DOE/ID/13331

Dilute Oxygen Combustion

Phase 3 Report

M. F. Riley

May 2000

Work Performed Under Contract No. DE-FC07-95ID13331

For
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC

By
Praxair, Inc.
Tarrytown, NY

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FOR:
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
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BY:
Praxair, Inc.
Applications Research and Development
Tarrytown, NY
Michael F. Riley, Ph.D., Principal Investigator

ACKNOWLEDGEMENTS

This work was conducted with the financial support of the U.S. Department of Energy, Office of Industrial Technologies, under Cooperative Agreement DE-FC07-95ID13331. In addition to this financial support, technical guidance was provided under the Cooperative Agreement by Joseph Keller, Lockheed Martin Idaho Technologies Co., and Robert Gemmer, Walter Mings, and Gideon Varga, U.S. Department of Energy.

Funding was also provided by Praxair, Inc. and by Auburn Steel Co., Inc. The outstanding efforts and excellent cooperation of the engineers, technicians, operators, and managers of each company were instrumental in the successful implementation of this technology. Sincere appreciation is extended to Harry Ryan and Craig Abbot, Praxair, Inc., and to Dick Farrar, James Mach, John Deacon, Kevin Mahoney, Walter Senenko, and Dan Czubat, Auburn Steel Co., Inc.

Thanks are extended to Charles Jankowsi, Pittsburgh Industrial Furnace Co., who supervised the turnkey installation, and to each of the subcontractors. Thanks are also offered to Lawrence Rich, North American Manufacturing Co., for his role in identifying and qualifying Auburn Steel as a host site.

The CS/PLIF water model studies were conducted by Mr. Choon Lee and supervised by Prof. Werner J.A. Dahm, University of Michigan, Laboratory for Turbulence & Combustion. Their talents and persistence produced several valuable insights into the commercial operation of this technology.

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ABSTRACT

Dilute Oxygen Combustion (DOC) burners have been successfully installed and operated in the reheat furnace at Auburn Steel Co., Inc., Auburn, NY, under Phase 3 of the Dilute Oxygen Combustion project. Two new preheat zones were created employing a total of eight 6.5 MMBtu/hr capacity burners. The preheat zones provide a 30 percent increase in maximum furnace production rate, from 75 tph to 100 tph. The fuel rate is essentially unchanged, with the fuel savings expected from oxy-fuel combustion being offset by higher flue gas temperatures. When allowance is made for the high nitrogen level and high gas phase temperature in the furnace, measured NO_x emissions are in line with laboratory data on DOC burners developed in Phase 1 of the project. Burner performance has been good, and there have been no operating or maintenance problems. The DOC system continues to be used as part of Auburn Steel's standard reheat furnace practice.

High gas phase temperature is a result of the high firing density needed to achieve high production rates, and little opportunity exists for improvement in that area. However, fuel and NO_x performance can be improved by further conversion of furnace zones to DOC burners, which will lower furnace nitrogen levels. Major obstacles are cost and concern about increased formation of oxide scale on the steel. Oxide scale formation may be enhanced by exposure of the steel to higher concentrations of oxidizing gas components (primarily products of combustion) in the higher temperature zones of the furnace. Phase 4 of the DOC project will examine the rate of oxide scale formation in these higher temperature zones and develop countermeasures that will allow DOC burners to be used successfully in these furnace zones.

1. INTRODUCTION

Controlling the generation of nitrogen oxides (NO_x) in industrial combustion processes is essential to mitigating acid rain, ground level ozone, and photochemical smog.[1,2] The primary mechanism for NO_x formation is the Zeldovich, or "thermal NO_x" mechanism, which is very sensitive to peak flame temperature, nitrogen level, and excess oxygen level.[1]

Dilute Oxygen Combustion (DOC) burners, patented by Praxair, Inc., provide very low levels of NO_x by controlling each of these sensitive parameters.[3,4] DOC burners inject fuel and oxygen *separately* into a furnace as high-velocity jets. As shown schematically in Figure 1-1, with DOC burners fuel and oxygen do not react directly. Instead, the high-velocity oxygen jet mixes rapidly into the furnace gas, and the fuel jet entrains and reacts with this high-temperature, dilute-oxygen furnace gas. This dilution leads to low peak flame temperatures. In addition, since DOC burners use oxygen rather than air for combustion, there is no nitrogen added to the combustion process. Lastly, the flow controls employed with oxy-fuel systems offer close control of excess oxygen. This combination of temperature control, nitrogen control, and excess oxygen control leads to very low NO_x generation by DOC burners.

In Phase 1 and Phase 2 of this project, laboratory-scale and commercial-scale DOC burners operated under controlled conditions were shown to produce NO_x levels as low as 0.009 lb/MMBtu at 2300°F in low-nitrogen furnace atmospheres (equivalent to 0.8 ppm from an air burner system at 3% oxygen, dry basis) and 0.03 lb/MMBtu (30 ppm air equivalent) at 2300°F with 77% nitrogen in the furnace atmosphere.[5] The goal of Phase 3 was to demonstrate the capabilities of DOC burners in a commercial application.

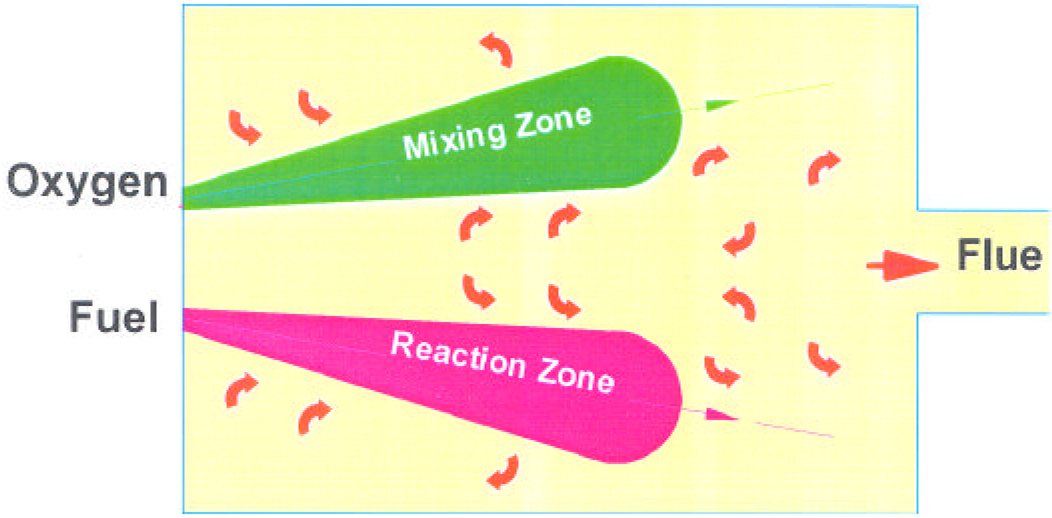

Figure 1-1 – Schematic of Dilute Oxygen Combustion (DOC) Concept

The ability to produce low NO_x even with high furnace nitrogen levels makes DOC burners attractive for partial conversion of existing air-burner furnaces. This is particularly important for steel reheating applications. In reheating steel for hot rolling, it is important to control the growth of iron oxides (scale) on the surface of the steel.[6,7] Steelmakers have traditionally been reluctant to use oxy-fuel burners in the highest temperature zones of their furnaces because of concern over excessive scale formation related to higher concentrations of species such as CO_2 and H_2O which are oxidizing to steel. Thus, retrofits in low-temperature furnace zones are an important potential market for DOC burners.

Several steel companies were identified as potential host sites for this commercial demonstration, and Auburn Steel Co., Inc. was selected. Auburn Steel's corporate strategy called for increasing peak productivity from their bar mill reheat furnace from 75 tons per hour (tph) to 100 tph. Additional air-burner capacity could not be installed without major changes to the flue gas system, and the option of a preheat furnace was too costly. The addition of an oxy-fuel preheat zone to boost productivity was the most cost-effective option since the small flue gas volume produced with oxy-fuel could be readily handled by the existing flue gas system, and the capital cost of a new zone was relatively low. Since Auburn Steel had recently installed low-NO_x air burners, maintaining the low-NO_x performance of the furnace was also part of Auburn Steel's plan. These factors made Auburn Steel an outstanding host site candidate.

Accordingly, the Phase 3 commercial demonstration was conducted at Auburn Steel with these goals:

- Demonstrate that DOC burners are robust for an industrial environment.
- Increase production on Auburn Steel's reheat furnace from 75 tph to 100 tph.
- Maintain or decrease NO_x emission levels while increasing production rate.

Auburn Steel contracted Pittsburgh Industrial Furnace Co. (PIFCOM), Pittsburgh, PA, as the turnkey contractor for the DOC system. The main subcontractors were:

- North American Manufacturing Co., Cleveland, OH (flow control valve skid and burner hardware),
- MicroControl Systems, McMurray, PA (control software),
- Burns Brothers Contractors, Syracuse, NY (piping and electrical), and
- Gaspare Amodei Construction Co., Auburn, NY (structural and excavation).

In addition, JHS Consulting, Glenwillard, PA, was contracted to perform heating audits using instrumented billets to determine furnace heating performance; and Galson Measurements, E. Syracuse, NY was contracted to perform stack emissions testing according to EPA protocols (40 CFR 60).

2. AUBURN STEEL CO., INC. – FACILITY DESCRIPTION

Overview

Auburn Steel Co., Inc., Auburn, NY, is a steel mini-mill located in the Finger Lakes region, about 30 miles south of Syracuse. Auburn Steel recycles steel scrap to produce 365,000 finished tons per year of round, square, and flat bar, angles, channels, and reinforcing bar.[8]

The Auburn Steel plant is equipped with a 16-ft diameter electric arc furnace (EAF) with a 40 MVA transformer. Molten steel from the EAF is continuously cast through a 3-strand Concast caster into 4½", 5", and 6" square billets. These billets are heated to rolling temperature in a modified Salem continuous pusher reheat furnace and then hot-rolled into the final products on an 18-stand in-line continuous bar mill.[8]

Reheat Furnace

The layout of the reheat furnace before addition of the DOC burners is shown in Figure 2-1. Steel is heated in four zones as detailed in Table 2-l. Primary heating is provided by top and bottom heating zones, and soaking (temperature equalization) is accomplished in an intermediate zone and a soak zone. The flue is positioned at the charge end of the furnace providing counter-current flow of steel and furnace gas. An unfired entry zone exploits this counter-current flow to extract additional heat from the furnace gas, lowering the flue gas temperature and improving furnace fuel economy. The furnace inside width is 15 ft, accommodating billets up to 14 ft in length.

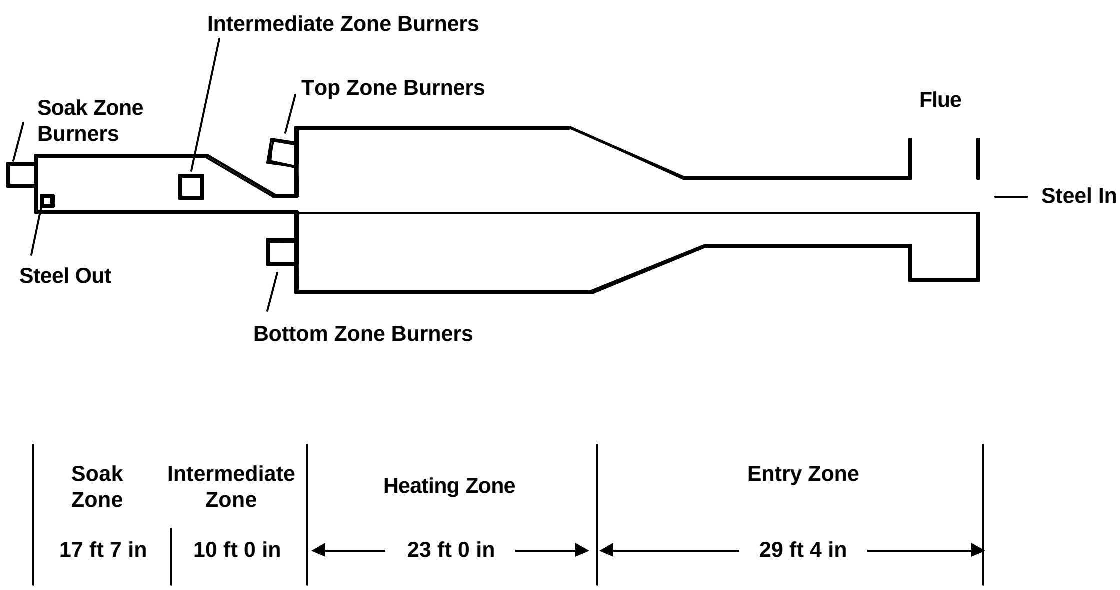

Figure 2-1 – Schematic of Auburn Steel Reheat Furnace

Table 2-I – Air-Burner Zones in Auburn Steel Reheat Furnace

Zone	Number of Burners	Total Input, MMBtu/hr
Top Heat	4	53.4
Bottom Heat	3	47.0
Intermediate	2	11.0
Soak	5	11.5
Total		122.9

Air-Fuel Burners

The burners in all four zones are North American LNI (Low NOx Injector) burners. This burner design, licensed from Tokyo Gas Co., Ltd.,[9] is shown in Figure 2-2.[10] The LNI burner provides a central jet of combustion air, surrounded by high-velocity fuel jets. The fuel jets entrain furnace gas before mixing and reacting with the combustion air. Dilution by the furnace gas lowers peak flame temperatures and minimizes NOx generation. North American Manufacturing Co. literature suggests LNI burner NO_x levels should be about 100 ppm with 900°F air preheat at 3% (dry) excess oxygen (0.12 lb/MMBtu).[11] Combustion air in the intermediate zone is preheated by a regenerator built into the burner (North American TwinBed™ II system). Combustion air for the other zones is preheated by a flue gas recuperator.

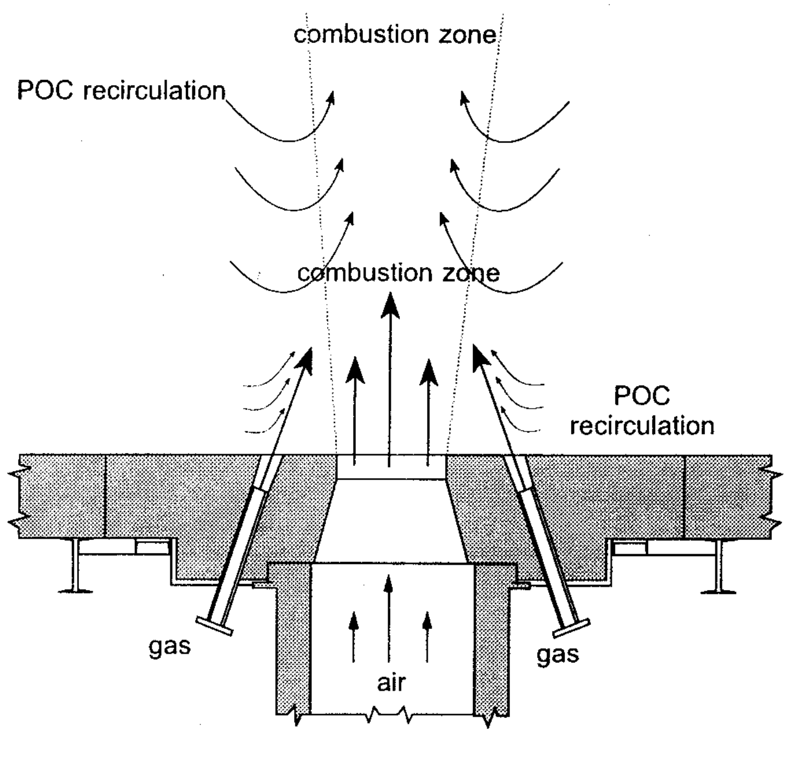

Figure 2-2 – Schematic of Low NOx Injector (LNI)[10]
"POC" means Products of Combustion (furnace gas)

Table 2-II - Composition and Heating Value of Natural Gas

Component	Wet Analysis
Methane	92.899
Ethane	2.939
Propane	0.257
i-Butane	0.033
n-Butane	0.039
Higher Hydrocarbons (C_6 +)	0.024
Moisture	1.740
Nitrogen	1.447
Carbon Dioxide	0.622
Molar Mass	16.957
Heating Value	1005.8 Btu/cf

Fuel Supply

The fuel in the Auburn Steel reheat furnace is natural gas supplied by New York State Electric and Gas. A typical analysis and heating value is given in Table 2-II.

Oxygen Supply

Praxair, Inc. supplies Auburn Steel with oxygen from an on-site air separation facility. The primary use of oxygen at Auburn Steel is to assist melting in the EAF. At the start of the project, the air separation facility consisted of two vacuum pressure swing adsorption (VPSA) units with an oxygen production capacity of 90 tons/day (tpd), or 90,000 standard cubic feet / hour (scfh). Oxygen compressors provide supply pressures up to 230 psig. Two oxygen receivers provide 4000 cubic feet of buffer storage to handle the periodic demands of the steel plant while maintaining constant operation of the air separation facility. During extended shutdowns, the VPSA units can be shut down and restarted to match the requirements of the steel plant. VPSA oxygen purity ranges from 90% to 93%.

While the on-line reliability of the VPSA units is greater than 99%, to ensure uninterrupted oxygen supply to Auburn Steel the air separation facility is backed up by a liquid oxygen supply system. The liquid oxygen system consists of two vacuum-insulated tanks with 35,000 gallons of capacity (approximately 4 million scf). Ambient temperature vaporizers convert the liquid to gaseous oxygen on demand, supplying peak flows up to 250,000 scfh. The purity of the vaporized liquid is 99.5%.

To facilitate testing of the DOC system, oxygen was supplied to the reheat furnace from the liquid oxygen system. This minimized the capital cost and lead time needed for testing the DOC system. The EAF continued to use the oxygen supplied by the VPSA units. The only drawback to this strategy was that if the

VPSA units were to go off-line, the EAF would have priority access to the liquid supply, and the DOC system would have to be shutdown. In fact, no shutdowns of this type were required.

Near the conclusion of the project, after the DOC system and its benefits were demonstrated, a third VPSA unit was installed at Auburn Steel, raising the on-site oxygen production capacity to 139 tpd (139,000 scfh). This provided lower-cost on-site oxygen for essentially all of Auburn Steels needs in the EAF and at the reheat furnace. The capacity of the liquid backup system was upgraded as well to provide complete backup of Auburn Steel's oxygen requirements.

3. ENGINEERING DESIGN ANALYSIS

To increase the production rate of the Auburn Steel reheat furnace to 100 tph, part of the entry zone had to be converted into two new side-wall-fired oxy-fuel preheat zones. In examining the basic engineering questions of number, location, and firing capacity for the burners in these zones, several other concerns were raised:

- The top and bottom entry zones of the Auburn Steel reheat furnace are only 3 ft high and 15 ft wide, raising the potential for interaction or impingement of the DOC burner flame with the furnace walls.
- In the small cross-section of the new preheat zone, the furnace gas from the heat and soak zones produces a significant cross-flow velocity for the DOC burner, raising the potential for unexpected interactions with the DOC burner flames.
- The preheat zone will place burners much closer to the flue than the original furnace design, raising the potential for unburned hydrocarbons in the flue.

The engineering design analysis for the Auburn Steel reheat furnace consisted of three tasks:

- determining the required firing rate through furnace heating models, and the number and location of the DOC burners;
- estimating the effect of DOC flame impingement in a laboratory furnace;
- simulating the behavior of DOC flames in the Auburn Steel reheat furnace in a water model using a chemically-sensitive planar laser-induced fluorescence (CS/PLIF) technique.

Firing Rate, Number and Location of Burners

The required firing rate was estimated separately by PIFCOM and Praxair, using furnace heating models developed by each company.

The Praxair model, CONFURNT, is a FORTRAN program that simulates continuous furnace performance under transient operating conditions. In the model, the furnace is divided into one-foot long segments. In each segment, heat transfer rates are calculated using a speckled, two-sink radiation sub-model in which the combustion gases are the heat source, and the furnace refractory and the steel are separate heat sinks which also exchange heat with each other by radiation.[12] The time-temperature history of the steel is calculated through a superposition technique which combines the results of each segment. The superposition technique avoids numerical integration of the differential equations and is much more efficient in computation compared to other methods.

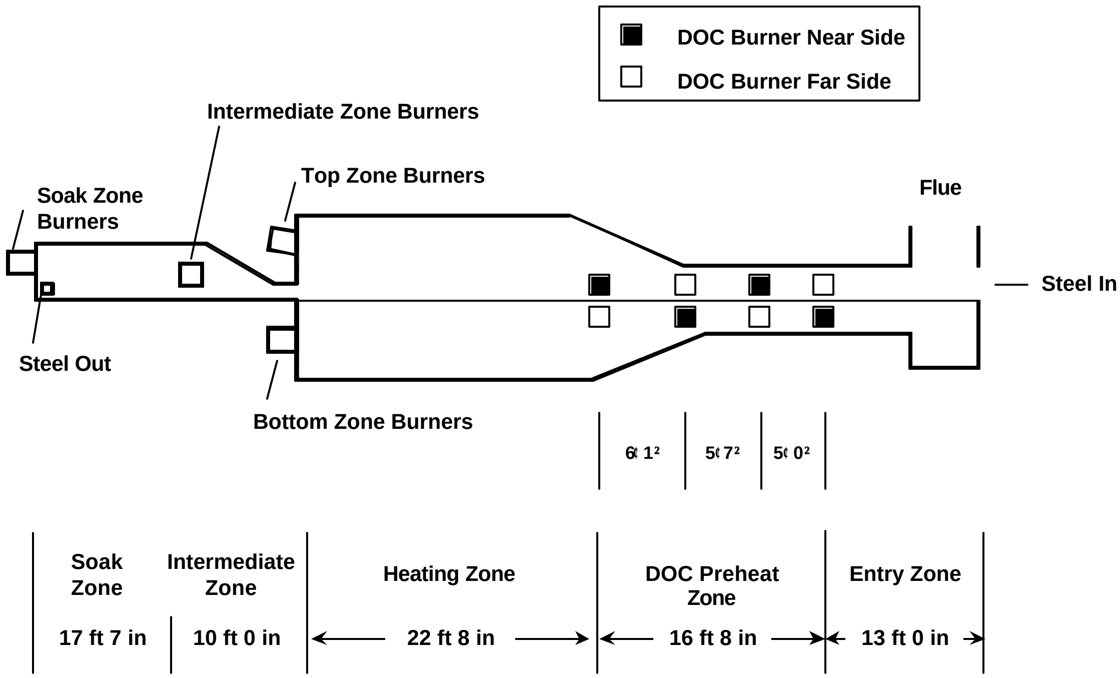

Figure 3-1 – DOC Burner Location

CONFURNT predicted that the oxy-fuel zones would require 47 MMBtu/hr to produce 100 tph through the Auburn Steel reheat furnace. The PIFCOM model predicted that 56 MMBtu/hr would be required. Since the project plan called for scaling up the DOC burner to the range of 5 – 7 MMBtu/hr, the Auburn Steel system was designed for a total of 8 burners, four each in top and bottom preheat zones, each with a nominal firing rate of 6.5 MMBtu/hr.

Since the flame length was expected to be of the same order as the furnace width, offset burner locations were selected. After consulting drawings of the Auburn Steel reheat furnace and a site survey, burner locations shown in Figure 3-1 were selected.

Impingement Tests

The effect of an impinging DOC flame on furnace refractory temperatures was tested in the 3 ft diameter, 10½ ft long laboratory furnace used in Phase 1. Water-cooled oxygen and natural gas lances were inserted through the side wall of the furnace and thermocouples were mounted in the opposite wall to monitor wall temperatures. Water cooling of the lances allowed the distance between the burner and the opposite wall to be easily varied. The furnace diameter of 3 ft represented a 1/5 scale of the Auburn Steel reheat furnace width. Since flame length varies with the square root of firing rate, the burner was scaled to 1/25 of the commercial burner, or 0.3 MMBtu/hr. Fuel velocity was 1150 ft/s and oxygen velocity was 780 ft/s.

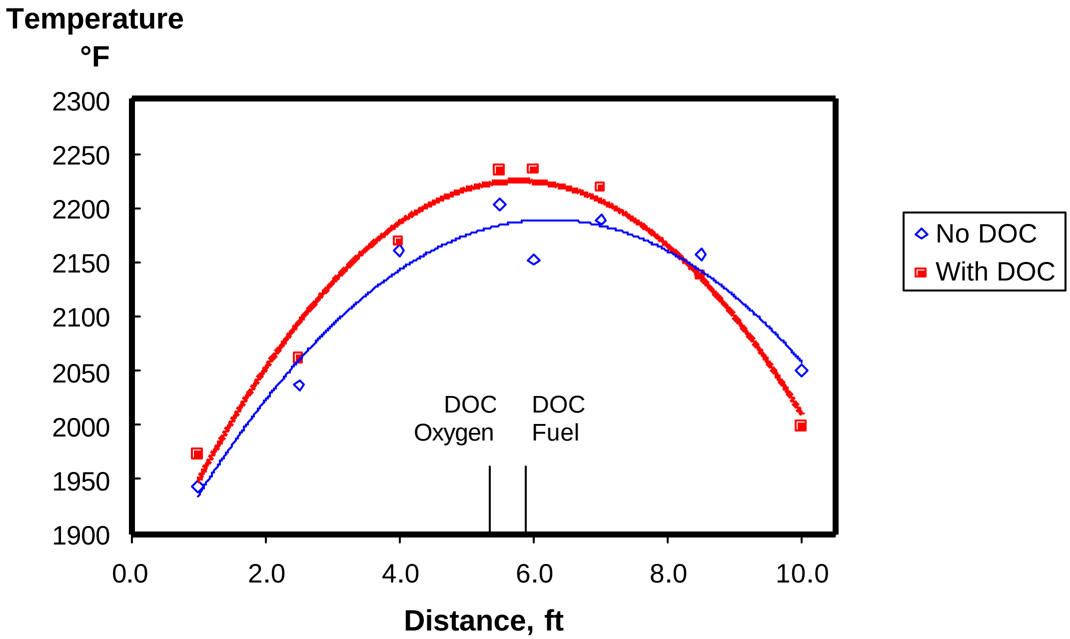

Figure 3-2 - DOC Oxygen and Fuel Injection Sites and Furnace Temperature Profile for DOC Laboratory Flame Impingement Test

The furnace was preheated to operating temperature by a 0.75 MMBtu/hr burner located in the furnace end wall. Fuel and oxygen were then injected through the lances, and the resulting furnace temperature profile was compared against the baseline profile established by the preheat burner. Figure 3-2 shows the laboratory furnace longitudinal temperature profile and the effect of the model DOC burner operating at 3 ft from the opposite wall. It is apparent that the DOC burner creates a higher wall temperature opposite the burner, but the magnitude of the increase is modest. Varying the distance between the burner and the opposite wall showed peak wall temperatures (indicating the apparent flame length) occurred with the burner 2½ ft from the opposite wall. The peak was approximately 50°F higher than the temperature observed with a 3 ft separation.

These tests indicated that any opposite wall heating from the DOC burners would be manageable.

CS/PLIF Water Model Tests

The chemically-sensitive planar laser induced fluorescence (CS/PLIF) technique is a non-invasive, quantitative method for visualizing flow, mixing, and chemical reactions in complex geometries such as those in a commercial steel reheat furnace. The technique is relatively simple, yet provides remarkable quantitative results.[13,14]

A geometrically-scaled, clear Lucite model of the furnace was constructed with hose connections for burners and the flue. Burner ports were simulated with drilled brass plugs. A dye tracer (disodium fluorescein) was homogeneously mixed with an aqueous base solution (sodium hydroxide) to simulate the fuel. An aqueous acid solution (sulfuric acid) containing no dye simulated the oxidant. The relative pH levels of the base and acid are chosen to yield a neutral pH when the two solutions are mixed in the fuel-oxidant stoichiometric ratio. The absolute pH levels are chosen so that the transition from fluorescing to non-fluorescing is sharp. Passing a thin (200 µm) 5 W Ar^{++} laser sheet (514 nm wavelength) through the model produces a dynamic, tomographic visualization of unburned fuel (bright fluorescing), unreacted oxidant (dark), and combustion products (intermediate). The visualizations provide unique views of a variety of jet-jet, jet-wall, and jet recirculation patterns.

The results are effective simulations of the flow, mixing, and overall reaction processes because of the high Reynolds numbers in both the commercial furnace and the model, and because chemical similarity is achieved in the simulations. At high Reynolds numbers, all flow and mixing processes are inertially-dominated and diffusive processes are not controlling. In addition, at these highly turbulent conditions, dynamic similarity is achieved without precise matching of the Reynolds numbers. Chemical similarity ensures that flame lengths and the related reaction quantities are accurately simulated. The effects of heat release are relatively unimportant in DOC systems since peak flame temperatures are close to furnace operating temperatures.

CS/PLIF experts at the Laboratory for Turbulence & Combustion at the University of Michigan, Ann Arbor, MI used this technique to predict DOC burner performance in the Auburn Steel reheat furnace. The 1:24 scale Lucite model of the Auburn Steel reheat furnace is shown in Figure 3-3. At this scale, the orifices for the simulated DOC burners would be impractically small, so scaling for these burners was based on momentum flux rather than geometric similarity. For simplicity, only the heat and entry zones were included in the model. The furnace gas volume from the heat zone burners was increased slightly to provide the flow that otherwise would come from the intermediate and soak zone burners.

Figure 3-4 shows representative data from tests with all DOC burners operating at 6.5 MMBtu/hr. These photos show a plan view of the furnace near the flue. The laser sheet is directed through the plane of the top preheat zone burners. For clarity, dye was added only to the top preheat zone burner nearest the flue. The differences among the photos in Figure 3-4 give some indication of the dynamic nature of the flow. The effect of the combustion products of the air burners acting in cross-flow to the DOC burners is obvious. The flame from the DOC burner is strongly deflected toward the flue. While this eliminated any concern about flame impingement on the opposite wall, it did heighten concern about unburned fuel reaching the flue. Passing the laser sheet through the flue revealed bright flashes, confirming that the flue gas did in fact contain unburned fuel.

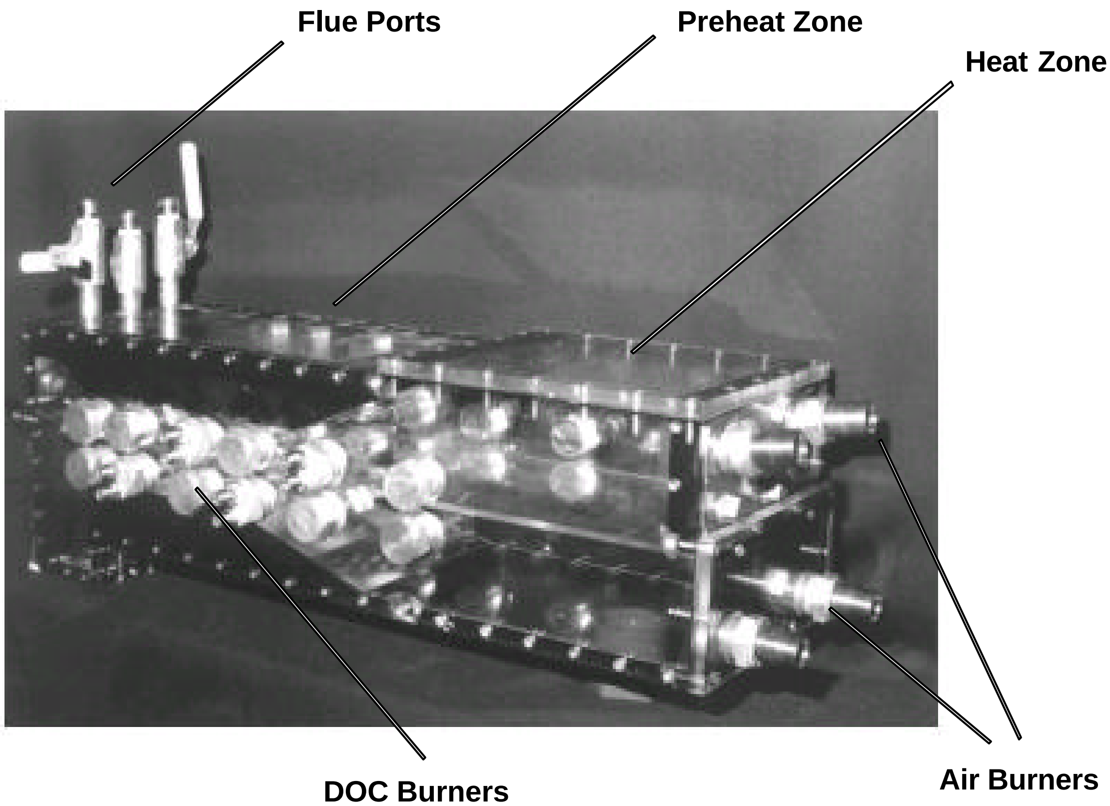

Figure 3-3 - Photograph of Auburn Steel Reheat Furnace CS/PLIF Model.

Figure 3-5 shows similar results with all DOC burners operating at 6.5 MMBtu/hr, but with dye added only for the bottom preheat zone burner nearest the flue. Cross-flow of the air burner combustion products has much less effect in the bottom zone. Apparently, combustion products migrate from the bottom zone to the top zone continuously along the preheat zone, rather than suddenly near the flue.

To eliminate the potential for unburned fuel reaching the flue, tests were conducted with preheat zone burner firing rates biased toward the six burners farthest from the flue. The firing rate for these burners was increased to 7 MMBtu/hr and the firing rate for the burners nearest the flue was decreased to 4 MMBtu/hr. The results for this scheme are shown in Figure 3-6. In this figure, dye has been added to both the top and bottom preheat zone burners nearest the flue, and the laser sheet is through the plane of the top preheat zone burners. It is apparent that the fuel is now all combusted within the furnace space; passing the laser sheet through the flue confirms that there is no unburned fuel in the flue gas.

Based on these results, the biased firing scheme was employed on the Auburn Steel reheat furnace.

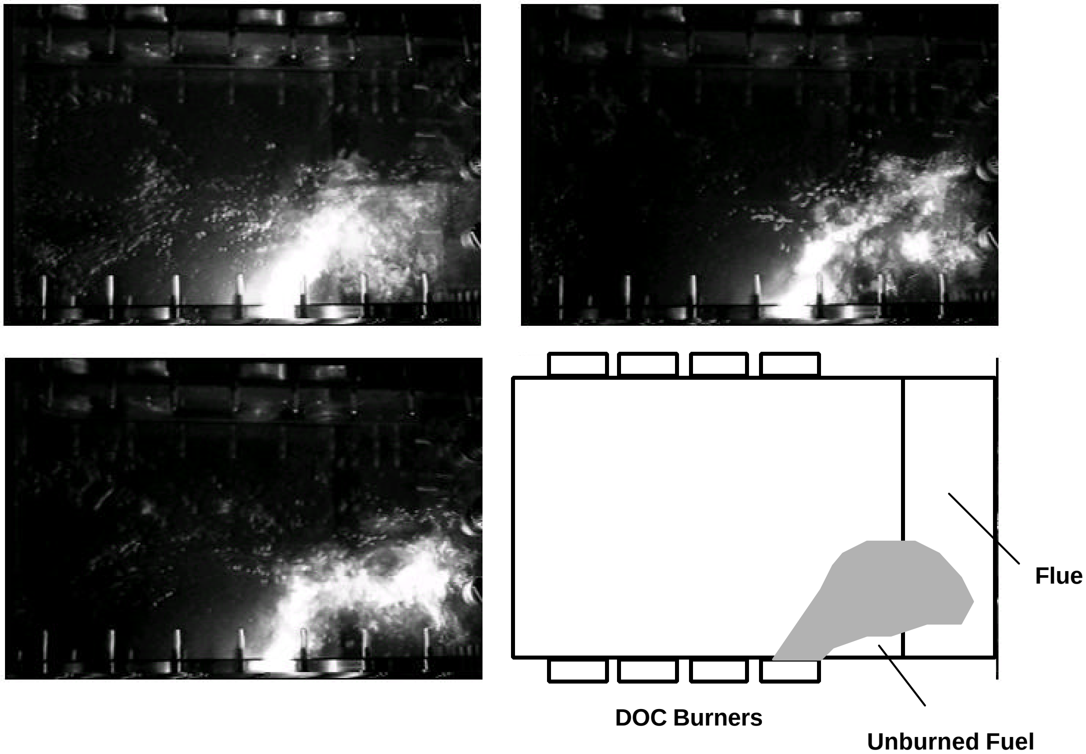

Figure 3-4 - Plan View of CS/PLIF Model Top Preheat and Entry Zones with all DOC Burners at 6.5 MMBtu/hr

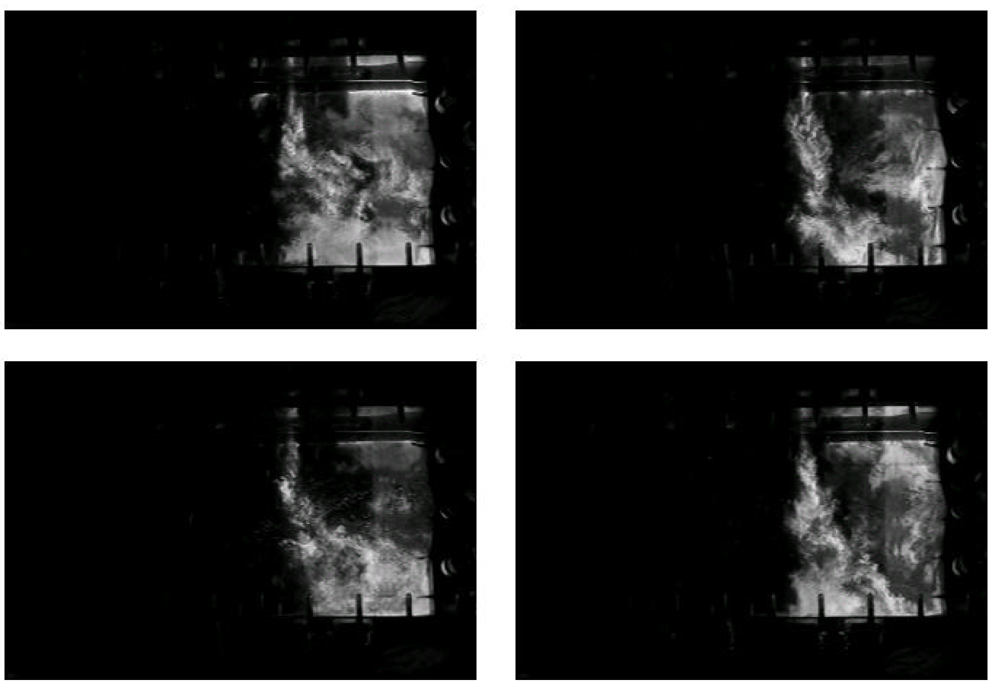

Figure 3-5 Plan View of CS/PLIF Model Bottom Preheat and Entry Zones with all DOC Burners at 6.5 MMBtu/hr

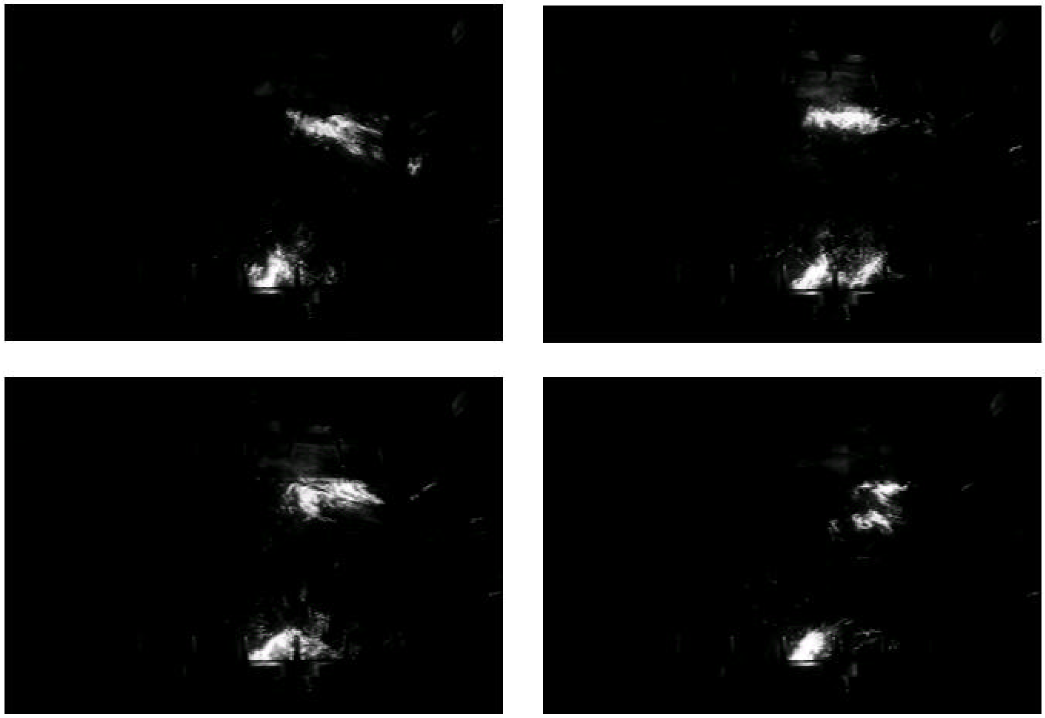

Figure 3-6 - Plan View of CS/PLIF Model Bottom Preheat and Entry Zones with DOC Burners at 4 MMBtu/hr Near Flue and 7 MMBtu/hr Elsewhere

4. OXY-FUEL EQUIPMENT

Commercial DOC Burner

The commercial DOC burner is shown in Figure 4-1. The burner consists of separate fuel and oxygen lances mounted in a 60% alumina refractory burner tile and fitted with a steel mounting plate to connect to the furnace shell. The design is a scaled-up version of the co-firing arrangement tested in Phase 1.

High-momentum fuel and oxygen jets are a key feature of the DOC process. The momentum of the fuel and oxygen jets from the burner is regulated primarily by the bore diameter of a replaceable nozzle threaded into the discharge end of each lance. Table 4-I shows the nozzle diameters used, the calculated jet discharge velocity, and the required supply pressure for fuel and oxygen to flow 7 MMBtu/hr and 4 MMBtu/hr as required for the Auburn Steel reheat furnace.

Although the plan for this demonstration was to inject fuel and oxygen separately, Phase 1 results raised some concern about DOC flame stability under certain conditions.[15] Stability was improved by flowing a small amount of oxygen at low velocity through an annulus surrounding the fuel lance. As a contingency, a crossover piping arrangement connecting the oxygen lance with a fuel lance annulus was included with the commercial DOC burner. The flow rate into the annulus was regulated by a replaceable orifice housed in a union in the crossover assembly. For the demonstration tests, a blind orifice was used, giving zero annulus flow and fully separate fuel and oxygen injection through the burner.

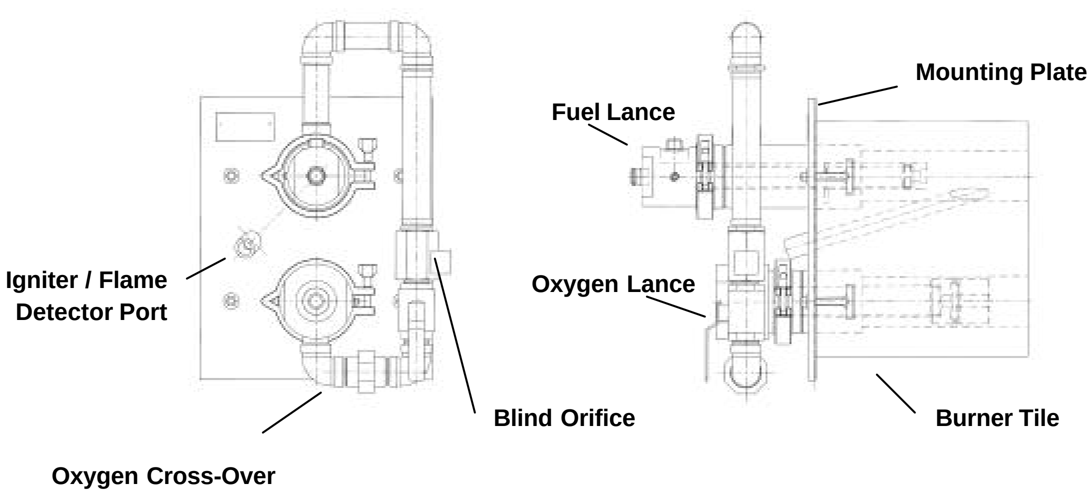

Figure 4-1 - Commercial DOC Burner

Table 4-I – DOC Burner Nozzle Data

	Nozzle diameter in.	Discharge velocity fps	Supply pressure psig
7 MMBtu/hr			
Fuel	0.578	990	5.4
Oxygen	1.125	540	2.9
4 MMBtu/hr			
Fuel	0.578	600	1.7
Oxygen	0.875	510	2.6

The preheat zones were designed to supplement the existing air-burner zones. As such, DOC burner ignition would occur only when the furnace was above the auto-ignition temperature of the fuel, and so the burners had no ignition or flame supervision system. However, a port was supplied in each burner for a pilot ignition / UV flame detector assembly, if one was needed or desired in future operation.

Flow Control Valve Skid

The flow control valve skid contains the manual and automatic valves, pressure regulators, orifice meters, and pressure switches required to control the flow of fuel and oxygen for the DOC burners. The skid has two identical flow control modules to provide separate control for the top preheat zone and bottom preheat zone.

Both the oxygen and the natural gas control legs consist of the same basic components. The inlet is protected by a manual shutoff valve followed by a 40-mesh strainer. Pressure gages on either side of the strainer indicate plugging of the strainer. A low-pressure switch downstream of the strainer provides indication of a loss of supply pressure upstream of the skid. Downstream of this pressure switch are automatic double blocking valves. These valves provide positive shutoff of process gas and can be opened only when all system safety interlocks are satisfied. The blocking valves are equipped with limit switches to provide positive feedback that the valves are correctly positioned. The blocking valves are followed by a pressure regulator which provides a constant supply pressure to an orifice metering system immediately downstream. The orifice metering system contains pressure and temperature transmitters to provide correct compensation for these factors in flow metering. It also contains a high-pressure switch to indicate failure of the pressure regulator and shut down the system. Although the planned control scheme called for on-off burner operation, a flow control valve was provided downstream of the orifice meter if continuous-range control was desired in the future. The delivery end was equipped with a manual shutoff valve for isolation.

Additional components were located in the oxygen and fuel supply lines at each DOC burner. This burner valve hardware included the following components:

- a manual shutoff valve for isolation;
- an adjustable orifice to compensate for minor differences in supply piping length to each burner, providing balanced flow among the burners in a given zone;
- a solenoid valve to activate / deactivate the burner; and
- a check valve to prevent cross-flow between fuel and oxygen lines.

A short length of braided stainless steel hose was also supplied in each pipeline to allow for expansion and for the breaking of connections during maintenance.

Control Hardware and Software

The DOC burner Level I flow control system was integrated into the overall reheat furnace control system. Control is directed by a SIMATIC 545 Programmable Logic Controller (PLC). The operator interface software is FIX32™, version 6.1.5, a supervisory control and data acquisition (SCADA) package supplied by Intellution, Inc. FIX32 operates under Microsoft Windows NT™, version 4.0, with additional programming in Microsoft Visual Basic, version 4.0.

The operator can set:

- zone temperature setpoints;
- flow setpoints;
- automatic or manual control,

and the operator can view:

- zone temperatures;
- combustion air and flue gas temperatures;
- fuel, air, and oxygen flows;
- furnace and combustion air pressures;
- alarms;
- historical trends of temperatures and flows.

Three control thermocouples were provided in each of the top and bottom preheat zones. Autoignition thermocouples verify that there is sufficient temperature in the zone for the DOC burners to safely ignite. These thermocouples are located in the sidewall at the middle of each zone. A minimum temperature of 1525°F is needed to satisfy the ignition criterion.

Setpoint thermocouples located in the center of each zone are used to control firing of the zones, and overtemperature thermocouples located near the flue provide warning of overheating of the refractory. A temperature of 2150°F or higher from an overtemperature thermocouple causes all DOC burners in the zone to be deactivated. An additional overtemperature thermocouple is positioned immediately upstream of the recuperator.

The control system also monitors the actual flow ratio of fuel to oxygen. If the measured ratio differs by more than a preset percentage from stoichiometric for 10 seconds, all burners in the zone are deactivated.

5. SITE PREPARATIONS

In addition to the components described in the previous section, several other site preparations were needed to implement the DOC system at Auburn Steel. These additional items are described below.

Skid Enclosure

A steel enclosure attached to the existing rolling mill building was constructed near the discharge end of the reheat furnace to house the flow control valve skid. The enclosure was built on a new concrete slab and was equipped with an access door, explosion-proof lighting, and a 10-ft roof vent.

Supply Piping

Supply piping was installed to connect the oxygen plant with the flow control valve skid. Approximately 2500 ft of 4" - schedule 40 carbon steel pipe, cleaned for oxygen service, was installed. Approximately 150 ft of 6' - schedule 40 carbon steel pipe was installed to connect the existing gashouse to the flow control valve skid to supply natural gas.

Connecting Piping

Piping was run to connect the flow control valve skid to the burners. Oxygen connecting piping for each preheat zone consisted of:

- a header of approximately 100 ft of 6" – schedule 40 carbon steel pipe, cleaned for oxygen service, from the skid to the furnace area;
- branches of 20 ft to 50 ft of 3" – schedule 40 carbon steel pipe, cleaned for oxygen service, to either side of the furnace;
- branches of approximately 20 ft of 2" – schedule 40 carbon steel pipe, cleaned for oxygen service, to each burner valve hardware package;
- short sections of 2" – schedule 40 stainless steel pipe, cleaned for oxygen service, between the burner valve hardware and the burner.

Stainless steel was used downstream of the burner valve hardware package to eliminate hazards from potentially excessive oxygen velocities during the opening and closing of the solenoid valves actuating the burners.

Similar piping was run for fuel:

- a header of 6" – schedule 40 carbon steel pipe;
- branches of 2½" – schedule 40 carbon steel pipe.

Inspection / Cleanout Doors

Cast billets charged into the reheat furnace carry a thin layer of iron oxide scale formed during solidification and cooling. This scale frequently breaks off the billets during the early stages of reheating and collects in the bottom entry zone of the reheat furnace. Before the addition of the preheat zones this had little impact on the operation of the reheat furnace. However, with sidewall burners now located in this area, a buildup of scale would interfere with flame patterns and potentially cause other operating problems. To allow for regular removal of this scale, four 6" square stainless steel doors were mounted in the new preheat burner zone at hearth level on each side of the furnace. The doors were lined with compressed fiber refractory blanket and were equipped with louvered inspection ports.

Furnace Skid Pipe Cooling Water Supply

As they pass through the furnace, the billets are supported by water-cooled, refractory-covered skid pipes. Approximately 32 ft of 12" cooling water header piping supplying these skids had to be rerouted to allow access to the new DOC burners for installation and maintenance.

6. BASELINE TEST DATA

Baseline tests were conducted to quantify furnace performance before the addition of the DOC preheat zones. The furnace was operated at the highest production rate possible while an instrumented billet was heated through the furnace. Peak production rates at the Auburn Steel bar mill occur during the rolling of 6" square billets. Accordingly, the baseline tests were conducted during an extended production run of 6" billets. Data was collected on furnace energy consumption, billet temperature during heating, furnace stack emissions, and power consumption by the rolling mill to process the heated billets.

Instrumented Billet

Holes were drilled to depths of 1", 3" and 5¾" from the top face of a 6" square, 13'6" long billet of grade ASTM A36 steel.[†] Type-R thermocouples were placed in each hole to provide temperature readings representative of the top surface, core, and bottom surface of the billet, respectively. Each thermocouple was certified from 600°F to 2400°F in increments of 200°F according to the international material testing standards listed in Appendix A. A fourth certified thermocouple was placed in a 5 ¾" deep drilled hole positioned over the second (from the mill side of the furnace) longitudinal water-cooled skid pipe to give temperatures representative of the billet “skid marks”. (“Skid marks” are sections of the billet which are noticeably darker [cooler] on discharge from the furnace because of contact with the water-cooled skids.) A fifth certified thermocouple was placed 3" *above* the top billet surface to give readings representative of the furnace walls.

Test Conditions

The instrumented billet was charged, heated, and discharged from the furnace in 108 minutes. A total of 159 billets were discharged during this time. Furnace zone setpoints and average zone thermocouple temperatures are shown in Table 6-I. Note that the average measured temperature in both heating zones was significantly lower than the normal setpoint temperature because of the high production demand rate. Air preheat temperature from the recuperator was 564°F on average.

There was a 5-minute mill delay 60 minutes into the heating of the instrumented billet. Aside from this delay, billets were discharged from the furnace at an essentially constant rate, averaging one billet every 38.9 seconds. Since each billet weighs 1652 lb on average, the peak production rate was 76.5 tph. Peak production rate was maintained after discharge of the instrumented billet to provide the three, 1-hour periods of stack emission monitoring required by protocol.

[†] ASTM A36 specifies composition and mechanical requirements for carbon steel bars and shapes for structural use.

Table 6-I - Zone Setpoints and Temperatures during Baseline Billet Test

Zone	Setpoint Temperature (°F)	Average Measured Temperature (°F)	Control Mode
Top Heat	2350	2268	Manual
Bottom Heat	2400	2341	Manual / Auto
Intermediate	2300	2357	Manual
Soak	2350	2354	Auto / Manual

Table 6-II – Furnace Energy Consumption during Baseline Billet Test

Method 1: Meter Reading

Time	Meter Reading (cf / 1000)
Charge Instrumented Billet	4170480
Discharge Instrumented Billet	4170630
Net	150

150,000 cf x 1005.8 Btu/cf† = 150.9 MMBtu

159 billets x 1652 lb/billet = 262,668 lb = 131.3 ton

Energy consumption = 150.9 MMBtu / 131.3 ton = 1.15 MMBtu/ton

Method 2: Controller Reading

Zone	Average Fuel Rate (% of scale)	Maximum Rate‡ MMBtu/hr	Average Fuel Rate MMBtu / hr
Top Heat	69.6	53.4	37.2
Bottom Heat	83.0	47.0	39.0
Intermediate	53.3	11.0	5.9
Soak	47.3	11.5	5.4
Total			87.5

Delay-free time = 108 min. heating time – 5 min. delay time = 103 min.

87.5 MMBtu/hr x (103/60) hr = 150.2 MMBtu

Energy consumption = 150.2 MMBtu / 131.3 ton = 1.14 MMBtu/ton

† – See Table 2-II

‡ – See Table 2-I

Energy Consumption

Energy consumption was evaluated by two methods, summarized in Table 6-II. The first method used the start and finish readings from the furnace gas meter, and the second used the instantaneous flow reading from the operator's control panel excluding delay time. Both methods agree, giving an average energy consumption of 1.15 MMBtu/ton during the instrumented billet test.

Billet Temperatures

Measurements from the billet thermocouples are shown in Figure 6-1. The core discharge temperature was 2081°F, and the top surface-bottom surface temperature difference was 55°F. The skid mark temperature was 84°F below the bottom surface temperature.

Table 6-III - Stack Emission Data for Baseline Billet Test

	Hour 1	Hour 2	Hour 3	Average
STACK				
Oxygen, pct	13.76	13.45	13.32	
Carbon Dioxide, pct	4.38	4.31	4.4	
NOx				
ppmv, dry act	28.88	28.93	26.43	
ppmv, dry 3%O_2	72.4	69.5	62.4	
lb/MMBtu	0.086	0.082	0.074	0.081
CO				
ppmv, dry act	2.130	3.450	6.630	
ppmv, dry 3%O_2	5.3	8.3	15.7	
lb/MMBtu	0.004	0.006	0.011	0.007

Stack Emissions

Emission data for NO_x and for CO is given in Table 6-III. Average NO_x emission during the three 1-hour tests was 0.081 lb/MMBtu, and average CO emission was 0.007 lb/MMBtu.

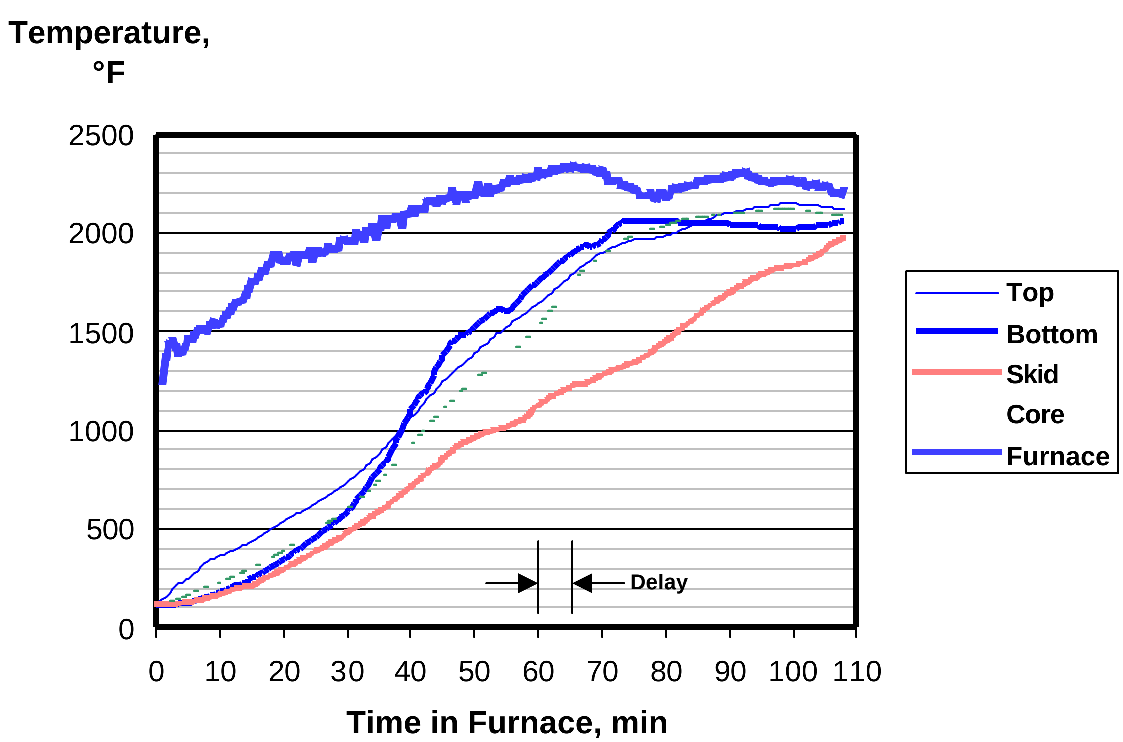

Figure 6-1 - Instrumented Billet Temperatures for Baseline Test

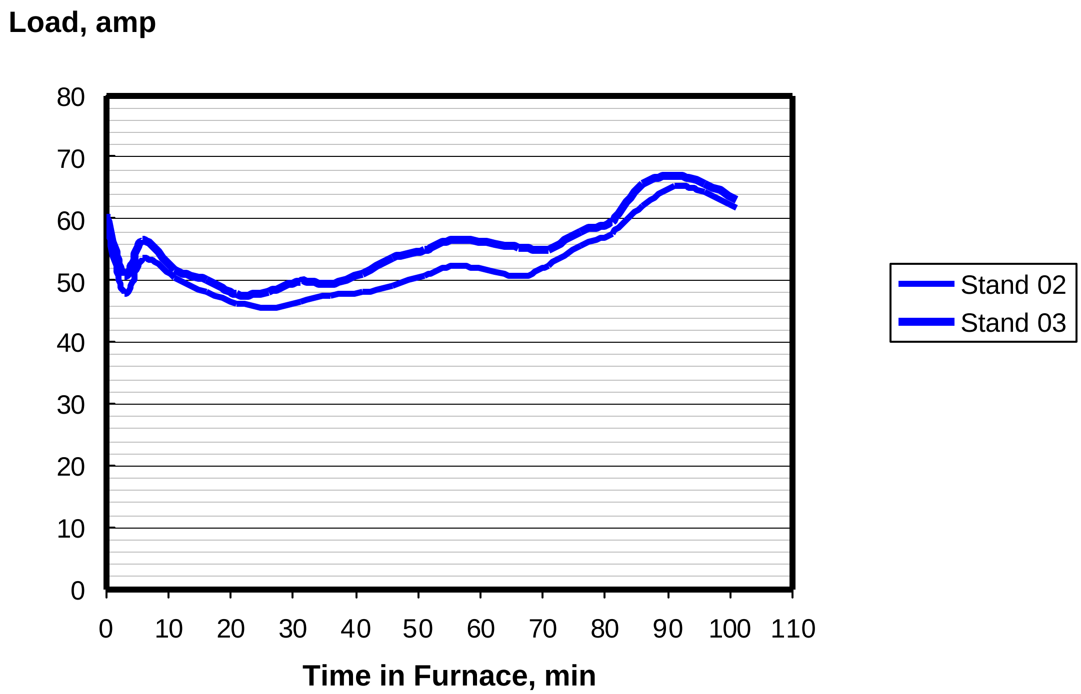

Figure 6-2 - Mill Loads for Baseline Billet Test

Rolling Mill Power Consumption

Power use on the rolling mill is a key measure of furnace heating performance. The current loads for mill stands 02 and 03 during the instrumented billet test are shown in Figure 6-2. The load values are acceptable; however, the upward trend of current load with time indicates that the peak production rate of 76.5 tph is at, or slightly higher than, the maximum sustainable rate for the baseline condition.

7. DOC BURNER TEST DATA

DOC burner tests were designed to provide data for a direct comparison with the baseline data. A second instrumented billet test was conducted with the furnace operating at the highest rate possible with the DOC burner zones firing. As for the baseline tests, the DOC burner tests were conducted during an extended production run of 6" billets, and again data was collected on furnace energy consumption, billet temperature during heating, furnace stack emissions, and power consumption by the rolling mill to process the heated billets.

Additional data was collected over a period of several months on NO_x emissions with the furnace operating under various conditions with the DOC burner zones firing.

Instrumented Billet Test Conditions

A 6" square, 13'5" long billet of ASTM A615 Grade 60 steel[‡] was drilled and equipped with certified Type-R thermocouples as was done for the baseline test. The instrumented billet was charged, heated, and discharged from the furnace in 98 minutes. A total of 159 billets were discharged during this time. Furnace zone setpoints and average zone thermocouple temperatures are shown in Table 7-I. Air preheat temperature from the recuperator was 866°F on average.

There was a 19-minute mill delay 15 minutes into the heating of the instrumented billet. Aside from this delay, billets were discharged from the furnace at an essentially constant rate, averaging one billet every 29.8 seconds. Since each billet weighs 1642 lb on average, the peak production rate was 99.2 tph. This represents a 30 percent increase in production rate over the baseline.

Energy Consumption

Energy consumption was evaluated by two methods, summarized in Table 7-II. The first method used the readings from the furnace gas meter, taken shortly after charging and shortly after discharging of the instrumented billet. As shown in the table, this method gives an energy consumption rate of 1.26 MMBtu/ton. The second method used the instantaneous flow reading from the operator's control panel from charge to discharge. As shown in the table, this method gives an energy consumption rate of 1.25 MMBtu/ton for the entire period from charge to discharge, in agreement with the furnace gas meter method. However, excluding the readings during the delay, the second method gives an energy consumption rate of 1.15 MMBtu/ton. This indicates that, unlike the baseline test, the amount of fuel consumed during the delay is not negligible. The value of 1.25 MMBtu/ton is an upper limit for the delay-free energy consumption rate reached if the steel heated at the same rate during the delay and during normal

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[‡] ASTM A615 specifies dimensional and mechanical requirements for carbon steel concrete reinforcing bars. From a reheating standpoint, this steel is equivalent to the A36 steel used in the baseline tests.

Table 7-I – Zone Setpoints and Temperatures during DOC Billet Test

Zone	Setpoint Temperature (°F)	Average Measured Temperature (°F)	Control Mode
Top DOC	1850	1803	Auto / Manual
Bottom DOC	1850 / 2080	2020	Auto / Manual
Top Heat	2400	2207	Auto
Bottom Heat	2225	2366	Auto / Manual
Intermediate	2350	2304	Auto
Soak	2325	2296	Auto

Table 7-II – Furnace Energy Consumption during DOC Billet Test

Method 1: Meter Reading

Time	Meter Reading (cf / 1000)
Charge plus 8 minutes	4599965
Discharge plus 29 minutes	4600163
Net	198

198,000 cf x 1005.8 Btu/cf[†] = 199.1 MMBtu
192 billets x 1642 lb/billet = 315,264 lb = 157.6 ton
Energy consumption = 199.1 MMBtu / 157.6 ton = 1.26 MMBtu/ton

Method 2a: Controller Reading (charge to discharge)

Zone	Average Fuel Rate, MMBtu / hr	Percent Capacity
Top DOC	14.0	53.8
Bottom DOC	6.8	26.2
Top Heat	21.3	39.9
Bottom Heat	41.8	88.9
Intermediate	7.5	68.2
Soak	8.1	70.4
Total	99.5	56.9

Heating time = 98 minutes
99.5 MMBtu/hr x (98/60) hr = 162.5 MMBtu
159 billets x 1642 lb/billet = 261,078 lb = 130.5 ton
Energy consumption = 162.5 MMBtu / 130.5 ton = 1.25 MMBtu/ton

Method 2b: Controller Reading (excluding delay period)

Zone	Average Fuel Rate, MMBtu / hr	Percent Capacity
Top DOC	16.6	63.8
Bottom DOC	7.9	30.4
Top Heat	24.2	45.3
Bottom Heat	48.0	102.1
Intermediate	8.3	75.5
Soak	9.0	78.3
Total	114.0	65.2

Delay-free time = 98 min. – 19 min. delay = 79 min.
114.0 MMBtu/hr x (79/60) hr = 150.1 MMBtu
Energy consumption = 150.1 MMBtu / 130.5 ton = 1.15 MMBtu/ton

[†] – See Table 2-II

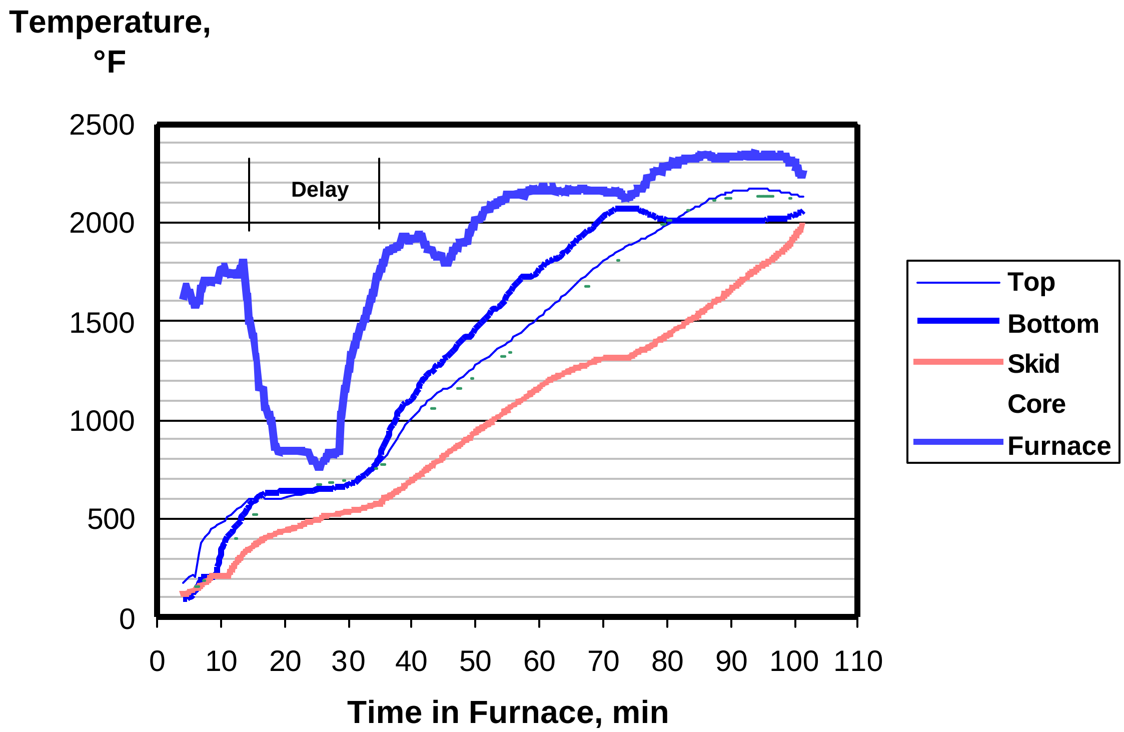

Figure 7-1 – Instrumented Billet Temperatures for DOC Tests

processing. The value of 1.15 MMBtu/ton is a lower limit reached if the steel was heated only during normal processing. The actual delay-free rate lies between these two values and can best be estimated by consideration of the billet temperature data.

Billet Temperatures

Measurements from the billet thermocouples are shown in Figure 7-1. The core discharge temperature was 2100°F, and the top surface-bottom surface temperature difference was 71°F. The skid mark temperature was 75°F below the bottom surface temperature. These results are comparable to the baseline and were achieved at a 30 percent higher production rate (23% less time in the furnace).

Figure 7-1 shows that during the delay period, billet temperatures increased only slightly. The top surface shows a temperature rise of 197°F and the bottom surface a rise of 242°F. (The core temperature rises 261°F, but this represents temperature equalization during the delay as well as heat added to the billet.) A temperature increase of about 200°F represents approximately 0.04 MMBtu/ton. Adding this to the lower limit value of 1.15 MMBtu/ton, derived in the previous section assuming no billet heating during the delay, gives an estimated delay-free energy consumption rate of 1.19 MMBtu/ton. This is comparable to the baseline energy consumption rate.

Table 7-III – Comparison of NOx Measurement Techniques

	EPA Protocol (Galson)	EnviroMate
NOx, ppm dry @ 3% oxygen	155	147

Table 7-IV – NOx Emission Data from DOC Tests

Period	Test	Production Rate (tph)	Air Firing Rate (MMBtu/hr)	DOC Firing Rate (MMBtu/hr)	Air Preheat Temperature (°F)	NOx (lb/MMBtu)	
						Galson (EPA Protocol)	EnviroMate
Base	A	74	80.8	--	553	0.086	
	B	80	96.2	--	578	0.082	
	C	80	96.4	--	587	0.074	
1	A	99	92.2	25.4	877	0.124	
	B	65	88.3	0.0	834	0.127	
2	A	87	85.7	13.6	819		0.106
	B	74	82.6	15.4	794		0.136
	C	80	94.4	0.0	729		0.117
3	A	83	87.4	14.0	725		0.130
	B	60	67.3	0.0	577		0.065

Stack Emissions

Emissions tests were conducted for a variety of operating conditions over several months. Data was collected with the DOC zones in operation and with the DOC zones shut off (air burner-only operation). Measurements for the instrumented billet tests were made by Galson Measurements using the formal EPA protocol. However, a number of measurements were made informally by Auburn Steel using a North American EnviroMate analyzer. A one-hour, side-by-side comparison of measurements made according to EPA protocol and with the EnviroMate analyzer is shown in Table 7-III. Agreement between the two techniques is very good.

NO_x data from these test periods is shown in Table 7-IV along with the baseline data. Each test represents the average of one hour of operation. To eliminate scatter caused by furnace delays, data was eliminated within each hour where furnace operation was significantly different from steady state. Specifically, data was discarded when the furnace firing rate fell below 60 MMBtu/hr, when the furnace air-fuel ratio exceeded 10.5 (> 10% excess air), or when flue CO levels exceeded 100 ppm.

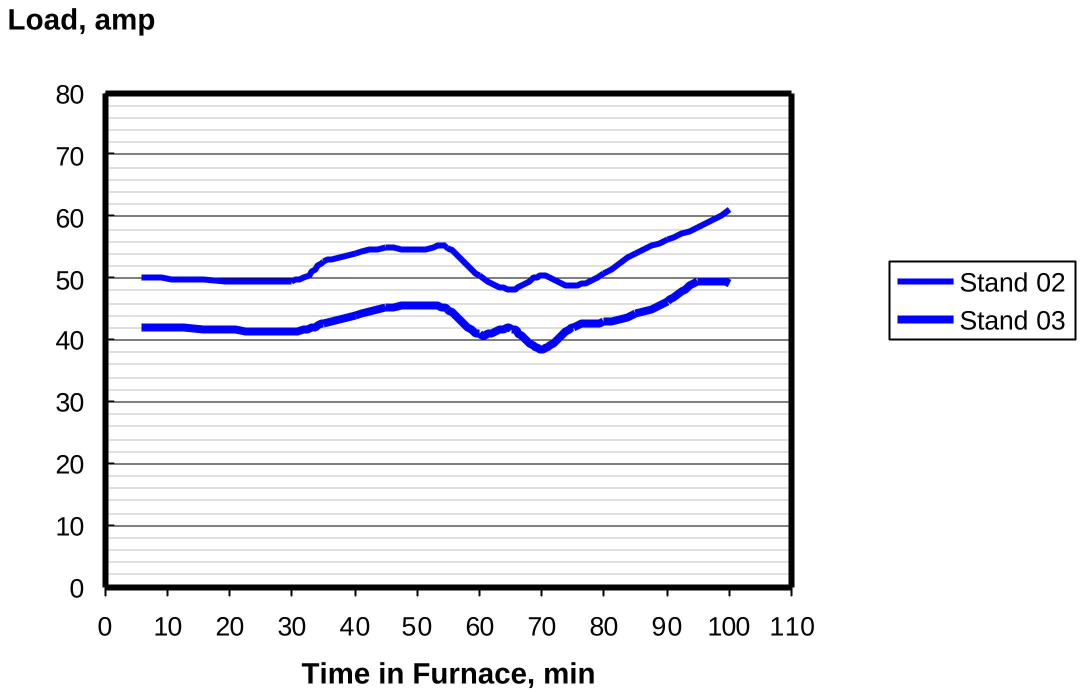

Figure 7-2 – Mill Loads for DOC Billet Test

Air preheat temperature and air burner firing rate appear to be the dominant parameters determining NO_x emission rates. Air preheat temperature is especially important in comparing DOC data with the baseline data. The high production rates achieved with the DOC zones firing and the proximity of the DOC zones to the flue lead to higher flue gas temperatures and an increase in heat recovered in the recuperator. These factors translate into generally higher air preheat temperatures. Looking at data with comparable air preheat temperatures, NO_x performance is similar with or without the DOC zones firing.

Rolling Mill Power Consumption

The current loads for mill stands 02 and 03 during the DOC instrumented billet test are shown in Figure 7-2. The load values are comparable to those from the baseline test. As in the baseline tests, the slight upward trend in the current loads with time indicates that the peak production rate of 99.2 tph is at, or slightly higher than, the maximum sustainable rate for the baseline condition.

Burner Performance and Durability

The burners performed very well and required no maintenance throughout the test periods. Burner performance was especially notable since they were used only during peak production period, which required the burners to sit unfired in the furnace for extensive periods and then to function properly on demand. Combustion was stable and no problems with pressure fluctuations or noise were encountered.

Summary

The DOC system has met the Phase 3 demonstration goals:

- The DOC burners have performed maintenance-free with no operational problems.
- Production rate on Auburn Steel's reheat furnace has increased from 75 tph to 100 tph.
- NO_x emission levels have been maintained while increasing production rate.

Having met these goals, the system is now operated by Auburn Steel as part of their standard practice.

Table 7-V summarizes the key comparisons of the baseline and DOC test data. The addition of the DOC preheat zones yielded essentially similar furnace and mill performance at a 30% higher production rate. When NO_x emissions are compared at similar air preheat temperatures, performance with the DOC preheat zones is essentially similar to performance without the DOC zones. The interplay of DOC firing, air preheat temperature, and NO_x generation is analyzed in more detail in the Discussion section of this report.

Table 7-V – Data Summary

Parameter	Air Burners Only	Air + DOC Burners
Heating time, min	103	79
Production rate, tph	76.5	99.2
Fuel rate, MMBtu/t	1.15	1.19
Dropout temperature, °F		
Billet top	2119	2126
Billet core	2081	2100
Billet bottom	2064	2055
NOx emission, lb/MMBtu (@ air preheat 500°F-600°F)	0.077 †	No Data
NOx emission, lb/MMBtu (@ air preheat 700°F-900°F)	0.122	0.124
NOx emission, lb/ton (@ air preheat 700°F-900°F)	0.140	0.148
Mill loads (avg), amp		
Stand 02	53.1	53.0
Stand 03	55.8	43.8

† - includes data from Table 6-III and Table 7-IV

8. DISCUSSION

Effect of DOC Preheat Zones on Fuel Rate

Farrell et al. show that, for constant furnace conditions, a conversion to oxy-fuel combustion lowers the fuel rate in a continuous furnace.[16] In the Auburn Steel furnace, however, the addition of the DOC preheat zones shortens the length of the entry zone considerably. This results in significantly higher flue gas temperatures which offset the fuel saving from oxy-fuel combustion. The energy loss to the flue gas is partially recovered by an increase in the air preheat temperature.

Table 8-I shows the flue gas temperatures calculated using the CONFURNT simulation for each baseline and DOC burner test. The increase in flue gas temperature is approximately 300°F for similar furnace production rates.

Table 8-II shows the results from using a simple energy balance to evaluate the individual effects of

- a 20 percent conversion to oxy-fuel burners,
- a 300°F increase in flue gas temperature, and
- a 300°F increase in air preheat temperature.

The calculations use the conditions found in baseline test B as a basis. Table 8-II clearly shows how the net energy loss in the flue gas balances the benefit from oxy-fuel combustion, giving no net change in the fuel rate.

Table 8-I – Calculated Flue Gas Temperatures

Period	Test	DOC Firing Rate / Total Firing Rate (percent)	Calculated Flue Gas Temperature (°F)
Base	A	--	1914
	B	--	1915
	C	--	1912
1	A	21.6	2220
	B	0.0	1775
2	A	13.7	2072
	B	15.7	2052
	C	0.0	1796
3	A	13.8	2073
	B	0.0	1774

Table 8-II – Fuel Effect of Process Changes

Change	Fuel Effect, MMBtu/hr†	Fuel Effect, MMBtu/ton‡
Oxy-fuel conversion (20%)	- 6.1	- 0.076
Flue gas temperature increase (300°F)	+ 15.5	+ 0.194
Air preheat temperature increase (300°F)	- 8.7	- 0.109
Net	+ 0.7	+ 0.009

† - Positive – additional fuel required
Negative – fuel saved
‡ - Based on 80 tph production rate

As noted in Section 2, the increase in production rate at Auburn Steel could not be accomplished with additional air burners because of the volume limitations of the flue gas system. If it had been possible, however, the fuel rate penalty would have been significant. Heat transfer considerations, as described by Farrell et al., require that the flue gas temperature from an air-fuel system be at least as high as that from an oxy-fuel system. So, if additional air burners had been used in place of DOC burners, the flue gas temperature and air preheat temperature effects of Table 8-II would be seen, giving a fuel penalty of at least 6.1 MMBtu/hr, or about 5-6 percent

Effects of Air Preheat Temperature and Firing Rate on NOx

As noted in the previous section, air preheat temperature and firing rate show a significant effect on the NO_x emission level from the Auburn Steel reheat furnace. A regression analysis was made on the baseline test data and the air burner-only DOC test data (Table 7-IV) as functions of air preheat temperature and firing rate. The analysis gives an increase in NO_x of 0.0192 lb/MMBtu for a 100°F increase in air preheat. The regression analysis also indicates that an increase in firing rate from 65 MMBtu/hr to 90 MMBtu/hr increases NO_x by 0.009 lb/MMBtu. Literature for the LNI air-fuel burners used in the Auburn Steel reheat furnace suggests that a 100°F increase in gas phase temperature raises NO_x emissions by 0.040 lb/MMBtu.[11] This indicates that the increase in firing rate raises the gas phase temperature by 25°F, which seems to be a reasonable value.

Figure 8-1 shows the air burner-only NO_x data plotted as a function of air preheat temperature and firing rate. The regression curves describe this data very well.

The magnitude of these estimates can also be compared with the comprehensive data compiled by Hsieh et al. from industrial furnaces firing over a range from 30 kW to 12 MW (0.1 MMBtu/hr to 40 MMBtu/hr).[17] Their results indicate that a 100°F increase in air preheat temperature causes NO_x levels rise by 0.0058 to 0.0231 lb / MMBtu. The regression data from the Auburn Steel furnace fall in this

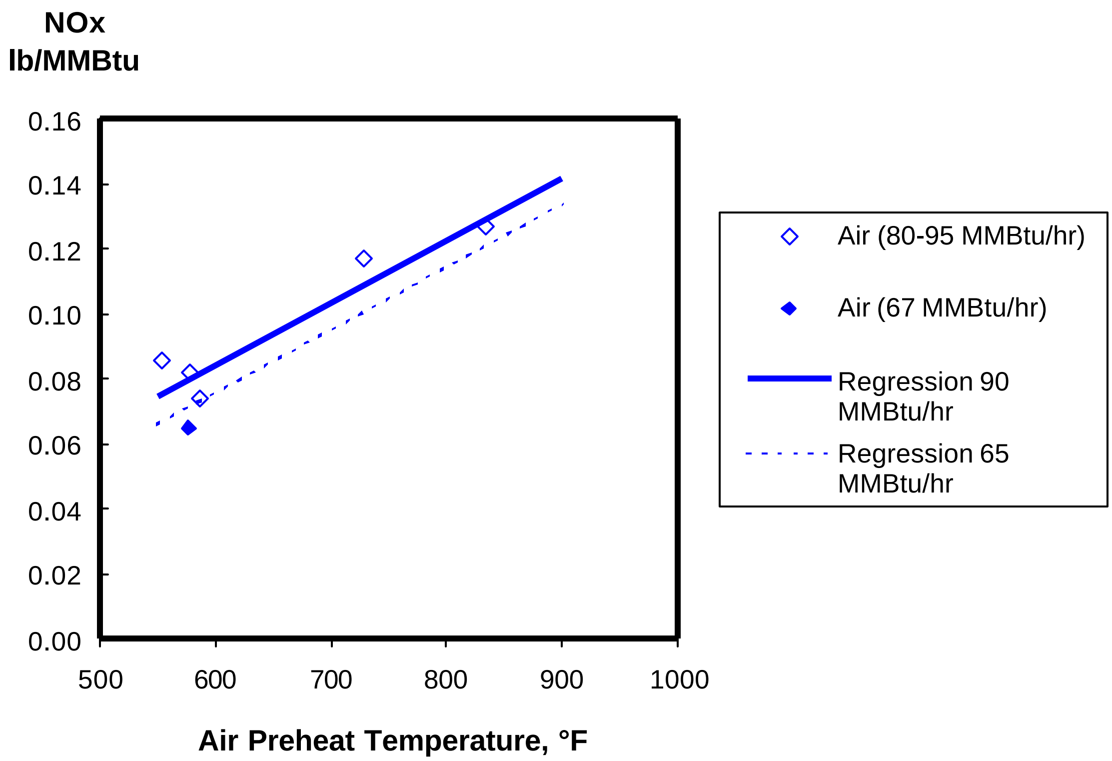

Figure 8-1 - Regression Analysis Results of NOx vs. Air Preheat Temperature and Firing Rate for Air Burner-Only Tests

range. The data from Hsieh et al. also indicate that under thermally similar conditions changing the firing rate within the range of 70% - 100% of the design rate has little effect on NO_x emission. However, changes in firing rate associated with changes in production rate do not produce thermally similar conditions. Heat transfer rates must be greater at higher production rates. If, for example, furnace wall setpoint are kept the same, higher production rates require higher gas phase temperature to increase heat transfer from the gas phase. Since most NO_x is produced by the thermally-sensitive Zeldovich mechanism, higher gas phase temperatures result in higher NO_x.

Estimation of NOx Generated by DOC Burners

It is difficult to accurately extract NO_x emissions values for the DOC zones from the stack emissions data. In theory, the NO_x emission from the air burners could be estimated from the correlation in Figure 8-1; the DOC zone emission would be the difference between the stack emission and this calculated air burner emission. In fact, the relatively small contribution of the DOC zones to the total firing rate magnifies any errors in the data giving unmanageable uncertainty in the calculated DOC zone emission value.

An estimate of DOC zone NO_x levels can be made analyzing the data under two hypotheses. The first hypothesis is that DOC zone NO_x levels are extremely low,

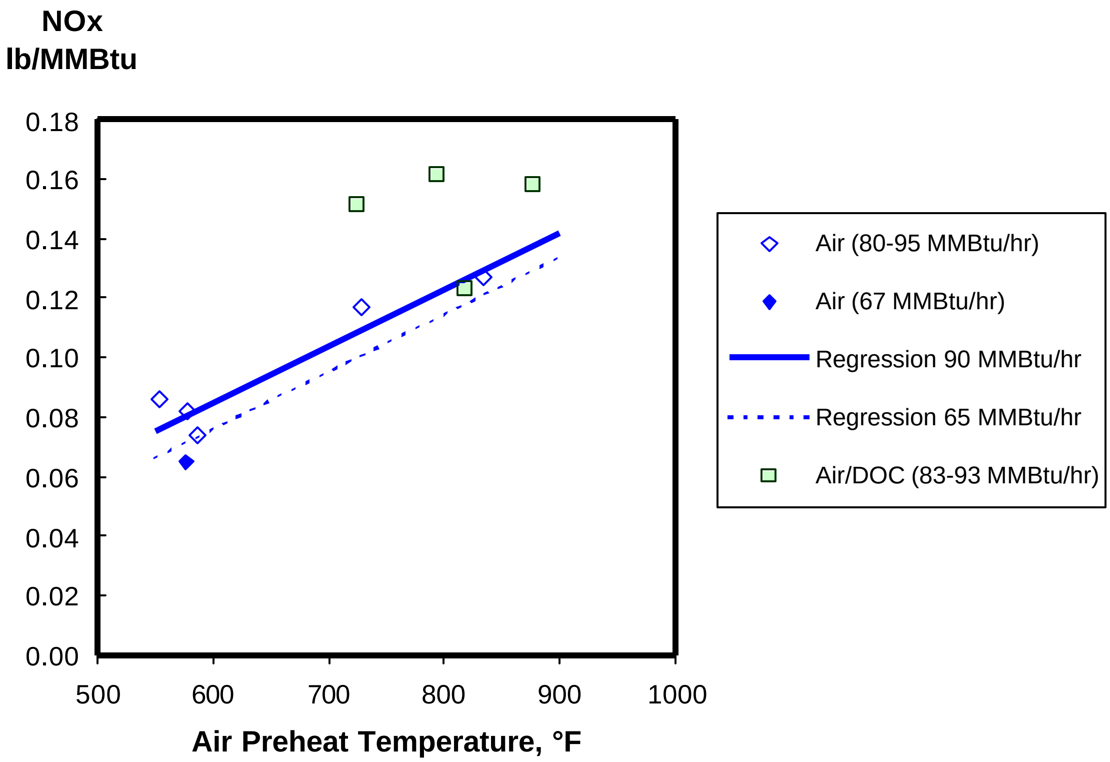

Figure 8-2 – Comparison of Air Burner-Only Data with Hypothetical Air Burner NOx Values Calculated Assuming Essentially No NOx Emission from DOC Burners

so that essentially all NO_x measured in the stack comes from air burner emissions. If this hypothesis is true, the air burner NO_x levels in the DOC tests could be calculated as

$$N_{air} = N_{stack}\left(\frac{F_{total}}{F_{air}}\right)$$

where N_{air} is the hypothetical NO_x emission (lb/MMBtu) from the air burners, N_{stack} is the measured NO_x emission (lb/MMBtu) at the stack given in Table 7-IV, F_{total} is the total firing rate (MMBtu/hr), and F_{air} is the air burner firing rate. These hypothetical air burner emission values are plotted in Figure 8-2 along with the data of Figure 8-1. If the hypothesis is correct, the two sets of data should coincide. Clearly, they do not, and the hypothesis that all NO_x comes from the air burners can be rejected.

The second hypothesis is that NO_x emissions from the air burners and the DOC burners are the same. If this hypothesis is true, air burner NO_x emissions in the DOC tests would be the same as the overall level measured in the stack. These hypothetical air burner emission values are plotted in Figure 8-3 along with the

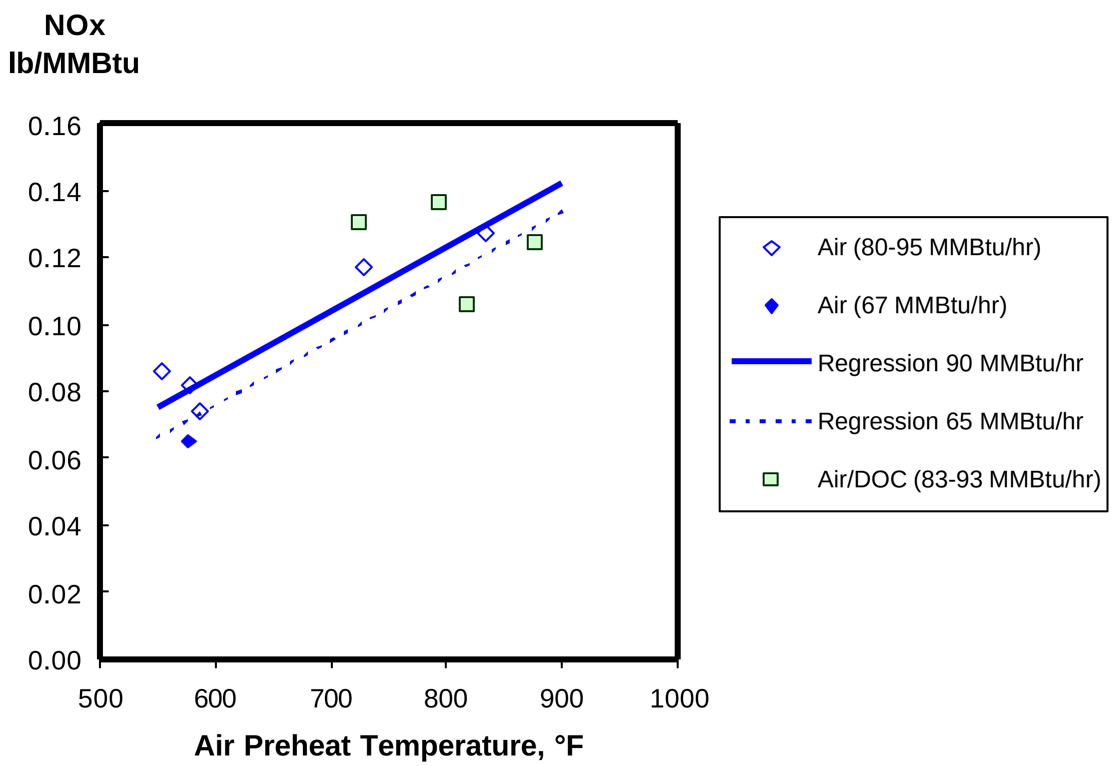

Figure 8-3 - Comparison of Air Burner-Only Data with Hypothetical Air Burner NOx Values Calculated Assuming the Same NOx Emission Rate from Air Burners and from DOC Burners

data of Figure 8-1. Here the two data sets roughly coincide, indicating that this hypothesis is approximately correct. The DOC zone NO_x emission rate can then be estimated as approximately equal to the overall emission rate for the DOC tests, which averages roughly 0.12 lb/MMBtu.

Comparison of Auburn Steel Data with Phase 1 Laboratory Data

The estimated NO_x emission value of 0.12 lb/MMBtu is higher than expected. To examine why this is so, it would be useful to compare the Auburn Steel reheat furnace data with the laboratory data generated in Phase 1 of this project. As mentioned earlier, gas phase temperature is a critical parameter. However, because it is much easier to collect data on furnace wall temperature, correlations are usually made to this rather than the gas phase temperature. In furnaces with small thermal loads, differences between the two will be small. This is usually the case in test furnaces. In high-production furnaces, such as the Auburn Steel furnace, however, the gas phase will be considerably hotter than the furnace walls. Thus, it becomes impossible to make a comparison between a test furnace and a high-production furnace on the basis of furnace wall temperatures.

Accordingly, estimates were made of gas phase temperatures with the CONFURNT simulation program. Simulations were made for the laboratory furnace tests in Phase 1 and for each of the baseline and DOC test periods. Measured wall temperatures and calculated gas phase temperatures from these simulations are shown in Table 8-III. For the Auburn Steel furnace, a single gas phase temperature was calculated as the average of the temperature in each zone, weighted by zone firing rate. The DOC data have been averaged to a single point with NO_x emission level of 0.12 lb/MMBtu and average gas phase temperature of 2633°F.

It is interesting to note in Table 8-III, that the air burner-only test with low production rate (test 3B) has a calculated gas phase temperature that is 44°F-106°F lower than the air burner-only tests at high production rate. As noted earlier, the regression analysis shown in Figure 8-1 suggested a difference of 25°F, in fair agreement with these calculated gas temperatures.

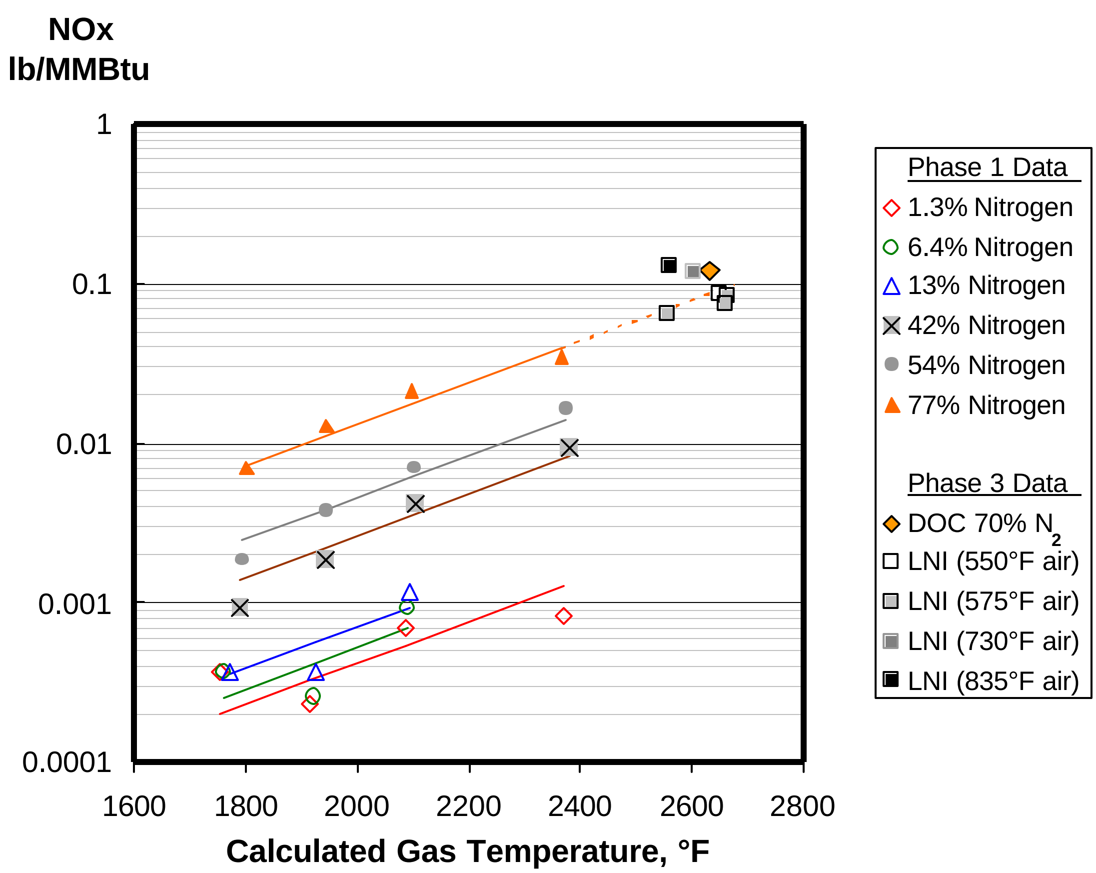

Figure 8-4 – Comparison of NOx Performance in Auburn Steel Furnace with Laboratory Data from Phase 1.[5]

Table 8-III – Summary of Gas Temperature Calculations

Laboratory Furnace Tests	Wall Temperature °F	Nitrogen in Oxidant %	Calculated Gas Temperature °F
	1600	0	1703
		20	1720
		50	1741
		79	1751
	1820	0	1915
		20	1927
		50	1943
		79	1945
	2000	0	2087
		20	2093
		50	2105
		79	2098
	2300	0	2370
		20	2374
		50	2382
		79	2367

Auburn Steel Furnace Data

	Calculated Gas Temperature, °F				
Test	Top DOC	Bottom DOC	Top Heat	Bottom Heat	Interm./Soak
Baseline	--	--	2710	2690	2350
1A	2570	2539	2557	2588	2565
1B	--	--	2555	2586	2506
2A	--	2733	2560	2739	2397
2B	--	2565	2577	2756	2443
2C	--	--	2575	2707	2360
3A	--	2675	2469	2723	2496
3B	--	--	2410	2706	2419

	Average Firing Rate, MMBtu/hr				
Test	Top DOC	Bottom DOC	Top Heat	Bottom Heat	Interm./Soak
Baseline	--	--	37.3	39.2	10.4
1A	17.1	8.3	25.9	48.6	17.7
1B	--	--	25.0	44.8	18.5
2A	--	13.6	20.3	50.0	15.4
2B	--	15.4	25.8	47.5	9.3
2C	--	--	28.9	48.2	17.3
3A	--	14.0	22.4	48.3	16.7
3B	--	--	21.4	33.4	12.5

	Average Gas Temperature (firing rate weighted), MMBtu/hr	
Test	DOC zones	Air zones
Baseline	--	2658
1A	2560	2575
1B	--	2560
2A	2733	2635
2B	2565	2665
2C	--	2603
3A	2675	2615
3B	--	2559

The Phase 1 laboratory data[5] and the Auburn Steel furnace data are plotted together in Figure 8-4 as functions of calculated gas phase temperature and gas phase nitrogen level. The estimated NO_x emissions for the DOC zones in the Auburn Steel furnace appear from Figure 8-4 to be in line with the Phase 1 results when gas phase temperature is taken into account. The LNI burner emissions are also in line with the DOC data at high furnace nitrogen levels although increasing NO_x levels are observed as air preheat temperature is increased. This similarity in performance reflects the similarity of burner design noted in Section 2.

The NO_x levels produced by the DOC zones are higher than originally expected because of the high nitrogen level produced by the air burners and the high gas phase temperature created by the high firing density required to achieve the improved production rates. Strategies to improve NO_x performance are presented in the next section.

9. FUTURE WORK

Future work should examine two potential ways to reduce NO_x emissions in the Auburn Steel furnace. First is to modify the ratio of dilution air into the recuperator to allow lower air preheat temperatures when the DOC zones are firing. This should also help better quantify the DOC zone NO_x emission level in the Auburn Steel furnace. The second way to reduce NO_x would be to convert additional zones to DOC burners. This would reduce the nitrogen content of the furnace atmosphere which according to Figure 8-4 would have dramatic effects in lowering NO_x. These additional conversions would also bring significant fuel savings.

Several simulations were made with the CONFURNT program as examples. Table 9-I shows the level of oxy-fuel conversion, the calculated flue gas temperature, and fuel rate for conversion of the bottom heating zone, for the conversion of both the top and bottom heating zones, and for the conversion of the entire furnace. The current level of conversion is shown for comparison. Table 9-II shows the resulting zone nitrogen levels and estimated NO_x reduction for each case. Nitrogen levels assume complete mixing in the gas phase and represent the average of the nitrogen level in and out of the zone. A residual nitrogen level of 5%, from furnace leaks and fuel and oxygen impurities, is assumed for the conversion of the entire furnace. NO_x reduction related to nitrogen level is assumed to occur only in the DOC fired zones since the LNI burners inject fuel into the combustion air stream.

These simulations predict that converting the bottom zone would cut fuel consumption by 10 percent. NO_x emission per unit of fuel would drop by 13 percent, giving a 22 percent drop in NO_x per ton of steel processed. Converting both the top and bottom zones would cut the fuel rate by 22 percent and NO_x per unit of fuel by 44 percent, giving an overall NO_x reduction per ton of steel of 57 percent. Conversion of the entire furnace cuts fuel use by 26 percent and NO_x per unit of fuel by 95 percent, giving an overall NO_x reduction per ton of steel of nearly 97 percent.

Table 9-I shows that the rate of fuel savings decreases with additional levels of conversion. This makes it increasingly difficult to justify conversion of additional zones. Besides cost, a major obstacle to converting these zones is the question of increased formation of iron oxide scale on the steel billets. As nitrogen concentration in the gas phase falls, the concentration of steel-oxidizing components rises. In zones where the steel temperature is greater than about 1800°F, this increased concentration of oxidizing components speeds the kinetics of the scale forming reactions.

Phase 4 of this project has been proposed and approved. The goal of Phase 4 is to develop a reheat furnace design that makes optimum use of the capabilities of

DOC burners. An optimized furnace design could lower the capital cost of a furnace, and eliminate drawbacks of mixed air burner-DOC burner operations. The first task of Phase 4 is to evaluate the effect of lower gas phase nitrogen levels on scaling kinetics and to propose counter-measures which will eliminate this obstacle to the conversion of higher-temperature furnace zones to DOC burners.

Table 9-I – Calculated Flue Gas Temperature and Fuel Rate for Increased Conversion Levels

Case	Calculated Flue Gas Temperature (°F)	Fuel Rate (MMBtu/ton)	Fuel Rate Improvement (percent)
Preheat Zone	2220	1.20	--
Bottom Zone	2170	1.07	10.8
Top + Bottom Zones	1878	0.93	22.5
All Zones	1653	0.89	25.8

Table 9-II – Calculated Nitrogen Level and Estimated NOx Emission for Increased Conversion Levels

Case	Heating Zone Nitrogen (percent)	Preheat Zone Nitrogen (percent)
Preheat Zone	71.8	69.5
Bottom Zone	67.1	59.3
Top + Bottom Zones	57.1	38.7
All Zones	5.0	5.0

Case	Estimated NOx (lb/MMBtu)	Improvement (percent)	Estimated NOx (lb/ton)	Improvement (percent)
Preheat Zone	0.124	--	0.148	--
Bottom Zone	0.108	12.9	0.115	22.3
Top + Bottom Zones	0.069	44.4	0.063	57.4
All Zones	0.006	95.0	0.005	96.6

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APPENDIX A

The thermocouples used for the instrumented billet tests described in Sections 6 and 7 were certified from 600°F to 2400°F in increments of 200°F. Certification data represents international standards for material testing procedures and adheres to the following specifications:

- MIL/STD/45662A;
- MIL/H/6875H;
- NIST SP 250-35;
- AMS 2750C;
- ANSI MC96.1;
- ASTM E220;
- BAC 5621;
- DPSI 700;
- PS23401.

The certification process is necessary in order to show the error of individual thermocouples at specified temperature ranges. Software proprietary to JHS Consulting, resident in the field data acquisition computers, continually applies the necessary correction factors and reverses internally the algebraic sign at respective limits for all values in order to derive accurate temperature readings.