Sponsor TBD Report No.:______________

AISI/DOE Technology Roadmap Program

Final Report

Hot Oxygen Injection Into The Blast Furnace

by

Michael F. Riley

October 21, 2002

Work Performed under Cooperative Agreement
No. DE-FC07-97ID13554

Prepared for
U.S. Department of Energy

Prepared by
American Iron and Steel Institute
Technology Roadmap Program Office
Pittsburgh, PA 15220

DISCLAIMER

Number of pages in this report: 31

DOE and DOE contractors can obtain copies of this report FROM: Office of Scientific and Technical Information, P. O. Box 62, Oak Ridge, TN 37831. (615) 576-8401.

This report is publicly available from the Department of Commerce, National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161. (703) 487-4650.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Executive Summary

Increased levels of blast furnace coal injection are needed to further lower coke requirements and provide more flexibility in furnace productivity. The direct injection of high temperature oxygen with coal in the blast furnace blowpipe and tuyere offers better coal dispersion at high local oxygen concentrations, optimizing the use of oxygen in the blast furnace. Based on pilot scale tests, coal injection can be increased by 75 pounds per ton of hot metal (lb/thm), yielding net savings of $0.84/tm. Potential productivity increases of 15 percent would yield another $1.95/thm.

In this project, commercial-scale hot oxygen injection from a "thermal nozzle" system, patented by Praxair, Inc., has been developed, integrated into, and demonstrated on two tuyeres of the U.S. Steel Gary Works no. 6 blast furnace. The goals were to evaluate heat load on furnace components from hot oxygen injection, demonstrate a safe and reliable lance and flow control design, and qualitatively observe hot oxygen-coal interaction. All three goals have been successfully met.

Heat load on the blowpipe is essentially unchanged with hot oxygen. Total heat load on the tuyere increases about 10% and heat load on the tuyere tip increases about 50%. Bosh temperatures remained within the usual operating range. Performance in all these areas is acceptable.

Lance performance was improved during testing by changes to lance materials and operating practices. The lance fuel tip was changed from copper to a nickel alloy to eliminate oxidation problems that severely limited tip life. Ignition flow rates and oxygen-fuel ratios were changed to counter the effects of blowpipe pressure fluctuations caused by natural resonance and by coal / coke combustion in the tuyere and raceway. Lances can now be reliably ignited using the hot blast as the ignition source.

Blowpipe pressures were analyzed to evaluate hot oxygen-coal interactions. The data suggest that hot oxygen increases coal combustion in the blowpipe and tuyere by 30%, in line with pilot scale tests conducted previously.

1. INTRODUCTION

High levels of fossil fuel injection are now a common blast furnace practice. Fuel injection replaces a portion of the coke requirement, lessening the impact of the increasing environmental pressures on coke making. Injected fuel also acts as a coolant, allowing higher levels of blast oxygen enrichment and increased furnace productivity.

At most sites, coal is the preferred injectant, because, compared to other fossil fuels, coal is less expensive and offers the largest coke replacement potential.[1,2,3] Coal injection rates of 200-300 pounds per ton of hot metal (lb/thm) are common,[4] and levels of 500 lb/thm have been achieved under well-controlled conditions.[5,6] Even at the lower injection rates, however, operating problems occur which are related to incomplete combustion of the injected coal. Carbon levels in the furnace off-gas may rise, and the pressure drop across the furnace may increase.[7,8] Improved combustion techniques are needed to achieve higher coal injection levels consistently throughout the industry.

The direct injection of oxygen into the furnace blowpipes or tuyeres offers the potential for better coal dispersion in the blast at high local oxygen concentrations. Material and energy balances on the blowpipe-tuyere zone show that oxygen use is optimized when the oxygen is injected at high temperature.[9]

Praxair, Inc.'s patented "thermal nozzle" system heats oxygen to 3000°F at the point of use, generating a high momentum jet.[10,11] Pilot-scale tests conducted at the CANMET Energy Technology Centre by Praxair, Bethlehem Steel Corp., and U.S. Steel Corp. demonstrated that hot oxygen from a thermal nozzle provides 20%-50% faster burnout of injected coal compared with ambient temperature injection or increased blast enrichment.[12]

Figure 1 shows the thermal nozzle concept. Oxygen is introduced into a combustion chamber along with a small amount of fuel, such as natural gas. The volume of fuel is kept well below the stoichiometric ratio, so that when the fuel and oxygen react in the combustion chamber they produce a hot gas which is still predominantly oxygen, with small amounts of CO_2 and H_2O. Table I shows the reactant and product compositions for hot oxygen at 2500°F and 3000°F.

Because the oxygen passing through the nozzle is very hot, its sonic velocity is very high.[13] This allows the hot oxygen to be accelerated to very high velocities with relatively low supply pressures and a simple converging nozzle at the exit of the combustion chamber. Sonic velocities for 2500°F and 3000°F oxygen are shown in Table I.

Through proper design of the combustion chamber, the thermal nozzle can be used without water cooling. A boundary layer of cold oxygen will separate the bulk of the hot oxygen flow from the converging nozzle, preventing overheating.

Combined with coal injection in a blast furnace blowpipe, hot oxygen creates excellent combustion conditions. The high momentum of the hot jet provides strong mixing, pulling the char and volatiles into a high-temperature, high-oxygen envelope.

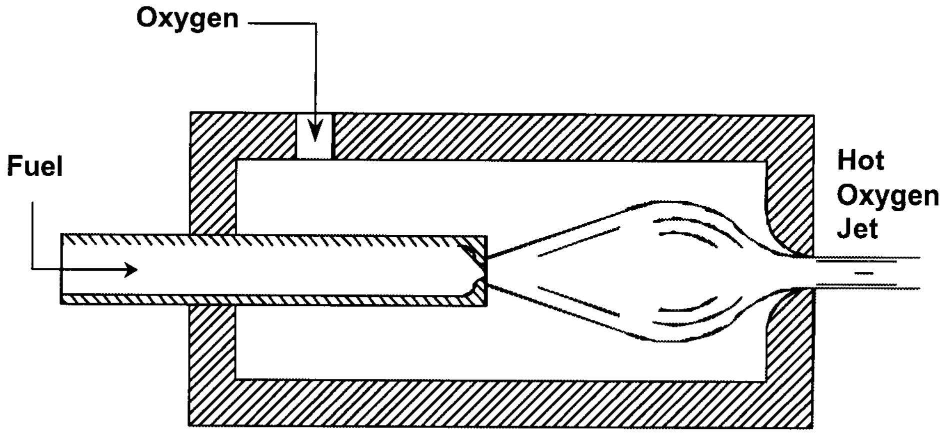


Figure 1 – Thermal nozzle. Ref. 10

With the ultimate goal to demonstrate the use of hot oxygen to increase coal injection on a commercial blast furnace, U.S. Steel Gary Works no. 6 furnace. In this project, hot oxygen was injected through two tuyeres of the furnace to evaluate:

- heat load from hot oxygen on blowpipes, tuyeres, and other furnace structures;
- reliability and durability of a commercial hot oxygen lance;
- qualitative effect of hot oxygen on coal combustion.

Tuyeres 8 and 9 were selected as test tuyeres because of their proximity to platforms that could accommodate flow controls and other test equipment and their distance from tapping and other hazardous furnace operations.

The following sections present the theory of thermal nozzle operation, an economic analysis of the benefits of hot oxygen injection, short descriptions of the commercial equipment & test instrumentation, and test results.

Table I – Hot Oxygen Chemistry

	2500°F	3000°F
Reactants		
Oxygen, scf	100	100
Natural gas, scf	6.4	8.2
Products		
Total volume, scf	106.4	108.3
Oxygen, pct	81.9	77.1
Carbon dioxide, pct	6.0	7.6
Water vapor, pct	12.1	15.0
Sonic velocity, ft/s	2,450	2,647

2. ECONOMICS OF HOT OXYGEN INJECTION

Improving the combustion of injected coal will lead to decreased coke consumption. The following analysis assumes that coal injection can be increased by 75 lb/thm with a replacement ratio of 0.9 with hot oxygen. This represents the lower end of the improvement range suggested by pilot-scale tests.[12] For a medium sized blast furnace producing 4000 tons per day (tdp), coke savings would be 135 tpd and coal consumption would increase by 150 tpd. The expected increase in oxygen consumption would be 75 lb/thm, or 150 tpd. Taking typical costs of $70/t for pulverized coal, $130/t for coke, and $30/t for oxygen, the annual material savings are roughly $900,000. In addition, increased coal injection will increase the net amount of blast furnace gas generated by an estimated 740 MMBtu/day. Allowing $1/MMBtu for blast furnace gas, this provides an additional $265,000/yr credit. This gives direct annual savings at the blast furnace of $1.17 million, or $0.84/thm.

There are also potential productivity benefits from the increased oxygen enrichment. Furnace productivity could be increased up to 15 percent with the 75 lb/thm increase in coal injection postulated above. For a hot metal value of $130/thm, this represents a $2.73 million annual benefit, or $1.95/thm. This potential will be especially valuable as the number of blast furnaces declines.

There will be additional future benefits from decreases in coke consumption. Fugitive emissions from coke making are reduced proportionally with reduced coke requirements. For a 4000 tpd furnace, the proposed technology is expected to reduce emissions by a total of 25,000 t/yr, with 95% of that total being CO_2 emissions, and the balance primarily SO_2, VOCs, and NOx. EPA estimates that compliance with health-based standards will add up to $4/t to coke production costs.[14] Coke prices could rise more if a significant number of batteries must close for non-compliance. Thus, the elimination of 67 lb/thm of coke with hot oxygen injection corresponds to an added saving of $190,000 or more annually at the coke oven.

The capital and installation costs for a 4000-tpd furnace is estimated at $1.05 million. Non-productivity direct savings give a payback period of less than 11 months. Including productivity benefits, the payback period becomes 3 months.

3. HOT OXYGEN EQUIPMENT

FUNCTIONAL DESCRIPTION

The hot oxygen system installed at the U.S. Steel Gary no. 6 blast furnace has three main components:

- the hot oxygen lances,
- the control valve skid, and
- the control computer system.

Each main component is described in this section.

Hot Oxygen Lances

The hot oxygen lance used at U.S. Steel Gary no. 6 furnace is designed to consume 7500 scfh of high-purity oxygen and 600 scfh of natural gas, creating a gas jet at 2950°F containing 6300 scfh of unreacted oxygen. Each hot oxygen lance consists of two concentric pipes. The center pipe carries natural gas; the annulus between the two pipes carries oxygen. The discharge end of the center pipe is recessed within the lance, creating a combustion chamber at the tip of the lance. The oxygen and natural gas burn within this combustion chamber, and the product gas is discharged through a nozzle at the lance tip.

The hot oxygen lances were mounted into the tuyere through the short-side blowpipe boss using the standard standpipe and Grafoil-Inconel packing. The general arrangement of the coal and hot oxygen lances in the blowpipe is shown in Figure 2. Initially, the lance tip was inserted roughly 36 inches into the standpipe, placing the lance tip roughly 2 inches from the short-side inner wall of the blowpipe and roughly 2 inches from the coal lance tip. The lance position was then adjusted to minimize ash buildup on the tuyere and maximize interaction with the coal.

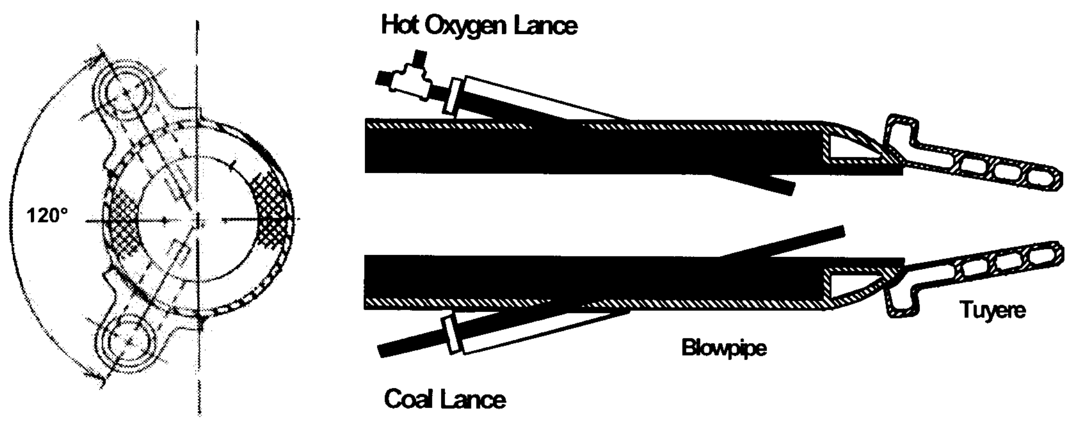


Figure 2 – Top view of general arrangement of coal lance, hot oxygen lance, blowpipe and tuyere at U.S. Steel Gary Works no. 6 blast furnace

Control Valve Skid

The control valve skid measures and controls the flow of natural gas and oxygen to each hot oxygen lance. An ignition bypass system was added during startup to provide better flow control during the lance ignition sequence.

The inlets for oxygen and for natural gas are equipped with a manual isolation valve and two pneumatically-operated blocking valves. The redundancy in blocking valves is required by code and ensures positive shut-off of each gas. The blocking valves have position-indicating switches that are monitored by the computer control system to provide positive feedback on valve positions.

The oxygen inlet flow branches into two separate process flows, one for lance no. 8 (corresponding to tuyere no. 8) and one for lance no. 9. The flow in each oxygen process line is measured by a vortex flow meter/transmitter (with pressure and temperature compensation) and controlled by a flow control valve.

A similar flow division is made for the natural gas. The flow in each natural gas process line is measured by an orifice plate meter (with pressure compensation) and controlled by a flow control valve.

The control valve skid also provides a purge flow of nitrogen in place of natural gas and oxygen under the appropriate conditions. The nitrogen inlet is equipped with a manual isolation valve. The nitrogen inlet flow then branches into an oxygen line purge flow and a natural gas line purge flow. Each purge flow branch is equipped with its own pair of pneumatically-operated blocking valves to ensure no cross-backflow between the oxygen and natural gas supplies through the nitrogen purge lines. These blocking valves also are equipped with position-indicating switches monitored by the computer control system. The nitrogen purge flows feed the oxygen and natural gas systems immediately upstream of the respective process line branches. This allows nitrogen flow in all process lines to be measured and controlled by the same equipment used for the oxygen and natural gas process flows. Nitrogen is also used for actuation of the pneumatically-operated valves on the skid.

Pressure transmitters are located at several points in the skid to provide diagnostic information to the computer control system.

Computer Control System

The computer control system contains a Level I computer platform and a Level II computer platform to monitor the hot oxygen lances and control valve skid and to control skid functions. Information is passed between the Level I and Level II systems via Ethernet.

The Level I computer system consists of an Allen-Bradley PLC-5/80E, and is located in the no. 6 blast furnace control room. The Level II computer system consists of a Dell Optiplex computer running on the Windows NT version 4.0 operating system. The computer station is used to display the operator screens via Rockwell Software's RSView32 HMI package. The Level II computer was used for integration and startup only.

The operator interface consists of three screen displays, titled "Main", "P&ID", and "Interlock". Each screen is displayed by pressing the appropriate button at the top of the display.

The "Main" screen contains the main operator controls. These consist of status lights indicating whether system power is on, and whether any interlocks have tripped. It also contains the selector buttons to activate Oxygen Preheat mode or Nitrogen Purge mode and corresponding status lights. The "Main" screen also displays the status of each hot oxygen lance. A graphic on the screen shows the 20 tuyeres of the furnace. Details on flow rates and set points for any lance can be displayed by clicking on the lance/tuyere number on the graphic. Details include the oxygen flow rate setpoint and hot oxygen temperature setpoint entered by the operator. Bar graphs at the bottom of the screen provide a quick visual summary of the flow rates on each hot oxygen lance.

The "P&ID" screen shows the status of the blocking valves and flow control valves on the control valve skid. The "Interlock" screen shows the status of the safety interlocks to facilitate troubleshooting. The "Interlock" screen also contains a button to Reset the interlocks to allow re-start of the system, and a button to Shutdown all gas flow to the system.

Manual E-stops are located on each screen display, and hard-wired, mushroom-button E-stops were located on the flow control skid and in the furnace mud gun room. Activating these E-stops shuts off the oxygen and natural gas flows, and starts a nitrogen purge.

MODES OF OPERATION

A normal operating sequence was developed with U.S. Steel Gary operating personnel, starting from an initial startup, followed by normal hot oxygen operation, an optional purge operation, and finally shutdown.

4. TEST PROCEDURES

INSTRUMENTATION

Several instruments were added to the furnace to provide additional test data on hot oxygen performance. Each test blowpipe was equipped with two low-cost external infrared optical pyrometers to detect overheating by the hot oxygen jet. These pyrometers were interlocked with the flow control to minimize any possibility of blowpipe failure. Cooling water flow rate and inlet and outlet temperatures were measured for the test tuyeres and for two control tuyeres, where instrumentation is already in place, to monitor heat load by the hot oxygen and the combustion of injected coal. Static pressure probes were added to the bustle pipe downcomer and to the blowpipe, upstream of the coal injection port, to measure actual blast flow rate in each test tuyere. Four additional bosh thermocouples were installed 7 ft and 10 ft above the test tuyeres, complementing a wide array of thermocouples already on the furnace. Data from the instrumentation was monitored by the existing U.S. Steel process monitoring software.

LANCE IGNITION SEQUENCE

To maximize the benefit of hot oxygen injection, the natural gas and oxygen must burn within the combustion chamber of the thermal nozzle. If combustion does not occur in the combustion chamber, the natural gas-oxygen mixture will flow through the nozzle at essentially ambient temperature. This cold jet will have low velocity and produce little mixing in the blowpipe. The mixture will ignite after mixing with hot blast air, but the oxygen content of the jet will be lowered considerably by the mixing.

Since the lance is lit by the hot combustion air in the blowpipe, conditions during lighting must favor "flashback" into the combustion chamber, i.e., the burning velocity of the natural gas-oxygen mixture must be higher than the flow rate of the mixture. Accordingly, an ignition sequence is needed to establish stable combustion in the combustion chamber. Once stable combustion is established, flow rates can be raised to operating levels.

The lance ignition sequence begins when the operator activates the Oxygen Preheat mode on the Main control screen and follows a programmed practice. The practice used at U.S. Steel Gary no. 6 furnace was as follows:

- Flow natural gas and oxygen at normal operating flow rates for one minute to clear nitrogen from the piping connecting the control valve skid to the lances;
- Change setpoints for natural gas and oxygen to zero on flow control valves and open ignition bypass solenoid valves;
- Allow natural gas and oxygen to flow through bypass legs into lances for 20 seconds to create flashback and establish stable flow in combustion chamber of each lance;
- Change oxygen setpoint on flow control valve to 50 percent of normal operating flow rate; allow one minute for flow to stabilize;
- Change natural gas setpoint of flow control valve to 50 percent of normal operating flow rate; allow one minute for flow to stabilize;
- Change oxygen setpoint to 100 percent of normal operating flow rate;
- When oxygen flow rate reaches setpoint, change natural gas setpoint to 100 percent of normal operating flow rate;
- When natural gas reaches setpoint, close ignition bypass solenoid valves.

Normal operating flow rates were usually maintained at 600 scfh natural gas and 7500 scfh oxygen during testing, producing a 2950°F hot oxygen jet. Purge rates for each lance were 600 scfh nitrogen through the natural gas line and 3300 scfh through the oxygen line.

Ignition within the combustion chamber can be detected by the high backpressure created when the hot gas flows through the nozzle at the lance tip. With proper ignition in the lance design used at here, oxygen backpressure should be 55 psig at the design flow rates of 7500 scfh oxygen and 600 scfh natural gas (oxygen stagnation temperature 2950°F), assuming a 29 psig blast air pressure. In comparison, oxygen backpressure is 39 psig when the natural gas-oxygen mixture ignites in the furnace blowpipe.

5. RESULTS

The performance of hot oxygen injection was evaluated by comparing results for three operating regimes:

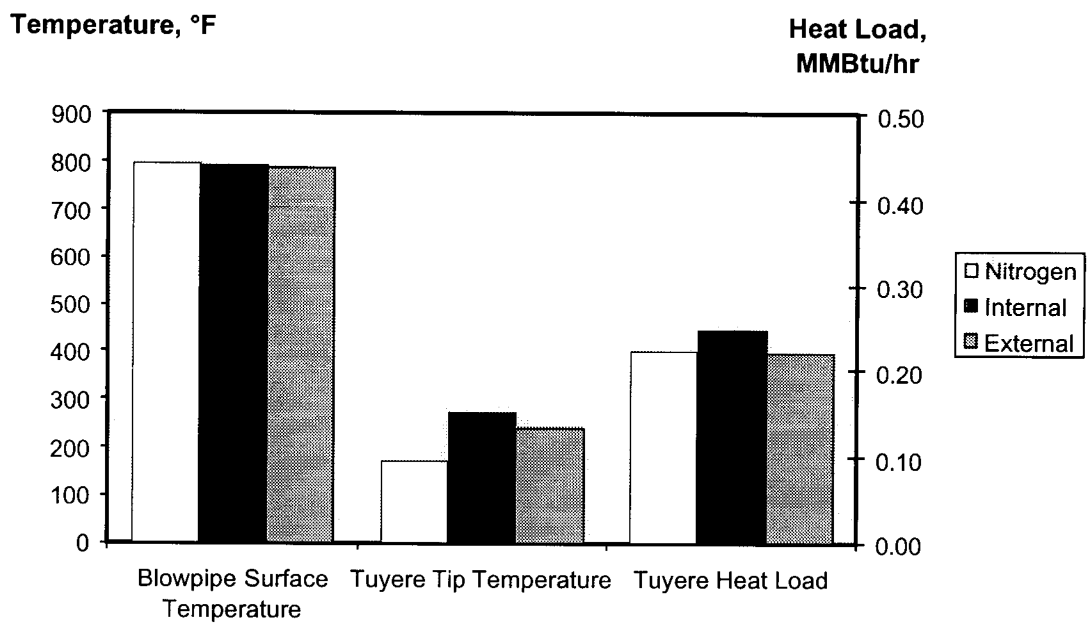


Figure 3 - Blowpipe and Tuyere Temperatures and Heat Loads

- Purge – where the lance flows only nitrogen;
- Internal ignition – where the lance flows oxygen and natural gas and ignition occurs in the combustion chamber as designed;
- External ignition – where the lance flows oxygen and natural gas but ignition is not established in the combustion chamber, occurring downstream of the lance nozzle instead.

FURNACE COMPATIBILITY

Thermal loads on the blowpipe, tuyere, and surrounding furnace structure were measured to identify any overheating problems related to hot oxygen injection.

The external surface temperature of each blowpipe was measured by a pair of infrared pyrometers. The results are shown in Figure 3, comparing internal ignition periods with external ignition and nitrogen purge periods. No effect of hot oxygen is seen.

The temperature of the tuyere nose was measured with a Type-K thermocouple. In addition, the heat load on the tuyere was calculated from the measured cooling water flow rate and the change in cooling water temperature across the tuyere. Figure 3 shows the results, again comparing internal ignition, external ignition, and purge operation. Internal ignition gives a sharp increase in tuyere nose temperature compared with the purge operation. External ignition gives a significant, but smaller, increase in tuyere nose temperature. Using ambient temperature (70°F) as a baseline, the data suggest hot oxygen doubles the heat load produced with nitrogen purge through the lance, and increases the heat load on the tuyere tip by about 50% compared with external ignition. Total heat load on the tuyere is about 10% higher with internal ignition compared with either the purge or external ignition operation. The results indicate a significant increase in heat released locally in the tuyere with internally ignited hot oxygen with an acceptable increase in equipment temperature.

Thermocouples were installed in the bosh above tuyere level. Minor fluctuations were observed in these readings, all within the typical ±3°F variation observed throughout the bosh. The bosh thermocouples near the hot oxygen lances stabilized at the same or lower temperature than observed elsewhere in the bosh.

LANCE PERFORMANCE

Reliable flashback during ignition is essential to achieving the full benefit of hot oxygen injection. Internal ignition reliability was measured as the amount of the time the expected high oxygen backpressure was observed as a percentage of the time hot oxygen is requested by the operator, i.e., outage and purge times are excluded. Several operating problems which prevented reliable flashback were encountered and overcome in the course of the project.

Fuel Tip Oxidation

The hot oxygen lance was originally designed with a copper tip because laboratory tests had shown that a high thermal conductivity material was needed to conduct heat from the hot end of the tip and prevent melting by the combustion reaction. Figure 4 shows the internal ignition reliability at U.S. Steel Gary no. 6 furnace using the copper fuel tip. Also shown in Figure 4 is the average daily natural gas backpressure on the lance.

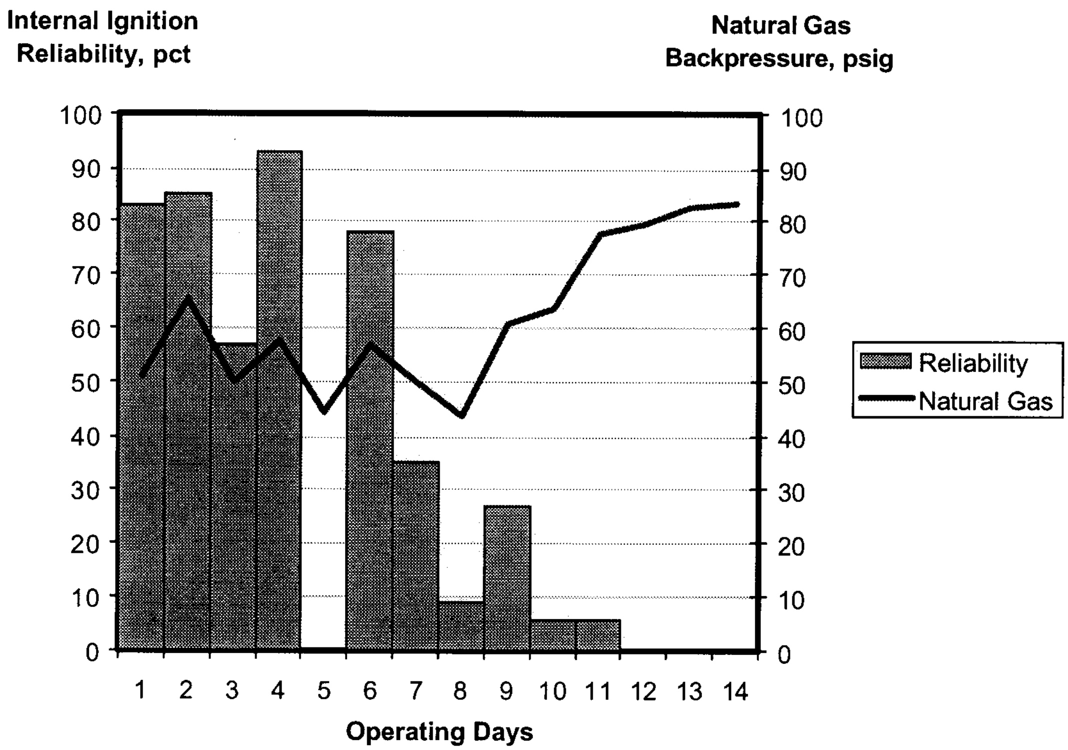


Figure 4 – Internal ignition reliability and natural gas backpressure with copper fuel tip

As seen in the figure, the reliability of internal ignition fell quickly with use while, at the same time, the natural gas backpressure began to rise sharply above the expected operating range. This suggested that blockage or damage was occurring at the copper fuel nozzle which was interfering with ignition.

Examination of the lance after removal from the tuyere showed distinctive damage to the fuel tip. A deposit formed in the fuel nozzle ports as seen in Figure 5. In addition, the fuel nozzle ports appeared wider, and the outer surface of the copper fuel tip was eroded away by about 0.020". The inner surface of the fuel tip was examined by cutting the tip open. A dark deposit was seen on the entire copper surface as shown in Figure 6. EDAX analysis conducted on the deposit indicated the presence of only copper and oxygen, i.e., a copper oxide.

The copper oxide is believed to form primarily during switching of gas flow from hot oxygen to purge nitrogen. During hot oxygen operation, the fuel tip becomes hot from the heat of the combustion reaction. This heat is difficult to dissipate in actual furnace operation since the outside of the lance is exposed to the hot blast. The flow controls for the lance were originally set up so that when switching from hot oxygen to nitrogen, the natural gas and oxygen flows are first shut off, then the nitrogen flow is started. There is likely to be a brief interval when there is no flow through the fuel tip and the tip is exposed to hot blast flowing back into the lance. When it contacts the hot fuel tip, oxidation occurs.

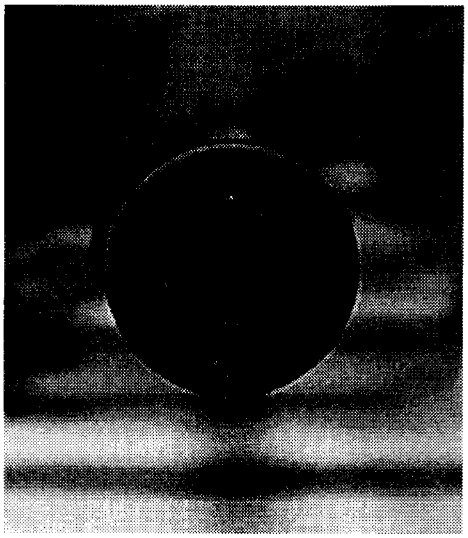


Figure 5 – Plugged copper fuel tip ports

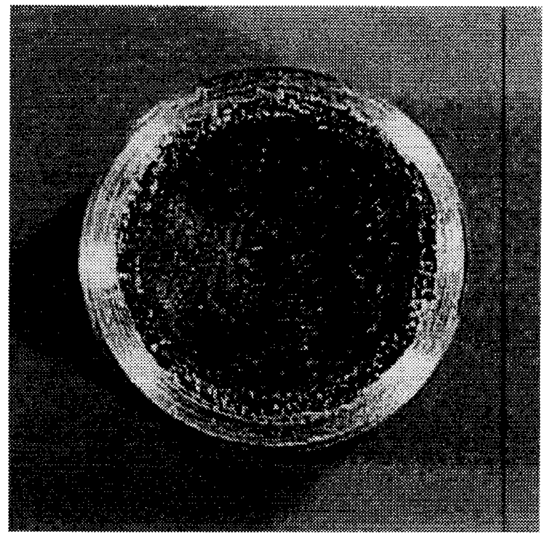


Figure 6 – Inside of plugged copper fuel tip

Oxide forming on the outside of the fuel tip will eventually spall off since the thermal expansion of the oxide is much smaller than that of the metal. However, the oxide inside the ports remains in place, restricting flow. When hot oxygen is reestablished, the oxide can heat to the melting point (the Cu-Cu_2O eutectic temperature is 1950°F [15]) causing a rapid plugging of the ports and a sudden increase in backpressure. After several purge cycles, significant oxidation will occur, eventually blocking the fuel tip.

The fuel nozzle restriction upsets the timing of the ignition sequence and thereby prevents internal ignition. With a new lance, it takes about 5 seconds for the natural gas flow rate to fall to the ignition level once the normal flow leg is closed, as shown in Figure 7. Added to the ~10 s response time of the valve, 15 s are needed to reach ignition flow rates. The ignition sequence allows 20 s, giving a 5 s ignition period. With a restricted fuel nozzle, two factors greatly increase the response time. The restricted nozzle generates a higher backpressure during the high flow period; consequently, there is a much larger standard volume of gas to discharge from the connecting piping during the transition from high flow to ignition flow. This larger volume, combined with the reduced flow rate from the fuel nozzle, results in a greatly increased transition time from high flow to ignition flow. As shown in Figure 15, at the end of the 20 s ignition sequence, the natural gas velocity from the fuel nozzle is far too high to flash back.

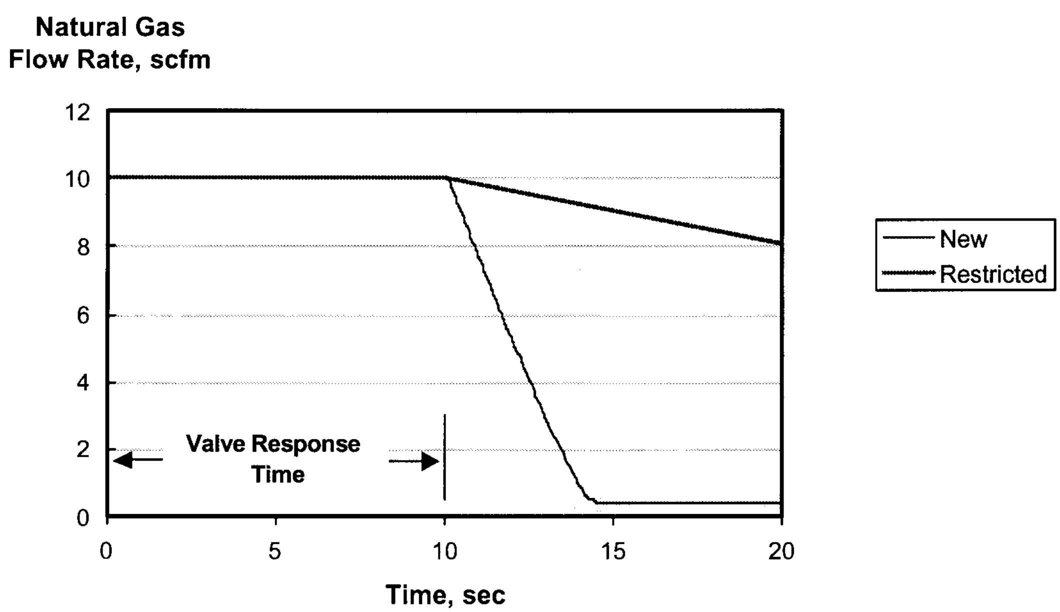
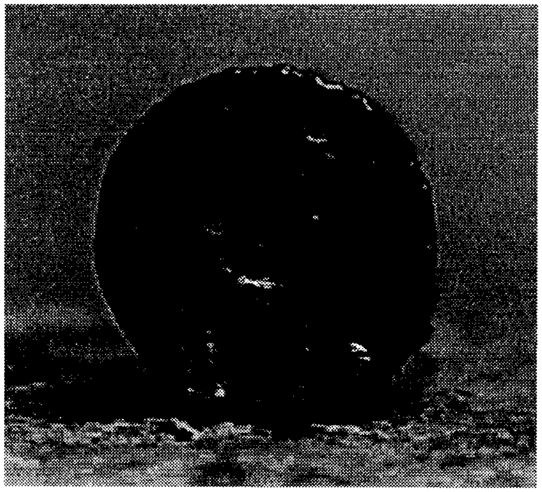


Figure 7 – Calculated natural gas flowrate during ignition sequence with new fuel nozzle and oxide-restricted fuel nozzle



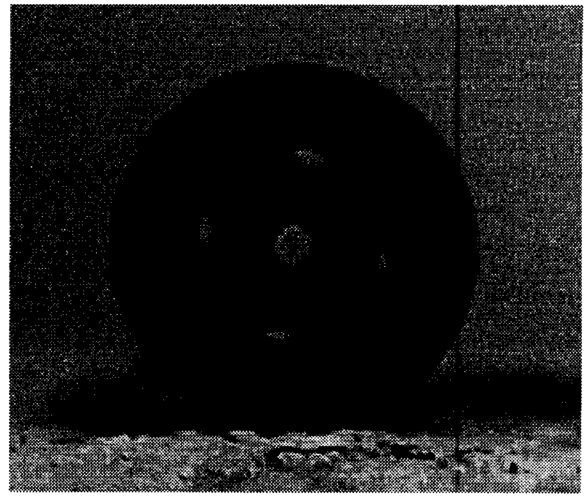


Figure 8 – Results of Tip Oxidation Tests in Air.
Left – Copper tip after 90 min at 1975°F **Right** – Nickel alloy tip after 90 min at 1975°F

It was apparent that a combination of high conductivity and lower oxidation rate was required for field service. Few heat resistant alloys offer conductivity more than a few percent that of copper. However, nickel does have a thermal conductivity 10%-20% that of copper.[16] In addition, it oxidizes at a much slower rate.[17]

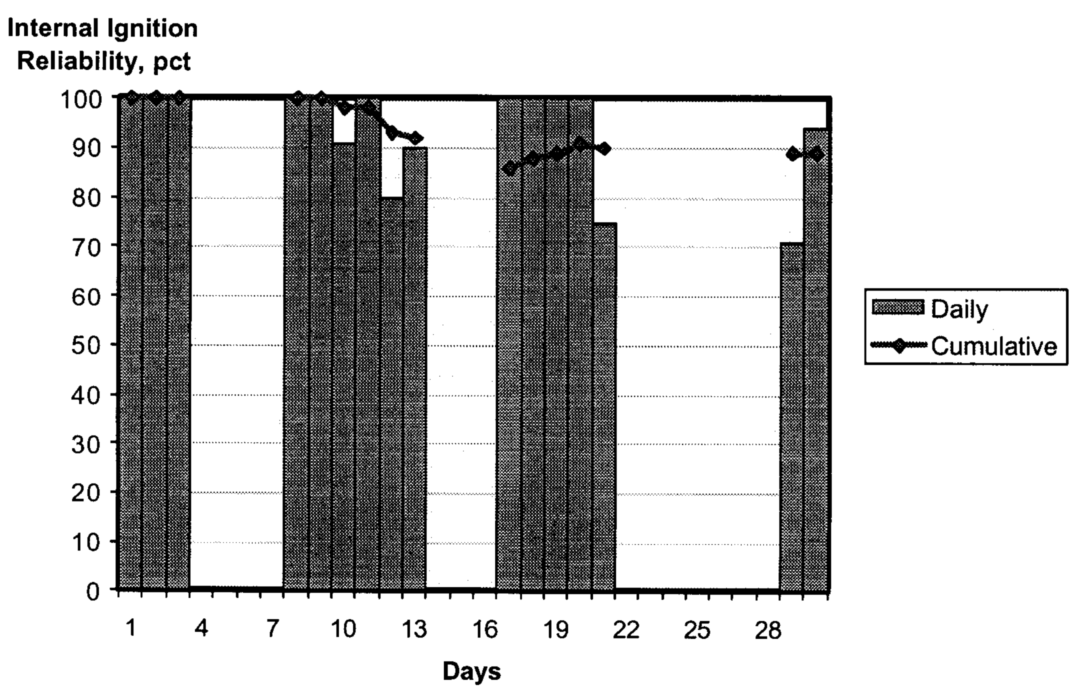


Figure 9 – Internal ignition reliability with nickel alloy fuel tip

Laboratory tests were made comparing copper and nickel. Fuel tips were machined from each material and the tips were heated in air to 1975°F. Figure 8 shows the tips after heating for 90 minutes. The copper tip failed catastrophically, which is expected since the temperature was above the Cu-Cu_2O eutectic temperature. The nickel tip was virtually unchanged. Very importantly, no reduction in port size was observed.

Based on these results, new tests were conducted with lances incorporating a nickel alloy fuel tip. The valve switching during ignition was also changed so that either natural gas or nitrogen was always flowing through the fuel tip. The reliability of internal ignition for a nickel-tip lance on U.S. Steel Gary no. 6 furnace is shown in Figure 9. This figure shows that by eliminating fuel tip oxidation with the nickel tip, reliability greater than 85% could be maintained over a 30-day period.

Blowpipe Pressure Fluctuations

Despite the success of the nickel fuel tip shown in Figure 9, other nickel-tip lances showed inferior results. Periods of reliable internal ignition would be interrupted by extensive periods where internal ignition could not be achieved, after which reliable ignition returned.

The ignition sequence had been developed from laboratory tests igniting a hot oxygen lance in a 500 fps flow of air at 1650°F – 1900°F. These laboratory tests had 100% internal ignition reliability, far better than was achieved in the U.S. Steel Gary no. 6 furnace. No clear reason for these ignition failures could be found from an examination of furnace process instrumentation or test instrumentation data.

The primary difference between ignition in the laboratory and at the U.S. Steel Gary no. 6 furnace was the presence of coal and coke combustion in the furnace blowpipe-tuyere-raceway region. Condensed-phase systems are noted for small pressure fluctuations associated with mixing and combustion processes.[18] An analysis of the ignition practice revealed that it was susceptible to these types of pressure fluctuations.

In the original ignition practice, the natural gas flow rate creates a pressure drop across the fuel tip of only about 0.1 in. H_2O. Pressure fluctuations of this magnitude could be expected from the combustion reactions in the furnace – fluctuations that would not be present in bench testing. These fluctuations could stop the flow of fuel, blowing out the flame.

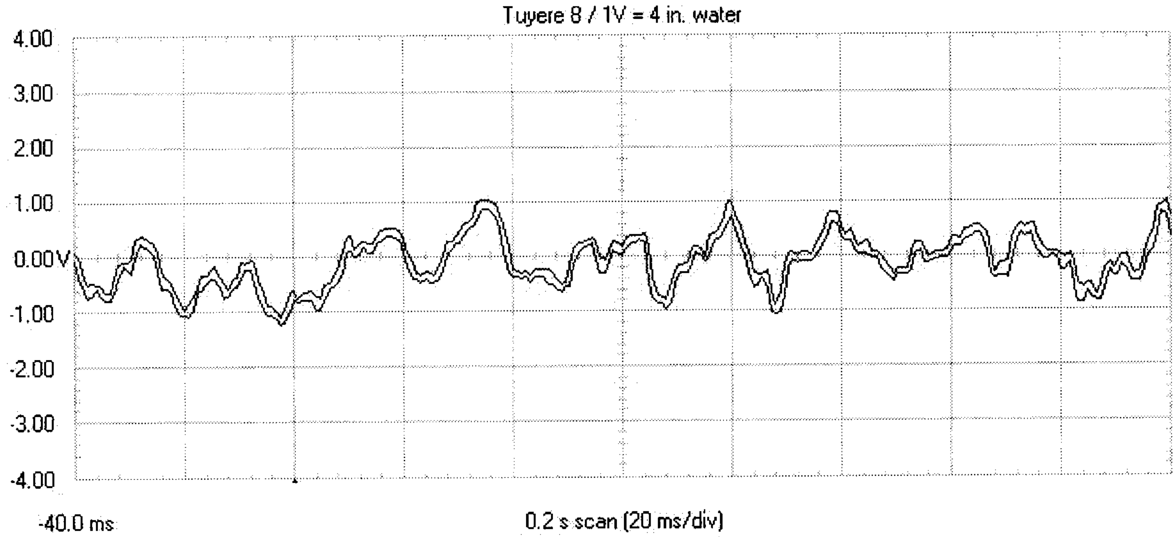
To verify and quantify this effect, pressure measurements were made in the no. 8 and no. 9 tuyere blowpipes on the no. 6 blast furnace at U.S. Steel Gary Works. Measurements were made with a Kistler Instruments 7261 high-impedence pressure transducer. This instrument can detect pressure fluctuations of 0.006 in. H_2O in a background pressure of 145 psig. The instrument piezoelectrical charge was detected by a Kistler Instruments 5010B dual mode amplifier and the output recorded on a PC through a Fluke 123 oscilloscope. The Fluke PC software includes a fast Fourier transform routine to identify the predominant flucutation frequencies. The transducer was connected to the static pressure tap in the blowpipe.

Typical output traces of pressure are shown in Figures 10-13. The trace shows amplifier output volts over a 0.2 second period. The sensitivity of the amplifier was set so that 1 volt represents 4 in. water column. Typical fluctuations are seen to be in the range of 2 to 4 in. H_2O within 40 ms. In each figure, the pressure trace is accompanied by a histogram showing the results of a fast Fourier transform (FFT) analysis of scan. The FFT analysis breaks the scan down into component sine waves of fixed amplitude and frequency.

Each of the FFT analyses shows frequency peaks at 10-25 Hz, 50-60 Hz, and 100-120 Hz. The natural resonant frequency of the blowpipe can be estimated from the equation

$$f = \frac{n}{2L}c$$

where f is the frequency (Hz), n is the wave number (1=fundamental, 2=first harmonic, etc.), L is the pipe length, and c is the speed of sound. Since this equation treats the blowpipe as open at both ends, the length is actually determined by the combined length of the downcomer, blowpipe, and tuyere, i.e., from the junction with the bustle pipe to the raceway discharge. This distance, from blueprints, is 18 ft (5.5 m). The speed of sound for the blast at 1800°F is 693 m/s (2,273 fps). This gives a fundamental frequency for the blowpipe of 63 Hz. The observed frequency peaks at 50-60 Hz are close to this calculated fundamental, and the 100-120 Hz peaks are close to the calculated first harmonic. The low frequency peaks are likely to be related to mixing and combustion stability in the raceway.



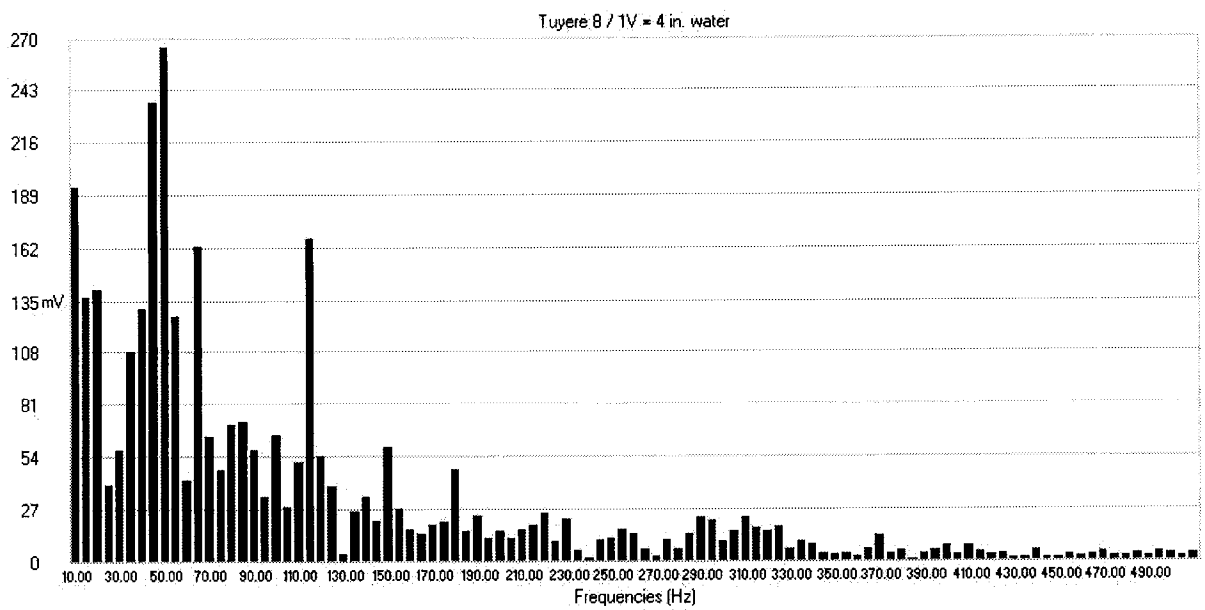


Figure 10 – Pressure trace and FFT profile from tuyere 8 scan

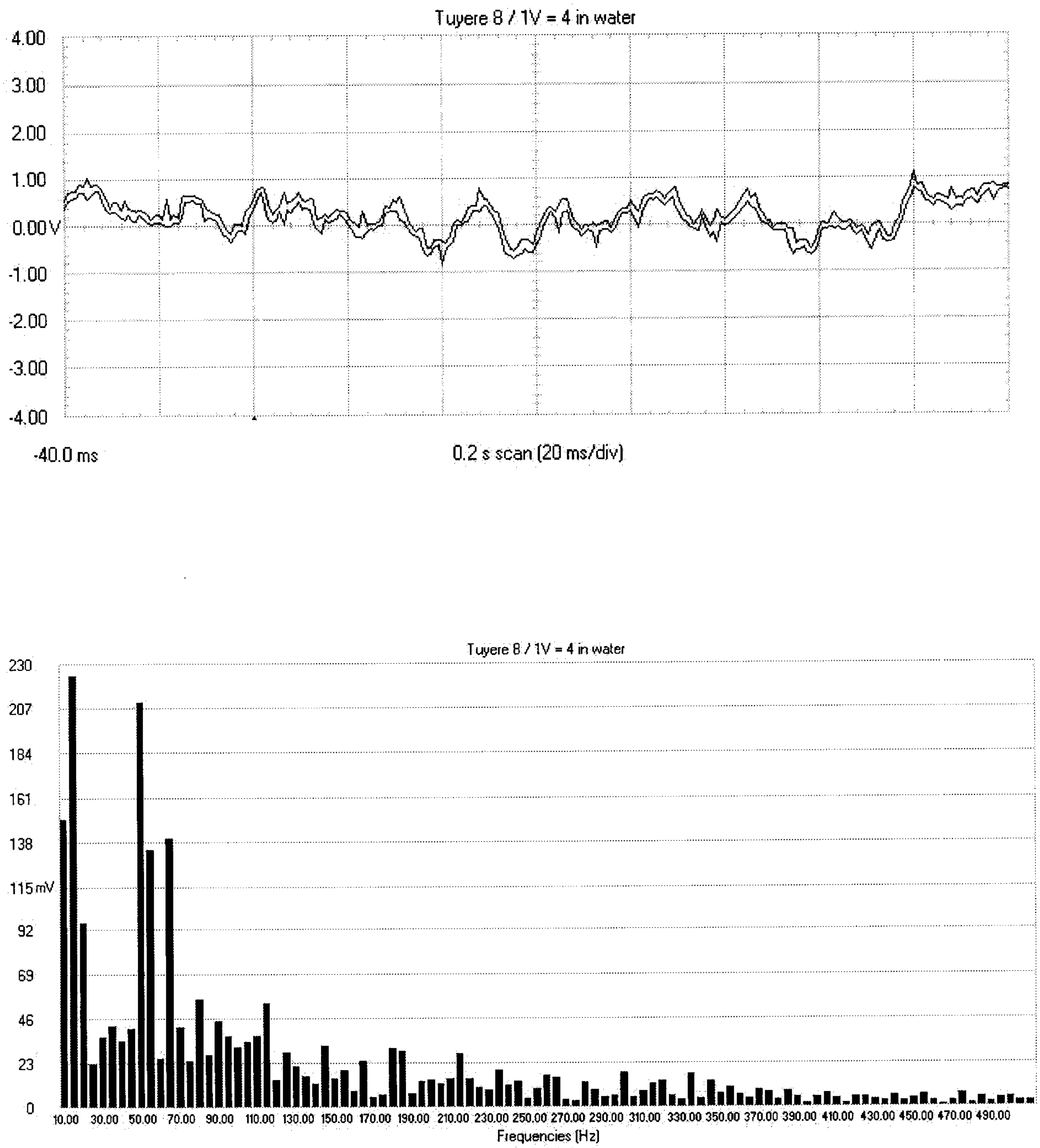
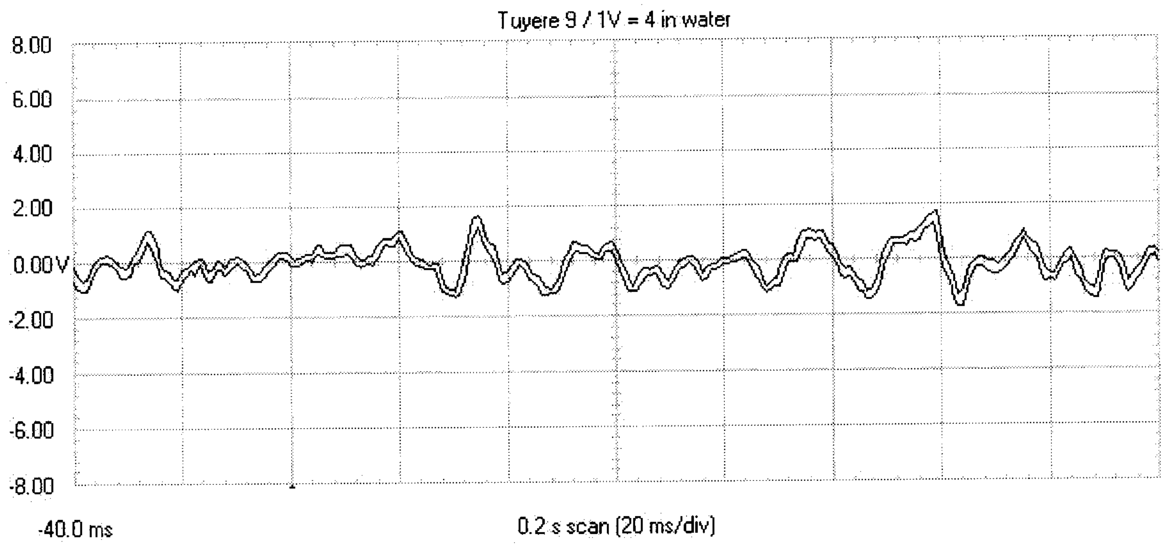


Figure 11 – Pressure trace and FFT profile from tuyere 8 scan



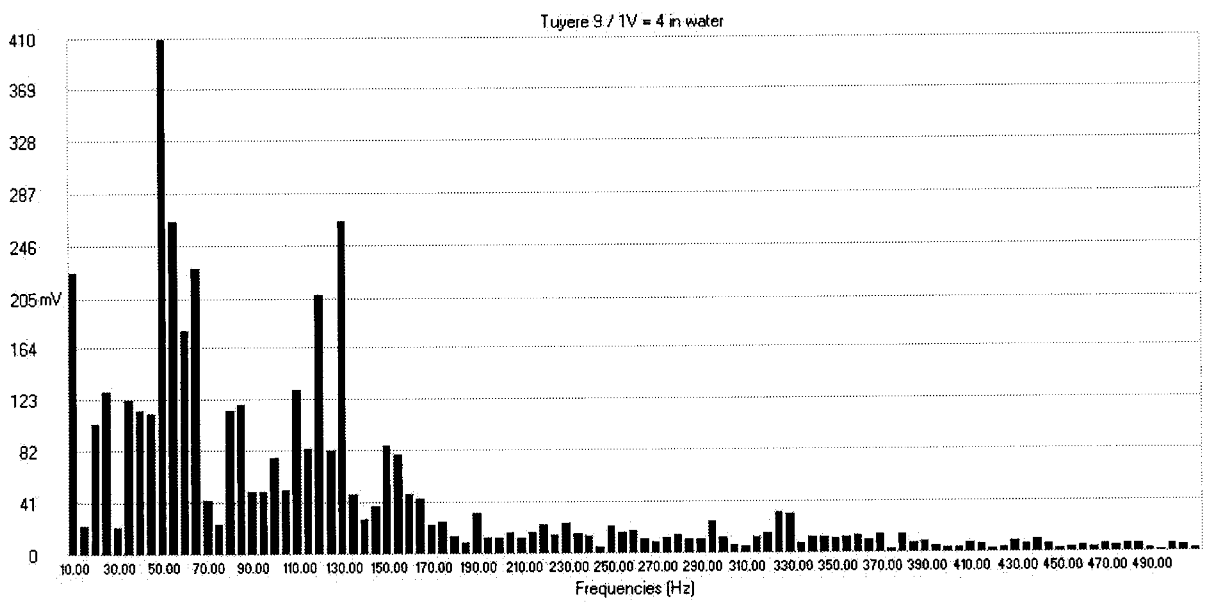
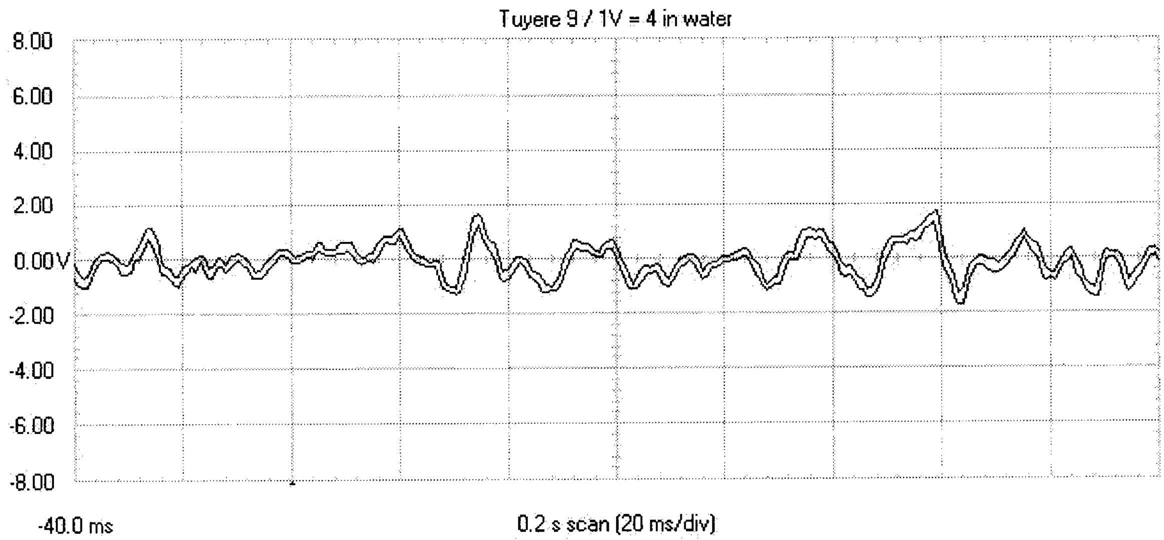


Figure 12 – Pressure trace and FFT profile from tuyere 9 scan



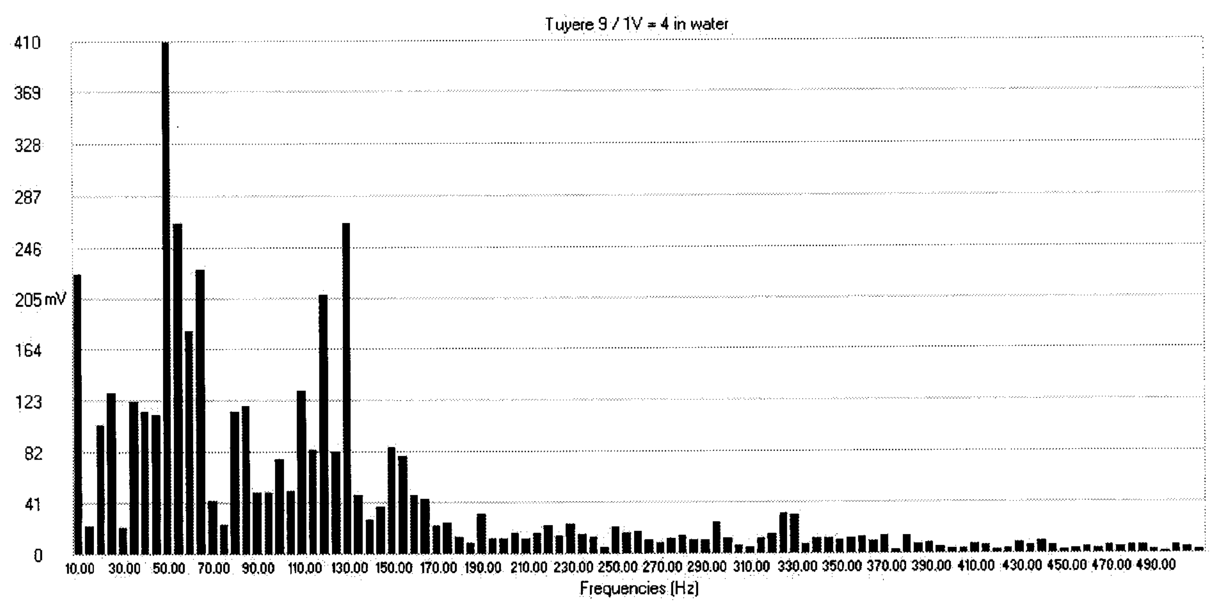


Figure 13 – Pressure trace and FFT profile from tuyere 9 scan

A calculation was made to estimate the ignition response of a hot oxygen lance to the pressure fluctuations described in the previous section. The piping upstream of the lance provides a relatively large reservoir of gas at fixed pressure. The flow control provides an essentially constant supply of natural gas to this reservoir during ignition. The discharge rate of natural gas from the lance was calculated assuming the outlet pressure varied by ± 4 in H_2O from the average outlet pressure at a frequency of 55 Hz, which is generally the strongest frequency found in Figures 10-13. The calculated discharge rate is shown in Figure 14. While the average discharge flow is at the desired rate, the instantaneous flow rate under these conditions occurs in spurts, with no flow, and hence no possibility of ignition, occurring nearly 70 percent of the time. If the flow control ramps up to operating conditions during one of these no-flow periods, it is expected that ignition would fail.

Higher natural gas flow rates can be maintained continuously against these pressure fluctuations. Figure 15 repeats this calculation, but for a significantly higher average natural gas flow. Under these conditions, the natural gas flow rate oscillates with the oscillating backpressure, but flow is continuous. Unfortunately, these higher flow rates will not allow flash back unless the flame speed is increased proportionately.

One method for increasing flame speed is to move the natural gas-oxygen ratio closer to stoichiometric. Additional bench tests were conducted where ignition was attempted at ambient discharge pressure under a variety of natural gas and oxygen flow rates. To successfully use the higher ignition flow rate of natural gas described in Figure 15, the oxygen-natural gas ratio must be lowered to a point where the resulting gas temperature is quite high, exceeding 4500°F, which could cause operating problems.

Additional tests were conducted on the U.S. Steel Gary no. 6 furnace with a modified ignition practice and lance. To mitigate concerns over the high gas temperature at ignition, the modified practice used a natural gas flow rate intermediate between those described by Figure 14 and Figure 15. As a further measure, the lance was also modified to shorten the combustion chamber by 1 inch to limit contact between the hot gas and the lance tip. Ignition reliability increased noticeably, and for the first time reliable internal ignition could be achieved simultaneously on both tuyeres.

EFFECT OF HOT OXYGEN ON COAL IGNITION

Although quantifying the effect of hot oxygen on coal combustion was not a primary goal of this project, some qualitative measurements were attempted. One of the most revealing measurements was the differential pressure between the tuyere upper assembly and the blowpipe.

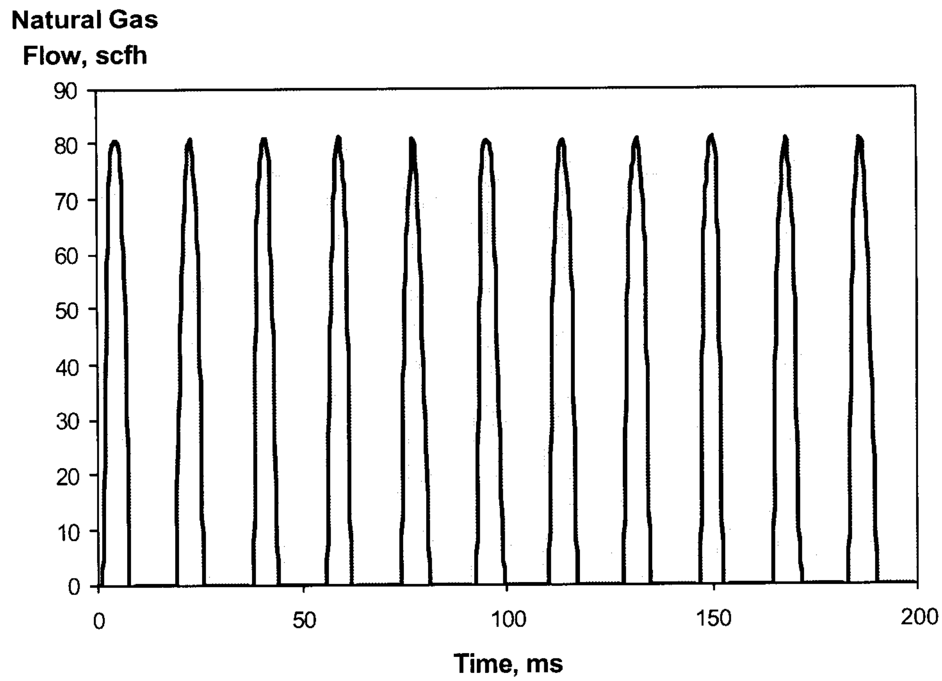


Figure 14 – Calculated natural gas flowrate for average ignition flow of 100% of original ignition setpoint with ± 4 in. H_2O outlet pressure oscillating at 55 Hz

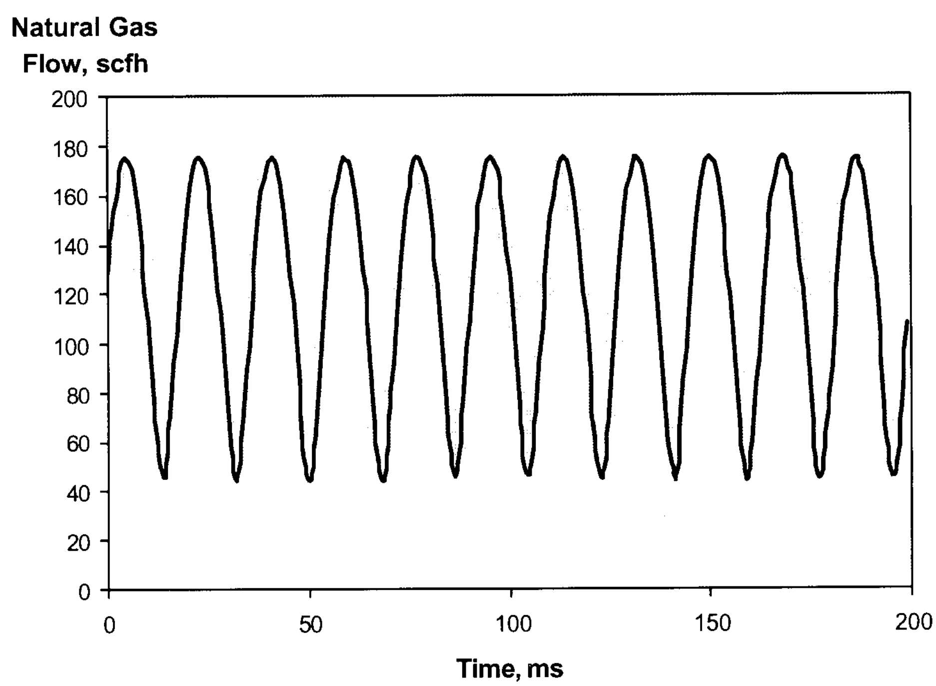


Figure 15 - Calculated natural gas flowrate for average ignition flow of 600% of original ignition setpoint with ± 4 in. H_2O outlet pressure oscillating at 55 Hz

Figure 16shows the distribution of observed differential pressures, comparing nitrogen purge, internal ignition, and external ignition. The nitrogen purge operation gives a tight distribution (standard deviation = 5 in. H_2O) with a mean value of 32 in. H_2O. For a blast temperature of 1830°F and supply pressure of 29 psig, this corresponds to a flow rate of 4265 scfm. This compares very well with the nominal blast rate per tuyere of 4500 scfm. The internal ignition data also fall in a tight distribution (s = 4 in. H_2O), but with a mean value of 20 in. H_2O. This corresponds to a flow rate of 3400 scfm, 20 percent less than observed with the nitrogen purge.

The external ignition data fall into a wide distribution. While these data can be described by a Gaussian curve (s = 19 in. H_2O), they can also be described as a linear combination of the nitrogen purge data and the internal ignition data. This is equivalent to saying the externally ignited oxygen reacts with the coal sporadically, sometimes giving the effect of internally ignited oxygen and sometimes the effect of the nitrogen purge.

The data suggest that enhanced coal combustion with internally ignited hot oxygen impedes the blast air flow into the tuyere. Assuming the raceway pressure remains unchanged, it also suggests that the pressure drop through the tuyere is higher, presumably from the increased flow of volatiles and/or combustion products. Ignoring any changes in gas properties or temperature, the increased flow of coal-generated gas would be 865 scfm, giving the same total flow rate from the tuyere. If the gas temperature increases, the coal-generated gas flow rate would be smaller. However, if the average molecular weight falls, the flow rate would be larger. It is likely that, in fact, these two effects both occur and largely offset each other.

For example, the specific heat of air at 1830°F is about 9 cal/mol-K. Increasing the temperature to 2000°F ($\Delta T \sim 100$ K) requires about 900 cal/mol. Assume the gas released from the coal is 67% hydrogen and 33% methane, and that heat is generated by combustion of hydrogen. Then, 57,800 cal are generated per mol H_2. This means 0.016 mol of hydrogen is burned per mol of air. Since the coal appears to release nearly 0.25 mol of gas per mol of air, the overall gas composition will still be essentially air plus low molecular weight volatiles at 2000°F.

Assuming the two effects do offset each other, the increased flow of coal-generated gas is roughly 865 scfm. Again assuming a composition of 67 H_2 – 33 CH_4, the average molecular weight would be 6.6, giving a volatiles mass flow rate of roughly 15 lb/min. Coal injection per tuyere is 45-50 lb/min. This suggests that internally ignited hot oxygen increases burnout in the tuyere by about 30%. Since externally ignited oxygen appears to act like internally ignited oxygen 1/3 of the time, the expected increase in burnout would be 10%. These very crude estimates compare well with the CANMET pilot data for this coal.

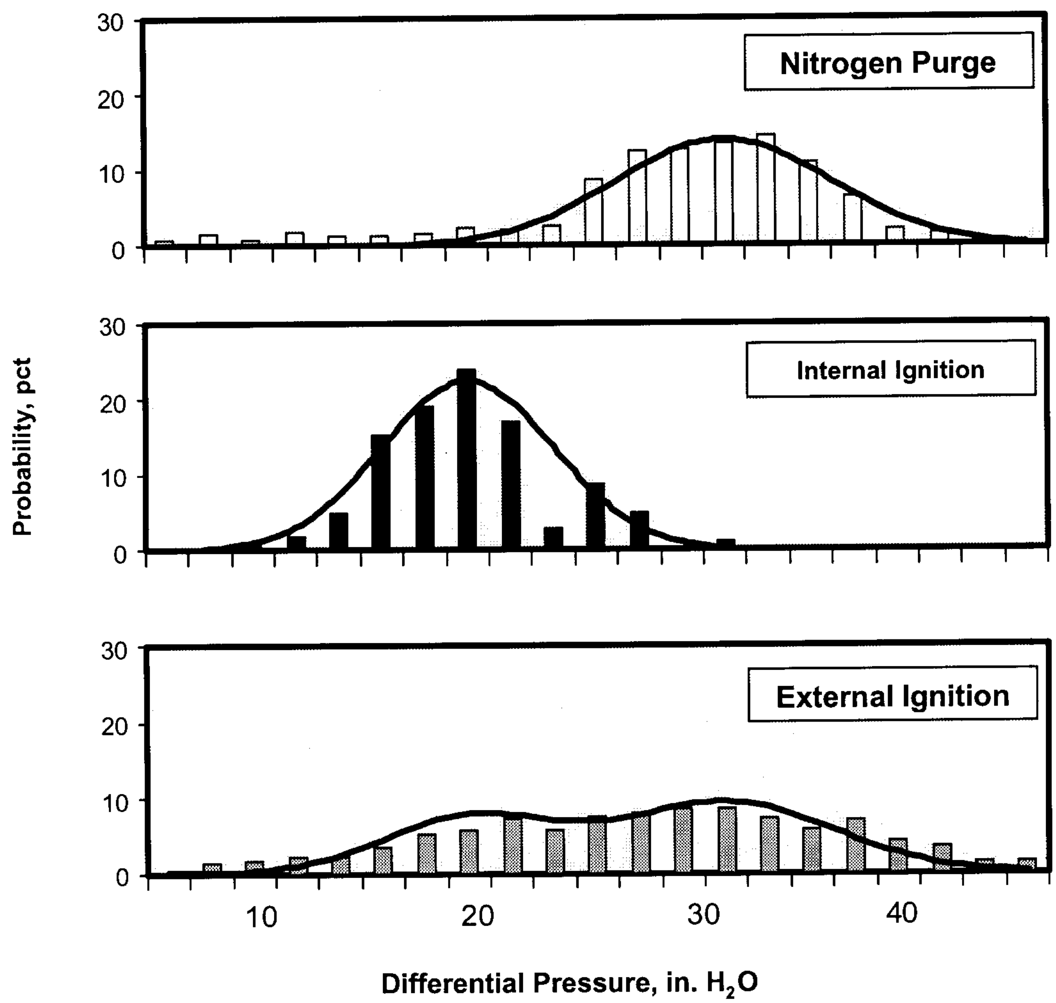


Figure 16 - Distribution of Differential Pressure for Nitrogen Purge, Internal Ignition, and External Ignition Modes

6. CONCLUSION

In this project, a commercial hot oxygen injection system has been developed, integrated with, and successfully demonstrated on the U.S. Steel Gary Works no. 6 blast furnace. All goals have been achieved. Heat loads have been measured on all furnace components affected by hot oxygen. The results reflect significantly higher levels of combustion in the blowpipe and tuyere with hot oxygen with acceptable increases in equipment temperature. Lance reliability has been improved by changes in fuel tip material and the lance ignition sequence, and reliable internal ignition of the lances using only the heat of the hot blast can now be routinely achieved. Qualitative observation of the hot oxygen-coal interaction suggests that improvements in coal combustion on the U.S. Steel Gary Works no. 6 blast furnace are in the same range observed in pilot tests at CANMET.

REFERENCES

1. "Blast Furnace Granular Coal Injection System Demonstration Project", Clean Coal Technology Topical Report no. 15, U.S. Department of Energy, Washington, November 1999.

2. J.A. Burgo, "The Manufacture of Pig Iron in the Blast Furnace", *The Making, Shaping, and Treating of Steel, 11th edition, Ironmaking Volume*, D.H. Wakelin, ed., AISE Steel Foundation, Pittsburgh, 1999, pp. 756-757.

3. J.C. Agarwal, et al., "Strategic Implications of and Results from High Rates of Natural Gas Injection into the Blast Furnace", *Blast Furnace Injection Symposium*, AISE, Pittsburgh, 1996, pp. 133-150.

4. "2001 Blast Furnace Roundup", *Iron & Steelmaker*, vol 28, no. 8, August 2001, pp. 72-77.

5. "Fukuyama Sets Record for Pulverized Coal Injection", *NKK News*, vol 38, no. 7, September 1998.

6. K. Nozawa, et al., "Practical Operation at an Ultra High Coal Injection Rate over 250 kg/thm in Kakogawa no. 1 Blast Furnace", pp. 87-90.

7. H. Ueno et al., "Operational Results for High Pulverized Coal Injection Rate at Kimitsu no. 3 Blast Furnace", *Proc. 54th Ironmaking Conference*, ISS, Warrendale PA, 1995, pp.

8. T. Akiyama and Y. Kajiwara, "Generation of fine [*sic*] in blast furnace at high rate PCI", *Advanced Pulverized Coal Injection Technology and Blast Furnace Operation*, K. Ishii, ed., Elsevier Science Ltd., Kidlington UK, 2000, pp. 169-216.

9. M.F. Riley, "Direct Tuyere Injection of Oxygen for Enhanced Coal Combustion", *Blast Furnace Injection Symposium*, AISE, Pittsburgh, 1996, pp. 119-131.

10. J.E. Anderson, "Thermal Nozzle Combustion Method", *U.S. Patent 5,266,024*, November 30, 1993.

11. M.F. Riley, "Blast Furnace Hot Oxygen Injection System", *U.S. Patent 6,090,182*, July 18, 2000.

12. M.F. Riley, T.J. Strayer, and Y. Zhao, "Effect of Direct Oxygen Injection on Combustion of Injected Coal, *Second International Congress of the Science and Technology of Ironmaking*, ISS, Warrendale PA, 1998, pp. 683-688.

13. P.H. Oosthuizen and W.E. Carscallen, *Compressible Fluid Flow*, McGraw-Hill, New York, 1997, p. 32.

14. D.C. Ailor, "Principal Environmental Issues Facing the U.S. Coke Industry in 1999 and Beyond", Meeting of the International Tar Association, Colorado Springs, CO, May 4, 1999.

15. E.M. Levin, C.R. Robbins, and H.F. McMurdie, *Phase Diagrams for Ceramists*, American Ceramic Society, Columbus OH, 1964, p. 38.

16. *Metals Handbook® Desk Edition*, J.R. Davis, ed., ASM International, Materials Park OH, 1998, p. 68,

17. *Heat-Resistant Materials*, J.R. Davis, ed., ASM International, Materials Park OH, 1997, pp. 32-42.

18. J. Chomiak, *Combustion: A Study in Theory, Fact and Application*, Gordon and Breach Science Publishers, New York, 1990, pp. 273-294.