**281 lb/THM NGI**
	9/13/96	13,900	4½-hr. downtime — no ladles, lost #5 blowpipe
	9/14/96	13,900	Good Day
	9/15/96	13,900	2½-hr. down due to lack of ladles
	9/16/96	13,900	Furnace ran hot — blast moisture increased to 12 gr/SCF and HBT decreased to 1,850°F for most of day
Data Point 6	**9/17/96-9/21/96**	**14,600**	**276 lb/THM NGI**
	9/22/96	15,200	2-hr. down due to lack of ladles — problem with trains
	9/23/96	15,200	Good Day
	9/24/96	15,200	2-hr. down due to lack of ladles
	9/25/96	15,200	8-hr. scheduled outage
Data Point 7	**9/26/96-9/30/96**	**15,800**	**292 lb/THM NGI**
	10/01/96-10/03/96	15,900	Hot Metal production curtailed — BOF down
Phase E — 300 lb/THM Period	**10/04/96**	**16,400**	**300 lb/THM target NGI rate** Top gas analyzer off-line
	10/05/96	16,400	**Record Day — 3,740 THM**
	10/06/96	16,800	Good Day
	10/07/96	17,000	Top gas analyzer back on-line
	10/08/96	17,000	2-hr. down — stock house problems
	10/09/96-10/10/96	17,000	Hot blast valve problems
	10/11/96	17,000	3-hr. down to repair skip axle
	10/12/96	17,000	2-hr. down — ladles tied up at BOF
	10/13/96	17,000	2½-hr. down — Burned #14 tuyere
	10/14/96	17,000	2½-hr. down — fixed hot blast valve and patch bustle pipe leak

Table 5-1 (continued)

Period Description	Dates	Natural Gas Consumption (SCFM)	Notes
Phase E — 300 lb/ THM Period (cont.)	10/15/96	17,000	Lost coke weigh hopper — fill changed to OCOC for 6 hr.
	10/16/96	17,000	22-hr. scheduled outage
	10/17/96	17,000	Start-up Day
Data Point 8	**10/18/96-10/22/96**	**16,700**	**304 lb/THM NGI**
	10/26/96	17,200	**Record Day — 3,899 THM**
	10/27/96	17,200	1 extra Hour/Daylight savings time ends
Data Point 9	**10/23/96-10/27/96**	**17,200**	**306 lb/THM NGI**
Data Point 10	**10/28/96-10/31/96**	**17,300**	**311 lb/THM NGI**
End high rate gas injection	11/01/96	15,400	Ramp down to 200 lb/THM NGI rate 3,400 TPD HM Target
Decrease NG	11/02/96	12,300	Decrease HM Production to 3,000 TPD
Decrease NG	11/03/96	10,900	
	11/04/96	8,900	2,850 TPD
	11/05/96	8,400	
Decrease NG	11/06/96		Scheduled 8-hr. Shutdown 100 lb/THM NGI Target Set
	11/07/96	4,000	HM production for BOF only, 2,700 TPD
Data Point 11	**11/08-96-11/17/96**	**4,300**	**97 lb/THM NGI**
	11/18/96		Down 6 hrs. for Mud Gun Repair
	11/19/96	4,400	Furnace Balancing Out
	11/20/96	4,400	
	11/21/96	4,400	Down 2 hrs. – lack of ladles
	11/22/96	4,600	
	11/23/96		Down 3½ hrs. – Hoist house problems
	11/24/96	4,300	NG changed from 4,600 cfm to 4,300 cfm
	11/25/96	4,500	Data System Down
	11/26/96		10 hr. Shutdown
	11/27/96	3,900	Furnace Balancing Out
Data Point 12	**11/28/96-12/11/96**	**3,800**	**98 lb/THM NGI**
	12/12/96		12 hrs. downtime
	12/13/96	3,900	Furnace Balancing Out
Data Point 13	**12/14/96-12/17/96**	**4,200**	**99 lb/THM NGI**
	12/18/96		9 hr. Shutdown
	12/19/96	3,800	Furnace Balancing Out
Data Point 14	**12/20/96-12/27/90**	**3,800**	**105 lb/THM NGI** **Low demand — 2,300 TPD**
End of monitoring	12/28/96		

5. Experimental Results

B. EVALUATION OF RATIONALIZED DATA

Rationalized data from four periods are evaluated in detail in this section. The periods are: the base case (at 250 lb/THM), periods with targeted gas injection at levels of 275 and 300 lb/THM, and an extended period of operation at an injection level of 100 lb/THM without oxygen enrichment. In addition, the results of operations in the ramp-up period and periods of non-targeted operations are discussed briefly.

The dates selected for each data point and the corrections required to burden and wind rates and top gas compositions to force material balances closure, i.e., rationalization, are shown for each period. The rationalized operating parameters, thermal and energy parameters, and hot metal and top gas compositions are shown as well as data describing the dynamic behavior of the furnace.

The terms used to describe furnace performance are defined in Table 5-2.

250 lb/THM Base Period

A period of operation at a target injection level of 250 lb/THM was scheduled in order to permit direct comparison of furnace operations at the conclusion of Phase C and at the initiation of Phase E testing at the same injection level. Although the test plan called for ramp-up and operation over 30 days at this condition (see Table 3–8), more than two months were required to obtain the data. Most of the extension was necessitated by a three-week period of limited oxygen supply, but problems with the data acquisition system limited the quality of information available during the first few weeks. Also, some limitations of the revised turbo control system became apparent during this period, and some time was required for the operators to learn how to react properly to them.

Table 5-2. Definitions of Process Parameter Terms

Parameter	Definition
Bosh Hydrogen	The total flow of hydrogen gas, in pound moles per ton of hot metal or as a percentage of the total gases in the bosh. It is calculated from the blast and supplemental fuel and oxygen rates.
Rho V^2 term, or Bosh Kinetic Energy	The ratio of the value of the kinetic energy of the bosh gases, ρV^2, to the average density of the burden constituents. The average burden density is calculated from the burden ratio, and the ρV^2 term is calculated from the flow rate, temperature, and composition of the bosh gases, which are determined by material and energy balances. Values below the maximum limit indicate that smooth burden descent should be expected. Analogous to the K value normally reported.
EGC	The extent of the endothermic gasification of carbon, also called the solution loss or Boudard reaction. The amount of carbon, in moles per ton of hot metal, consumed by the reaction is calculated by overall material balance when analyzing furnace performance, or established based on bosh gas composition.
Energy Balance RAFT	The Raceway Adiabatic Flame Temperature, in °F, calculated by a rigorous energy balance. Gases consist only of N_2, Ar, CO, and H_2. Coke temperature is assumed to be either 2,900°F or 50°F below the hearth gas temperature, whichever is higher.
Energy Above 2,700°F	The total thermal energy content of the hearth gases above the reference temperature of 2,700°F, in units of millions of Btu per ton of hot metal. The flow rate of the gases is calculated for the blast and supplemental fuel and oxygen rates, and their temperature is calculated by an energy balance on the hearth zone assuming the burden constituents enter the zone at 2,700°F.
Hearth Zone Gas Temperature Difference	The difference in temperature, in °F, between the gases leaving the hearth zone and the hot metal. The gas temperature is calculated by material and energy balance on the hearth zone based on blast conditions and supplemental fuel and oxygen rates, and hot metal and slag production rates. Burden constituents are assumed to enter the zone at 2,700°F.
Reduction Zone Duty	The amount of energy, in billions of Btu per hour, required for direct and indirect reduction of iron and for heating burden constituents in the reduction zone. It is calculated by material and energy balance with the solids' temperatures entering and leaving the zone normally set at 1,800°F and 2,700°F, respectively.
Reduction Zone "Pinch" Temperature	The difference in temperature, in °F, between the gases leaving the reduction zone and the solids entering the zone. The limit of this zone is usually defined as the location at which the solids temperature is 1,800°F, and the gas temperature is calculated by material and energy balance based on the temperature of the gases leaving the hearth and the known or estimated extent of the solution loss reaction. Corresponds to the temperature difference in the thermal reserve zone.

Table 5-2 (continued)

Parameter	Definition

5. Experimental Results

Parameter	Definition
Thermal-plus-Chemical Energy Above 2,700°F	The sum of the thermal energy above 2,700°F leaving the hearth zone (see "Energy Above 2,700°F") and the energy-equivalent of the hydrogen content of the hearth gases. The latter is calculated by estimating, based on the bosh gas hydrogen content, the extent to which the hydrogen in the gases will reduce iron, thus decreasing the extent of the solution loss reaction. The decreased thermal energy requirements arising from the decreased extent of direct reduction are then added to the thermal energy of the rising gases to calculate their thermal-plus-chemical (i.e., due to H_2) energy content.
Total Energy Released	The amount of energy, in millions of Btu per hour, required for heat losses and metallurgical reactions in the hearth zone, and to heat the gases leaving the hearth. It is calculated by material and energy balance from the production rate and blast rate, assuming that burden constituents enter the hearth zone at 2,700°F. It is analogous to the driving rate.
Pressure Drop-to-Burden Density Ratio	The dimensionless ratio of the gas pressure drop per unit height of the furnace to the average burden density. The pressure drop is estimated from the reported blast pressure minus reported top gas pressure less a correction of 3 psi for losses through the tuyere. The height difference is taken from the tuyere line to the normal stock line, and average burden density is calculated from the burden charge composition.
Cast-to-Cast Variation in the Thermal State of the Hearth, dQ/dt	The change in the amount of energy required, in millions of Btu, to produce successive casts with different temperatures and compositions divided by the time between casts. It is calculated from the amount of hot metal and slag produced in each cast, their temperatures, the hot metal silicon and manganese contents, and the estimated material inventory in the hearth zone that also responds to the changes. It is a measure of the variability of the burden descent to the hearth.

Table 5–3 shows the correction factors used to rationalize the base case data. All of the adjustment factors were within acceptable ranges except for the coke rate adjustment factor which was beyond the usual ±2% limit for the first three points. The persistence of the high negative correction factors for coke, and a higher than expected uncorrected fuel rate of 1,020 lb/THM (vs. 975 lb/THM in Phase C at this injection rate), led Acme to review the coke weighing system and an instrumentation error was found at the coke weigh hopper. One of the four load cells had been mis-wired during routine maintenance causing erroneously high readings. The error was detected and corrected on August 22, so that only periods 1 through 3 were affected.

Table 5–3. Correction Factors Used for Rationalizing the 250 lb/THM Base Cases — Data Points 1–4

	Units	1	2	3	4	Wtd. Avg.
Dates		7/9-12/96	7/16-20/96	8/1-4/96	8/29-9/1/96	
No. of Days		4	5	4	4	
H.M. Rate	%	0.00	0.00	0.00	-0.50	-0.12
Iron-Bearing Burden	%	-2.26	-2.15	-2.05	1.43	-1.31
Tilden Pellet (SiO_2+Al_2O_3)	%	0.35	0.41	0.21	0.35	0.34
Coke Rate	%	-5.56	-9.36	-3.95	1.90	-4.54
Wind	%	8.25	4.97	5.14	0.21	4.66
Supplemental Oxygen Rate	%	0.00	0.00	0.00	0.00	0.00
Top Gas						
CO	%	0.00	0.00	-0.01	-0.89	-0.21
CO_2	%	0.00	0.00	-0.01	0.77	0.18
N_2	%	0.00	0.00	0.02	0.11	0.03

Retrospective evaluation of the data suggests that the error introduced a bias of at least +6% into the coke weight measurement. Accounting for a bias of this magnitude would bring the weighted average coke correction factor to below 0.1%, well within the range found to be required in the tests in Phases A and C. All other correction factors are also within the ranges required during the earlier test work except for the iron-bearing burden factors, where the previous absolute average correction factor was 1%. It is of interest that, while the wind correction for Point 4 appears somewhat low, the average is within the range found previously in Phase C suggesting that installation of the revised turbo control system did not affect the calibration of the wind measurement system.

The results of the application of these correction factors to the blast furnace operating data are summarized in terms of the estimated operating parameters, thermal parameters, and the hot metal chemistry in Tables 5–4 through 5–6.

Table 5–4. Rationalized Operating Parameters for 250 lb/THM Base Cases — Data Points 1–4

	Units	1	2	3	4	Wtd. Avg.
Productivity						
Production	TPD	3,144	3,165	3,337	3,004	3,163
% Increase	@ 2,597 Base	21.1%	21.9%	28.5%	15.7%	21.8%
Production	TPD/100cfwv	7.65	7.70	8.12	7.31	7.69
Burden						
Coke	lb/THM	741	707	730	746	730
B-Scrap	lb/THM	0	0	0	0	0
Tilden Pellets	lb/THM	2,154	2,086	2,027	2,034	2,076
Wabush Pellets	lb/THM	923	995	1,044	1,048	1,002
Dolomite	lb/THM	0	0	0	35	8
BOF Slag	lb/THM	94	90	105	70	90
Wind						
Wind, delivered	scfm	71,627	67,924	72,460	71,463	70,695
Wind	MSCF/THM	32.8	30.9	31.3	34.3	32.2
Blast Moisture	gr/SCF	9.6	9.4	6.9	11.4	9.3
Supplemental O_2	lb/THM	254	301	281	255	274
Supplemental O_2	TPD	399	476	469	383	434
Total O_2	TPD	1,299	1,327	1,378	1,281	1,321
Total O_2	TPD/100cfwv	3.16	3.23	3.35	3.12	3.22
Natural Gas	lb/THM	232	268	242	245	248
Others						
Fuel Rate	lb/THM	974	976	972	991	978
Slag Production	lb/THM	376	367	376	369	372
dP/B.Density		0.339	0.342	0.341	0.341	0.341
Top Gas Production	MSCF/THM, Dry	55.2	54.6	54.2	57.6	55.4
Top Gas H_2	%	11.12	12.95	11.88	11.78	11.99
Top Gas CO	%	21.47	22.21	22.00	21.08	21.72
Top Gas CO_2	%	20.84	20.47	20.96	20.59	20.70
Top Gas N_2	%	46.58	44.36	45.16	46.55	45.59

Table 5-5. Thermal/Energy Parameters for 250 lb/THM Base Cases — Data Points 1–4

Parameters	Units	1	2	3	4	Wtd. Avg.
Blast Temp	°F	1,904	1,905	1,896	1,908	1,903
H.M. Temp	°F	2,648	2,616	2,654	2,641	2,638
AISI RAFT	°F	3,155	3,008	3,186	3,076	3,100
Rho V^2		20.9	19.9	22.3	20.6	20.8
Hearth Zone Gas	°F	2,801	2,748	2,848	2,753	2,785
dT Hearth	°F	154	132	194	113	147
Bosh H_2	lb mol/THM	29.7	33.7	30.0	31.7	31.4
Therm + Chem Energy	MMBtu/THM	0.75	0.77	0.81	0.73	0.77
EGC (solution loss)	lb mol/THM	6.19	5.62	7.06	5.33	6.02
dT Bosh	°F	51	30	47	55	45
Top Gas Temp	°F	365	348	357	370	359
HHV	Btu/SCF	105	114	110	106	109
Top CO/CO_2		1.03	1.09	1.05	1.02	1.05
H_2 Util. Eff.	%	45.5	44.5	43.4	43.7	44.3
Heat Loss	MMBtu/hr	74	76	70	86	77

Table 5–6. Summary of Hot Metal and Slag Chemistry for the 250 lb/THM Base Cases — Data Points 1–4

Hot Metal	Units	1	2	3	4	Wtd. Avg.
Average Silicon	%	0.54	0.46	0.42	0.55	0.49
Standard Deviation	%	0.10	0.11	0.09	0.13	0.11
Average Sulfur	%	0.056	0.064	0.065	0.058	0.061
Standard Deviation	%	0.007	0.011	0.013	0.011	0.011
Average Temperature	°F	2,644	2,617	2,654	2,641	2,638
Standard Deviation	°F	23	26	20	30	25
dQ/dt Avg. Variability	MMBtu/hr	14.9	14.1	12.6	14.1	13.9
dQ/dt Avg. Var. SD	MMBtu/hr	11.4	11.3	9.8	9.0	10.4
Average Cast Amount	Tons/Cast	191	198	209	186	196
Slag						
Basicity	B/A	0.96	0.93	0.97	0.99	0.96
S	%	0.96	0.90	0.96	1.06	0.96
FeO	%	0.44	0.54	0.49	0.45	0.49

During the period of base case data acquisition the required hot metal production rate was about 3,200 TPD, well below that achieved in Phase C and below the test plan value, so that the aim value for natural gas injection was about 12,000 SCFM. This is somewhat lower than the 13,400 SCFM average injected under comparable conditions in Phase C because the production averaged about 280 TPD lower. The lower production rate required less total oxygen: an average of 1,321 TPD was contained in the blast plus supplemental oxygen during this period whereas 1,443 TPD had been provided in the Phase C tests at an injection level of 250 lb/THM. While the decrease in total oxygen consumption was consistent with the decrease in production, the source of the oxygen changed: slightly less was supplied by the wind and slightly more by the enrichment, which increased from about 1.08 lb O_2/lb NG in Phase C to about 1.1 lb/lb in these tests.

The changes in wind and oxygen rates changed the thermal profile in the furnace somewhat, decreasing the AISI RAFT, Thermal-plus-Chemical Energy, and hearth pinches somewhat vis-à-vis the previous (Phase C) tests at 250 lb/THM. The bosh pinch increased slightly, however, (from 33°F to 45°F) because the extent of the solution loss reaction was about 0.8 mol/THM lower than in the previous tests. The hot metal chemistry was virtually unchanged (Si increased by 0.04%) and the decrease in the extent of the solution loss reaction essentially compensated for the increased coke consumption due to increased blast moisture: the estimated fuel rate was almost unchanged at 978 lb/THM versus 974 lb/THM in Phase C. The decreased oxygen consumption and extent of solution loss led to a decrease in the CO/CO_2 ratio from 1.11 to 1.05, but the hydrogen utilization efficiency was unchanged at 44%.

The slag rate and hot metal chemistry were close to those found in Phase C and by all of the usual measures the variability in the chemistry was decreased. The low slag basicity is a consequence of the burdening practice, producing hot metal with acceptable sulfur contents. The slag sulfur content reported here has been calculated to force closure of the sulfur balance.

The impacts of other process- and equipment-related differences between the tests in Phase C and Phase E at this injection rate are described in the next chapter.

Ramp-Up Data: 275 lb/THM

The ramp-up from 250 to 275 lb/THM coincided with an increase in the demand for hot metal, and the aim value for the natural gas flow rate was increased for each data point during this period. Most of the delays experienced were due to a lack of ladles, and the only furnace problems resulted from failure of a blowpipe that terminated an otherwise smooth sequence of operations over data point 5. As shown in Table 5–7 below, the correction factors are well within their expected limits and are consistent with those found in previous periods at Acme.

Table 5–7. Correction Factors Used for 275 lb/THM Ramp-Up Periods — Data Points 5–7

	Units	5	6	7	Wtd. Avg.
Dates		9/9-12/96	9/17-21/96	9/26-30/96	
No. of Days		4	5	5	
H.M. Rate	%	0.00	-0.50	0.00	-0.18
Iron-Bearing Burden	%	-0.74	-0.91	-1.31	-1.01
Tilden Pellet (SiO_2+Al_2O_3)	%	0.36	0.31	0.32	0.33
Coke Rate	%	1.45	1.94	0.50	1.28
Wind	%	3.28	9.35	9.62	7.97
Supplemental Oxygen Rate	%	0.00	0.00	0.00	0.00
Top Gas					
CO	%	0.00	-0.59	0.00	-0.21
CO_2	%	0.00	0.54	0.00	0.19
N_2	%	0.00	0.05	0.00	0.02

The data collection plan shown in Table 3–9 called for ramping up through a production level of 3,350 TPD for about 10 days, and then holding production constant at 3,400 TPD for 30 days at an injection level of 275 lb/THM before ramping up to the 300 lb/THM. As shown in Table 5–8, however, the production and injection rates were ramped up more rapidly, with target conditions being met and held within two weeks. Then, in response to increasing demand for hot metal, the operators chose to deviate from the test plan and initiate ramp-up to the 300 lb/THM condition. Data point 7, at an injection rate of 291 lb/THM, is included in this period although it could also be considered as a ramp-up to the higher injection rate.

Table 5-8. Rationalized Operating Parameters for 275 lb/THM Ramp-Up Periods — Data Points 5–7

	Units	5	6	7	Wtd. Avg.
Productivity					
Production	TPD	3,249	3,451	3,536	3,424
% Increase	@ 2,597 Base	25.1%	32.9%	36.1%	31.8%
Production	TPD/100cfwv	7.91	8.40	8.60	8.33
Burden					
Coke	lb/THM	732	714	693	712
B-Scrap	lb/THM	0	0	0	0
Tilden Pellets	lb/THM	2,038	2,039	2,039	2,039
Wabush Pellets	lb/THM	1,050	1,051	1,051	1,050
Dolomite	lb/THM	35	35	36	35
BOF Slag	lb/THM	56	56	56	56
Wind					
Wind, delivered	scfm	70,644	74,277	75,086	73,528
Wind	MSCF/THM	31.3	31.0	30.6	30.9
Blast Moisture	gr/SCF	8.4	7.4	4.3	6.6
Supplemental O_2	lb/THM	322	328	336	329
Supplemental O_2	TPD	523	565	594	564
Total O_2	TPD	1,407	1,495	1,533	1,483
Total O_2	TPD/100cfwv	3.42	3.64	3.73	3.61
Natural Gas	lb/THM	281	276	291	283
Others					
Fuel Rate	lb/THM	1,013	990	985	995
Slag Production	lb/THM	364	366	363	364
dP/B.Density		0.357	0.364	0.352	0.358
Top Gas Production	MSCF/THM, Dry	56.4	55.1	54.5	55.3
Top Gas H_2	%	13.32	12.88	12.94	13.03
Top Gas CO	%	23.78	22.37	23.00	23.00
Top Gas CO_2	%	19.45	20.72	20.12	20.14
Top Gas N_2	%	43.44	44.03	43.93	43.83

Table 5-9. Thermal/Energy Parameters for 275 lb/THM Ramp-Up Periods — Data Points 5–7

Parameters	Units	5	6	7	Wtd. Avg.
Blast Temp	°F	1,871	1,867	1,892	1,877
H.M. Temp	°F	2,638	2,649	2,649	2,646
AISI RAFT	°F	2,993	3,058	3,061	3,041
Rho V^2		21.9	23.9	24.7	23.6
Hearth Zone Gas	°F	2,755	2,775	2,772	2,768
∆T Hearth	°F	117	126	123	122
Bosh H_2	lb mol/THM	34.9	33.9	35.0	34.6
Therm + Chem Energy	MMBtu/THM	0.79	0.81	0.83	0.81
EGC (solution loss)	lb mol/THM	6.51	5.19	5.22	5.58
∆T Bosh	°F	30	70	65	57
Top Gas Temp	°F	399	375	356	375
HHV	Btu/SCF	120	114	116	117
Top CO/CO_2		1.22	1.08	1.14	1.14
H_2 Util. Eff.	%	42.7	44.8	46.8	44.9
Heat Loss	MMBtu/hr	62	89	92	83

Table 5-10. Summary of Hot Metal and Slag Chemistry for 275 lb/THM Ramp-Up Periods — Data Points 5–7

Hot Metal	Units	5	6	7	Wtd. Avg.
Average Silicon	%	0.46	0.39	0.42	0.42
Standard Deviation	%	0.09	0.09	0.10	0.09
Average Sulfur	%	0.068	0.066	0.064	0.066
Standard Deviation	%	0.009	0.012	0.007	0.009
Average Temperature	°F	2,638	2,649	2,649	2,645
Standard Deviation	°F	23	30	25	26
dQ/dt Avg. Variability	MMBtu/hr	17.2	15.4	15.4	15.9
dQ/dt Avg. Variability SD	MMBtu/hr	15.4	12.1	13.7	13.6
Average Cast Amount	Tons/Cast	181	195	199	193
Slag					
Basicity	B/A	0.95	0.95	0.96	0.95
S	%	0.98	0.91	0.95	0.94
FeO	%	0.44	0.59	0.51	0.51

The increases in productivity were achieved by increasing both the supplemental oxygen injection rate and the wind rate, although the specific wind consumption (MSCF/THM) decreased as called for in the test plan. The total amount of oxygen delivered to the furnace increased by 126 TPD during this period, with about 55% of the increase being obtained from the injection of supplemental oxygen. The ratio of oxygen to natural gas injection was increased from about 1.1 lb/lb at the 250 lb/THM natural gas injection level to about 1.15 lb/lb in these tests. The additional enrichment, which increased from 7.2% to 8.9%, mitigated the decrease in RAFT, which dropped by less than 60°F. While the hot metal silicon content decreased slightly, its temperature increased slightly, and while the hearth gas pinch decreased by 25°F the gases' thermal-plus-chemical energy content increased by 0.04 MM Btu/THM because of their higher hydrogen content. By this measure the furnace was slightly hotter than it had been at the 250 lb/THM injection level, and while the hot metal silicon content decreased somewhat, its variability was essentially unchanged from the 250 lb/THM condition. Slag chemistry also was only slightly changed.

The extent of the solution loss reaction decreased significantly in points 6 and 7 as would be expected given the higher bosh gas hydrogen contents. An increase vis-à-vis the 250 lb/THM average is shown in point 5, however, and the fuel rate for this point is also abnormally high and the hydrogen utilization efficiency lower than average. While the variability in the hot metal chemistry was improved by the usual measures (SDs in % Si, % S and T), the variability in cast-to-cast dQ/dt increased significantly in Point 5. While the correction factors for this point are all within acceptable limits (see Table 5–7), the indicated approaches to equilibrium in the reduction and lower stack zones are abnormally low, indicating either a problem with the data or with the charge or burdening practice. The latter were not changed throughout this period, although the dolomite content of the burden was increased and the BOF slag content was decreased from the values used at 250 lb/THM. While the ratio of pressure drop to burden density increased slightly (by 0.017), it was accompanied by a significant increase in the bosh gas kinetic energy term (in points 6 and 7 but not in point 5). Taken together, these observations suggest that the furnace was experiencing transients during the period covered in point 5 as the injection level was being ramped up.

300 lb/THM Period

The continued strong demand for hot metal and smooth furnace operation during the ramp-up period motivated the operators to increase the natural gas flow rate still further in early October in an attempt to achieve the aim values set for testing at 300 lb/THM. A series of minor mechanical problems around the furnace and a scheduled outage prevented attainment of the requisite minimum of three continuous days of steady operation until October 18. This was followed, however, by a period of 14 days of continuous operation at injection rates exceeding 300 lb/THM. This extended period has been divided into three subperiods within which production, natural gas, wind and oxygen flow rates were held within somewhat tighter ranges, and the correction factors required to rationalize the data for these points are summarized in Table 5–11. The final column in this and the following tables shows the results of rationalizing the entire period as one set of data.

Table 5–11. Corrections Required for 300 lb/THM Period — Data Points 8–10

	Units	8	9	10	Wtd. Avg.	Entire Period
Dates		10/18-22/96	10/23-27/96	10/28-31/96		10/18-31/96
No. of Days		5	5	4		14
H.M. Rate	%	0.00	0.00	0.10	0.03	0.30
Burden	%	0.28	-0.53	-2.00	-0.67	-0.40
Tilden Pellet (SiO_2+Al_2O_3)	%	0.33	0.31	0.23	0.30	0.31
Coke	%	-1.69	1.10	-2.40	-0.89	-2.40
Wind	%	4.02	3.28	3.60	3.63	1.90
Oxygen	%	0.00	0.00	0.00	0.00	0.00
Top Gas						
CO	%	-0.07	0.00	1.16	0.31	0.00
CO_2	%	-0.07	0.00	-1.29	-0.39	0.00
N_2	%	0.13	0.00	0.13	0.08	0.00

The magnitudes of the correction factors required for data rationalization are within acceptable limits, and are consistent with those found in previous test work for the first two data points, but not for the last one, which shows very large top gas correction for CO and CO_2. The correction factors for point 10 lead to a very high CO/CO_2 ratio (1.3), an abnormally high solution loss extent for this bosh gas hydrogen content, a very low bosh pinch (11°F) and somewhat unusual stack zone balances. It is not obvious from inspection of the raw data that the furnace was experiencing transients or that instrumentation problems had arisen, but these results do not appear to be consistent with those from the previous points. Treating all of the data in this period as a single set permits them to be rationalized without correction to the top gas composition with a coke rate correction factor of -2.4%. If the coke rate correction factor were limited to ±1.4%, the average of the correction factors for all previous data points for the tests at Acme, top gas correction factors of +0.16% on CO and -0.16% on CO_2 would be required, which are within the acceptable range. The operating and thermal parameters reported in Tables 5-12 and 5-13 would not change significantly, but the average coke and fuel rates would increase to 646 lb/THM and 952 lb/THM, respectively.

The natural gas injection rate was increased to an average of about 17,400 SCFM for this period, and the total oxygen delivered to the furnace averaged 1,496 TPD. While this is not significantly different from the amount of oxygen consumed at the higher injection rates during the pervious ramp-up period, the source of oxygen was changed significantly. The delivered wind (and specific wind rate) was decreased and the enrichment was increased from 8.9% to 10.5%, although the ratio of supplemental oxygen to natural gas increased only slightly from about 1.15 to about 1.18 lb/lb. The decrease in specific wind rate and increase in supplemental oxygen rate were somewhat greater than called for in the test plan (see Table 3–8), but were required to maintain burden movement and pressure drop given the burden permeability; the ratio of pressure drop to burden density had increased slightly from the previous ramp-up period to 0.383.

The only changes made in the burdening practice during this period were the removal of the dolomite and returning the amount of BOF slag to levels that had been used in the base case period. This caused a small decrease in slag basicity, from about 0.95 to about 0.94, but the hot metal sulfur content fell slightly (from 0.066 to 0.062%) because the decrease in coke rate reduced the sulfur load to the furnace from about 5.9 to about 5.3 lb/THM. The hot metal temperature and slag FeO content were nearly unchanged, but the hot metal silicon content decreased from the 0.42% obtained in the ramp-up period to 0.34% here. This decrease, together with the decrease in wind rate and blast moisture and the increase in blast temperature, contributed about 20 lb/THM decrease in the observed coke rate.

The higher than called for enrichment mitigated the projected decreases in RAFT and hearth gas temperature pinch, and resulted in the thermal-plus-chemical energy content of the hearth gases remaining constant. While the extent of the solution loss reaction decreased by less than 0.5 mol/THM from the ramp-up period, a substantial productivity increase was realized at essentially the same total oxygen consumption, and that resulted in decreases in the coke and fuel rates. The hydrogen utilization efficiency remained high at over 49%, and the CO/CO_2 ratio increased only slightly. The variability in hot metal chemistry remained low by the usual measures (the S.D.s about the averages), and the cast-to-cast thermal variability reached the lowest levels recorded in these tests.

Table 5-12. Rationalized Operating Parameters for 300 lb/THM Period — Data Points 8–10

	Units	8	9	10	Wtd. Avg.	Entire Period
Productivity						
Production	TPD	3,585	3,658	3,622	3,622	3,633
% Increase	@ 2,597 Base	38.1%	40.9%	39.5%	39.5%	39.9%
Production	TPD/100cfwv	8.72	8.90	8.81	8.81	8.84
Burden						
Coke	lb/THM	648	654	655	652	641
B-Scrap	lb/THM	0	0	0	0	0
Tilden Pellets	lb/THM	2,032	2,033	2,036	2,033	2,033
Wabush Pellets	lb/THM	1,047	1,047	1,049	1,047	1,047
Dolomite	lb/THM	0	0	0	0	0
BOF Slag	lb/THM	91	91	91	91	91
Wind						
Wind, delivered	scfm	68,405	69,521	68,490	68,831	67,688
Wind	MSCF/THM	27.5	27.4	27.2	27.4	26.8
Blast Moisture	gr/SCF	5.2	4.0	3.2	4.2	4.2
Supplemental O_2	lb/THM	355	364	363	361	360
Supplemental O_2	TPD	636	665	658	653	653
Total O_2	TPD	1,488	1,531	1,511	1,510	1,496
Total O_2	TPD/100cfwv	3.62	3.72	3.68	3.67	3.64
Natural Gas	lb/THM	304	306	312	307	306
Others						
Fuel Rate	lb/THM	953	960	967	960	947
Slag Production	lb/THM	364	365	369	366	365
dP/B.Density		0.347	0.355	0.387	0.361	0.383
Top Gas Production	MSCF/THM, Dry	51.0	51.3	51.3	51.2	50.3
Top Gas H_2	%	13.89	14.08	14.10	14.02	14.02
Top Gas CO	%	23.52	23.81	25.05	24.06	23.75
Top Gas CO_2	%	20.37	20.26	19.28	19.02	20.41
Top Gas N_2	%	42.22	41.84	41.57	41.90	41.82

Table 5-13. Thermal/Energy Parameters for 300 lb/THM Period — Data Points 8–10

Energy Parameters	Units	8	9	10	Wtd. Avg.	Entire Period
Blast Temp	°F	1,899	1,913	1,912	1,908	1,908
H.M. Temp	°F	2,650	2,647	2,625	2,642	2,642
AISI RAFT	°F	2,906	2,954	2,926	2,929	2,911
Rho V^2		21.8	22.7	24.1	22.7	23.5
Hearth Zone Gas	°F	2,717	2,747	2,749	2,737	2,724
dT Hearth	°F	67	100	124	95	82
Bosh H_2	lb mol/THM	36.6	36.6	37.0	36.7	36.6
Therm + Chem Energy	MMBtu/THM	0.79	0.83	0.84	0.82	0.80
EGC (solution loss)	lb mol/THM	4.86	5.24	6.18	5.38	5.11
dT Bosh	°F	44	49	11	36	32
Top Gas Temp	°F	388	385	350	376	373
HHV	Btu/SCF	121	123	127	123	122
Top CO/CO_2		1.15	1.18	1.30	1.20	1.16
H_2 Util. Eff.	%	49	48	48.4	48.5	49.1
Heat Loss	MMBtu/hr	60	63	62	61.7	61.0

Table 5-14. Summary of Hot Metal and Slag Chemistry for 300 lb/THM Period — Data Points 8–10

Hot Metal	Units	8	9	10	Wtd. Avg.	Entire Period
Average Silicon	%	0.36	0.30	0.30	0.34	0.34
Standard Deviation	%	0.08	0.07	0.06	0.07	0.07
Average Sulfur	%	0.064	0.060	0.063	.062	0.062
Standard Deviation	%	0.010	0.007	0.012	0.010	0.010
Average Temperature	°F	2,650	2,647	2,625	2,642	2,642
Standard Deviation	°F	29	28	35	30	30
dQ/dt Avg. Variability	MMBtu/hr	14.8	13.8	9.3	12.9	12.9
dQ/dt Avg. Var. SD	MMBtu/hr	14.3	13.3	9.9	12.7	12.7
Average Cast Amount	Tons/Cast	209	202	201	204	204
Slag						
Basicity	B/A	0.94	0.94	0.94	0.94	0.94
S	%	0.81	0.81	0.77	0.80	0.80
FeO	%	0.48	0.54	0.69	0.57	0.44

Ramp Down and Operation at 100 lb/THM

The demand for hot metal dropped substantially at the beginning of November, and the ramp down period was initiated. The injection rate was dropped to 200 lb/THM over four days in preparation for a scheduled shutdown, and was reset at a nominal rate of 100 lb/THM with no oxygen injection upon restart. This was sufficient to produce the desired 2,700 TPD without metallics addition to the burden. Although the requirements of the test plan had been met, it was decided to extend the data collection effort by an additional two months during the period of planned low production and low-rate gas injection. The primary objective of extending the analyses to a period of low gas injection was to bridge back to the data collected in Phase A, particularly to evaluate changes in burden permeability. The correction factors used to rationalize the data are summarized in Table 5-15.

Table 5-15. Corrections Required for 100 lb/THM Period — Data Points 11-14

Dates	Units	11 11/8–17/96	12 11/28–12/11/96	13 12/14–17/96	14 12/20–27/96	Wtd. Avg.
No. of Days		10	14	4	8	
HM Rates	%	-0.50	-0.50	-0.50	0.0	-0.40
Iron-Bearing Burden	%	1.40	2.00	2.60	0.10	1.51
Tilden Pellet (SiO_2 + Al_2O_3)	%	0.07	0.18	0.08	0.13	0.12
Coke Rate	%	2.40	-0.70	-0.90	-1.70	0.13
Wind	%	11.9	13.0	11.8	10.1	11.9
Supplemental Oxygen Rate	%	0	0	0	0	0
Top Gas						
CO	%	-1.77	-1.24	-1.32	-1.41	-1.44
CO_2	%	-0.77	-1.24	-1.32	-1.41	-1.14
N_2	%	2.54	2.48	2.63	2.82	2.58

It is obvious that the corrections to the reported wind rate and top gas compositions are significantly greater than have been required for any of the previous data analyzed at Acme. The large wind rate correction may be a consequence of a miscalibration of the meter at the high flow range, because the corrected absolute and specific wind rates are quite consistent with those obtained during the Phase A ramp-up period at injection rates of 90-125 lb/THM. The corrections to the top gas CO and CO_2 composition are not only relatively large but consistent in sign over this period which also suggests a calibration error had developed. The other correction factors are within expected ranges, however, and applying them to the data gives operating parameter values and thermal/energy parameters within the expected ranges as shown in Tables 5-16 and 5-17.

Table 5-16. Rationalized Operating Parameters for 100 lb/THM Period — Data Points 11-14

	Units	11	12	13	14	Wtd. Avg.
Productivity						
Production	TPD	2,826	2,498	2,720	2,305	2,586
% Increase	@ 2,597 Base	8.8	-3.8	4.7	-11.2	-0.4
Production	TPD/100 cfwv	6.88	6.08	6.62	5.61	6.29
Burden						
Coke	lb/THM	854	879	870	886	872
B-Scrap	lb/THM	0	0	0	0	0
Tilden Pellets	lb/THM	2,036	2,033	2,036	2,028	2,033
Wabush Pellets	lb/THM	1,049	1,047	1,049	1,045	1,047
Dolomite	lb/THM	0	0	0	0	0
BOF Slag	lb/THM	119	126	126	144	127
Wind						
Wind, delivered	scfm	84,055	76,721	82,478	72,440	78,785
Wind	MSCF/THM	42.8	44.2	43.7	45.3	43.9
Blast Moisture	gr/SCF	3.0	2.4	3.0	2.8	2.7
Supplemental O_2	lb/THM	0	0	0	0	0
Supplemental O_2	TPD	0	0	0	0	0
Total O_2	TPD	1,071	977	1,050	92.3	1,004
Total O_2	TPD/100 cfwv	2.60	2.38	2.56	2.24	2.45
Natural Gas	lb/THM	97	98	99	105	99
Others						
Fuel Rate	lb/THM	951	977	969	991	971
Slag Production	lb/THM	382	387	393	399	389
dP/B. Density		0.353	0.305	0.326	0.275	0.316
Top Gas Production	MSCF/THM, Dry	59.4	61.3	60.8	62.7	60.9
Top Gas H_2	%	3.90	3.99	4.19	4.20	4.03
Top Gas CO	%	19.72	20.41	20.25	20.55	20.21
Top Gas CO_2	%	20.01	19.24	19.40	18.80	19.41
Top Gas N_2	%	56.37	56.36	56.16	56.45	56.35

Table 5-17. Thermal/Energy Parameters for 100 lb/THM Period — Data Points 11-14

Parameters	Units	11	12	13	14	Wtd. Avg.
Blast Temp	°F	1,900	1,893	1,895	1,876	1,892
H.M. Temp	°F	2,683	2,695	2,666	2,705	2,690
AISI RAFT	°F	3,661	3,678	3,654	3,635	3,661
Rho V^2		23.3	20.8	23.4	19.2	23.2
Hearth Zone Gas	°F	3,084	3,097	3,102	3,055	3,085
dT Hearth	°F	401	402	436	350	395
Bosh H_2	lb mol/THM	12.3	12.3	12.9	13.2	12.5
Therm + Chem Energy	MMBtu/THM	0.74	0.77	0.78	0.75	0.76
EGC (solution loss)	lb mol/THM	12.3	12.8	12.9	12.4	12.6
dT Bosh	°F	30	32	25	27	27
Top Gas Temp	°F	298	296	275	291	293
HHV	Btu/SCF	76.4	78.9	79.0	80.0	78.4
Top CO/CO_2		0.99	1.06	1.04	1.09	1.04
H_2 Util. Eff.	%	50.2	47.4	46.7	47.3	48.2
Heat Loss	MMBtu/hr	73	71	78	72	73

The average productivity obtained here is some 420 TPD below that achieved during the Phase A ramp-up, when maximizing productivity was a goal. This was obtained with 230 TPD less total oxygen and, more importantly, with the elimination of almost 170 TPD of supplemental oxygen and reductions in the coke and fuel rates of 14 lb/THM and 24 lb/THM, respectively. The decreases in energy consumption are consistent with the effects expected from the net results of increases in blast temperature and hot metal silicon and the decrease in blast moisture, which would account for about 18 lb/THM using the normal correction factors. The elimination of more than 100 lb/THM supplemental oxygen addition was enabled by the 100°F increase in blast temperature, which maintained the RAFT and thermal-plus-chemical energy values nearly constant. Since productivity was lower, the bosh gas kinetic energy (the ρV^2 term) and pressure drop were lower even though the specific wind rate was higher than in the Phase A testing at comparable injection rates. In most other respects the parameters are comparable to those estimated previously, although the calculated heat loss is lower by some 17 MMBtu/thm. The hot metal and slag chemistries are shown in Table 5-18.

Table 5-18. Summary of Hot Metal and Slag Chemistry for the 100 lb/THM Period — Data Points 11-14

Hot Metal	Units	11	12	13	14	Wtd. Avg.
Average Silicon	%	0.71	0.72	0.59	0.73	0.70
Standard Deviation	%	0.17	0.16	0.14	0.17	0.16
Average Sulfur	%	0.058	0.059	0.069	0.066	0.061
Standard Deviation	%	0.012	0.014	0.013	0.018	0.014
Average Temperature	°F	2,683	2,695	2,666	2,705	2,690
Standard Deviation	°F	34	29	26	32	31
dQ/dt Avg. Variability	MMBtu/THM	19.9	16.6	14.0	13.4	15.4
dQ/dt Avg. Var. SD	MMBtu/THM	13.2	14.2	13.0	11.4	13.2
Average Cast Amount	Tons	203	185	196	169	188
Slag						
Basicity	B/A	1.05	1.03	1.02	1.07	1.04
S	%	1.43	1.34	1.24	1.48	1.39
FeO	%	0.60	0.53	0.54	0.50	0.55

As described above, the hot metal silicon content is somewhat higher than observed in Phase A (0.7% vs. 0.57%), but this may be due to the lower production rate and an increase in hot metal temperature of about 50°F. The increase in basicity of almost 0.1 units from the value obtained at the 300 lb/THM injection level was achieved by increasing the amount of BOF slag in the charge, and was sufficient to maintain the hot metal sulfur content at an acceptable level in spite of the 35% increase in sulfur load at the higher coke rate. The variability of the chemistry is substantially greater than observed in these trials at injection levels of 250-300 lb/THM, but is comparable to that obtained during the Phase A ramp-up testing at injection levels of 90-125 lb/THM. This increase in variability occurred at much lower production rates (and lower pressure drops for points 12 and 14), confirming the beneficial effects of natural gas injection on burden movement at levels up to at least 150 lb/THM.

The implications of process changes made at Acme and of natural gas injection practices at levels up to 300 lb/THM are discussed in the next two chapters.

6. Effects of Process Changes

Fifty years ago, furnaces typically operated with hot blast temperatures in the range of 800-1,000°F and with blast moisture contents trimmed to just above ambient levels, usually below 6 gr/SCF. As stove and auxiliaries designs improved and hot blast temperatures increased, operators found that the tight furnace conditions that often developed at the higher blast temperatures could be alleviated through addition of more steam to the blast. By twenty-five years ago, hot blast temperatures of 1,600-1,800°F were the norm and some furnaces operated with temperatures above 2,000°F. Supplemental fuel injection and blast enrichment were not common, but most operators humidified the blast to control the RAFT in the range of 3,800-4,000°F. This practice improved burden movement, but over time the practice became viewed as necessary to provide a physical flame temperature that was high enough to heat the burden and provide sufficient energy for reduction and production of hot metal at about 2,700°F. Thus, a physical interpretation became associated with a practice that was instituted for quite different reasons.

In time, operators lost track of the fact that the earlier generations of furnaces had operated quite satisfactorily with RAFTs in the range of 3,100-3,300°F. More recently, the emergence of high-rate natural gas and coal injection practices has confounded the issue since gas injection has been shown to be feasible with AISI RAFTs below 3,200°F (and in these tests to 2,900°F) while coal injection apparently requires RAFTs in the vicinity of 3,800-4,000°F or even higher.[10] In the Phase E testing Acme made a number of changes to the tuyeres and injection lances that had consequences for furnace operations and the interpretation of the role of natural gas in the reactions taking place in the tuyeres and the raceway and bosh zones. Operating practice was also affected by the changes in burden properties that took place throughout these tests. The effects of these changes are discussed in this chapter.

[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), July 1996.

6. Effects of Process Changes

A. TUYERE AREA AND IMPLICATIONS FOR RAFT

Acme changed the sizes of six of the fourteen tuyeres on the furnace during the course of Phase E testing, as shown in Table 3-1. At a given blast condition, the effect of the changes was to decrease the *average* velocity by about 6%, but much greater changes were effected on the individual tuyeres switched out. If the assumptions of uniform bustle pipe and raceway pressures and equal pressure drops in the drops/blowpipes/tuyeres are made, tuyere velocities would be essentially equal and the volumetric flow would be proportional to the tuyere area. This is probably not literally true because of nonuniform pressure drops and circumferential differences in the raceway as well as the effects of natural gas injection, but is a starting point for illustrative calculations.

Prior to the initiation of this phase of testing, the two tuyeres over the taphole were 5.5 inches in diameter while the remaining tuyeres were 6.5 inches in diameter. If one assumes that the flow of natural gas is the same to all tuyeres and that no combustion occurs *within* the tuyeres, the 12 larger tuyeres would have taken almost 90% of the wind, with average velocities of about 740 ft/sec in each tuyere, for the conditions prevailing during the 250 lb/THM test period in Phase C. If these conditions prevailed, the natural gas flow would have been about 17% of the wind in the large tuyeres and about 24% of the wind in the small tuyeres. The AISI RAFT, then, would have been about 3,200ºF in front of the large tuyeres but only 2,500ºF in front of the small ones where the temperature of the gas-blast mixture would have been reduced to only 1,600ºF if none of the natural gas burned. While it has been shown that hot metal can be produced at temperatures above 2,600ºF with an AISI RAFT below 2,500ºF during upset conditions (see reference 9), the feasibility of operating with a RAFT that low over the taphole while producing hot metal with temperatures approaching 2,700ºF routinely might well be questioned.

It will be shown in the next section of this chapter that the assumption of essentially uniform natural gas flow through all lances is proper. The assumption that no combustion occurs within the tuyere is not proper, however, and the process of partial mixing and the initiation of combustion can be observed through the peephole. Previous analytical modeling work has shown that natural gas injected at high rates either through lances in the blowpipe or orifice ports in the tuyere is only partially combusted at the tuyere nose because mixing is incomplete and reaction times are short.[11] This modeling also showed that combustion was rapid and essentially complete within the raceway zone and that maximum flame temperatures of the order of 4,000ºF were produced, even when the overall ratio of oxygen to natural gas was less than that required for complete combustion to CO_2 and H_2O. At an injection level of 250 lb/THM, the modeling predicted that about 40% of the natural gas would be combusted at the tuyere nose, producing combustion products with a CO/CO_2 ratio of about 1.9 and a H_2/H_2O ratio of about 1.4 and increasing the average temperature of the mixture by about 500ºF. This would consume about 20% of the amount of oxygen required for complete combustion, increase the molar flow of the mixed, reacting blast by about 5%, and increase its total volumetric flow by about 40% by virtue of the increase in flow and temperature, assuming no change in pressure. The question here is: what effect (if any) would the existence of uniform gas injection through the lances but different blast flows through the tuyeres have on furnace performance?

If it occurred, non-uniform extents of combustion would cause differences in the average temperature and composition of the gases leaving the tuyere and therefore their average density. If bustle pipe and raceway pressures are uniform, the flow of wind would be redistributed in such a way that the values of the kinetic energy of the gases exiting the tuyeres would tend to be equalized. That is, instead of having nearly equal velocities, the tuyeres in which densities were relatively lower would support flows at relatively higher velocities to equalize the product ρV^2. The previously cited modeling of natural gas combustion within the tuyere/raceway indicated that as the percentage of natural gas in the blast increased the percent that combusted increased, the fraction combusted completely changed, and the average temperature of the tuyere nose increased in a nonlinear fashion. Interpolating from the trends shown through modeling and applying them to the conditions prevailing during the 250 lb/THM test period of Phase C suggests that the volumetric flow of hot blast to the two smaller (5.5″ dia) tuyeres would have decreased by about 12% from a no-injection condition, and the flow to all others increased by about 1.5%, while the resulting differential increase in the extent of combustion would have decreased the average gas density in the smaller tuyeres by about 17% vis-à-vis the larger ones. The energy released by partial combustion would have boosted the velocities at the tuyere noses to the

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

vicinity of 1,000 to 1,100 ft/sec, well above the velocities in the blowpipe but far below sonic velocities at these temperatures. Increases in velocity of this magnitude would be expected to increase pressure drop at the tuyere by about 0.5 PSI.

If the sense of these approximations is correct, the effect of uniform injection of natural gas under conditions in which different tuyere sizes (or other factors) that would lead to differing blast volumetric flows would be to *accentuate* the blast flow differential, decreasing flows further to the smaller tuyeres and vice versa. This, in turn, would lead to an *expansion* of the differences in calculated AISI RAFTs in front of the smaller and larger tuyeres from about 700 to about 1,000°F! Notwithstanding this substantial difference in calculated RAFT, however, the furnace operated smoothly throughout Phases A and C with this tuyere arrangement, and throughout all of the changes in tuyere sizes — and by implication blast flow rates — throughout the Phase E trials. By the end of the trials, the blast flow to the tuyeres over the taphole had been increased to the same level as that of 8 other tuyeres. This insensitivity of performance to calculated AISI RAFT, especially very low RAFT over the taphole, suggests that this parameter is not a significant determinant of furnace performance at high levels of natural gas injection.

Clearly, the CO_2 and H_2O formed as products of combustion within and in front of the tuyere and then further into the raceway eventually must be largely reduced to CO and H_2 through endothermic reaction with hot coke as they penetrate the dead man and rise through the bosh. However, the implication of these findings is that the combustion of natural gas in the tuyere/raceway generates physical flame temperatures that are high enough and persist over a sufficient area (or volume) to drive the gas-to-solid/liquid heat transfer processes that heat the descending burden and form hot metal and slag at temperatures above the calculated RAFT. The sensitivity of estimated physical flame temperature, calculated by energy balance, to the presence of CO_2 and H_2O in front of the various tuyeres is shown in Table 6-1.

The flame temperatures estimated with no formation of CO_2 or H_2O correspond to the conventional definition of RAFT, and the RAFTs calculated by energy balance are some 200°F higher than calculated by the AISI formula. Clearly, the flame temperatures on either side of the taphole throughout the 250 lb injection tests during Phase C would have been just slightly above the hot metal temperature for a

Table 6-1. Effect of Extent of Combustion to CO_2 and H_2O on Adiabatic Flame Temperature

Data Points	Phase C Nos. 12-14 (1)		Phase E No. 7 (2)		
Injection Level, lb/THM	**258**		**291**		
Tuyere Dia., inches	5.5	6.5	5.5	6.5 (3)	6.75
Estimated Tuyere Flow, SCFM					
Natural gas	965	965	1,130	1,130	1,130
Wind	3,600	5,710	3,200	5,340	5,960
Supplemental O_2	380	605	420	700	780
Estimated Temperature, °F for					
0% CO_2/H_2O (4)	2,744	3,301	2,517	3,194	3,335
1% CO_2/H_2O	2,791	3,345	2,563	3,239	3,368
2% CO_2/H_2O	2,836	3,387	2,611	3,284	3,413
5% CO_2/H_2O	2,966	3,513	2,746	3,410	3,542
10% CO_2/H_2O	3,168	3,709	2,960	3,618	3,744
Hot Metal Temp., °F	2,635		2,649		
Hot Metal Temp., S.D., °F	37		25		

(1) See reference (9) for furnace operating parameters.
(2) See Tables 5-8 through 5-10 for furnace operating parameters.
(3) Flows through these tuyeres are close to numerical average.
(4) Percentage of total C and H_2 burned to CO_2 and H_2O. Zero percent represents the conventional RAFT condition. Coke temperature taken at 2,700°F.

period of at least two weeks if no CO_2 or H_2O persisted beyond the immediate vicinity of the tuyere. In fact, there were 16 casts during this period for which hot metal temperatures were above 2,700°F, and five that were within 20°F of the energy balance RAFT.

A similar condition would have occurred during the initial stages of testing during Phase D, before No. 1 tuyere was switched from 5.5″ to 6.5″ diameter on August 14. After that change, injection levels were increased beyond the 250 lb/THM range, and this action diverted more blast flow to the larger set of tuyeres, reducing the blast flow to the remaining small tuyere (No. 14) to about 15% below the average for that tuyere area. Switching out the additional four tuyeres from 6.5″ to 6.75″ exacerbated the imbalance, finally creating the extreme condition shown above during Point No. 7. Here, one would calculate a RAFT that was some 130°F *below* the hot metal temperature on one side of the taphole. As discussed in Chapter 5, however, these changes had little discernible effect on hot metal chemistry or temperature: in fact, the variability at the highest injection rates was lower than at any time throughout these tests.

The details of the circumferential mixing of gases in the raceway are not known, but if CO_2- and H_2-free gases from tuyeres Nos. 1 and 14 were completely mixed their average temperature would be about 2,900°F, which would probably have been high enough to produce hot metal at 2,649 ± 25°F without giving any indication that a cold furnace condition could arise. On the other hand, if circumferential mixing were not quite efficient — with at least 25% of the higher temperature combustion products mixed into those exiting from the small tuyere — the furnace would have experienced a region in which a temperature cross would have occurred if no CO_2 and H_2O were present.

Whatever the detailed mechanisms of combustion and mixing in the raceway, it is evident that achieving uniform flows throughout the various tuyeres, and uniform flame temperatures in front of them, is not a necessary condition for stable furnace operation at high rates of natural gas injection. Furthermore, these estimates of flame temperature strongly suggest that modest amounts of CO_2 and H_2O — perhaps 2 to 5% of the gases combusting — can persist at significant distances beyond the raceway zone. Concentrations of CO_2 (and by inference H_2O) at these levels have been observed in the raceway zone of a test furnace injecting oil in amounts corresponding to about 125 lb/THM,[12] although the concentration decreased rapidly with distance from the tuyere nose. At that injection level, the maximum possible concentration of CO_2 from combustion of the oil in front of the tuyere would have been about 8.5%. For the 250 lb/THM injection condition shown in Table 6-1, however, the maximum CO_2 concentration for combustion of the natural gas could have been of the order of 12 to 13%, and it is not unreasonable to expect that the higher concentrations would persist further from the tuyere than is the case with oil injection.

If this condition does exist it would provide an additional margin of safety to provide the thermal driving forces necessary to drive furnace operation during upset conditions. This would be consistent with the observation that RAFT can

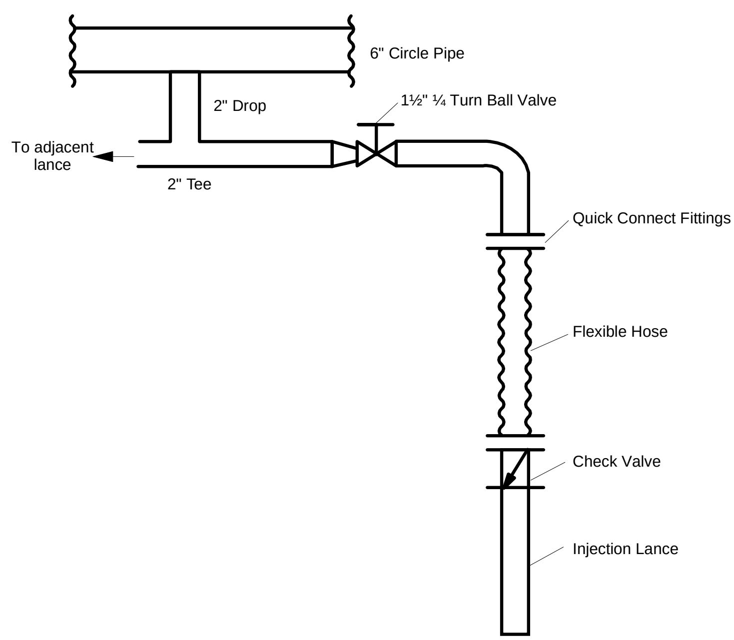
[12] *Fuel Combustion in the Blast Furnace Raceway Zone*, J.M. Burgess, Prog. Energy Combust. Sci., 1985, Vol. 11, pp. 61-82, Pergamon Press Ltd.

be decreased by almost 300°F/100 lb/THM increase in injection level while decreasing the variability of hot metal chemistry in a properly balanced furnace.

B. EFFECT OF INJECTION SYSTEM DESIGN ON FURNACE PERFORMANCE

A number of lance and flexible hose diameter combinations were used throughout these tests as shown in Table 3-2, but the piping configuration did not change. It is shown schematically in Figure 6-1.

Figure 6-1. Schematic of Natural Gas Injection System at Acme



Seven 2″ drops connected to tees that fed natural gas to adjacent lances: the total length of 2″ piping was less than 5 feet. The 2″ pipe was reduced to 1½″, and a short run connected to a 1½″ quarter-turn ball valve. Another short run connected to quick-connect fittings to permit easy installation of the flexible hose. Both 1″ and 1½″ hoses with lengths of about 10 feet were used. The hose was attached via a second quick connect fitting to a check valve which was, in turn, connected to the lance, which was about 5½ feet long. The lance was inserted into the blowpipe through a boss positioned so that the tip of the lance was on the centerline of the blowpipe at the joint with the tuyere. Three pressure gauges were installed on the circle pipe: one where the natural gas feed line entered between tuyeres Nos. 8 and 9, and the other two at the far ends of the pipe at tuyeres Nos. 1 and 14.

The 1″ hose/½″ lance combination was in place prior to the initiation of these tests and was used satisfactorily throughout Phase A at injection levels up to about 150 lb/THM. Since maximum circle pipe pressure exceeded 100 psig during this phase, and since natural gas flow rates in Phase C were expected to increase by more than 80%, the lance diameter was increased to 1″ for Phases B and C. This arrangement was fully satisfactory, although circle pipe pressures increased to 150 psig at injection levels of 250 lb/THM. The arrangement was replaced by a 1½″ hose/1½″ lance combination during restart after Phase D. This decreased pressure drop significantly, as expected, but the operators noticed a marked changed in the appearance of the flame and its behavior, and the 1½″ lances were replaced by the previously used 1″ ones. Use of a larger diameter hose decreased pressure drop to an acceptable value at injection levels beyond 300 lb/THM, and this arrangement was used until the injection level was dropped to 100 lb/THM. At that point the larger hoses were replaced by the smaller ones, returning to the combination that had been used satisfactorily throughout Phases B and C. Estimates of the distribution of pressure drop across the injection system for the extremes of flow used in each combination are presented in Table 6-2.

Table 6-2. Estimated Distribution of Pressure Drop Across the Natural Gas Injection System at Acme

Lance Dia., in.	**½**	**1**	**1**	**1½**
Hose Dia., in.	**1**	**1**	**1½**	**1½**
Natural Gas Rate, MSCFM (1)	7.4	13.1	17.0	13.1
Circle Pipe Pressure, psig	117	153	110	51
Pressure Drop, psig across 2″ drop, valve, and contraction	0.2	0.6	0.3	0.3
Hose	32.0	101.5	46.9	14.3
Check valve and contraction	1.2	6.4	6.0	6.8
Lance	55.6	16.5	28.8	1.6
Total	89	125	82	23

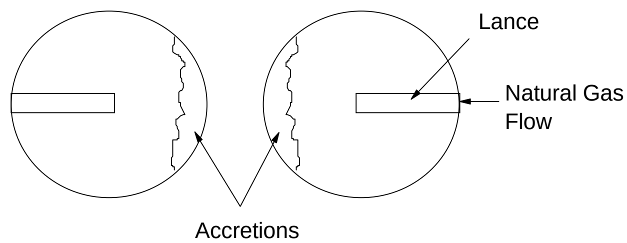
(1) Total gas flow rate; assumed uniformly distributed across 14 injection systems. Blowpipe pressure estimated at 28 psig for all cases.

Sonic velocity in natural gas is about 1,400 ft/sec at these conditions, and in none of these cases was the flow found to be critical, or "choked." Therefore, non-uniformity in blowpipe pressures could cause non-uniform flow even if the circle pipe pressure were absolutely uniform along the length. However, with pressure drops of 80 to 125 PSI across the delivery system, the impacts of small variations in downstream pressure on the flow through individual tuyeres is negligible. Pressure drop calculations for flow in the circle pipe show negligible changes along its length, and this was confirmed by the readings on the pressure gauges. Therefore, flows should be uniform across all hose/lance assemblies unless some individual component of the system differs hydraulically from the components installed in other assemblies.

It is obvious from these estimates that, except for the 1½″/1½″ combination, the hoses and lances are the key determinants of pressure drop. The hoses of each diameter were all supplied by the same manufacturer, and the lances of each diameter were fabricated in the same way and to the same nominal dimensions. The most likely determinant of changes in hydraulic conditions under these circumstances would be either mechanical damage (e.g., a kink in a hose), an inadvertent process change (e.g., one of the quarter turn shutoff valves not being fully opened), or loss of integrity of a lance. The latter condition has occurred when, from time to time, the ends of the tuyeres were burned off. Both the loss of lance length and the non-uniformity of the discharge end could induce significant changes in pressure drop, and so induce changes in flow. To minimize damage to the lances during upset conditions, Acme has installed a cooling system that introduces a flow of nitrogen to the circle pipe when the natural gas flow is turned off, and has developed improved back-draft procedures that involve withdrawing the lances during shutdowns.

It was mentioned above that when the injection system was switched from a 1″/1″ to a 1½″/1½″ hose/lance configuration the operators noticed differences in furnace behavior. Specifically, the appearance of the flame changed to a condition that the operators characterized as “twinkling” because of its variability and the increase in apparent concentration of bright particulate matter in front of the tuyeres. In addition a tendency for partial blockage of some tuyeres developed, with accretions usually forming in adjacent tuyeres according to the patterns shown in Figure 6-2.

Figure 6-2. Blockage Pattern in Some Tuyeres – View from Peep-site



The occurrence of accretions on the tuyere wall at which the flow of natural gas was directed suggested that they were caused by the cooling effect of unburned fuel. No such tendency had been observed previously when injecting natural gas at the same level (250 lb/THM) through a 1″ lance, and the blockage could be cleared within a minute by partially closing the quarter turn shutoff valve. When the 1½″ lances were changed out for 1″ lances these phenomena were never observed again at either higher or lower injection levels. Since this behavior does not appear to be related to injection level *per se*, it is likely that it is the result of a change in the process of mixing and partial combustion within or immediately in front of the tuyere. The extent of mixing is determined mainly by the underlying turbulence field of the blast and by the ratio of the kinetic energy of the natural gas flow to that of the blast (see reference 11 for a more comprehensive discussion of the mixing process). Some key aerodynamic parameters for the blast and natural gas over the range of natural gas flows in each lance are presented in Table 6-3.

Table 6-3. Aerodynamic Conditions for Various Lances Over a Range of Natural Gas Flows

Lance Diameter, in (1)	½	½	1	1	1	1½	1½
Natural Gas Flow, MSCFM	3.9	7.4	3.8	10.3	17.3	11.2	14.0
Tip Velocity, ft/sec (2)	689	1,128	238	686	1,013	324	397
Tip Kinetic Energy, PSI (2)	7.22	23.1	0.79	6.95	16.4	1.45	2.13
Blast Velocity, ft/sec (3)	599	589	516	605	562	557	539
Blast Kinetic Energy, PSI (3)	1.98	1.91	1.42	1.95	1.69	1.64	1.55
Oxygen/Natural Gas, mole/mole	5.23	2.87	4.10	2.21	1.47	1.93	1.70
Gas/Blast Kinetic Energy Ratio	3.65	12.1	0.50	3.57	9.70	0.89	1.37

(1) Nominal pipe diameter for schedule 40 pipes.
(2) For natural gas at the pressure at the tip of the lance. Kinetic energy is $\rho V^2/2g_c$.
(3) For hot blast in the blowpipe just upstream of the lance. Kinetic energy is $\rho V^2/2g_c$.

While specific wind rates (SCF/THM) decrease with increasing levels of gas injection, the corresponding increase in enrichment tends to keep volumetric flows more nearly constant, so that the blowpipe velocities do not change greatly. The Reynolds numbers for these blast flows are in the vicinity of 500,000 so that the flow is fully turbulent, but not extremely so. The range of minimum to maximum velocities and kinetic energies is much greater for the natural gas, of course, since injection rates and flow areas were both varied significantly. However, the range of velocities, kinetic energies, and oxygen-to-natural gas flow rate ratios for the 1½″ lances all lie within the ranges defined by flow from the 1″ lances for which no “twinkling” problem appeared. The only apparent difference is that the low velocities/kinetic energies from the 1½″ lances issued into a blast with less than half the oxygen-to-natural gas ratio than the low velocity/kinetic energy flow from the 1″ lance did.

It is possible that a low ratio of natural gas to blast kinetic energy, which tends to decrease the extent of mixing, does not retard the partial combustion of the fuel within the tuyere enough to cause a cooling effect if the blast contains a sufficient amount of oxygen. Conversely, high ratios of kinetic energies may be sufficient to promote enough mixing to generate combustion energy so that the cooling effect is avoided even at relatively low blast oxygen contents. The ranges of conditions that have been found to be acceptable and unacceptable in these tests are shown in Figure 6-3.

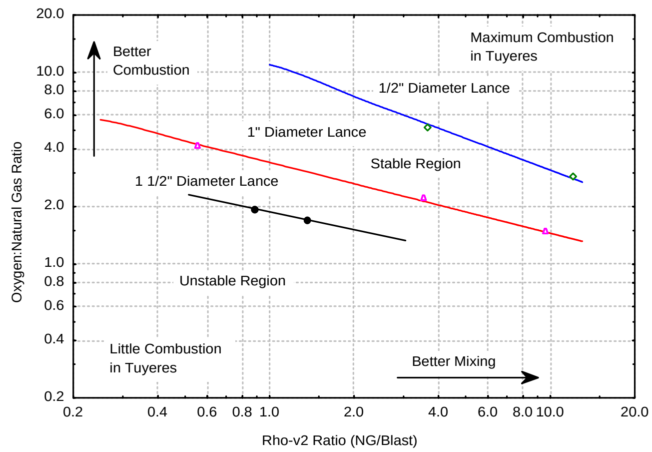
6. Effects of Process Changes

The region of fully acceptable operation may not be far below the acceptable range for the 1″ lance shown in Figure 6-3, since partial closure of the quarter turn ball valve, which cleared the problem, probably reduced the flow of natural gas by 50-67%, thereby reducing the ratio of natural gas to blast kinetic energy to about 0.2 while increasing the ratio of oxygen to natural gas to 4-5:1.

To a first approximation, curves in the coordinates of Figure 6-3 would be hyperbolic in form. More precise delineation of regions of acceptable and unacceptable operation would require testing over a wider range of flow rates and lance diameters. The location of the stability curve would be expected to depend on such factors as the angle of entry and tip design of the lance (e.g., square or mitered) and such process variables as blast temperature and level of enrichment.

6. Effects of Process Changes

Figure 6-3 Tuyere Blinking Analysis at Acme



The pressure drop calculations shown in Table 6-2 and the wide range of acceptable conditions shown in Figure 6-3 show that, while certain ranges should be avoided, it is possible to design natural gas injection systems that will provide acceptable performance over a wide range of operating rates.

C. EFFECT OF BURDEN CHANGES

The iron-bearing burden consisted only of Tilden and Wabush 2% and 1% Mn pellets and BOF slag for almost all of periods evaluated in these tests: B scrap was charged prior to the initiation of natural gas injection and for a short period at the conclusion of Phase C testing. Small amounts of dolomite were also charged from time to time, and the average burden composition for each of the test phases is summarized in Table 6-4.

The BOF slag was reclaimed from Riverdale, and while its composition was variable the amount charged did not change greatly: the total of BOF slag plus dolomite ranged between about 90 and 130 lb/THM. The composition of the Wabush pellets and the ratio of Wabush to Tilden pellets in the charge did change considerably, however, increasing from about one-third 2% Mn in Phase A to about one-half 1% Mn in Phase E. Furthermore, the pellets were obtained from three seasons' supply.

Table 6-4. Average Burden Compositions for These Tests

Test Phase	A	B/C	E
Test Dates	**10/7-11/5/94**	**4/7-7/16/95**	**7/9-12/27/96**
Composition, lb/THM			
Tilden	2,254	2,114	2,045
Wabush (1)	782	914	1,036
BOF Slag	76	106	91
Dolomite	41	0	11
Ratio Wabush/Tilden	0.347	0.432	0.507

(1) In 1994, 2% Mn pellets; in 1995 and 1996, 1% Mn.

Fresh (not stockpiled) ore was used throughout the tests. At Acme, pellets are discharged from the ore carriers to the ore yard, and are retrieved from the ore piles and transferred to the stockhouse without blending. The pellets are not screened prior to being charged at the furnace.

It is well known that the permeability of the burden decreases as the amount of fines in the burden increases. There are no data on the amount of fines ($-^{1}/_{8}$″) actually charged into the blast furnace from these two sources of pellets during the three pellet shipping seasons to make any informed judgment on the extent of permeability reduction. It is known, however, that the amount of –¼″ material in the Tilden pellets increased by about 0.4% from 1994/95 to 1996 and this could not have helped.

All of the coke required for these tests was produced at Acme’s adjacent coke plant and transferred by conveyor to a screening station at the stockhouse. Essentially all of the coke used throughout these tests was fresh, with only small amounts occasionally retrieved from the stockpiles. A number of changes were made over the test periods in the coal mix and coking practice used: in general, less high- and more medium- and low-volatile coals were used and coking time was reduced as the tests progressed. Some of the properties of the cokes produced during each phase are summarized in Table 6-5.

The physical and chemical properties of the coke did not change over the test period: the apparent differences in the average values reported were all within the standard deviations of the estimates. The only apparent trend is a tendency toward a somewhat larger size.

Table 6-5. Properties of Coke Used for these Tests

Test Phase	A	B/C	E
Test Dates	**10/7-11/5/94**	**4/7-7/16/95**	**7/9-12/27/96**
Coke Properties (1)			
Hardness	67.2	67.4	67.5
Reactivity	22.8	24.9	23.5
Stability	60.1	59.3	61.2
CSR	65.9	62.2	63.8
% Ash	7.77	7.67	7.86
% +2″	49.1	50.6	51.5
% + 1½-2″	29.0	29.2	28.9
% + 1-1½″	15.9	15.4	15.7
% – 1″	6.0	4.8	3.9

(1) Average of reported values during each phase.

Thus, even though the coke slit decreased by almost 30% during these tests, the furnace operated smoothly and the decrease apparently did not contribute to the loss in permeability.

Burden descent was smooth throughout these tests and the furnace pressure drop per unit of active height divided by the average burden density, a dimensionless pressure drop, did not change greatly with natural gas injection rate, as shown in Figure 6-4. The average value was about 0.36, and good burden movement can be obtained with values as high as 0.5. In the absence of changes to the burden, the condition of constant dimensionless pressure drop should be achieved by holding the bosh gas kinetic energy term (the rho V^2 term in the table in Table 5-2) constant. This occurred *within* each of the phases of the testing, but the average value of the bosh gas kinetic energy term was about 20% lower in Phase E than in the previous phases as shown in Figure 6-5.

Figure 6-4. Pressure Drop per Unit Height Divided by Burden Density

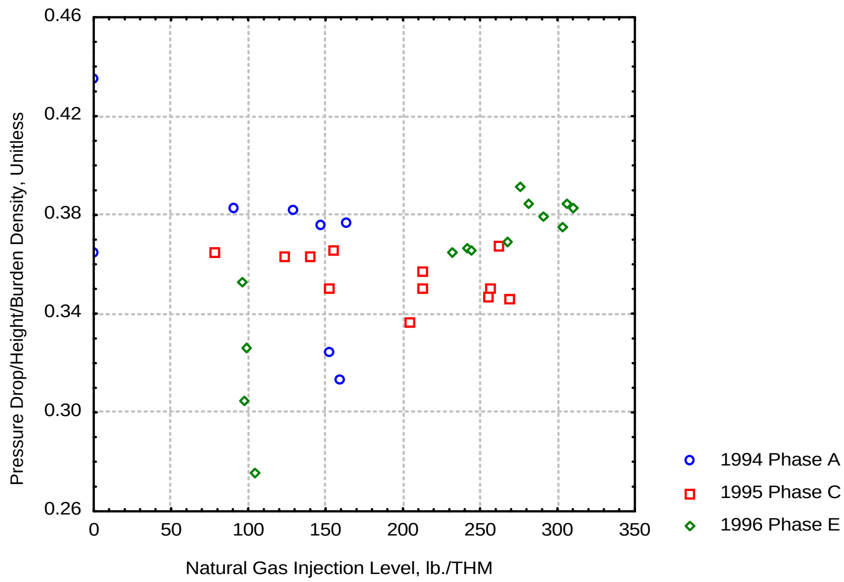
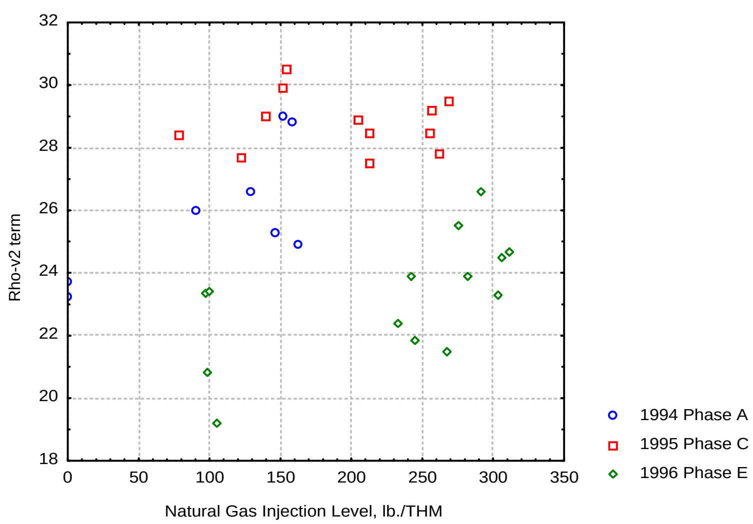


Figure 6-5. Rho-v2 Term vs. Natural Gas Injection Level



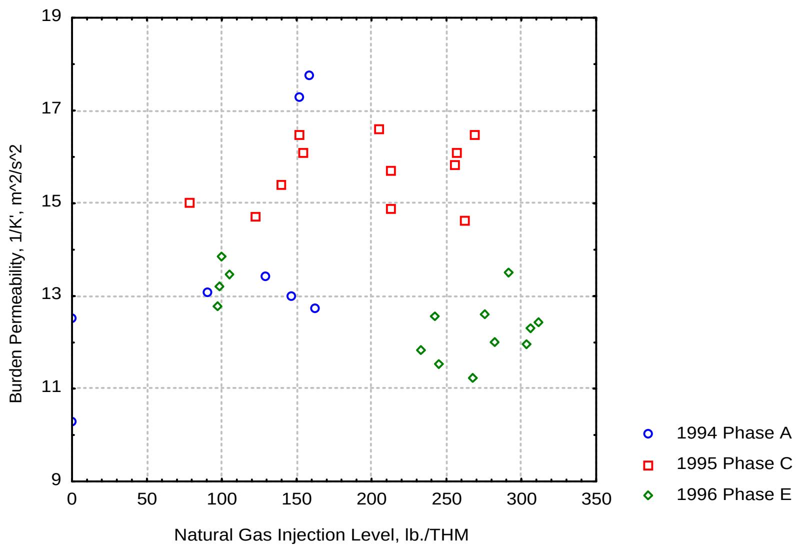
A decrease in the allowable value of the bosh gas kinetic energy at a constant pressure drop implies an increase in burden resistance, or a decrease in permeability, has occurred because the two are related through the well known

Ergun equation. Combining the void fraction, shape factor, equivalent diameter and dimensional consistency terms into a single "constant" gives an expression of the form:

$$\Delta P/L = K\rho V^2$$

The burden permeability, the reciprocal of the constant in this equation, is shown as a function of natural gas injection rate in Figure 6-6.

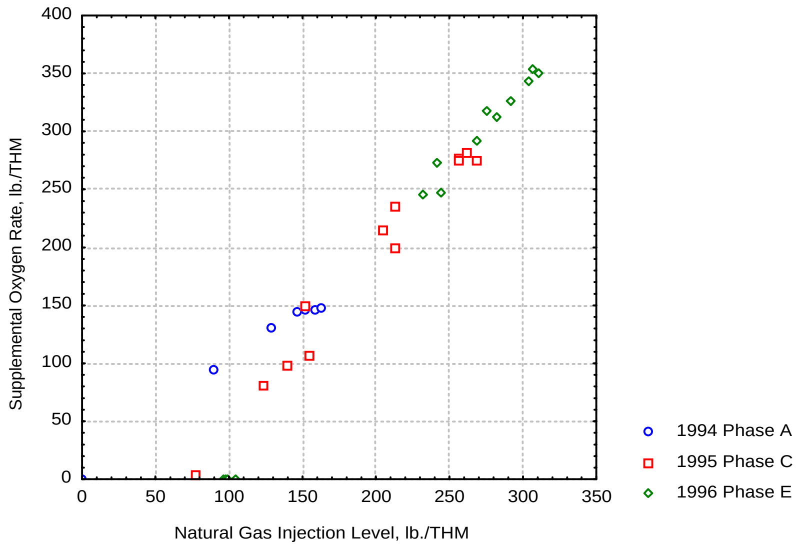
Figure 6-6. Burden Permeability as a Function of Natural Gas Level



The slightly high permeability points at about the 100 lb/THM injection level during Phase E occurred when production was quite low (2,300 and 2,500 TPD), wind rates were low (72 and 77 MCFM), and the furnace was not being pushed. There were also two apparently very high permeability points in Phase A, as well, at injection levels of about 150 lb/THM. At these times (Data points 4 and 5 in reference 9) not only was pressure drop lower, but bosh gas kinetic energy was higher than average for this phase. The reason for this is unknown, lost in the mists of time. Clearly, the average permeability was highest in Phase C and lowest in Phase E. Given the previous discussion of the changes that occurred in burdening, it is highly likely that the increased amount of fines in the pellets used in 1996 and the increase in Wabush-to-Tilden pellet ratio were the primary causes of the permeability loss because the physical and chemical properties of the coke were essentially the same from 1994 to 1996 — the period of tests.

Since the permeability in Phase E was lower than in the previous phases, it became necessary to enrich the blast to a higher level to obtain the desired production rate and drive the furnace at a given rate, since it would not accept as much wind. The result was a somewhat higher consumption of supplemental oxygen at a given natural gas injection level in Phase E than in Phase C, as shown in Figure 6-7.

Figure 6-7. Supplemental Oxygen Use at Acme



The relative increase in enrichment levels is most noticeable at the highest injection rates, where the furnace was being pushed for maximum productivity. If the burden permeability in Phase E had been the same as in Phase C, the oxygen consumptions could have been reduced by more than 10% at the 250 and 300 lb/THM injection levels.

7. Effect of Natural Gas Injection Level on Furnace Performance

This chapter presents an analysis of the performance of Acme's A furnace at the various injection levels tested in Phases A, B/C, and E of these trials. A comparison of the performance of Acme's furnace at injection rates up to 250 lb/THM with other fuel-injecting furnaces has already been reported (see reference 9). The emphasis here is on extending these results to natural gas injection levels up to 300 lb/THM.

A. TUYERE AND HEARTH LEVEL CONTROL

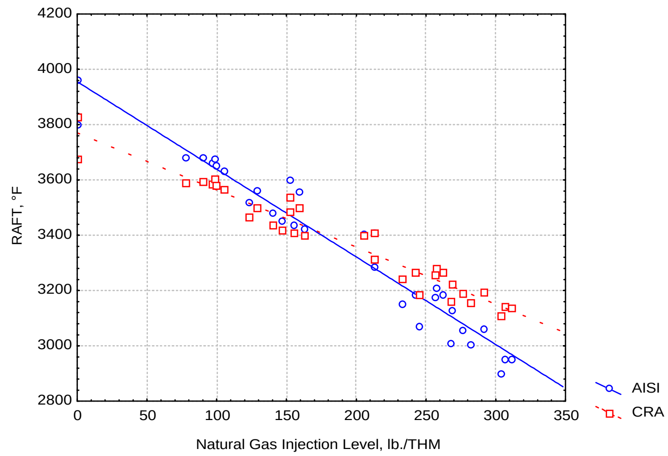
The deficiencies in using RAFT as a control parameter with high-rate natural gas injection have been discussed in the previous chapter and elsewhere. The difficulties are compounded by the fact that values calculated by the AISI formula for RAFT diverge significantly from those calculated by rigorous energy balance at high injection rates as shown in Figure 7-1.

While RAFTs calculated by the AISI formula and by CRA energy balance have essentially the same values at injection levels of about 150 lb/THM, the energy balance RAFT is some 200°F higher at an injection level of 300 lb/THM. However, RAFT should decrease with injection level regardless of the method used to calculate this parameter: only the slope will change.

Over the range of injection rates tested in these trials, the AISI RAFT decreased by about 320°F/100 lb/THM increase in injection level whereas the RAFT calculated by energy balance decreased by only about 210°F/100 lb/THM. In either case the decrease was linear over the entire range in spite of the changes in burden properties and other changes in practice described in the previous chapter.

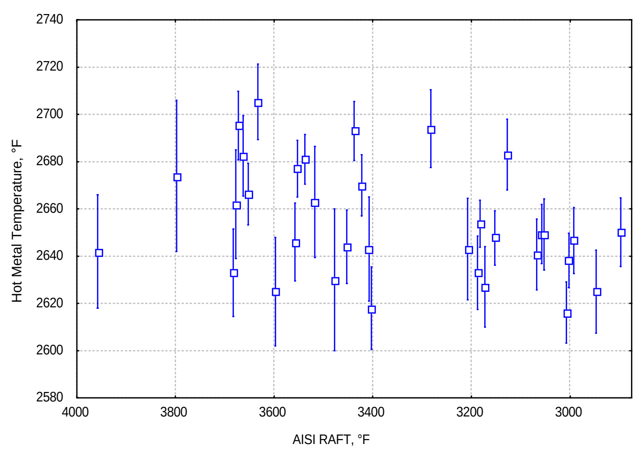
7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-1. AISI and CRA RAFT vs. Natural Gas Injection Level



A properly balanced furnace will have sufficient total oxygen, and the proper ratio of supplemental oxygen to oxygen in the wind, to drive the furnace at the desired productivity while minimizing coke consumption given the temperature and moisture content of the blast, the properties of the burden, and the furnace heat loss. The necessary balance can be obtained with low RAFTs at high levels of natural gas injection without compromising hot metal temperature aim values as shown in Figure 7-2.

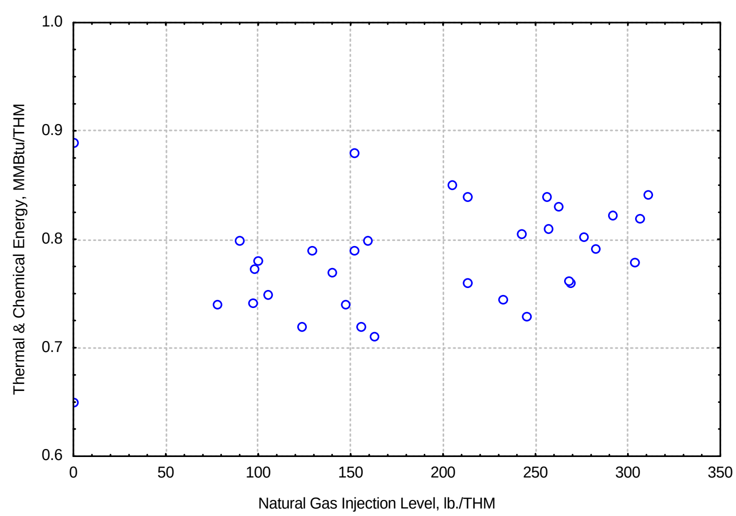
Figure 7-2. Hot Metal Temperature and Standard Deviation vs. AISI RAFT



7. Effect of Natural Gas Injection Level on Furnace Performance

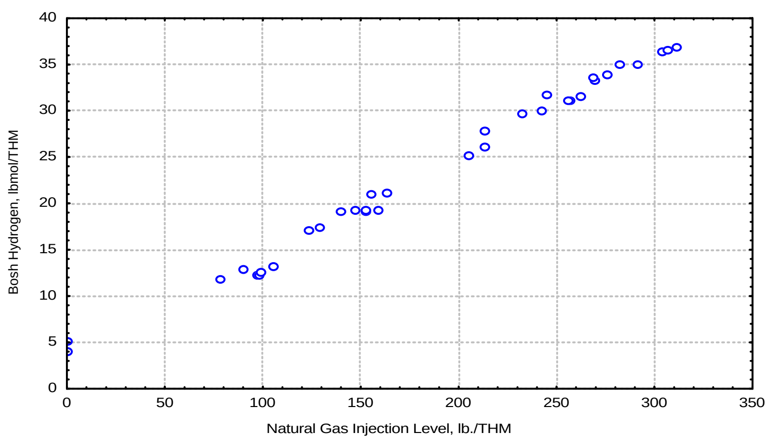
This constancy of hot metal temperature was obtained with wind rates and supplemental oxygen consumptions that varied with natural gas injection rate and with burden composition. In general, aim values were set in such a way as to maintain roughly constant values of the thermal-plus-chemical energy term, as shown in Figure 7-3. The only constraints involved with the use of this parameter are the requirements to limit the total flow of bosh gases so that pressure drop limitations are not exceeded (see Figures 6-4 and 6-5) and that thermal "pinches" do not develop in the hearth or bosh. Because allowing RAFT to drop does tend to decrease pinches in the hearth and bosh, and because the pinches must be maintained above some minimum value to provide the thermal driving force necessary for heat transfer, the thermal-plus-chemical energy will tend to increase at higher levels of injection because of the increase in the bosh gas's hydrogen content.

Figure 7-3. Thermal Condition of Acme's "A" Furnace vs. Natural Gas Injection Level



The fundamental reason why it is entirely appropriate practice to allow the RAFT to decrease as the injection level is increased is that natural gas's high hydrogen content shifts the reduction mechanisms in the furnace: indirect reduction in the stack is favored and so direct reduction in the bosh is decreased. While the bosh gas hydrogen contents were increased by almost an order of magnitude during these trials, the overall hydrogen utilization efficiency remained essentially constant at about 45% as shown in Figures 7-4 and 7-5. The same behavior has been observed in other furnaces injecting natural gas over wide ranges.

Figure 7-4. Bosh Hydrogen Content vs. Natural Gas Injection Level



The changes in the extents of indirect and direct reduction with bosh gas hydrogen content in Acme's A furnace are shown in Figure 7-6. The algebraic sum of the best fit slopes of direct plus indirect reduction curves is essentially zero as expected, and the slope of the direct reduction curve is -0.275 mol/mol. That is, each additional mole of hydrogen introduced reduces the extent of the solution loss reaction by 0.275 mole. These data are best fit by a linear relationship over the range of 5-35 mole/THM H_2 indicating that hydrogen utilization efficiency in the bosh is not adversely affected as temperature and gas-flow profiles shift at higher injection rates. Ultimately, however, it is likely that the slope of the curve would diminish because high utilization efficiency would become very sensitive to upsets and maldistribution of gas flows.

7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-5. Overall Hydrogen Utilization Efficiency vs. Natural Gas Injection Level at Acme

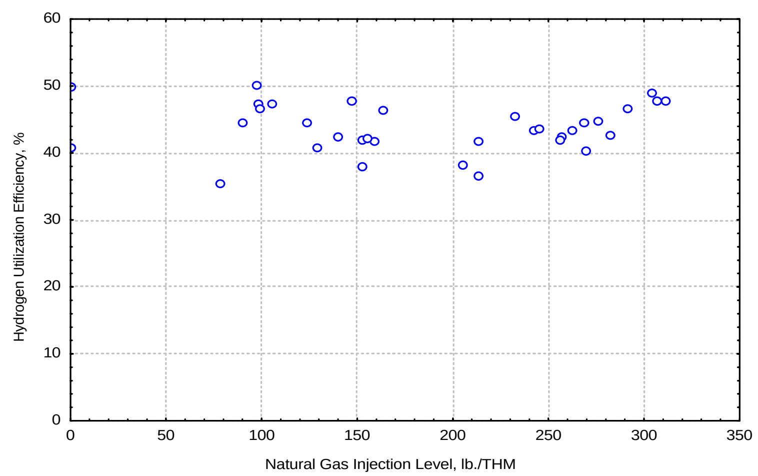
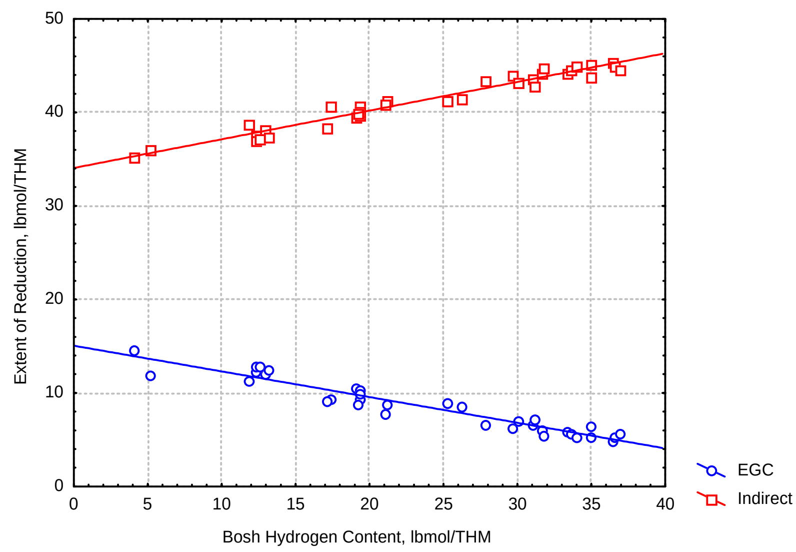


Figure 7-6. Extents of Direct and Indirect Reduction vs. Bosh Hydrogen Content at Acme "A" Furnace

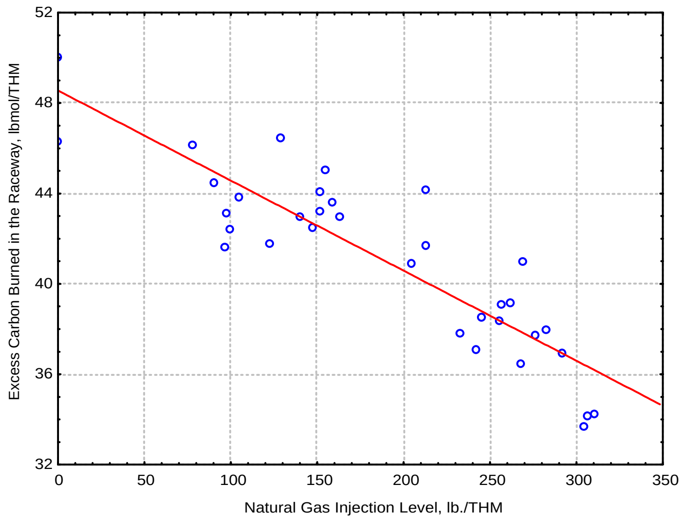


Under typical conditions, reducing the extent of the solution loss reaction by 0.275 mol/mol H_2 would reduce the high temperature energy requirements in the

7. Effect of Natural Gas Injection Level on Furnace Performance

hearth and bosh by about 540 MBtu/THM/mol H_2 if there were no changes in hot metal chemistry. This should permit a reduction in the amount of carbon burned in the raceway to supply high-temperature energy of about 1.05 mol C/mol EGC avoided, and less carbon was burned as the natural gas injection level was increased as shown in Figure 7-7.

Figure 7-7. "Excess" Carbon Burned in the Raceway (1) vs. Natural Gas Injection Level



(1) Carbon burned above that required to satisfy hot metal and blast temperature reactions and bring all gases to 2,700°F.

Here, excess carbon is defined as the amount burned by the oxygen remaining in the blast after sufficient carbon has been burned to provide energy for producing hot metal and for the blast reactions, and to heat all gases to 2,700°F. The slope of the best fit through the data is 0.040 mol C/lb natural gas, and since the gas contained about 0.12 mol H_2/lb, this is equivalent to a slope of about 0.34 mol C/mol H_2. Thus, the decrease in "excess" carbon consumption was about 1.24 mol/mol EGC avoided (.34/.275), slightly higher than would be required to simply offset the decrease in EGC. Some of the additional decrease was made possible by the drop in hot metal silicon content, which amounted to about 0.001%/lb/THM natural gas injected, but the rest would have simply resulted in a slight reduction in the thermal energy content of the gases leaving the hearth.

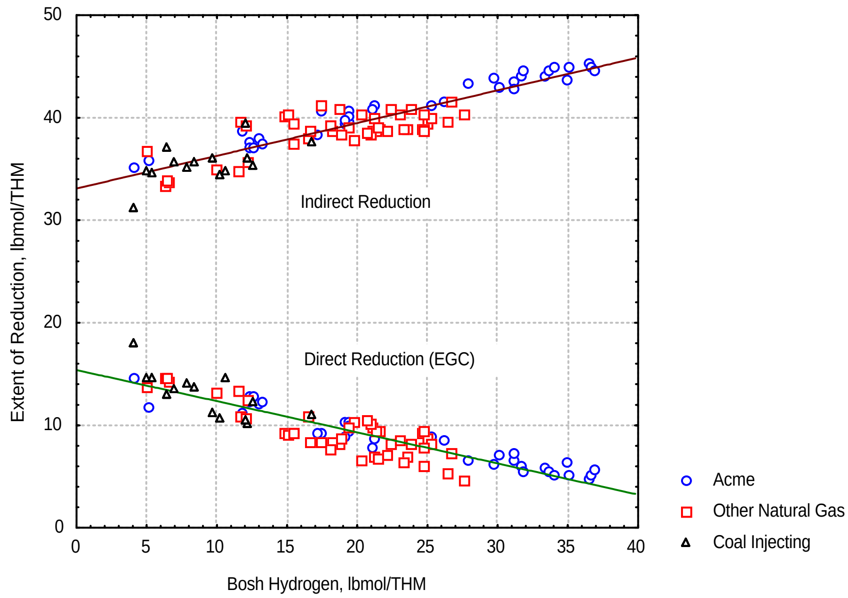
The thermal energy carried from the hearth depends on the blast enrichment as well as the amount of "excess" carbon burned because of the sensible heat carried by nitrogen. The balance between wind and supplemental oxygen rates, and so the ratio of supplemental oxygen to natural gas required, is sensitive to burden permeability as well as the high temperature zone thermal balances (see Figures 6-6 and 6-7). Also, the extents of direct and indirect reductions are sensitive to burden composition and properties (e.g., burden metallics content, pellet reducibility, coke reactivity) and burdening practice (gas flow distribution). The slopes of the curves do not depend on the types of supplemental fuel injected, however, as shown by the data in Figure 7-8. For all furnaces in this sample, the reduction in the extent of the solution reaction is about 0.285 mol/mol H_2, slightly higher than achieved at Acme.

If the decreases in the extent of the solution loss reaction shown in Figures 7–6 and 7-8 had not occurred, therein permitting the decrease in carbon combustion shown in Figure 7–7, the endothermic partial combustion of natural gas in the raceway/hearth would have required substantially more oxygen than was actually consumed. Maintaining a constant physical hearth gas temperature while increasing natural gas injection levels would require about 1.8 lb O_2/lb gas, whereas the marginal consumption was less than 1.2 lb/lb at high injection rates and relatively low permeability as shown in Figure 6–7. At the higher oxygen consumption level, the RAFT would have been some 70°F higher than necessary, the replacement ratio would have been reduced by about 0.15 lb/lb, and the furnace would have run considerably hotter than necessary. In practice, furnace operation was quite smooth and hot metal temperatures were held at aim values during the tests at Acme while the hearth gas temperature was allowed to decrease by almost 600°F. Thus, maximizing the benefits of natural gas injection requires

that the RAFT be allowed to decrease and consumption of supplemental oxygen be minimized, subject to the constraints on bosh gas flow imposed by burden permeability and the need to achieve zonal thermal balances.

7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-8. Extents of Direct and Indirect Reduction vs. Bosh Gas Hydrogen Content



B. FURNACE PRODUCTIVITY AND FUEL CONSUMPTION

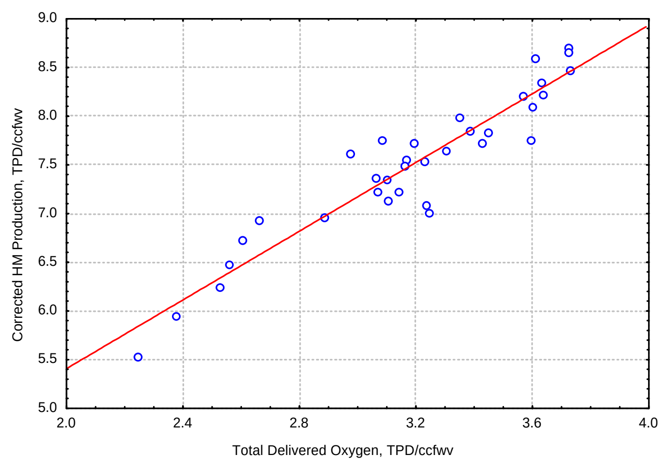
Increases in furnace productivity can be obtained by driving the furnace harder, i.e., supplying more oxygen, or reducing the specific furnace energy requirements by putting metallics on the burden, or both. Throughout most of this test work Acme did not charge any scrap to the burden, so that increases in productivity were achieved by putting more oxygen to the furnace as shown in Figure 7-9.

In Phase A testing the hot blast temperature averaged about 1,800°F, but the subsequent upgrades resulted in an increase in blast temperature to about 1,900°F. Statistical analyses of productivity data from all furnaces in North America injecting natural gas indicate a sensitivity of productivity to blast temperature of 0.31 TPD/CCF/100°F. The data in Figure 7-9 have been normalized to a blast temperature of 1,850°F using this factor, and the slope of the productivity — total oxygen consumption curve is about 1.8 tons of hot metal per ton of oxygen. The

7. Effect of Natural Gas Injection Level on Furnace Performance

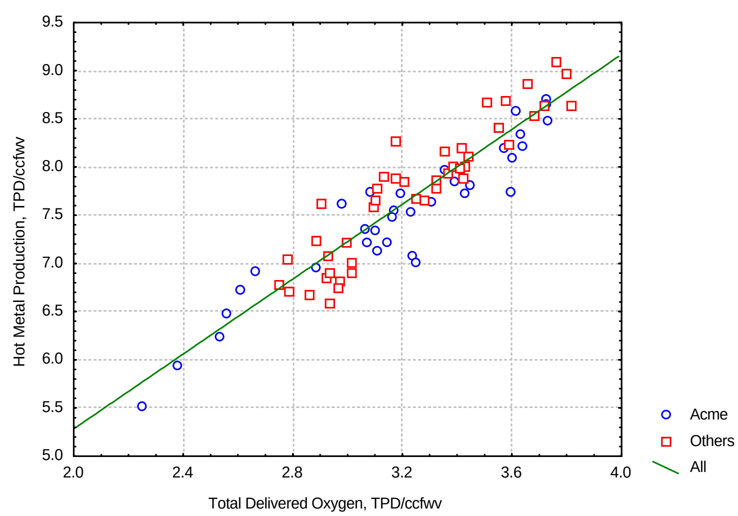
normalized slope for all furnaces in the sample is about 1.9 tons of hot metal per ton of oxygen on a scrap-free basis as shown in Figure 7-10.

Figure 7-9. Normalized Hot Metal Production vs. Total Delivered Oxygen with No Scrap on the Burden



Note: Productivity normalized to 1850°F and no scrap. Correction factors used are 0.54 TPD/ccfwv per 100 lb./THM metallic iron and 0.3 TPD/ccfwv per 100°F HBT

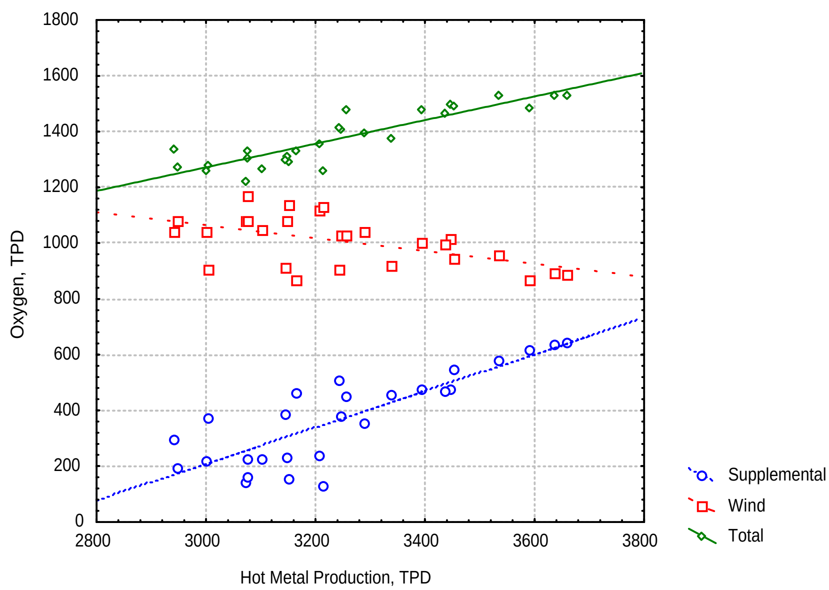
Figure 7-10. Normalized Hot Metal Production vs. Total Delivered Oxygen



7. Effect of Natural Gas Injection Level on Furnace Performance

There are two key reasons for the difference between the marginal productivities obtained at Acme and those obtained with a wider sample of furnaces: different furnaces require different ratios of supplemental oxygen to wind at a given injection level because of differences in burden permeability and blast temperature, and the energy contribution for supplemental oxygen is different from that of wind. The latter results from the fact that the nitrogen content of the wind contributes an additional 2.5 MM Btu/ton oxygen in being cooled from blast to top temperature under typical conditions. The former can also result from a change in the ratio of supplemental oxygen to natural gas with increasing injection rate even with a relatively constant burden as shown in Figure 6-7. The amounts of oxygen provided by the wind and from supplemental oxygen throughout these trials are shown in Figure 7-11.

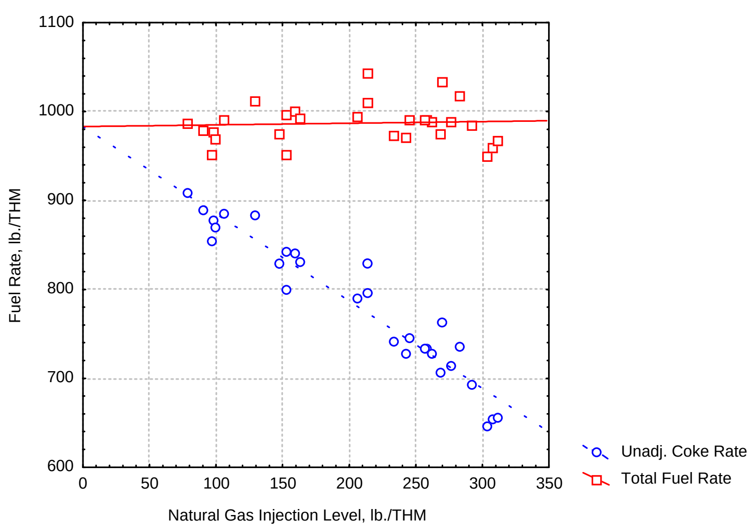
Figure 7-11. The Contribution of Wind and Supplemental Oxygen to Production at Acme



Statistical analysis of the available productivity data on North American blast furnaces shows that the contribution to productivity is about 2.5 tons hot metal/ton of oxygen from wind and about 2.0 tons/ton from supplemental oxygen. The combined effect of total oxygen on productivity at Acme's blast furnace is presented in Figure 7-11. As the production rate is increased, the amount of oxygen contributed by wind decreases and the amount of supplemental oxygen increases. One implication of these data is that, since the fraction of total oxygen supplied from supplemental oxygen does not necessarily increase linearly with productivity, and that supplemental oxygen does not bring the enthalpy associated with nitrogen, curves such as those shown in Figures 7-9 and 7-10 will not necessarily show linear behavior over a wide range.

Values for the furnace coke rate and fuel rate uncorrected for changes in practice are shown in Figure 7-12 for tests in which there was no scrap on the burden. The average replacement ratio obtained over the range of natural gas injection rates between 78 and 312 lb/THM was about 1.0 lb coke/lb gas. The furnace fuel rate averaged 985 lb/THM over the course of these tests. The coke rate actually achieved at a natural gas injection rate of 312 lb/THM was 660 lb/THM.

Figure 7-12. Coke and Fuel Rates vs. Natural Gas Injection Level



The replacement ratio was somewhat higher, about 1.2 lb/lb, at injection levels below about 150 lb/THM because of the savings that resulted from blast moisture reductions and from operation with no or low levels of blast enrichment. Throughout most of the trials, however, the primary objective of the operators was to maximize furnace productivity and not to minimize the coke rate. As discussed in Chapter 6, significant changes occurred in the properties of the burden as the tests were run over a two-year period. In addition, operating practices were changed as upgrades were made and operators became more comfortable with the high-rate injection practice, hot metal chemistries changed and ambient conditions ranged from late spring to early winter.

All of these factors influence the furnace coke rate, and make it difficult to establish furnace performance at the margin. To normalize for these changes, furnace performance has been projected for the average conditions that existed throughout these trials. The projections were done for the conditions summarized in Table 7–1 at the average production rate and natural gas injection level for each point tested. The extent of the solution loss reaction and the RAFT were taken from the trend line data at each injection rate (see Figures 7–6 and 7–1, respectively), and the contributions of the supplemental oxygen and wind were taken from the productivity trend line data (see Figure 7-11). The results of projected performance are shown in Figure 13 together with the un-normalized data.

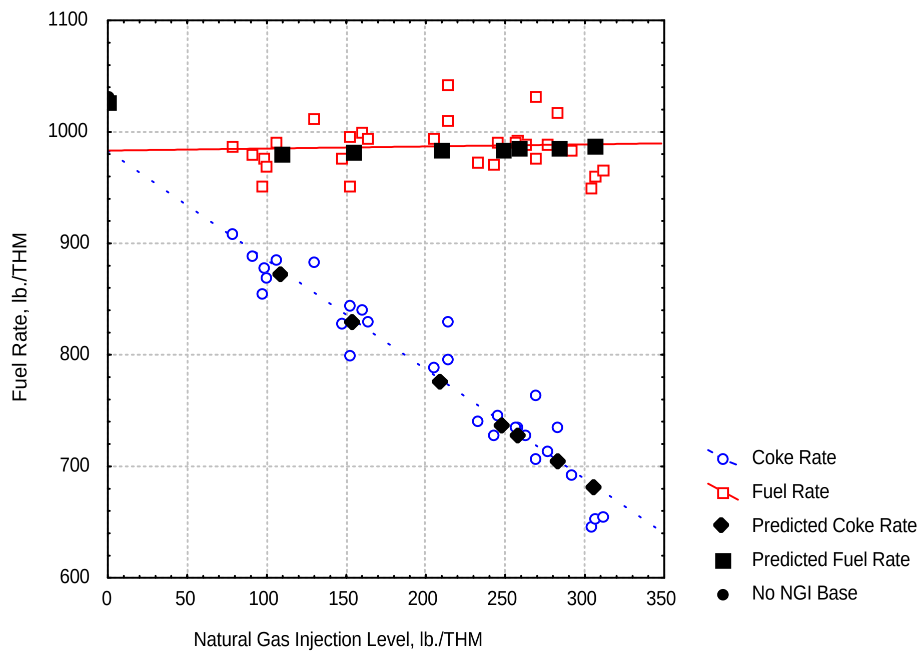
Table 7–1. Projection of Furnace Performance for Average Conditions at Acme[(1)]

Natural Gas Injection	lbs/THM	0	109	154	209	258	248	283	306
HM Production	TPD	2,597	2,586	3,117	3,267	3,431	3,163	3,424	3,633
Coke Rate	lbs/THM	1,026	871	828	775	727	736	703	681
Total Fuel Rate	lbs/THM	1,026	980	982	984	985	984	986	987
Ordered Wind	MSCF/THM	46.00	43.62	40.59	36.54	32.95	33.80	30.91	29.36
Ordered Oxygen	lbs/THM	0	50	120	210	290	270	335	370
Bosh Kinetic Energy, ρV^2		22.2	19.4	26.2	26.0	26.1	22.6	24.6	26.5
Overall H_2 Efficiency	%	65.2	56.0	55.7	53.3	51.9	51.3	50.9	50.7
Total Delivered Oxygen	TPD/CCF	2.49	2.51	3.08	3.30	3.53	3.24	3.56	3.81

[1] Blast moisture at 15 grains/SCF for no fuel injection; blast moisture reduced to 6.5 grains/SCF for subsequent cases. Blast temperature at 1,887^{o}F, hot metal silicon content at 0.51%, and overall heat loss at 86 MMBtu/hr.

7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-13. Furnace Coke and Fuel Rates at Average Conditions



The projected coke and fuel rates shown in Figure 7–13 agree quite well with the linear best fit curves shown in Figure 7–12. The replacement ratio is about 1.3 lb coke/lb gas at injection levels up to 154 lb/THM because of savings that resulted from blast moisture reduction (from 15 gr/SCF at no injection) and the low level of blast enrichment (0.46 and 0.75 lb O_2/lb gas at 109 and 154 lb/THM injection levels, respectively). At injection levels between 154 and 306 lb/THM the average and marginal replacement ratios were about 1.0 lb/lb, and the furnace fuel rate averaged 984 lb/THM with natural gas injection.

The projections for Phase C (see Table 7-1) show the effects of the changes in burden permeability and hot metal chemistry that occurred during the trials. The productivities that were obtained in Phase C at 154, 209, and 258 lb/THM injection levels cannot be achieved at the average bosh gas kinetic energy level of 24.6 at the trend line values of RAFT and EGC: values of about 26.1 are required. If the ρV^2 value of 24.6 were, in fact, an absolute constraint, the blast would have had to be enriched further, the RAFT would have increased by about

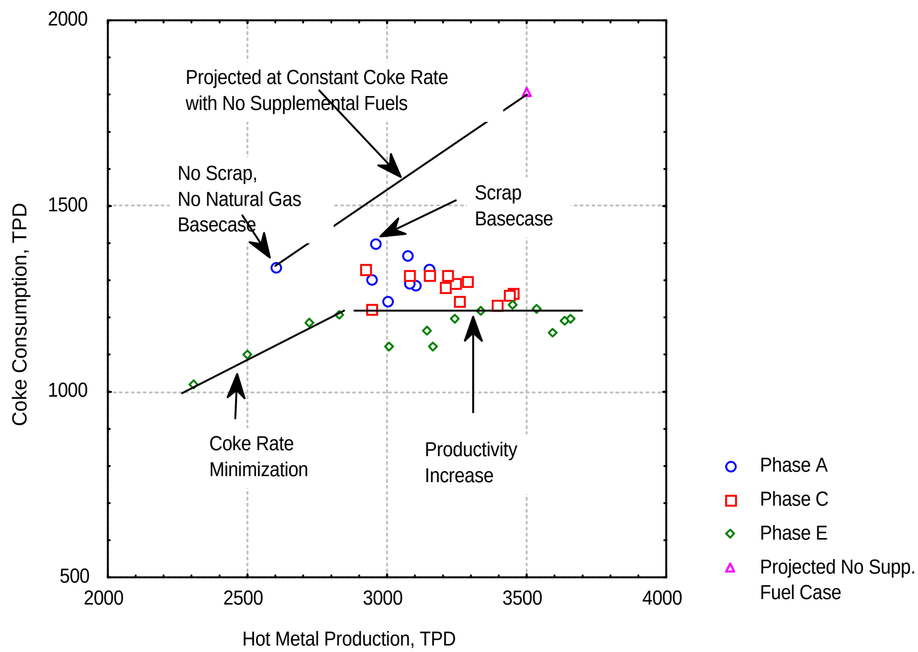
125°F, more total oxygen would have been required, and the coke rates under these conditions would have increased by about 10 lb/THM. Also, the productivity actually achieved at an injection level of 306 lb/THM with 0.34% silicon and 4.2 gr/SCF moisture cannot be achieved with the same total oxygen at the 0.5% Si–6.5 gr/SCF conditions in the projection because of the increased high temperature energy requirements. The projected increase of 0.17 TPD/CCF in total oxygen over that actually required (3.81 TPD/CCF projected oxygen minus 3.64 TPD/CCF actual used in 300 lb test; see Table 5-12) burns more coke (projected coke rate of 681 lb/THM vs. period average of 641 lb/THM) and so increases the bosh gas total flow and the bosh gas kinetic energy term to about 26.5

These calculations show the sensitivity of furnace performance to burden permeability, and may show one important reason for the variability observed in the values of RAFT that operators select at a given natural gas injection rate: low-permeability burdens require more enrichment and higher RAFTs to obtain a given level of productivity than do high-permeability burdens at a given injection level.

The daily coke consumption required to support the furnace production achieved at Acme throughout these trials is shown in Figure 7-14. The productivity-coke consumption relationship projected at constant coke rate from the no-scrap baseline point probably could not have been obtained in practice. This is because it would not have been possible to manage the change in the furnace thermal balance brought about by the need for higher blast enrichment without increasing the blast moisture content, which would have increased coke consumption. Prior to these tests the operators increased productivity and decreased coke consumption by adding scrap to the burden, as shown for the scrap baseline point. Addition of more scrap with higher blast enrichment and more moisture additions could have boosted productivity, but it is likely that total coke consumption would have increased since significant coke rate decreases would not have been possible without injection of some supplemental fuel.

7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-14. Total Coke Consumption versus Hot Metal Production



The benefits of gas injection when productivity increases are not being sought is shown by the reductions in coke consumption that were achieved at hot metal production rates less than about 2,900 TPD. Coke consumption was reduced from the no-scrap baseline condition by more than 200 TPD through injection of natural gas at levels of about 100 lb/THM. At hot metal production rates greater than about 3,200 TPD, coke consumption was held essentially constant at about 1,200 TPD by increasing the level of gas injection beyond about 200 lb/THM. The progressive decreases in coke consumption observed from Phase A to Phase C at hot metal production rates between about 2,900 and 3,200 TPD are the results of changes in injection levels that were required to maintain productivity at a given level while burden permeability changed as well as the improvements in practice that were realized as the operators climbed the learning curve for gas injection at high levels.

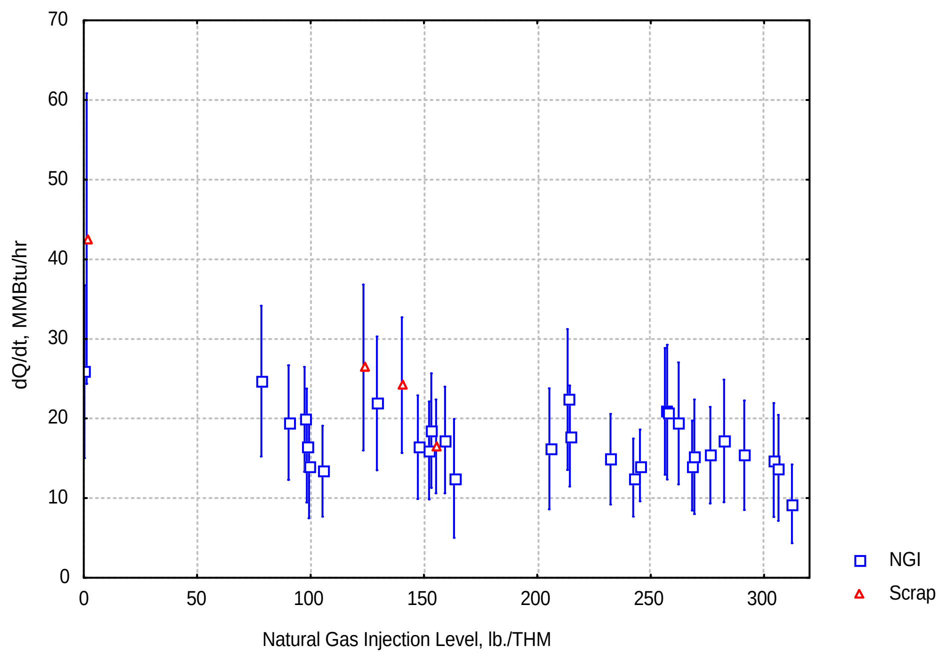
Thus, Acme was able to obtain productivity increases of 1,036 and 663 TPD from the no-scrap and scrap baselines, respectively, while decreasing coke consumption by 176 and 242 TPD from these baseline conditions. The trends in graphs of hydrogen utilization efficiency, extent of direct reduction, “excess” carbon consumption in the raceway, and furnace coke rate versus natural gas injection as well as the trends in furnace productivity versus oxygen consumption shown in this chapter suggest that even higher furnace production rates could be achieved at constant coke consumption through injection of natural gas at levels higher than 300 lb/THM.

C. HOT METAL QUALITY

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 Table 5-2 and Reference 9 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 MM Btu/hr. The greater the changes in temperature and composition, the greater the variability. Over time, positive and negative changes from the mean (or aim value) will sum to zero for any furnace, but furnace operation becomes smoother and hot metal chemistry is more consistent when changes in operating practice lead to smaller values of this parameter. The effects of natural gas injection level on the cast-to-cast variability in the thermal state of the hearth are shown for each data point recorded in these tests in Figure 7-15.

7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-15 Cast to Cast Variability in the Hearth vs. Natural Gas Injection Level

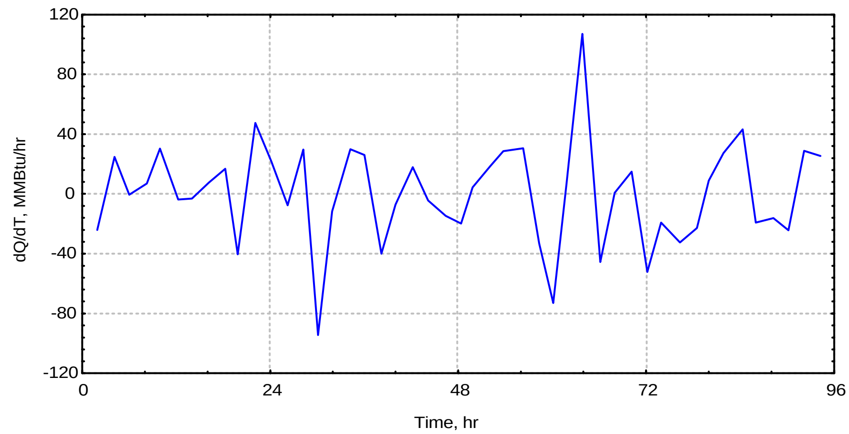


These data show the same general trends as the other measures of the variability in hot metal chemistry: the average value and standard deviation in this parameter are higher when B scrap is on the burden than when it is not, and the averages decrease with increasing level of natural gas injection. We attribute this increase in stability, which occurs even as RAFT is decreasing, to the high bosh gas hydrogen content, which facilitates burden movement. This can occur even when burden permeability decreases: note that at the same injection level the value of this parameter is lower in Phase E than in Phases A and C.

The improvement in the stability of furnace operation with increasing levels of natural gas injection is shown by the changing shapes of the traces of the variability of the hearth energy requirements shown in Figures 7-16A through 7-16E.

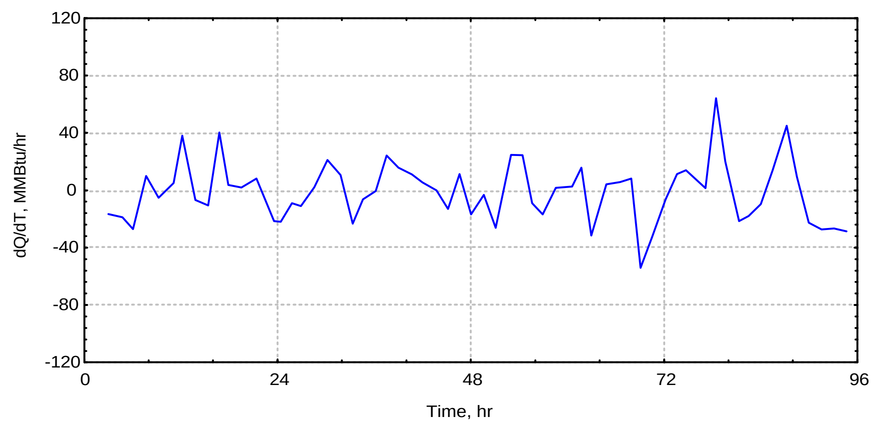
7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-16A. Cast-to-Cast Variations in the Hearth at Acme: Phase A, Base Period, No Natural Gas Injection, No Scrap



Average = 25.9 MMBtu/hr
Standard Deviation = 21.7 MMBt

Figure 7-16B. Cast-to-Cast Variations in the Hearth at Acme: Phase A, Period 3, 147 lb/THM Natural Gas Injection Rate



Average = 16.4 MMBtu/hr
Standard Deviation = 13.0 MMB

Figure 7-16C. Cast-to-Cast Variations in the Hearth at Acme: Phase E, Period 1, 232 lb/THM Natural Gas Injection Rate

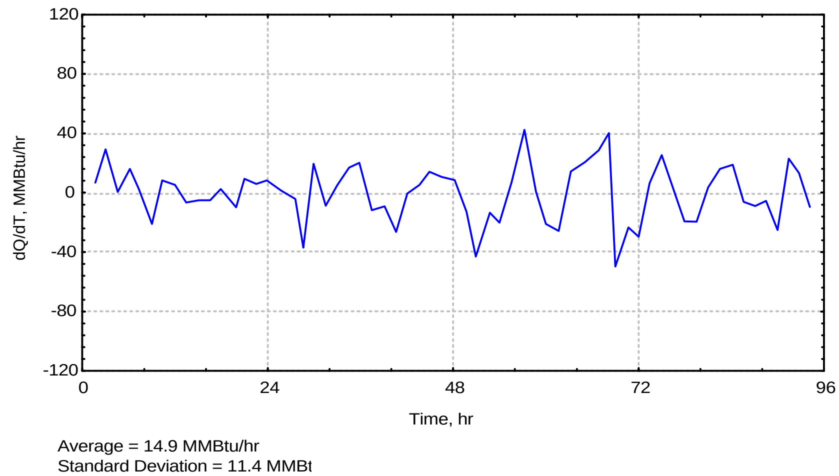


Figure 7-16D. Cast-to-Cast Variations in the Hearth at Acme: Phase C, Period 1, 232 lb/THM Natural Gas Injection Rate

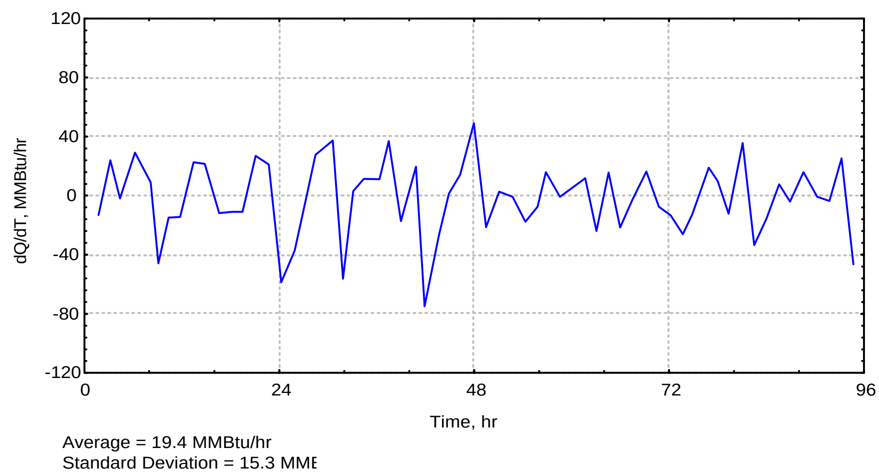
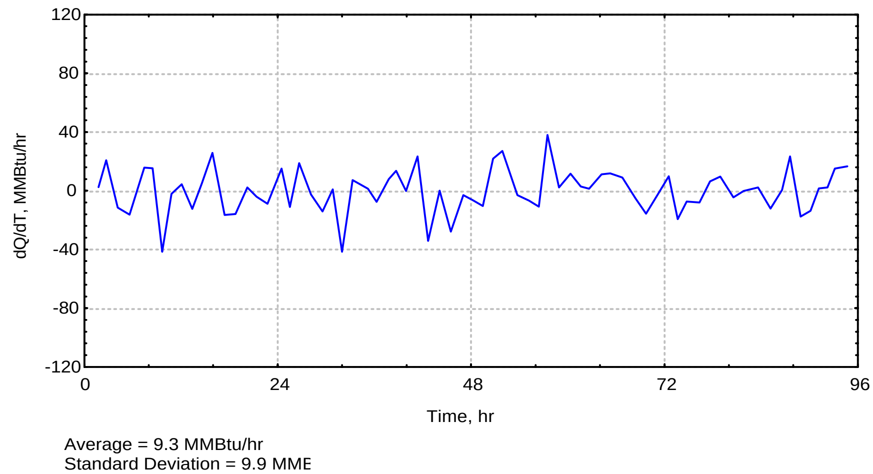


Figure 7-16E. Cast-to-Cast Variations in the Hearth at Acme: Phase E, Period 10, 312 lb/THM Natural Gas Injection Rate



The average steady state rate of heat release from the blast reaction in the raceway/hearth in these trials was about 231 MM Btu/hr. Thus, the variability of the hearth energy consumption with no injection of natural gas was rather large, at about 10% of the average value and up to 15% when there was scrap on the burden as shown in Figure 7-15. With high rates of injection the variability drops to less than 5% of the average, and operators report that burden movement is smoother and there are less out-of-range casts.

Since the coke rate decreases as the level of natural gas injection increases the sulfur load to the furnace drops as shown in Figure 7-17. However, Acme's burdening practice resulted in decreases in slag basicity as the injection level was increased and the hot metal sulfur content remained essentially constant as shown in Figures 7-18 and 7-19.

7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-17. Furnace Sulfur Load at Acme

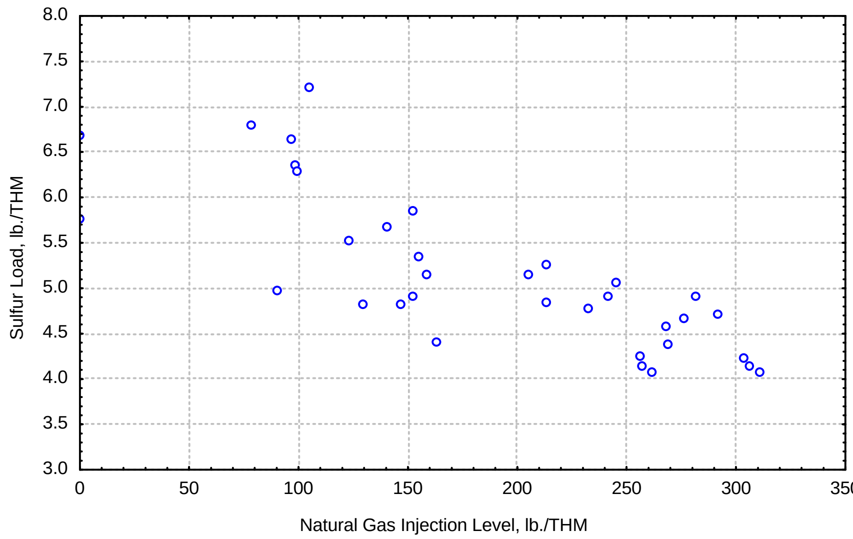
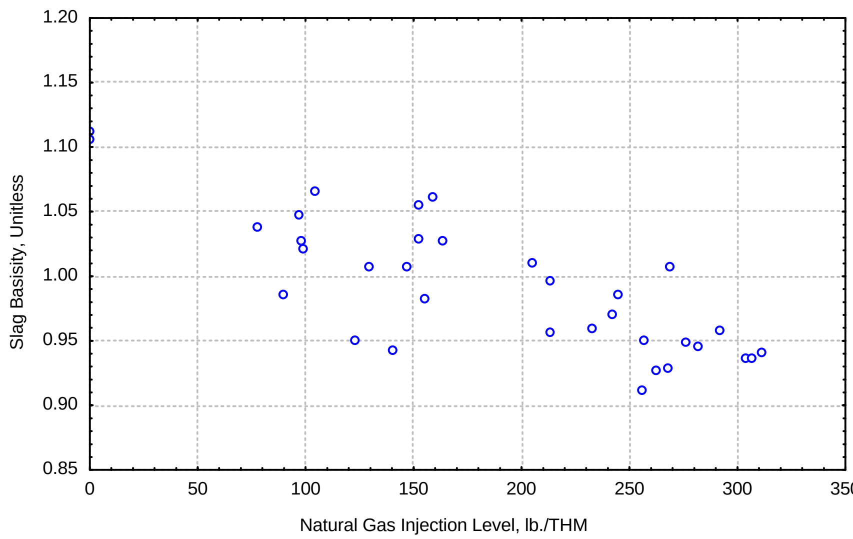
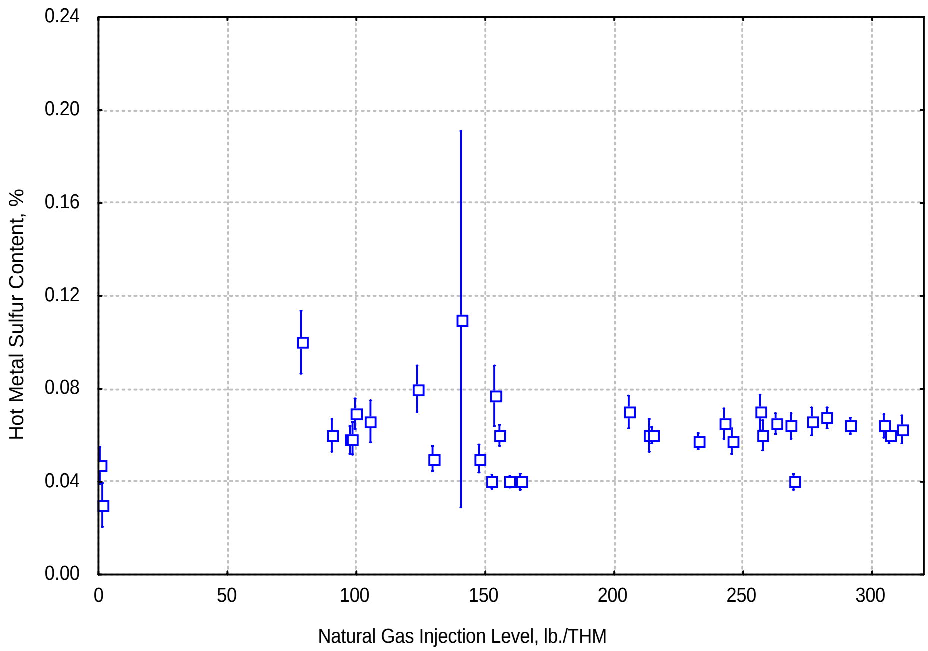


Figure 7-18. Slag Basicity at Acme



7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-19. Hot Metal Sulfur Content versus Natural Gas Injection Level at Acme



The behavior is in sharp contrast with the performance obtained in high-rate natural gas injection tests at National Steel Granite City Division and at Armco Middleton, where hot metal sulfur contents decreased by about 0.007 and 0.0085% per 100 lb/THM increase in injection level, respectively, and reached values below 0.02% at Granite City.[13] There was a systematic error in the sulfur balance throughout these trials, and closure was forced by increasing the sulfur content of the slag to higher than reported values. It is possible that this adjustment contributed to the scatter in the calculated values of the partition ratio for sulfur shown in Figure 7-20. Attempts were made to correlate the calculated values of the partition rate with the parameters tested in Table 7-2.

[13] *The Impacts of High Rates of Fuel Injection on the Quality of Hot Metal*, Gas Research Institute (GRI-91/0227), June 1996.

7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-20. Slag-to-Hot Metal Partition Rate for Sulfur vs. Natural Gas Injection Level

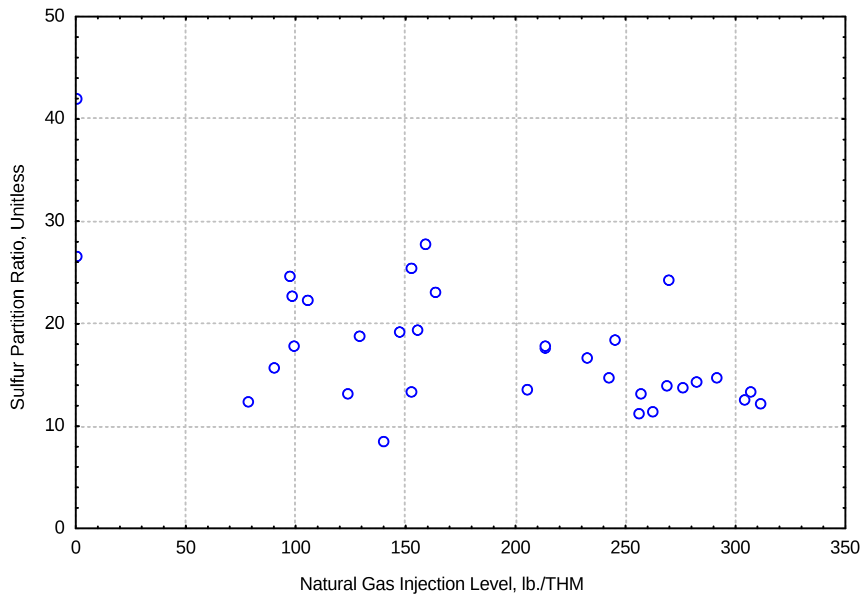


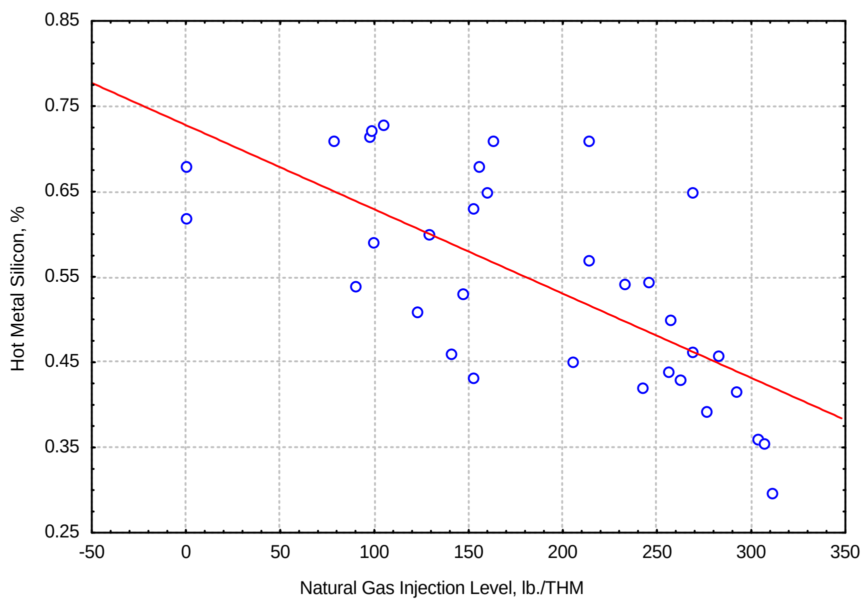
Table 7-2. Parameters Tested for Correlation of Hot Metal Chemistry

Parameter	Tested for S	Tested for Si
Hot Metal Temperature, °F	√	√
Hot Metal Production, TPD		√
Casts per Day	√	√
Slag Basicity, B/A	√	√
Slag FeO, %	√	√
Slag MgO, %	√	√
Slag Volume, lb/THM	√	√
Hearth Gas Temperature, °F	√	√
Bosh Gas Hydrogen, lb/THM	√	√

Multiple linear regression of these parameters showed a positive relation between partition coefficient and basicity, as expected, but the result was barely significant statistically, and other parameters such as slag FeO content showed relations that were contrary to expectations. Restricting the parameters in the regression to hot metal temperature and slag basicity and FeO content removed the difficulty of relationships with counterintuitive signs and greatly increased the statistical significance of basicity and hot metal temperature, but the overall correlating ability was poor with an R^2 value of less than 0.68. The scatter in the data shown in Figure 7-20, particularly in the data at about 100 and 150 lb/THM injection rates, precludes development of a more reasonable correlation between operating parameters and hot metal sulfur content.

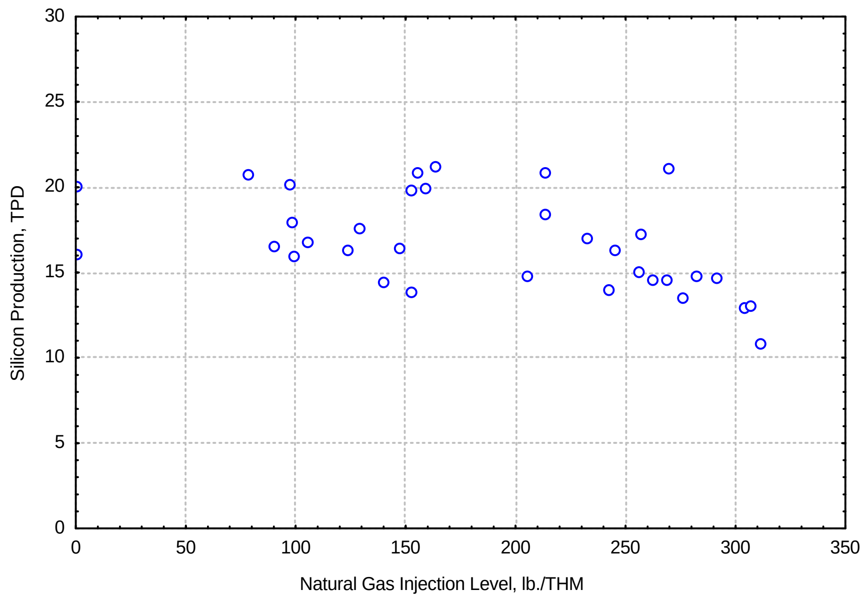
Even though the temperature of the hot metal did not decrease with increasing levels of injection (see Figure 7-2), the hot metal silicon content did decrease as shown in Figure 7-21. The decrease in silicon content, which became pronounced at injection levels above 300 lb/THM natural gas, was a significant contributor to the decrease in coke rate observed at the highest injection levels. This behavior also contrasts with the observation of nearly constant hot metal silicon contents and increasing amounts of silicon production per day at Armco and National Steel: at Acme, the production of silicon contained in the hot metal decreased with increasing levels of natural gas injection as shown in Figure 7-22.

Figure 7-21. Hot Metal Silicon Content vs. Natural Gas Injection Level



7. Effect of Natural Gas Injection Level on Furnace Performance

Figure 7-22. Silicon Production in Hot Metal at Acme vs. Natural Gas Injection Level



Attempting to correlate the data in Figure 7-22 with only hot metal production and temperature and slag FeO content gives very poor results, with an R^2 value of about 0.55 and a high degree of statistical significance only to hot metal temperature. Including all of the parameters in Table 7-2 in the regression only improves the R^2 value to 0.70, introduces counterintuitive relationships among the variables, and reduces the statistical significance of others (such as hot metal temperature) that are certain to be important.

In sum, while the variability in hot metal chemistry decreased with increasing levels of injection of natural gas, the sulfur partition coefficient and hot metal silicon contents do not show the expected correlation behavior with process parameters. The behavior of the A furnace at Acme with respect to sulfur partition and silicon production is different from the behavior of the furnaces at Armco Middleton and National Granite City at high levels of injection.