Advanced Steel Reheat Furnaces Research and Development

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Final Report

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Executive Summary

Energy and Environmental Research, Corporation (EER) under a contract from the Department of Energy, DOE Grant No. DE-FG03-96ER 12200/A000, has conducted a multiphase program to assess the feasibility of developing and commercializing an Advanced Steel Reheating Furnace. This report summarizes the results of Phase I, Research, and Phase II, Development which evaluated an advanced furnace concept which incorporates two previously proven and commercialized technologies for other high temperature combustion applications:

- EER's gas reburn technology (GR) for post combustion NO_x control
- Air Product's oxy-fuel enrichment (OEA) for improved flame heat transfer in the heating zones of the furnace.

The combined technologies feature:

- greater production throughput with associated furnace efficiency improvements
- lowered NO_x emissions
- better control over the furnace atmosphere, whether oxidizing or reducing, leading to better control over surface finish.

In the Advanced Steel Reheat Furnace, the heating process is conceptually divided into three zones. Starting at the finish end of the furnace where fully reheated steel is discharged:

- Soak Zone: In this zone, fuel and air are fired through the existing furnace burners at normal or reduced primary fuel stoichiometry. This zone is not significantly changed from normal operation. The level of NO_x exiting the zone is likely to be fairly significant because of high furnace temperatures. The exhaust then flows into the next zone.

- Heat/Reburning Zones: Immediately upstream of the soak zone, the heating zones require highly radiant heat transfer for rapid ramp up to approximately rolling temperature. Oxygen enrichment of the combustion air in these zones promotes heat transfer and decrease furnace volumetric gas flows, all with the beneficial result of increased productivity and thermal efficiency. Reburning fuel is injected downstream of the primary zone to create a fuel-rich, NO_x reduction zone. The input NO_x reacts with the hydrocarbon fragments formed during oxidation of the reburning fuel, primarily CH species, to produce intermediate species such as HCN and NH_3, which then undergo a reaction sequence whereby they reduce NO_x to molecular nitrogen, N_2.

- Preheat/Burnout Zone: In this final zone the flow from the preceding zones provides heat, primarily by convection, to the incoming cold steel. Additional air is added in this zone to produce overall fuel lean conditions and oxidize all remaining fuel fragments. Overfire air (OFA) is added through new overfire air or existing burners at furnace gas temperature greater than 1,600°F to insure good CO burnout without significantly increasing thermally generated NO_x. The burn out is accomplished sufficiently upstream to ensure that almost all of the fuel heating value is recovered by heat transfer to the steel or in the recuperator.

The Phase I Study concluded through an evaluation of USA furnace demographics that the technology should be cost effective for furnaces with firing rates >50 MMBtu/hr which are the mill bottleneck or which are found in the Title I non-attainment areas. A number of steel processing furnaces (reheat, annealing and galvanizing) are target applications as they comply with general requirements of high firing rate and operates at high temperatures (>2,000°F) and with high NO_x (>0.2 lb/MMBtu). About 250 retrofit furnace projects for either one or a combination of the proposed technologies define the market over the next ten to 15 years. Any new furnace, although currently a small market, is a concept candidate.

Several computational models were developed and used to evaluate the impact of OEA and gas reburn on heat zone NO and thermal performance. These models predicted that 20 % or more increases in productivity was feasible, albeit with high NO_x generation, perhaps ten times baseline levels, and gas path peak temperature elevations of 200 to 400°F. Refractory temperatures were less effected. Modelling predicted that a 20 % increase in zone heating could be accomplished with about 52 lb O_2/MMBtu fired.

This work led to a development phase wherein a sooting, stratified burner with a rating of 400 to 800 MBtu/hr was designed and evaluated at pilot plant scale. The burner was optimized with respect to NO_x emissions and radiant heat transfer. The optimized burner was then coupled with gas reburn for final NO mitigation.

The optimized burner NO increased proportionally with OEA; NO levels were about 4 times baseline levels with sufficient OEA to increase zone heat transfer by 20%. The feasibility of obtaining NO_x reductions of 60 and 70% with gas reburn was also validated in pilot scale experiments for stand-alone and oxygen enriched heat zones, respectively. Thermal efficiency improvements of 10 to 15% are projected and result from a combination of higher furnace through put, 20 to 30%, and lower stack exhaust sensible heat loss since there is less N_2 in the flue gas. These results are obtained for oxygen enrichments predicted from the pilot scale experiments of about 88 lb O_2/ MMBtu fired, somewhat higher than the modelling results and believed to be overestimated.

Modelling and pilot testing also confirmed the feasibility of controlling the furnace atmosphere and temperature time profiles to match or improve those of an operating furnace. Thus no significant impact on steel quality or scaling is anticipated.

Cost effectiveness was estimated using the modelling and experimental results for the reference furnace, a 115 TPH billet reheat furnace of modern design having a fuel efficiency of 1.2 tons steel/MMBtu fired. These results are:

- Stand-alone gas reburn can reduce NO by up to 65% if about 23% of the burner fuel is directed to the reburn zone with a cost effectiveness of between 1,000 and 2,000 \$/ton NO_2 removed

- OEA firing with oxygen consumption of between 4.4 and 7.5 TPH can improve zone heat transfer/productivity by 20 to 30%, and generate net before tax but after operational expenses and capital charge annual revenues of several million dollars.

1.0 Introduction

1.1 Overview

The purpose of this report is to present the results of two phases of a three-phase project to develop and evaluate an Advanced Steel Reheat Furnace (ASRF) concept which incorporates two proven and commercialized technologies, *oxy-fuel enriched air* (OEA) combustion and *gas reburning* (GR). The combined technologies aim to improve furnace productivity with higher flame radiant heat transfer in the heating zones of a steel reheat furnace while controlling potentially higher NOx emissions from these zones. The project was conducted under a contract sponsored by the Department of Energy (DOE). Specifically, this report summarizes the results of a modeling study and an experimental study to define and evaluate the issues which affect the integration and performance of the combined technologies.

Section 2.0 of the report describes the technical approach used in the development and evaluation of the advanced steel reheat furnace. Section 3.0 presents results of the modeling study applied to a model steel furnace. Experimental validation of the modeling results obtained from EER's Fuel Evaluation Facility (FEF) pilot-scale furnace discussed in Section 4.0. Section 5.0 provides an economic evaluation on the cost effectiveness of the advanced reheat furnace concept. Section 6.0 concludes the report with recommendations on the applicability of the combined technologies of steel reheat furnaces.

1.2 Background

Steel reheat furnaces are a work horse of the industry, processing some 100 million tons of steel annually while consuming about 150 to 200 10^{12} Btu. These furnaces fire a variety of fuels, most commonally by-product and natural gas with heat inputs ranging from 50 to 400 MMBtu/hr. Because high temperature steel (<2,200°F) is produced, furnace efficiencies tend to be low (30 to 60%), even when exhaust heat is recuperated. Further, these furnaces can be bottle necks when expanding a rolling mill, requiring major modifications such as hearth enlargement and/or burner zone additions. They are also typically large source emitters of NO_X, 0.2 to 0.4 lb/MMBtu. Permitting for expansions potentially increases NO emissions and may trigger offset requirements. Therefore, what required is a technology which can address the issues of NO reduction and capacity expansion singularly or in combination.

The proposed technology should generally be cost effective for steel heating furnaces with firing rates >50 MMBtu/hr. These furnaces will typically be the mill bottleneck and/or are found in the Title I ozone non-attainment areas. A number of steel processing furnaces (reheat, annealing and galvanizing) are target applications as they comply with general requirements of high firing rate at high temperatures (>2,200°F) and with high NO_x (>0.2 lb/MMBtu). The total number of furnaces within this demographic range is estimated at about 250, most of which may be candidates during some part of their economic life as industrial modernization proceeds and air emission regulations stiffen. One of the major objectives is an improvement in steel throughput by up to 20%, without major structural or combustion system modifications. Using gas reburn, NO_x reductions of the order of 60 to 70% have been demonstrated for glass furnaces, and by analogy, are targeted for steel furnaces. Thermal efficiency improvements are an ancillary benefit; 20% increases are targeted and result from a combination of higher productivity and lower stack exhaust sensible heat loss, e.g., less N_2 in the flue gas. It appears feasible to control the furnace atmosphere and temperature/time profiles to match or improve those of an operating furnace.

The steel industry is an ideal target for enhanced oxygen combustion because the infrastructure (oxygen separation plants and pipelines) already exists in integrated steel. These facilities are frequently under-utilized due to retrenchments in the 80's and the greater use of recycled scrape, reducing the demand on basic oxygen furnaces. Small scale, energy efficient (>40 TPD) oxygen separation plants using pressure and vacuum swing absorption are now available for mini-mill applications. High purity oxygen is not required for the applications and concepts under consideration. Therefore, where oxygen pipelines are not available oxygen can be produced by relatively inexpensive membrane separation technologies.

1.3 Program Objectives

The objective of the project was to develop and evaluate the application of the combined oxy-fuel enriched combustion and gas reburning technologies for steel reheat furnaces. The specific objective of the project is to demonstrate that the application of the combined technologies would result in:

- greater production throughput with associated furnace efficiency improvements,
- lowered NO_x emissions, and
- better control over the furnace atmosphere, whether oxidizing or reducing, leading to better control over surface finish.

1.4 Description of ASRF Concept

The Advanced Steel Reheat Furnace concept incorporates two proven technologies: oxy-fuel enriched air combustion and gas reburning. Oxygen-enrichment concepts are currently being used to improve the performance of high temperature pyroprocessing processes in the energy intensive industries. It is important to note that experience with OEA in many of these industries has lead to the development of specific burner technologies. One example is the tube bundle burner commonly seen today on the electric arc furnace as well as the Clean Fire HR burner system, which has been successfully applied to glass and aluminum melters. Productivity gains up to 40% have been achieved as well as a 30% decrease in NOx emissions. Newly developed O_2 injection methods for the iron cupola have shown significant reductions in percentage of coke in the charge. Limited experience, mostly overseas, has shown that oxy-fuel burners in the heating zone of a billet furnace can increase productivity by 30%. OEA (3%) applied to the heating zone of a billet reheat furnace decreased fuel consumption by 20%, all at the expense of higher NOx emissions.

Gas reburn technologies for NOx control are being commercially offered for glass furnaces, large boilers and MSW incinerators. In a study for the Gas Research Institute [GRI], the feasibility and effectiveness of applying gas reburning technology to industrial equipment was established for the pyroprocessing industries, and specifically, steel reheat furnaces.

In the Advanced Steel Reheat Furnace concept, the heating process is conceptually divided into three zones. Starting at the finish end of the furnace where fully reheated steel is discharged we have:

- *Soak Zone*: In this zone, fuel and air are fired through the existing furnace burners at normal or reduced primary fuel stoichiometry. This zone is not significantly changed from normal operation. The level of NO_x exiting the zone is likely to be fairly significant because of high furnace temperatures. The exhaust then flows into the next zone.

- *Heat/Reburning Zones*: Immediately upstream of the soak zone, the heating zones require highly radiant heat transfer for rapid ramp up to approximately rolling temperature. Oxygen enrichment of the combustion air in these zones promotes heat transfer and decreases furnace volumetric gas flows, all with the beneficial result of increased productivity and thermal efficiency. Reburning fuel is injected in the cold steel zone downstream of the primary zone to create a stratified fuel-rich, NO_x reduction zone. The input NO_x reacts with the hydrocarbon fragments formed during oxidation of the reburning fuel, primarily CH species, to produce intermediate species such as HCN and NH_3, which then undergo a reaction sequence whereby they reduce NO_x to molecular nitrogen, N_2. The atmosphere directly over the steel is controlled to reduce metal oxidation.

- *Preheat/Burnout Zone*: In this final zone the flow from the preceding zones provides heat, primarily by convection, to the incoming cold steel. Additional air is added in this zone to produce overall fuel lean conditions and oxidize all remaining fuel fragments. Overfire air (OFA) is added through new overfire air or existing burners at furnace gas temperature greater than 1,600°F to insure good CO burnout without significantly increasing thermally generated NO_X. The burnout is accomplished sufficiently upstream to ensure that almost all of the fuel heating value is recovered by heat transfer to the steel or in the recuperator.

2.0 Technical Approach

2.1 Overview

The objective of the project was to develop and evaluate the application of the combined oxy-fuel enriched combustion and gas reburning technologies to steel reheat furnaces. The specific objective of the project is to demonstrate that the application of the combined technologies would result in:

- greater production throughput with associated furnace efficiency improvements,
- lowered NO_x emissions, and
- better control over the furnace atmosphere, whether oxidizing or reducing, leading to better control over surface finish.

The technical approach has been designed to address and quantify the following key issues:

- Which temperature zones can effectively use OEA or O_2, and what is the impact on refractory temperature?
- Where are the preferred furnace locations for injecting reburn fuel and overfire air, and are there potential process impacts?
- Are there secondary emissions or potential product quality issues caused by O_2 enrichment and/or low temperature substoichiometric operation?
- What are the costs of implementation (O_2 purchases and refractory service) and revenues (production increases and fuel reduction) which can be expected?
- How much NO_x and furnace gas temperature change can be expected?
- What are the critical design issues to be addressed in subsequent phases?

The work is being conducted in three phases:

- Phase I — Research and Development Definition, market research and computational modeling to define a reference furnace and evaluate concepts.

- Phase II — Design and Development, pilot-scale hardware development, test, and evaluation to validate concepts.

- Phase III — Field Demonstration, partial or full conversion of a furnace, and its testing and evaluation.

At present, Phase I and II have been completed and the results are presented in this report. In Phase I, a model furnace was specified based upon an evaluation of US furnace demographics. Computational modeling studies were conducted on the model furnace to select and quantify heat transfer and performance improvements. In Phase II, a test facility at EER's Test Site was selected and tests were conducted to address critical issues which were not addressed by computational modeling due to limitations of the modeling tools. In Phase III, a host site will be selected and a two-month demonstration test program will be carried out to evaluate and optimize the performance of the combined technologies. The tasks which have been performed during Phase I and II are shown graphically in Figure 2-1. The objectives and activities during these two phases are discussed below.

2.2 Phase I — Research and Development Definition

The objective of this phase was to perform a marketing evaluation to define the target furnaces and sites suitable to the proposed technology. A typical model reheat furnace was then defined and used to evaluate the performance of the combined technologies of oxygen-enhanced combustion and gas reburning.

The activities during this phase consisted of conducting a complete survey on the steel reheating furnaces throughout the United States, defining specifications for a model furnace, conducting modeling studies to quantify heat transfer and performance improvements, and specifying a conceptual design to establish capital and operating costs and benefits.

2.2.1 Database Acquisition

A literature survey was conducted to obtain information on steel reheating furnaces in the US, economic drivers affecting reheat furnace operation, and current and future environmental regulatory issues likely to affect their operation. In addition, EER and its subcontractor Air Products and Chemicals (APC) have participated in an American Iron and Steel Institute (AISI) technical panel meeting to solicit industry interest and advice in advancing the development of the technology. AISI supported this activity by providing peer review through their Energy and Environmental Committee. The results of the survey and contacts with the industry were used select and define a model furnace for the modeling work.

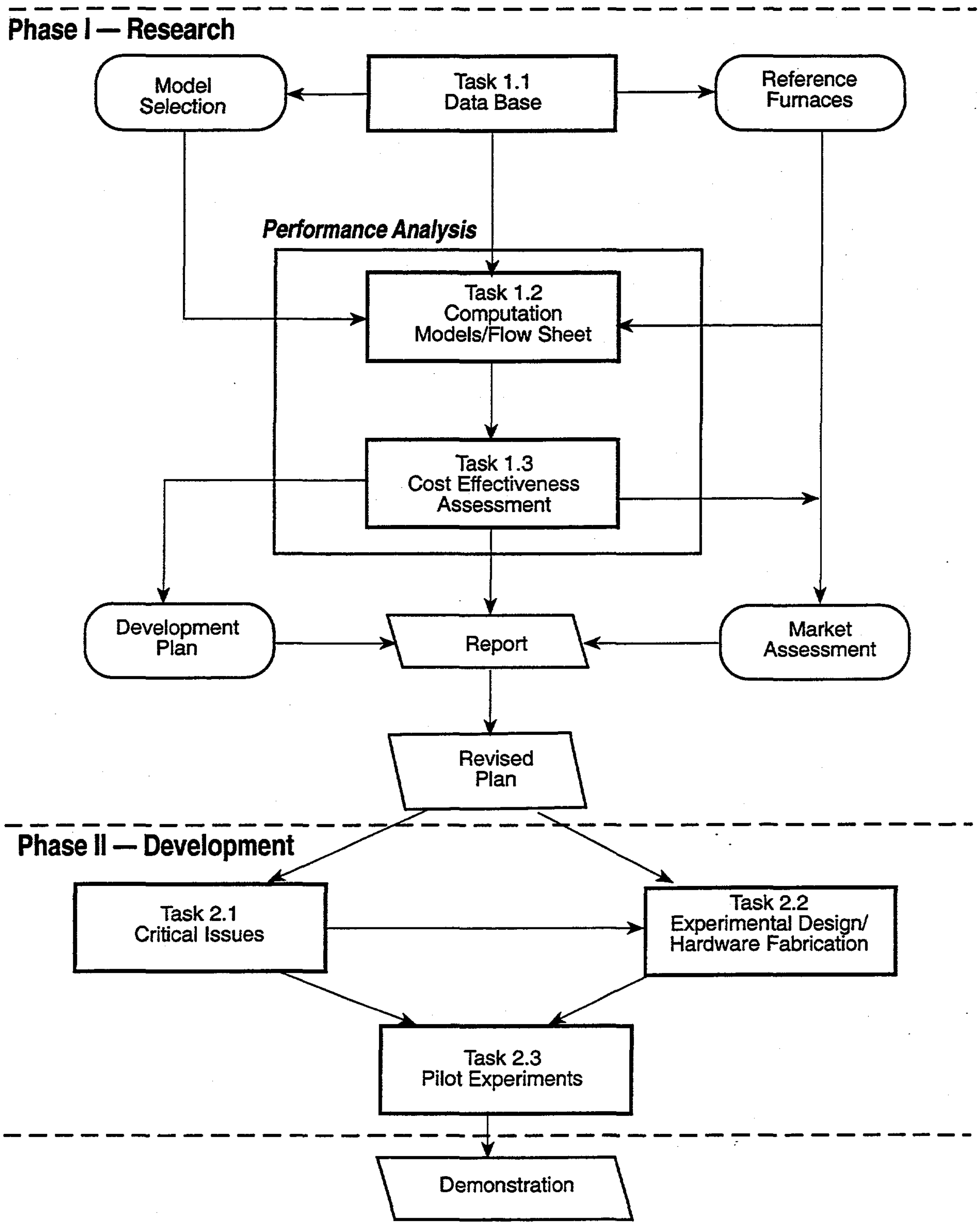


Figure 2-1. Work task flow sheet for Phase I, Research and Phase II, Development.

2.2.2 *Computational Modeling*

Once a model furnace had been defined, a review of the existing Computational Fluid Dynamics (CFD) modeling codes was conducted to identify one applicable to the development project. The review outlined the general specifications, capabilities, principles, bases, assumptions, required inputs, and form of output for the applicable models. Figure 2-2 outlines the approach for model development and linkage. The CFD model shown in this figure was developed by APC to support the analysis of oxygen enhancing heat zone combustion to preferentially improve heat transfer to the steel. As illustrated in the figure, CFD modelling results (flow field structure, temperatures, and species composition) were used as boundary conditions for the other computational models:

- computational (jets in cross flow) model to evaluate the effectiveness of mixing the reburn fuel into the post heat zone flue gases, and overfire air sufficiently downstream to accommodate the mixing and chemistry of the reburn zone,
- a unifying zoned system model to integrate the results from the CFD and gas reburn physical flow modelling into a prediction of performance attributes including thermal and production efficiency, and final NO emissions, and
- an economic model to assess the impact of operating cost and revenues on cost effectiveness parameters.

Sufficient computational modeling runs were conducted to compare base case operation with several oxygen-enriched scenarios of interest. The modeling effort considered the enrichment of the existing burners and its impacts on steel production. The outputs of this combustion modeling study were then used in combination with the aforementioned process models to project the effect of gas reburning for NO_x reduction and overall furnace performance efficiency, Section 3.

2.3 Phase II — Design and Development

The objectives of this phase of the project were to:

- Provide experimental, pre-demonstration validation of the process model,
- Resolve critical issues not ammnenable to computational modeling, i.e., evaluate impacts of flame radiation on furnace performance and impacts on NO_x formation when oxy-fuel enriched air is used, and
- Evaluate impacts of reburning process parameters such as zone stoichiometries, reburn zone residence time and temperature, and initial NO_x concentrations.

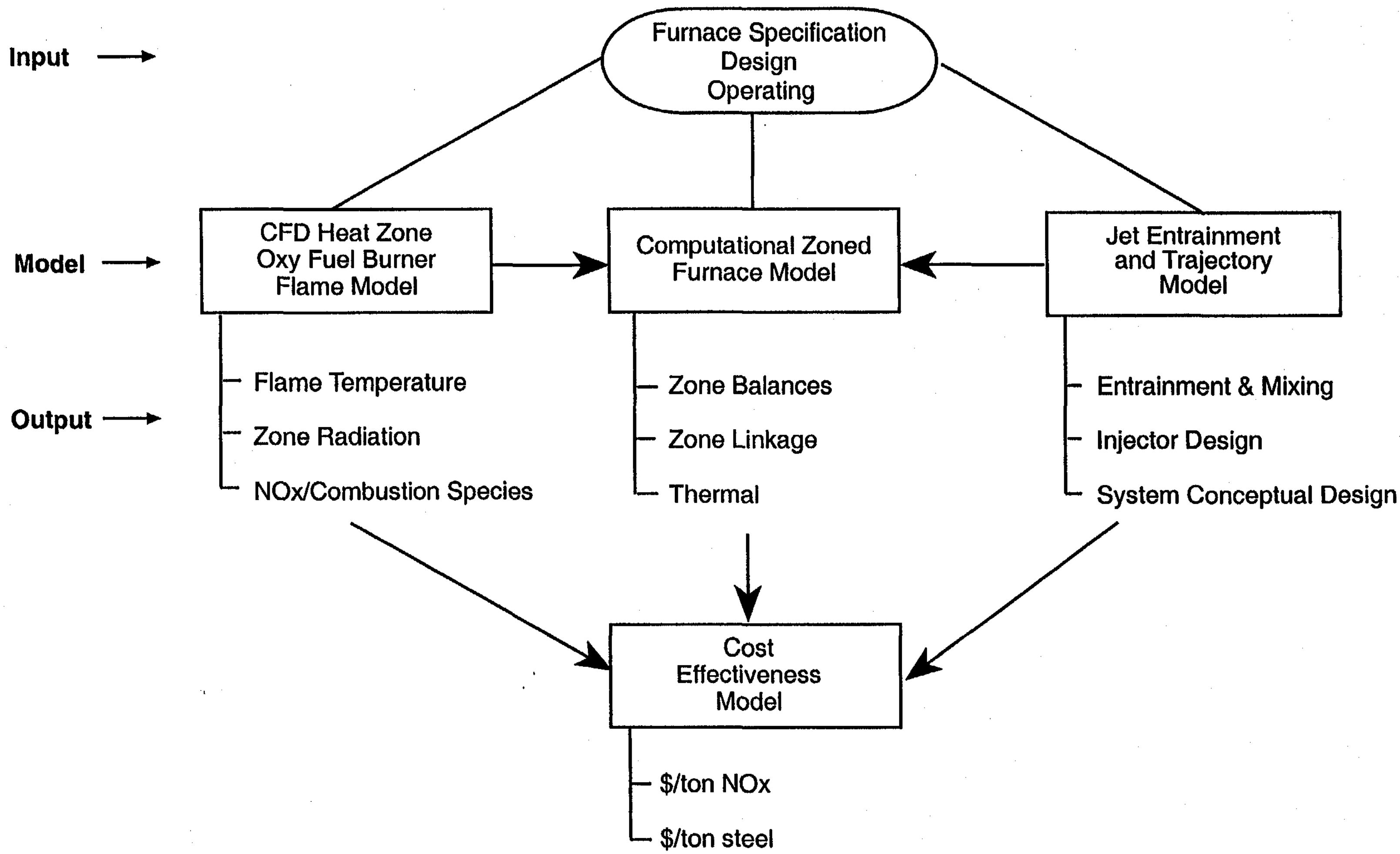


Figure 2-2. Phase I model development and linkage.

The activities during Phase II included selecting an appropriate pilot-scale test facility to experimentally resolve the critical issues, designing and fabricating pilot scale test equipment, and conducting tests to obtain the necessary data.

2.3.1 Critical Issues

Critical issues which were evaluated experimentally included:

- the design and optimization of an integrated air, oxygen and fuel burner,
- the effects of oxygen-enriched sooting radiation on furnace performance and NO_x emissions, and
- the impacts of gas reburning on furnace performance and NO_x emissions in the presence of oxygen enriched air.

2.3.2 Experimental Design and Hardware Fabrication

A pilot-scale test facility, the Fuel Evaluation Facility (FEF), located at EER's Test Site was selected to address issues which could not be resolved through computational modeling conducted during Phase I. The temperature profile in the FEF furnace was altered to closely match the temperature profile predicted by CFD modeling for a model steel reheat furnace. Steel heat absorption was simulated by placing several back cooled steel panels in the burner zone. A pilot-scale OEA burner was designed and fabricated to simulate oxygen enriched combustion. Pilot-scale gas and OFA injectors were also designed and used for the tests. An elliptical radiometer was used to measure heat fluxes to several components of the furnace. A continuous emissions monitoring system which consisted of NO_x, O_2, CO, and CO_2 analyzers was used to monitor gaseous emissions. Thermal and suction pyrometers were used to measure temperature at several locations along the furnace axis.

2.3.3 Pilot-Scale Experiments

Several series of simulation tests were conducted to obtain test data on the performance of the pilot-scale OEA burner. Data review was carried out concurrently with the testing to provide necessary and timely adjustments to the test conditions and/or hardware. Several combinations pilot-scale burner stream velocities were adjusted and measurements were made to determine their impacts on furnace heat absorption and NO_x emissions. Several levels of fuel heat input typical of reheat furnace combustion intensity were tested over a wide range of OEA burner and gas reburn stoichiometries. Detailed discussions of the pilot-scale experiments are discussed in Section 4.

2.3.4 Cost Effectiveness Assessment

The overall cost-effectiveness of the ASRF concept was developed based upon the results of the CFD modeling study and pilot-scale tests. The cost effectiveness assessment considered (a) capital costs to retrofit the technologies to the model (b) most practical, or optimum, method and cost of oxygen supply, and (c) production gains, operating efficiency, and restrictions affecting reheat furnace operations.

3.0 Computational Modeling

3.1 Steel Reheat Furnaces

Continuous steel reheat furnaces are used to raise the temperature of the steel shapes for further high temperature processing. The product flow in a reheat furnace is countercurrent to the flue gas flow as shown in Figure 3-1. It is common for reheat furnaces to have multiple heating zones or individually controlled banks of burners. Zone flue gas, with temperatures ranging from 2,150°F to 2,650°F, is ultimately exhausted through a recuperator to the stack at 700 to 1,200°F. Even with recuperation overall furnace efficiencies are low (45 to 60%) and stack gas sensible heat losses relatively high. This and the need to transfer heat by radiation in the heat zones suggest that oxygen enrichment of these zones would offer some significant benefit in thermal efficiency and productivity. Figure 3-2 shows three typical ways that oxygen can be used to enhance combustion in steel reheat furnaces:

- Oxygen Lancing: This method is generally used for low levels of oxygen enrichment. One advantage of this method is that it produces lower levels of NO_x emissions compared to other methods since this is a form of air staging.

- Air-Oxy/Fuel Burner: This method involves separately injecting air and oxygen through a burner. It can be used with higher levels of oxygen enrichment, which yields higher benefits. One advantage of this method is it allows the flame shape and heat release to be adjusted by controlling the amount of oxygen used in the process.

- Oxy/Fuel Burner: In this method, the fuel and the oxygen remain separated inside the burner and do not mix until reaching the outlet of the burner. It is generally used for very high levels of oxygen enrichment. Oxy/fuel combustion has the greatest potential for improving a process, but it may also have the highest operating cost and NO_x emissions.

Chemical equilibrium calculations at adiabatic conditions predict furnace gas temperatures in the reheat furnace zones which are sufficiently elevated to produce high levels of NO_x, as shown in Figure 3-3. In reality, the process is far from adiabatic due to the highly stratified, radiating flames developed through burner modifications, which result in flame and mixing zone temperatures somewhat higher than conventional burners. These increases will result in initial conditions that are more favorable for gas reburning, e.g., greater than 2,200°F and NO_x levels approaching 600 ppmv, as shown in the experimental data presented in Figure 3-4. This figure also shows a block

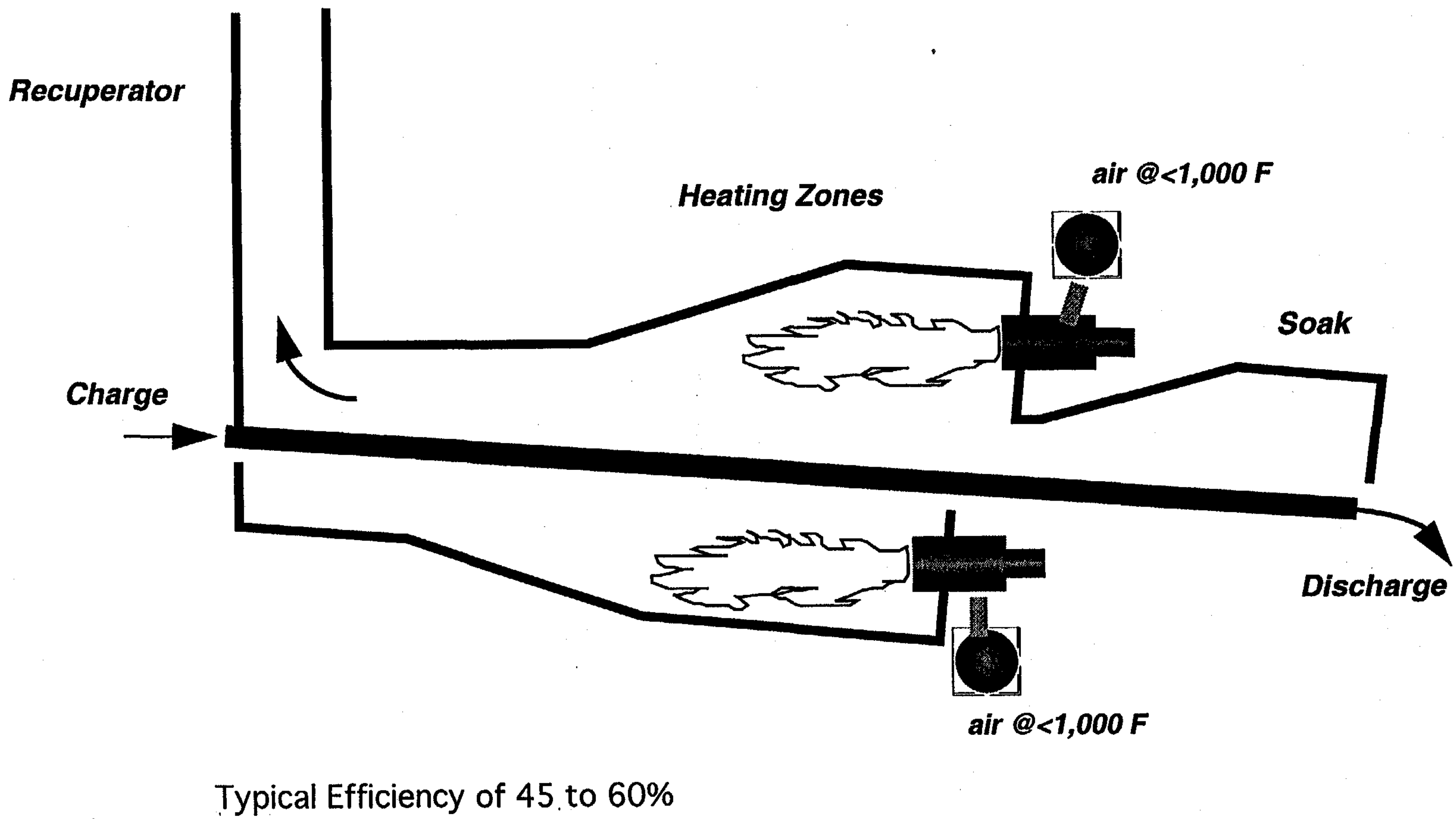
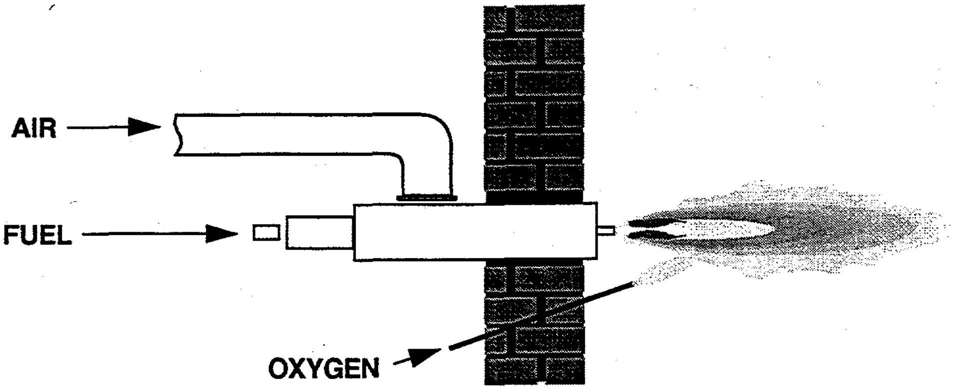
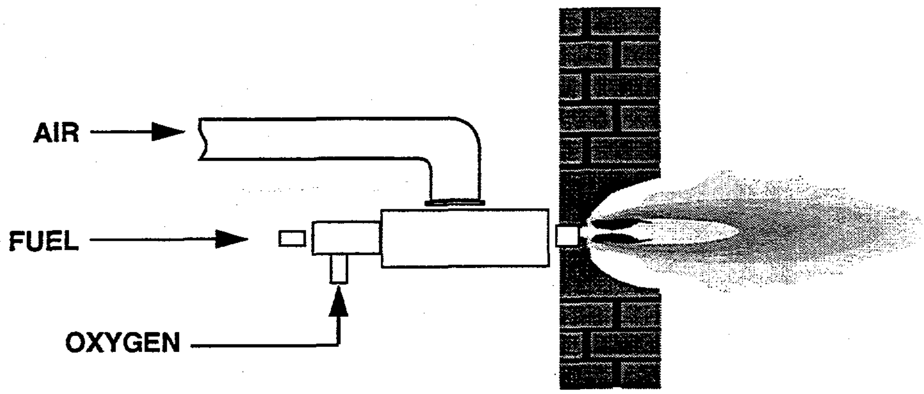


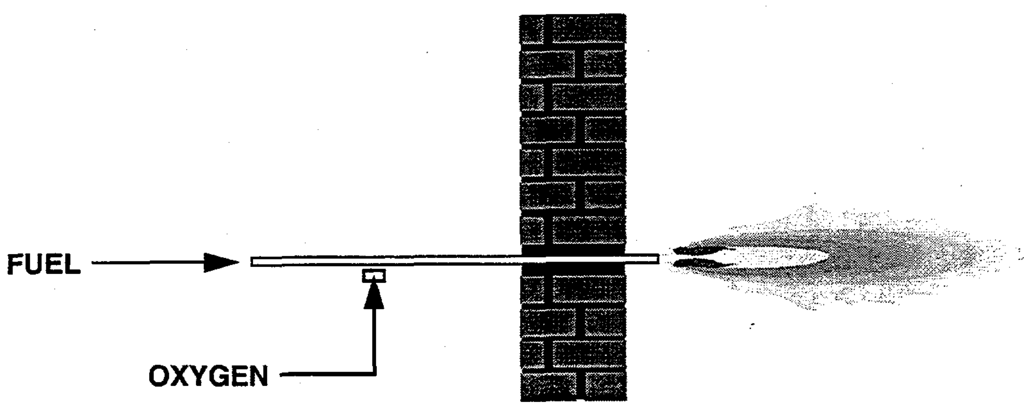
Figure 3-1. Typical pusher reheat furnace with three separately controlled combustion zones.



a) Oxygen Lancing



b) Air-Oxy/Fuel Burner



c) Oxy/Fuel Burner

Figure 3-2. Oxygen enrichment concepts.

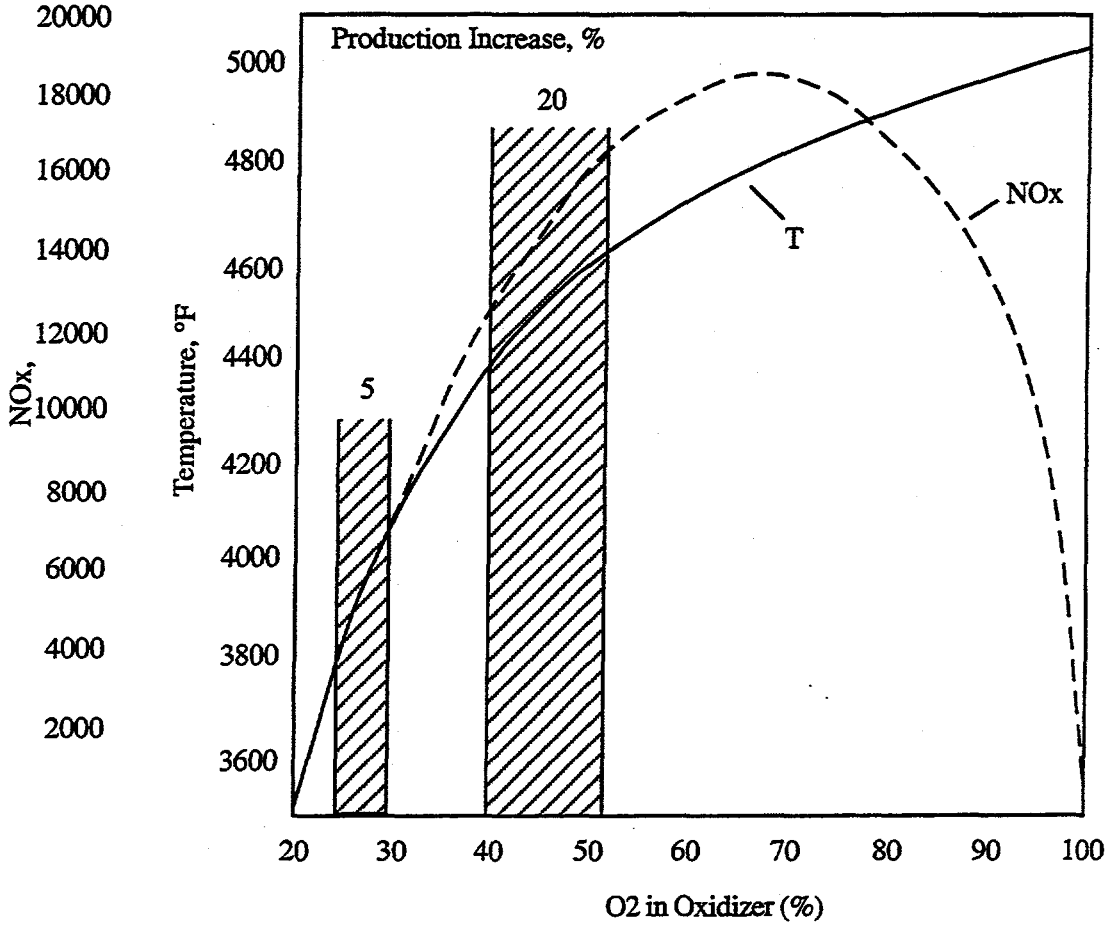
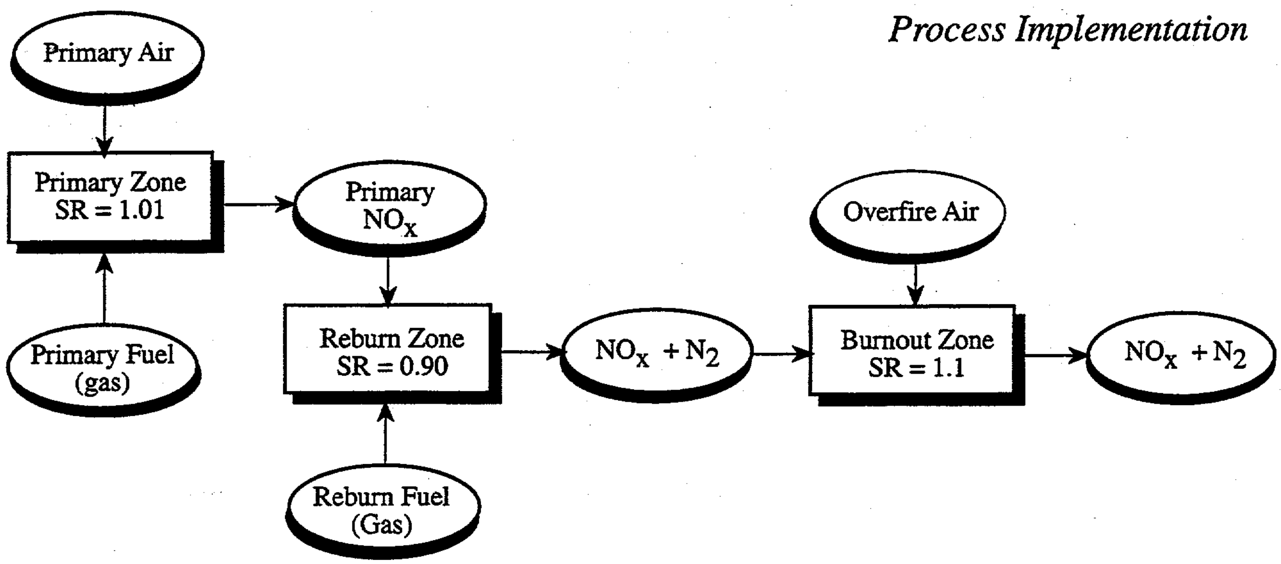


Figure 3-3. Oxygen enriched theoretical flame temperatures and NO emissions.



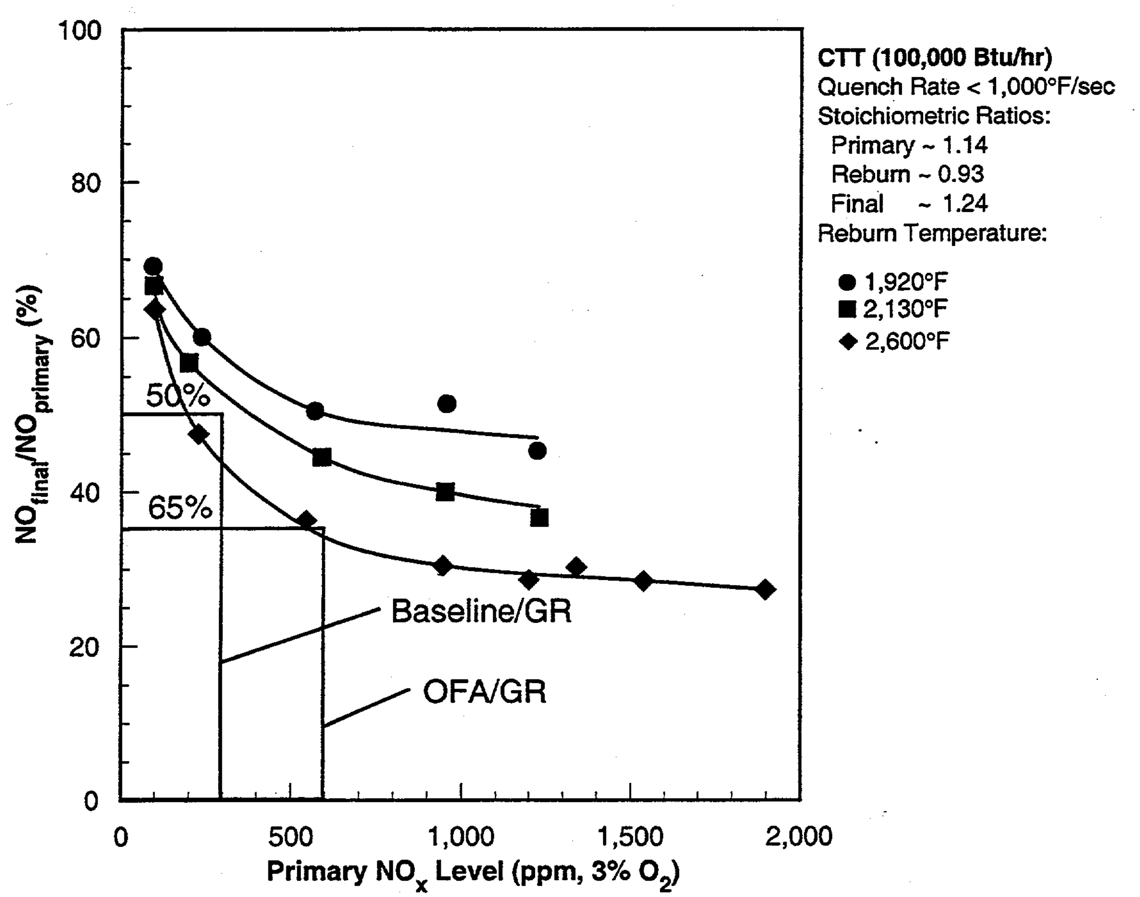


Figure 3-4. Gas reburn process conditions and pilot scale NO_x performance.

diagram of the gas reburn process zones and their typical stoichiometries to be implemented in the steel furnace heat zones. The soak (holding) zone would be conventionally operated as part of the primary zone, perhaps at slightly lower excess air, and therefore should be neutral with respect to fuel efficiency, scale formation, and NO. Any CO slip from the soak zone will ultimately be controlled in the overfire air (OFA) section of Zone 3. The gas reburn (GR) injectors are located in the last reheat zone or the preheat section. The GR injection location must be substantially post combustion, near stoichiometric, and at a temperature sufficient for effective free radical formation. For a walking beam furnace with multiple ceiling burners gas reburn could conceivably be implemented by operating the last burner set fuel rich. OFA injectors are located downstream based on considerations of optimum NO_x reduction by maximizing reburn zone residence times subject to constraints of complete combustion and maintenance of furnace heat transfer efficiency.

The design of an advanced reheat furnace system is site and equipment specific. In order to perform an evaluation in sufficient detail to support the design and development phases of the project, a model furnace was first developed. This model was identified from market derived data, by matching an actual furnace for which design and operational data was available to typical furnaces, as shown in Table 3-1.

3.2 Process Analysis

Two computational models based on the model furnace specification have been developed and refined:

- a two-dimensional computational fluid dynamic model of the entire furnace
- a zoned system model based on heat transfer and mass balances

These models had been partially validated at baseline with furnace design and field operating data. The models were then used to predict the performance and economics of two scenarios: gas reburn with and without OEA.

3.2.1 Furnace Process Modelling

This assessment was based on the following approach which serves as a model for the first phase of the proposed work:

- The development of a reference furnace specification and flow sheet which is typical of modern practice,

TABLE 3-1. TYPICAL AND MODEL FURNACE DESCRIPTION

Parameter	Units	Slab	Boom/Billet	Model
Hearth				
Width	ft	32	25	30
Length	ft	110	60	65
Charged Steel				
Thickness	in	9	6	5.5
Width	in	60	6	5.5
Length	ft	28	22	2.3
Production	tph	250	100	115
Efficiency	MMBtu/ton	1.8	1.5	1.2
Steel Residence Time	hr	2.4	1.6	1.8
Zones		4	3	3
NOx	lb/MMBtu	0.4	0.3	0.3

- A parametric study of the effects (heat transfer and thermally efficiency improvement and the resulting NO_x increase due to high temperature operation) of an oxygen, air, and fuel burner as applied to the heat zones,

- The effectiveness of GR as the primary control of NO_x and CO.

3.2.2 Reference Furnace

A market survey was conducted prior to the CFD analysis to assess the market size and define the "reference" reheat furnace. The survey showed that a pusher type billet reheat furnace is representative. A schematic of the furnace is shown in Figure 3-5. The furnace is 65 foot long, 30 foot wide with three zones: soak, top heat zone and bottom heat zone. The furnace is fired with natural gas with No. 2 oil as backup. Steel billets are end charged and side discharged. This furnace was designed by Bricmont, Inc. in 1992 and was brought online in June of 1993. It is a modern furnace with computer control and high fuel efficiency. The design production rate is 115 TPH and the steel discharged temperature is 2,150°F. The recuperated furnace preheats combustion air to 1,000°F and exhausts flue gas at 1,600°F. The total fuel firing rate at the design condition is 140 MMBtu/hr, or approximately 1.2 MMBtu per ton of steel reheated. The heat distribution among the zones during different modes of operation is shown in Table 3-2. During full load operation, 50% of the fuel input is distributed to the top heat zone. Burners of this furnace are from Bloom Engineering Co., Inc. (Pittsburgh, PA). The type, quantity, and key geometry information are shown in Table 3-3. The overall furnace dimension is large as compared to the details of the burners, which is critical to establishing the correct flames in the furnace. This large difference in geometric scale poses a challenge in the numerical solution because it results in a large computational grid.

Two applications using gas reburning with or without oxygen enrichment, as shown in Figure 3-6, have been studied:

- A gas fired furnace operating in a nonattainment area for ozone and requiring 50% NO_x reduction.

- A furnace requiring about a 20% increase in billet heating capacity, and a NO_x reduction of 30 to 40% relative to the NO_x baseline to achieve offset emissions.

3.2.3 Computational Fluid Dynamic (CFD) Model

The CFD modeling was used to establish steel and flue gas temperature profiles for key operating conditions (oxygen enrichment and gas reburn) and to support the location of reburn and overfire air (OFA) injectors. The furnace was sufficiently wide to be modeled as two dimensional (2D).

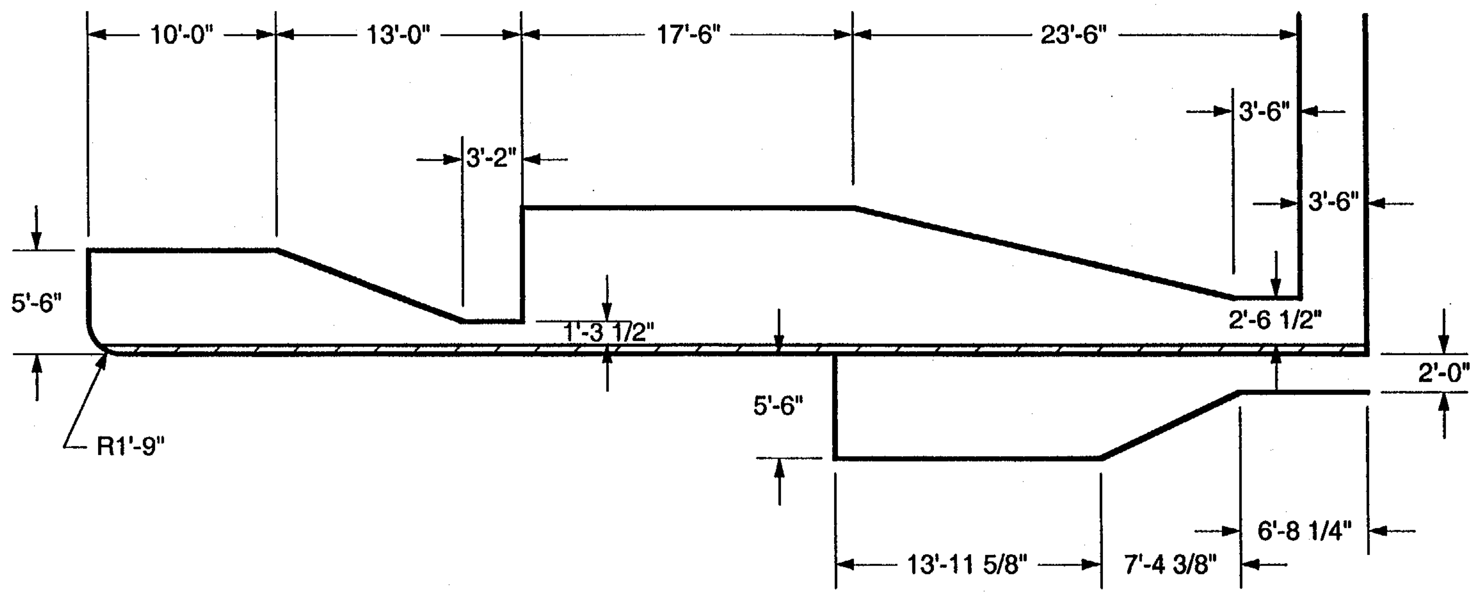


Figure 3-5. Geometry of the representative reheat furnace.

TABLE 3-2. FIRING RATES AT VARIOUS OPERATING MODES.

Parameter	Units	Full Load	Part Load	Idle
Production Rate	ton/hr	115	70	0
Heat Input				
Soak Zone	MMBtu/hr	25	25	2.5
Top Heat Zone	MMBtu/hr	70	40	7.0
Bottom Heat Zone	MMBtu/hr	45	19	4.5
Total	MMBtu/hr	140	84	14.0

TABLE 3-3. BURNER SPECIFICATIONS

Bloom Burner Number	Quantity	Zone	Air Diameter, in	Gas Diameter, in.	Gas Lance (5%) OD, in.	Gas Lance (5%) 4 Holes @ in
S-1070-080 FTR	25	Soak	9.25	1.625	n/a	n/a
S-1070-160 FTR	8	Top	18.00	3.500	1	0.120
S-1070-125 FTR	7	Bottom	16.00	3.000	1	0.104

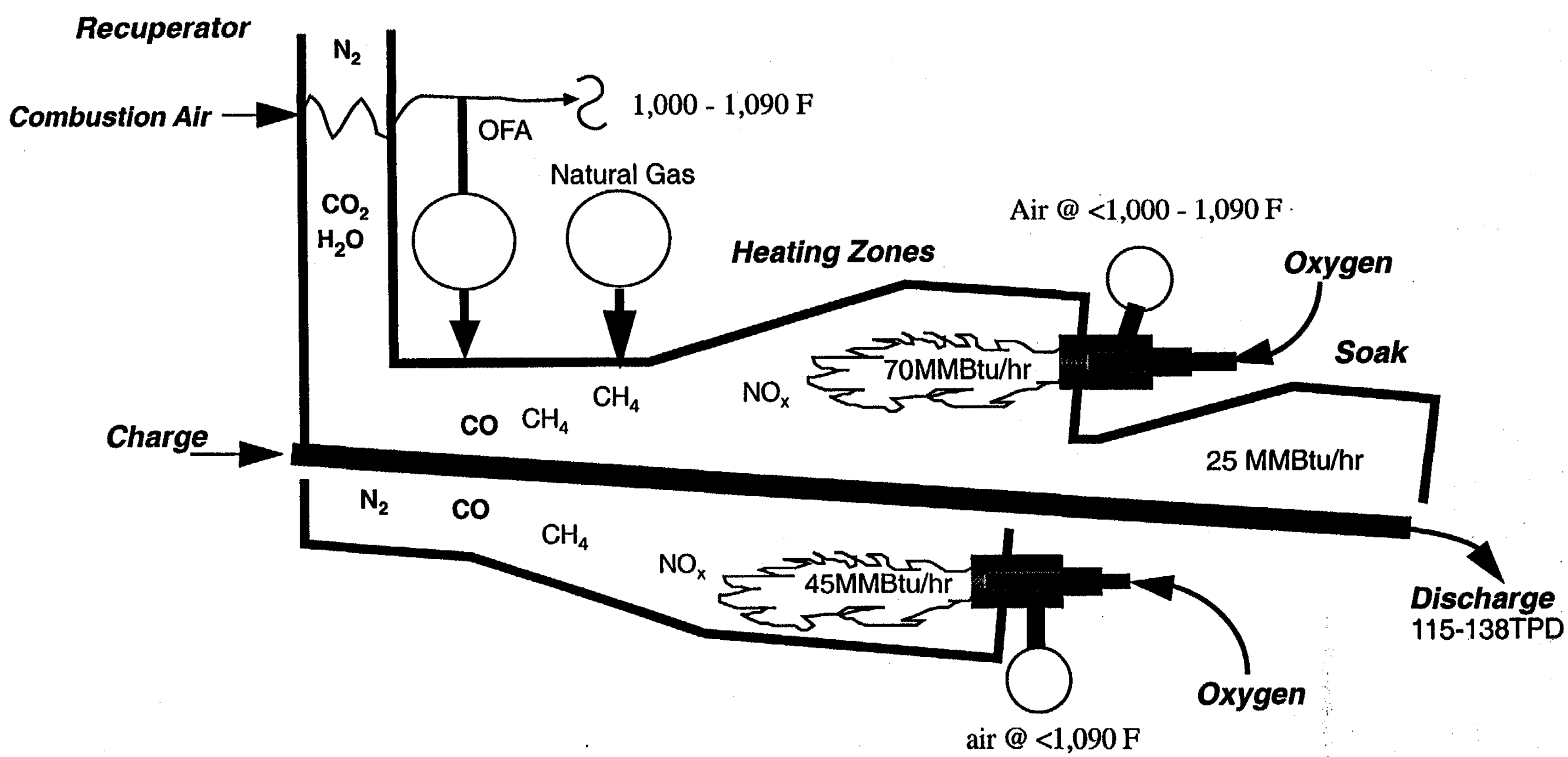


Figure 3-6. Typical reheat furnace modified for heat zone oxygen enrichment and gas reburn.

This implied that the heat loss from the side walls could be neglected. This was reasonable since losses account for about 4% of the gross fuel energy input, and the side-wall areas were small as compared to the roof and bottom walls. Another implication was the amount of energy distribution by radiation as a result of the side walls. Since the refractory walls had very little heat loss, they were close to perfectly reflective walls of the third coordinate direction as assumed in the 2D model. Therefore, the 2D result would be representative of the true situation except, perhaps, in a small steel volume immediately next to the side walls. The bottom zone was assumed to have no radiative communication with the top heat zone except through the steel, and their flue gas flows were assumed not to merge until the flows were vertically directed. In reality, the furnace width increased under the chimney, a feature known as "ears" in the industry. The ears would allow flue gas from the bottom zone to join the rest of the flue before leaving the furnace. Without the flue gas from the bottom zone, the average velocity in the tail end of the model furnace would be lower, providing more residence time for CO burnout when operating in the reburn mode.

Natural gas was assumed (90% CH_4, 5% C_2H_6 and 5% N_2 by volume) with a molecular weight of 17.3. Its gross heating value (HHV) was 1,001 Btu/scf, and required 15.76 pounds of air per pound of gas. These fuel characteristics were used consistently in both the CFD model and the process model.

A flame soot model had not been incorporated into the CFD modeling. Soot formation is a complex topic and only qualitative models were available for prediction. The accuracy of such a prediction depends critically on the flow and temperature fields, which in turn were intimate with mixing patterns. Since the 2D model could not predict the 3D mixing pattern in the furnace, even qualitative trends of soot may not have been feasible for this geometrical approximation.

The governing equations for the conservation of mass, momentum, energy and chemical species were solved with the FLUENT software package (FLUENT User's Guide, 1996). A finite difference scheme was used where nonlinear variations were included inside each control volume, similar to the concept of a shape function in a finite element scheme. This method was a variation of the original approach by Patankar (1980). This formulation ensured the balances of mass, momentum, energy and species locally (within each control volume) to achieve physically realistic results even on coarse grids. A grid of 131 by 112 computational nodes was used. Exploratory calculations had shown that the results were independent of further grid refinement. To further assure the accuracy of the solution, a second order discretization scheme (Leonard, 1979) was used. The solution was allowed to iterate until the residuals were reduced by at least 5 orders of magnitude. More importantly, field variables were monitored to ensure they did not vary with further iterations, and the overall mass, species, and energy balances were satisfied. The overall error in the energy balance was believed to be on the order of 3% of gross firing rate.

CFD solutions are presented for two conditions, beginning with a baseline case representing design operation. Overall, about 55% of the fuel energy (140 MMBtu/hr) was absorbed by the steel to reach an average discharge temperature of 2,120°F. Water cooling amounted to 11% loss, and refractory loss was 4%. At an average exhaust temperature of 1,725°F, flue loss amounted to 27% of total input. The flue temperature was in reasonable agreement with the recuperator design inlet temperature of 1,600°F. The average gas velocity at the nose was 9.8 ft/s, and the average gas temperature was 2,166°F. Axial furnace temperatures at baseline, Figure 3-7, showed upper zone peak flame and bulk temperatures at around 3,700 and 3,200°F, respectively. Temperatures were sufficiently high mid way along the top heat zone, about 2,800°F, to inject reburn fuel. The model also predicted primary combustion to be substantially complete at this location, e.g., CO<200 ppmv. The velocity profiles are shown in Figure 3-8. Note that the velocity at the point of reburn fuel and overfire air (OFA) injection is approximately 30 ft/s. Jet velocities were selected to penetrate at least 70% through the bulk gas at these locations.

The second case evaluated the impact of increasing furnace production by 20% through oxygen enrichment. Enrichment was implemented by premixing oxygen into the air supply duct for the top zone only. Furthermore, 75% (10.5 MMBtu/hr) of the reburn fuel energy was assumed to be recovered inside the furnace. Iterative calculations predicted the need for the top zone combustion air to be enriched to 50% oxygen. The CFD model showed that the average steel discharge temperature was 2,159°F, and that the average exhaust flue temperature was 1,640°F, all within expectations.

At the nose, the average velocity was 10 ft/s, and the average gas temperature was 2,213°F. Since the soak zone firing pattern had not changed, the increase in temperature was solely due to radiation from the top zone. The slight velocity increase was due to the increased temperature. The temperature distribution is compared to the baseline in Figure 3-9. Although the peak flame temperature is considerably higher by 460°F, the peak ceiling refractory temperature increased more modestly from 2,822°F to 2,950°F (128°F). Examination of the steel temperature profile indicated that the heat transfer rate in the top zone with oxygen enrichment was higher, since the temperature curve had a steeper slope and crossed that of the baseline case. The velocity profiles were similar to the base case. Fuel efficiency, at 1.014 MMBtu/ton, improved inversely to the production increase.

Combustion is a complex phenomenon that presents great challenges for numerical modeling. Some of the fundamental aspects involved in combustion, such as turbulence, chemistry, radiation and soot are not even well understood today. Therefore, the results presented are only approximate, consistent with the accuracy of the inputs and that of the physical models. However, experience shows that the results are helpful in predicting trends and supporting engineering design decisions.

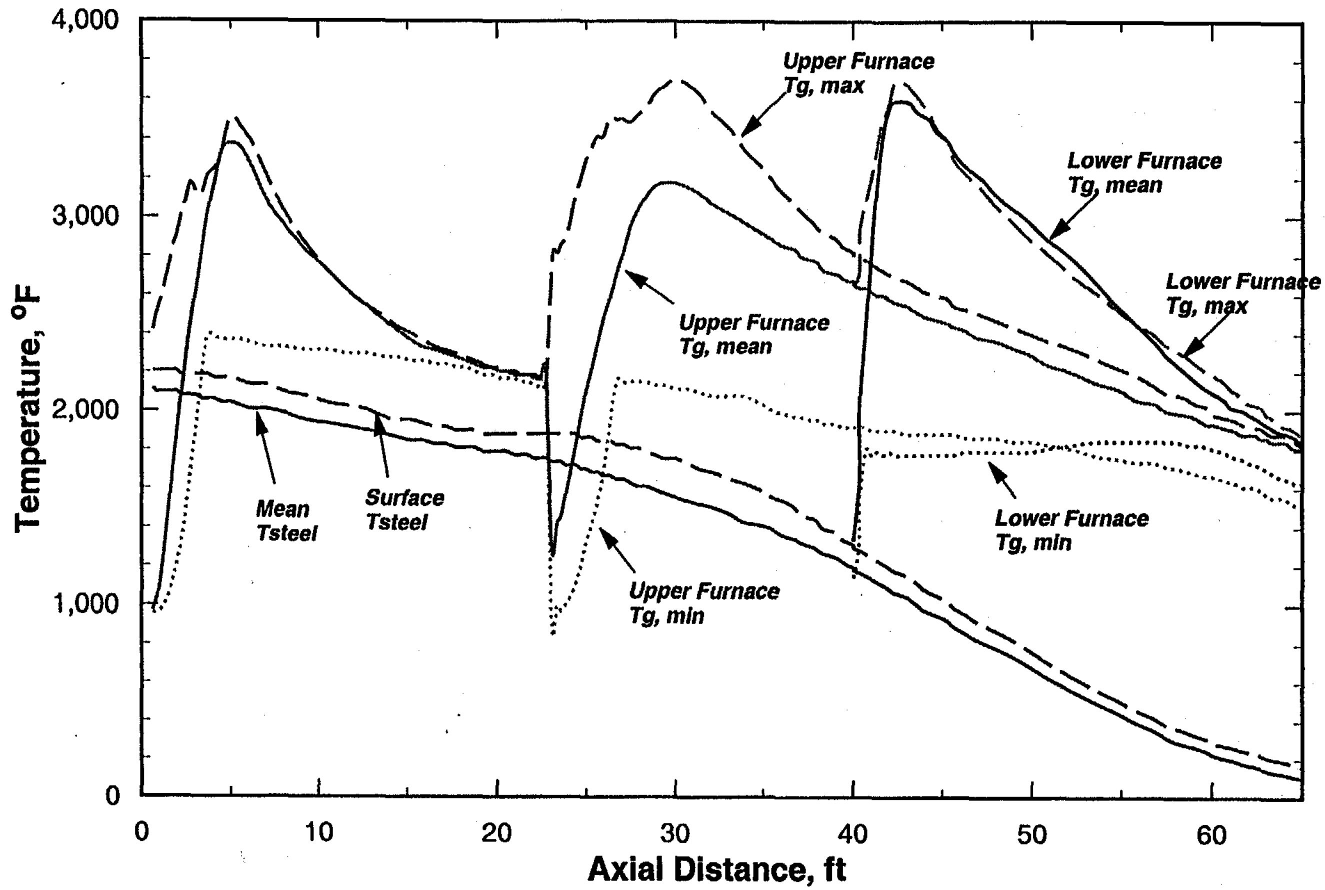


Figure 3-7. Baseline axial flue gas and steel temperatures.

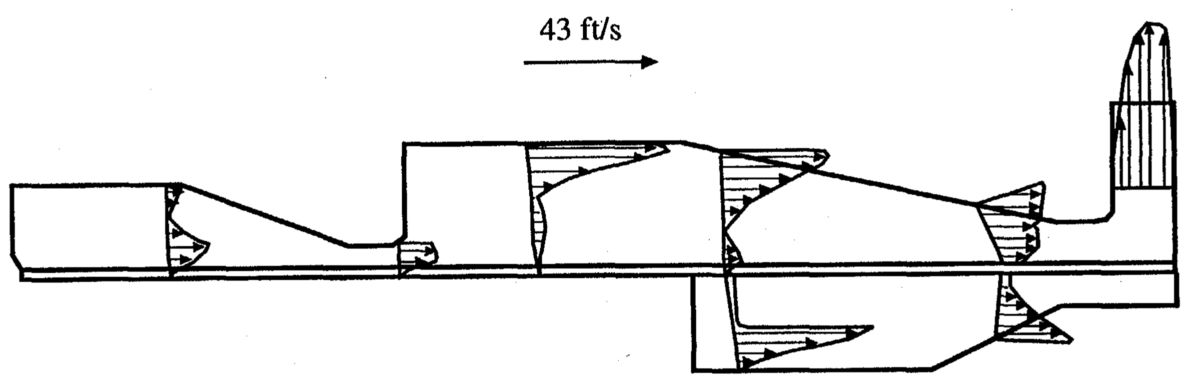


Figure 3-8. Velocity profiles at various furnace cross sections.

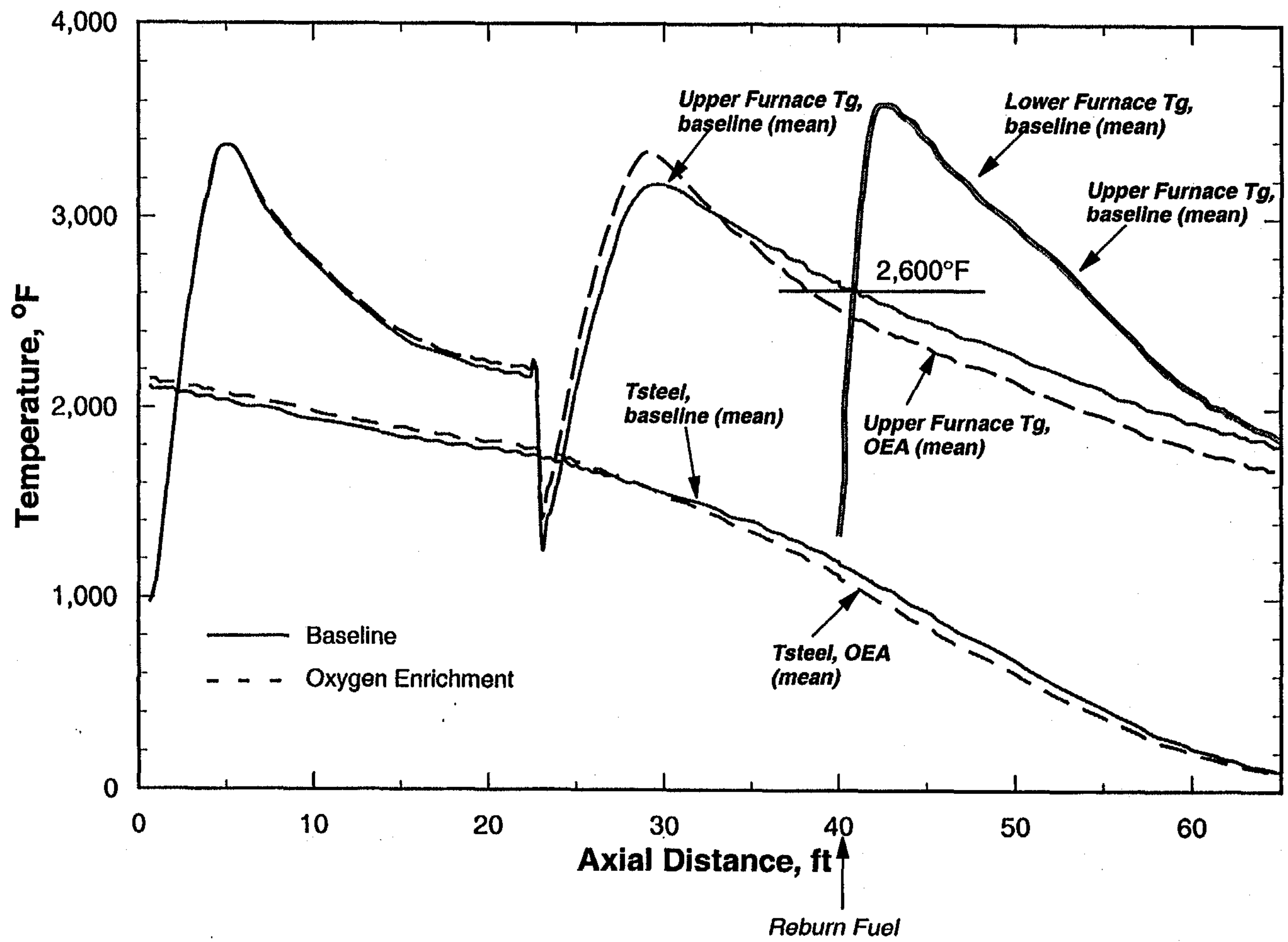


Figure 3-9. Axial flue gas and steel temperatures at baseline and oxygen enriched conditions.

3.2.4 Zoned System Model

The CFD model is labor intensive to construct and modify, and requires long computational times. Therefore a Zoned System Model using a simple mass and energy balance calculation was developed to evaluate the primary impacts of changes in operating conditions such as variation in gas reburn or oxygen enrichment parameters. The model divided the furnace into distinct zones. A simplified, *zero dimensional radiative and convective heat transfer model* was applied to each zone. Gas radiative properties were estimated based on Smith, Shen & Friedman (1982), considering the participation of CO_2 and H_2O but not soot, consistent with the Fluent model. There was no direct heat transfer between zones except for the carryover of sensible heat as furnace gases passed from one zone to another, and through interaction with the steel which passed through each zone. Because the steel moved counter to the gas flow direction, the steel heat transfer was marched backwards from a known exit temperature to the inlet temperature, matched by adjustment of other input parameters (heat transfer constants for the initial Baseline case, and steel feed rate for conditions where furnace efficiency varies). The results of the detailed CFD model were used to refine the model.

This decoupled zone approach allowed for quicker evaluation of performance impacts than was possible with a full CFD simulation. Since the impact of oxygen enrichment based on CFD are presented above, only Zone System Model predictions of the impacts of gas reburn by itself are included here.

Gas reburning as applied to the top heat zone alone was modeled by dividing the furnace into four zones: soak, bottom, and a subdivision of the top heat zones into an upstream and downstream sections. The two upper heat zones were separated by a vertical plane coincident with the burner wall of the bottom zone, at about the location where reburn fuel is injected in the top zone. OFA was also assumed to follow shortly in the second section of the top heat zone, so that the zone may be considered to operate at the burnout stoichiometry. Figure 3-10 shows a block diagram of the zones for this furnace and the interaction between them. (However, the upper heat zone and OFA zones have been combined into one section in the current model.)

The model assumes gases from the bottom zone bypass the upper heat zone entirely and mix with the flue gases from the top before entering the recuperator. The ducts leading from the heat zones to the recuperator were not modeled separately but were implicitly included in the regenerator calculation. Heat losses in these ducts and the recuperator were neglected but were expected to be minor.

The input assumptions were kept consistent with the Fluent modeling approach as much as practical. The wall area and thermal resistance was updated to include side walls (not possible in the 2D Fluent model), but on the other hand did not allow for heat losses underneath the steel in the

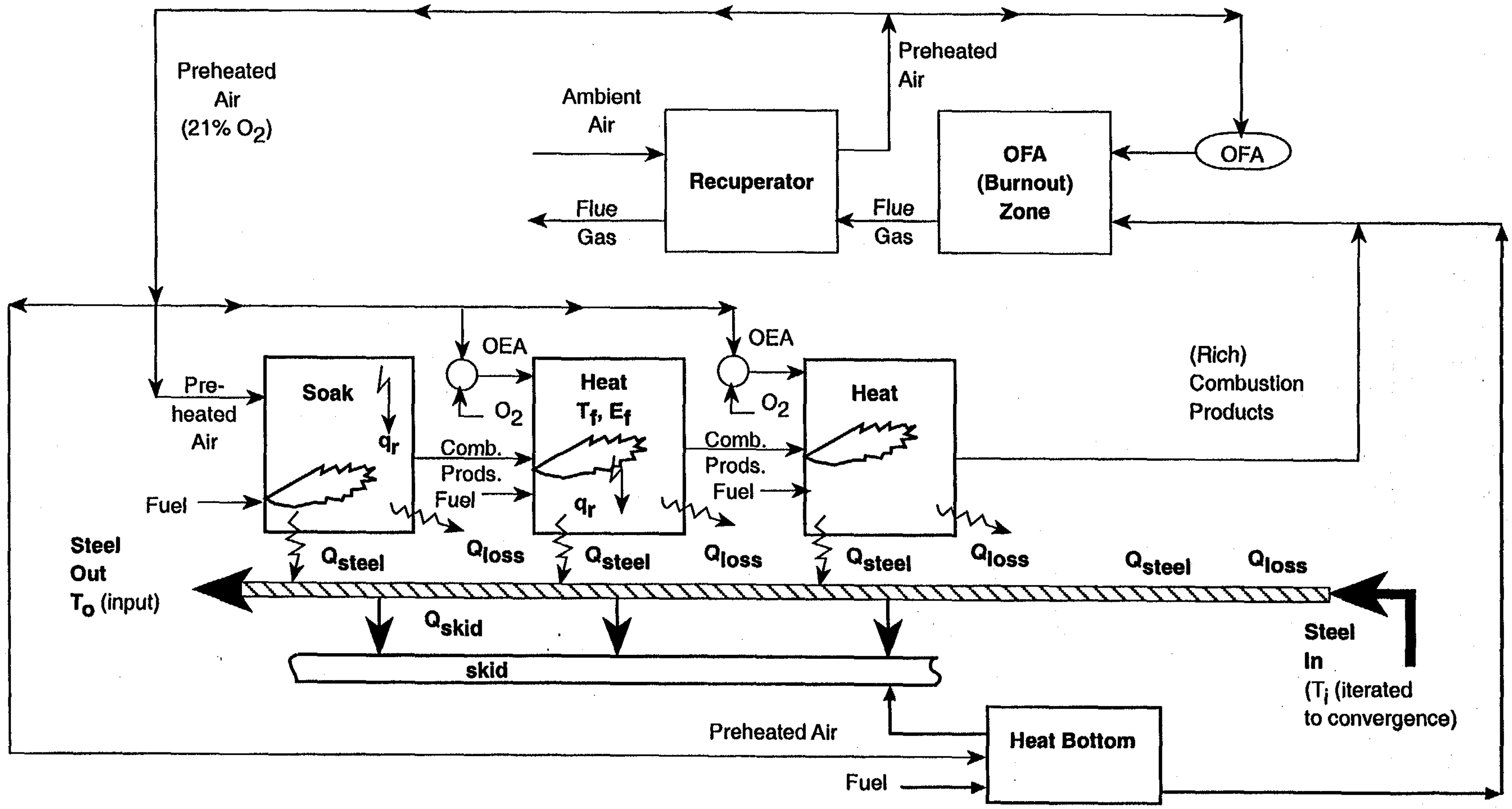


Figure 3-10. Schematic of mass and heat balance in steel reheat furnace.

region without a bottom heat zone. To match steel energy absorption in the baseline case, wall thermal resistances and steel emissivity were modified from the Fluent model parameters, but to values reflective of available information and experience.

Recuperator performance was incorporated into the model using the effectiveness method based on a NTU (Number of Transfer Units). This value was established initially from baseline operating conditions and held constant at all other conditions. Heat removal from the steel skids (by cooling water flow) was included in the furnace model, and was assumed constant (15 MMBtu/hr) over the configurations investigated.

Figure 3-11 shows baseline mass and energy parameters of interest. Reburning in the top heat zone was then applied as a perturbation to the baseline model, with a given percentage of the total fuel heat input diverted from the first to the second section of the upper heat zone. This effectively moved the heat release further downstream.

Figure 3-12 shows the impact of a variation of 0 to 15% total fuel in the reburn zone on the energy demand, measured in MMBtu per ton of steel produced. The impact of 15% reburning was a reduction in overall furnace efficiency of about 2.3%. One way of viewing this was that only about (2.3%/15%) or about 16% of the reburn fuel heat input was stack lost, implying 84% heat recovery of the reburn fuel.

Reburn fuel heat recovery results from direct heat transfer to the steel within the heat zone and recuperated heat in the form of higher air preheat temperatures. This temperature impact is shown as a function of the amount of reburn fuel in Figure 3-13. At 15% reburning, the additional air preheat energy accounted for about 1.2% of the 140 MMBtu/hr fuel heat input. This implies that most of the reburn fuel heat input was recovered directly in the furnace. Indirect heat recovery in the recuperator was less efficient and thus less desirable than direct heat transfer to steel, but did represent an additional mitigation of the heat loss due to delayed combustion of reburn fuel.

3.2.5 Flow Sheet Performance

The above modelling results have been used to develop flow sheets with which to establish performance and economics. The previously discussed CFD results were used to locate furnace cross sections for agent injection (reburn fuel and overfire air). The temperature and CO profiles established the fuel injection location, e.g., just downstream of the CO<200 ppmv contour (complete combustion) and at the highest bulk furnace temperature, T>2,400°F. The zoned system model was then used to determine the impact of these locations on the amount of the reburn fuel heat that was usefully recovered, i.e., in the steel and recuperator. For purposes of the proforma economic analysis the furnace baseline NO_x emission was assumed to be 0.3 lb/MMBtu.

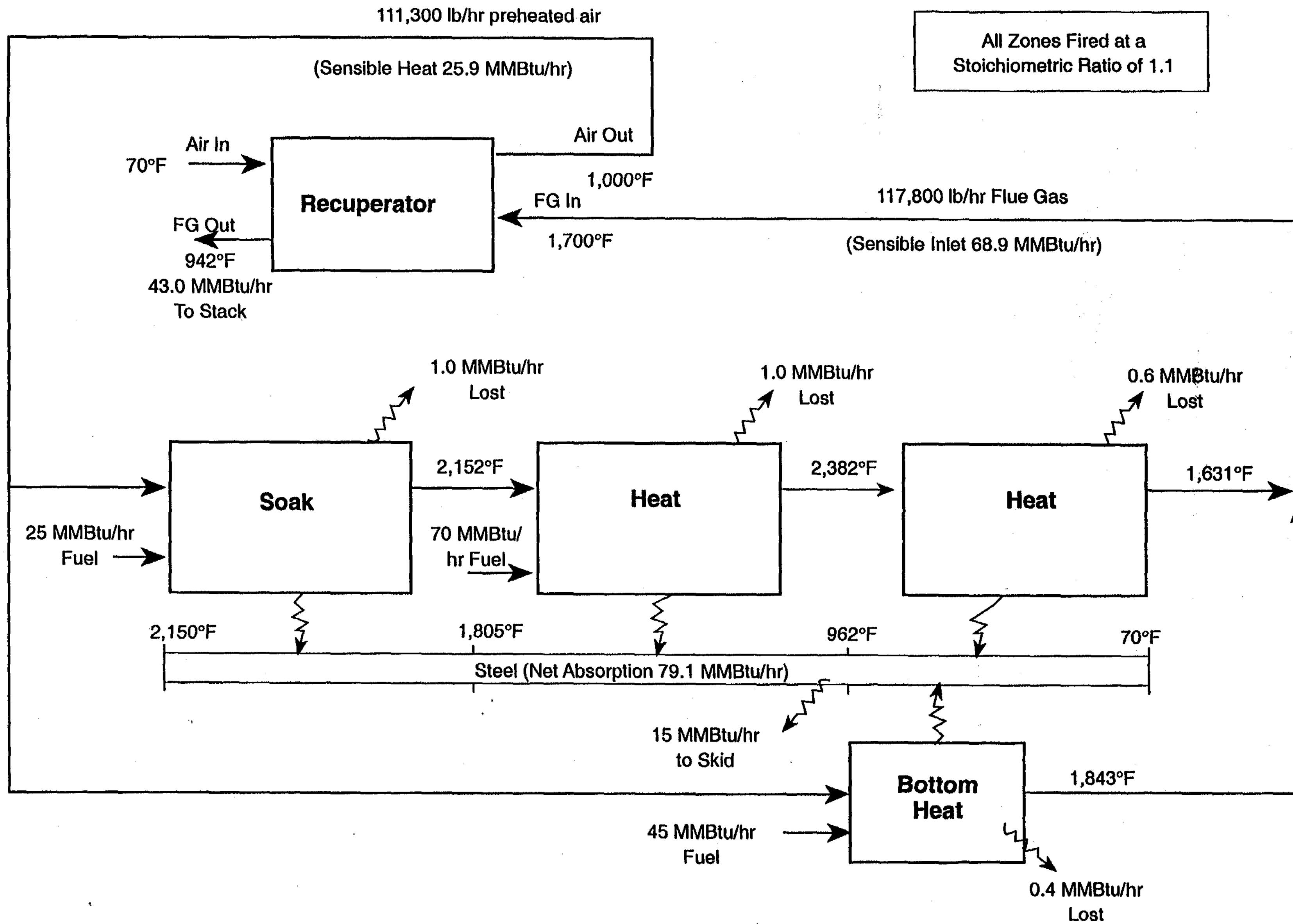


Figure 3-11. Heat and mass balance for baseline conditions.

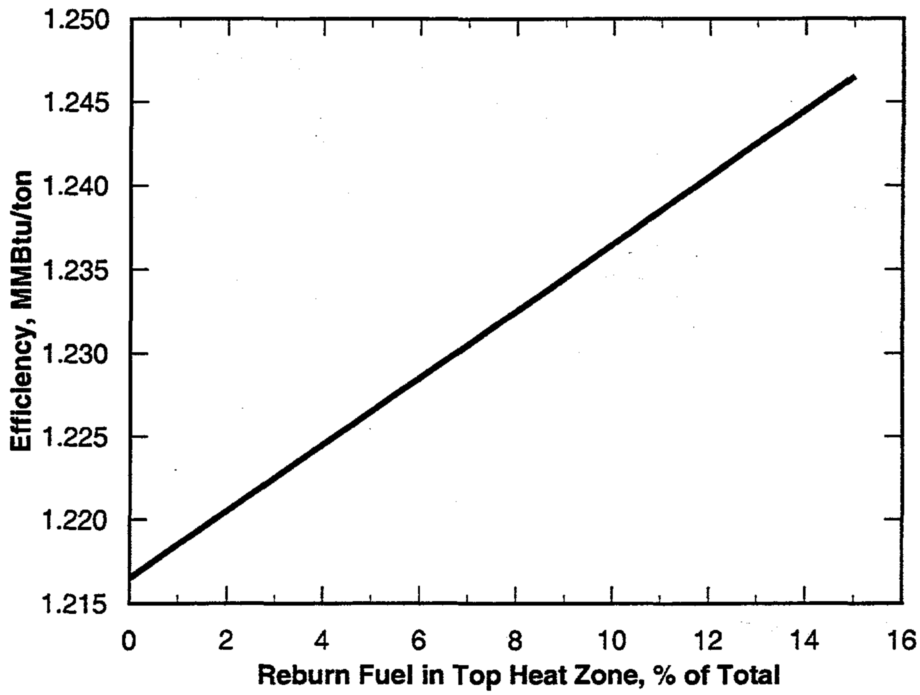
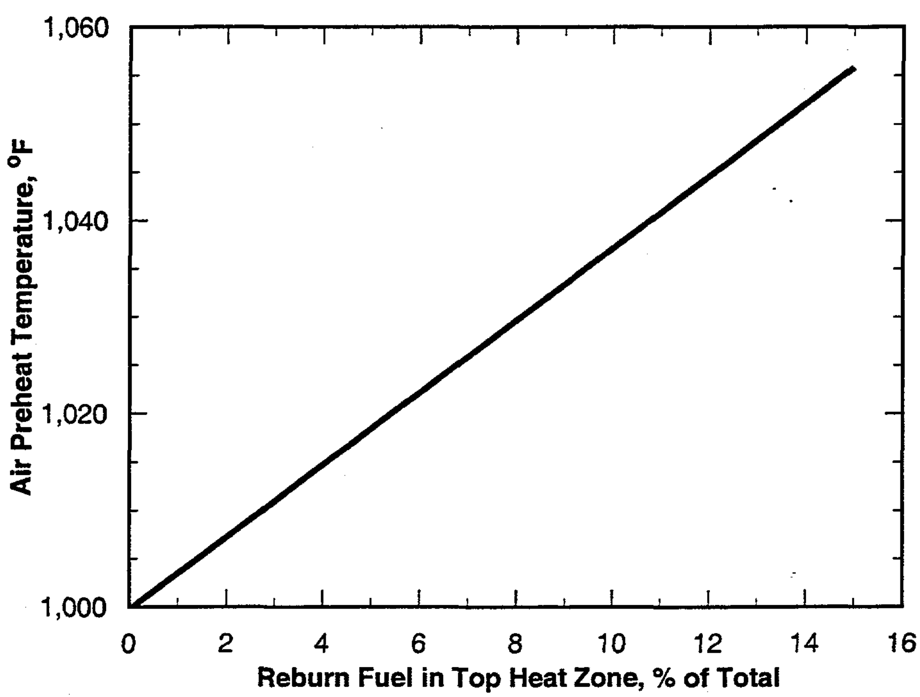


Figure 3-12. Impact of gas reburn on fuel requirements.



Figue 3-13. Impact of gas reburn on air preheat temperature.

CO and CO_2, respectively. The carbon potential for this mixture was estimated and indicated that even at low stoichiometries the potential for carbonization was several orders of magnitude lower than that used for steel heat treating. On extremely long delays the GR system can always be adjusted to a less severe CO level or shut down to control carbon potential.

3.3 Summary

The utility of developing several interrelated models to assess the impacts of combined oxygen enrichment and gas reburn on steel furnace NO emissions, thermal and production efficiencies has been demonstrated. CFD modelling is useful in determining the temperature and velocity profiles. This data can then be used to determine impacts on refractories and steel surface, and in placing the gas reburn fuel and OFA injectors. The CFD model also provides boundary conditions for other predictive models. The tuned zoned system model has utility in its ability to quickly parametrically investigate design and operating variations from the CFD model results with simple input changes. For the stand alone gas reburn system the importance of optimizing the recovery of heat released late in the heating zone was demonstrated.

4.0 Critical Experiments

A series of pilot scale combustion experiments was conducted in a test facility configured to simulate a steel reheat furnace. The tests were designed to characterize the impacts of oxygen enrichment on system heat absorption and NO_x emissions and to provide experimental, pre-demonstration validation of the computational process models.

Two test series were conducted. The first series involved a preliminary set of operability studies in which the impacts of oxygen enrichment and reburning upon furnace conditions and emissions were characterized. Results of these tests were used to optimize the burner design to facilitate the second test series, which involved a more detailed series of parametric optimization tests.

4.1 Critical Issues

Critical issues evaluated in the pilot-scale test facility included:

- The effects of oxygen-enriched sooting radiation on furnace performance and NO_x emissions, and
- The impacts of gas reburning on furnace performance and NO_x emissions after oxygen enriched air.

4.1.1 Sooting Flame Radiation

One of the critical issues addressed in the pilot experiment was to address the impact of oxy-fuel enriched sooting flame radiation on refractory temperature and steel heating rates. The computational modeling work performed during Phase I indicated that oxygen enrichment would result in negligible impacts of flame radiation on refractory temperatures and up to 20% increase in steel production. The result, however, was based upon wall and radiating gas species and two dimensional flow. The modeling study also did not incorporate sooting flame radiation due to limitation on the prediction of soot formation. Since the modeling work used only the 2D model which could not predict 3D mixing patterns in the furnace, even qualitative trends of soot may not have been feasible. Thus, one of the key objectives of the pilot-scale tests was to address the soot radiation issues with respect to oxy-fuel enrichment.

4.1.2 NO_x *Increases*

The modeling work utilized the NO_x formation mechanisms available in the FLUENT NO_x Module to predict changes in NO_x emissions. The result of the NO_x modeling study showed that oxy-fuel significantly increased NO_x emissions. Since the assumptions made in the data input were simplified to make calculations less intensive, the results needed to be validated against experimental data. Therefore, the experimental work was also focused on evaluating the impacts of OEA quantity on NO_x formation.

4.1.3 Gas Reburn Integration

Gas reburn consists of introducing fuel fragments (reburn fuel injection) downstream of the primary combustion zone which react with the "primary" NO to form either bound nitrogen species or N_2. After sufficient residence time, overfire air is injected to complete combustion of the reburn fuel. The introduction of overfire air initiates a second series of reactions which result in either reduction or oxidation of bound nitrogen species to N_2 or NO, respectively. Under conditions typical of coal fired utility boilers which have high initial NO_x (600 to 1,200 ppmv), up to 70 percent reduction in emissions of NO_x have been achieved.

The key parameters affecting the reburn system performance are:

- Primary NO_x level
- Gas temperature in the reburn zone
- Reburn zone residence time
- Reburn zone stoichiometry

Previous reburning studies have shown that primary NO_x concentration has a direct impact of reburning efficiency, with high primary NO_x levels tending to result in higher NO_x reduction efficiencies. Primary NO_x concentrations in steel furnaces would be expected to increase with oxy-fuel enrichment. Burner effects on NO_x formation were characterized as a function of OEA quantity and reactant injection velocity. NO_x concentrations entering the reburning zone were found to vary widely. Therefore, reburning performance was also evaluated at two levels of primary NO_x concentrations resulting from two pilot-scale burner designs.

The furnace gas temperature at which the reburning fuel is injected will have an impact on the process efficiency, with higher temperatures preferred. Oxy-fuel enrichment air, in turn, would be expected to alter the baseline furnace temperature profile. Therefore, the impacts of furnace temperature on reburning efficiency in the presence of OEA were also evaluated.

Similarly, zone residence time has been shown from previous reburning work to have an impact on NO_x control efficiency. Sufficient residence time in the reburning zone should be available to allow mixing and reaction of the reburning fuel with the residual oxygen and the products from the primary combustion zone. In addition, OEA would be expected to alter zone residence times since the furnace flue gas throughput would change with OEA. Therefore, tests were conducted to investigate the impacts of reburn zone residence time on reburning efficiency as applied to steel furnaces with OEA. The reburn zone residence time was varied in the test facility by varying the location of the overfire air ports.

Previous reburning work has also shown that zone stoichiometries, especially that of the reburning zone, would also have strong influences on reburn performance. For gas reburning, optimum reburn zone stoichiometry is typically about 0.9. Since no air would be added in the reburning zone, primary zone stoichiometry would influence reburning performance by affecting reburning zone stoichiometry at a given level of reburn fuel input. Overfire air would then be added to bring the furnace back to its normal operating stoichiometry. The quantity of overfire air is optimized to ensure complete CO burnout and to help improve the thermal efficiency of the unit. Therefore, all three zone stoichiometries were evaluated during the pilot-scale tests to determine optimum operating conditions for the application of gas reburning on steel furnaces at baseline with air and with OEA.

4.2 Experimental Facility

An existing experimental, pilot-scale furnace rated at 800,000 Btu/hr was modified to simulate the essential features of a steel furnace heating zone. Various hardware and process variations were characterized as to heat transfer and NO_x performance.

4.2.1 Experimental Set-up

The combustion tests were conducted in EER's Fuels Evaluation Facility (FEF). The FEF is a downfired research combustor with a nominal firing capacity of 800,000 Btu/hr. It is designed to provide an accurate subscale simulation of the combustor flame conditions, furnace gas composition, and residence time-temperature profile found in a full scale furnace. A schematic of the FEF is shown in Figure 4-1. The furnace is designed with a high degree of flexibility with regard to fuels, furnace conditions, and heat extraction rates. The FEF consists of a burner, vertically down–fired radiant furnace, and horizontal simulated convective pass. The burners used in the project are described in Section 4.3. A divergent quarl is located at the top of the furnace for flame stabilization. The radiant furnace is equipped with numerous ports to allow access for supplementary equipment such as sampling probes, cooling panels, and suction pyrometers. The cylindrical furnace section is constructed of six modular refractory–lined sections with an inside diameter of 22 inches.

Municipal natural gas was used as the primary fuel. It was delivered by means of static line pressure and was metered using a calibrated rotameter. Combustion air was supplied using a forced draft blower. Air flow rate was measured using a venturi meter. An indirectly-fired natural gas preheater was used to preheat the combustion air up to 600°F. Pure oxygen was metered into

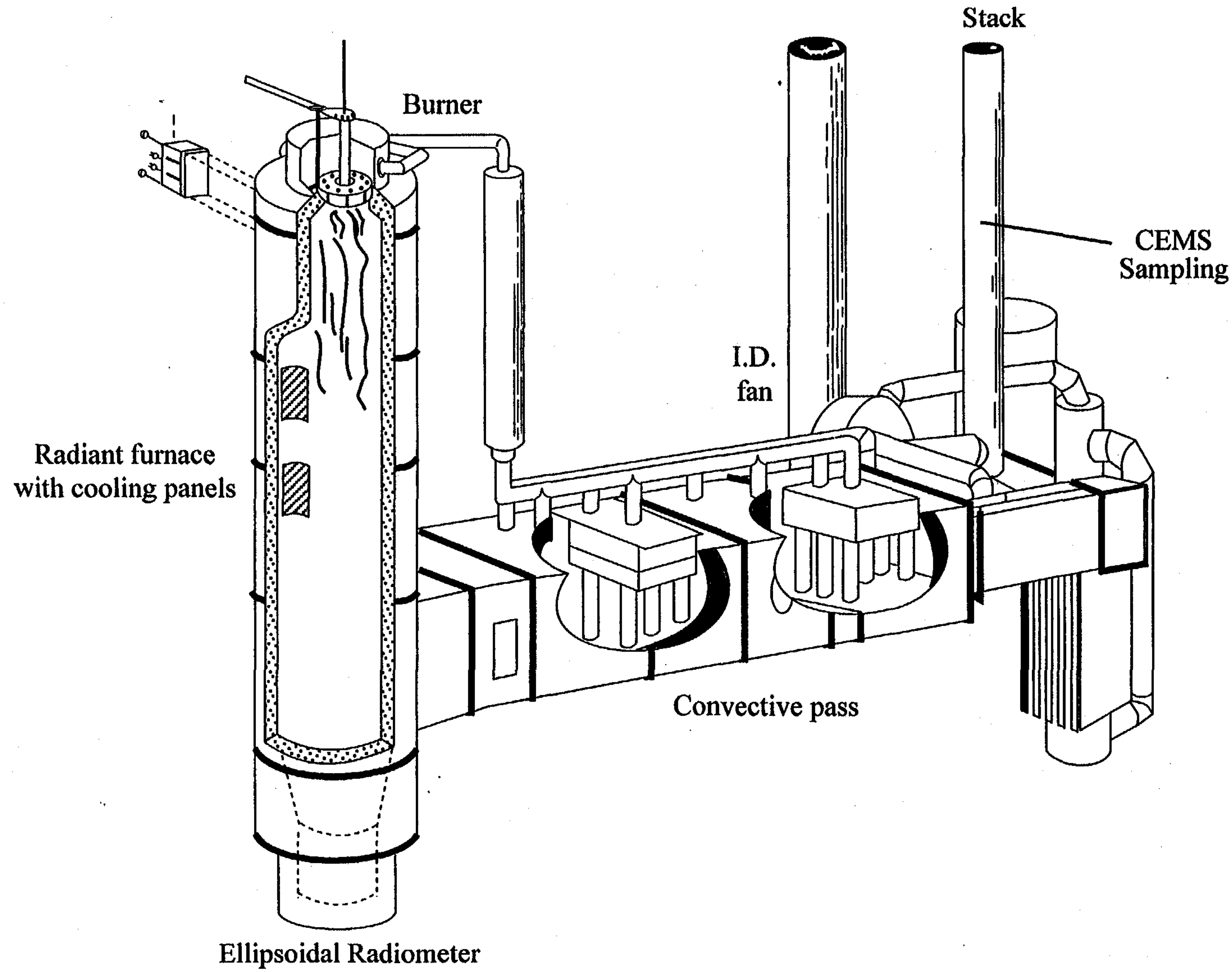


Figure 4-1. Fuels Evaluation Facility (FEF)

the furnace from compressed gas bottles. Flow rate was measured using a calibrated rotameter.

Natural gas was also used as the reburn fuel. It was injected into the furnace just below the flame at a gas temperature of 2,800°F using a radial injector aligned on the centerline of the furnace. A transport gas (nitrogen or air) was injected along with the reburn fuel to provide sufficient momentum for effective mixing with the furnace gases. Overfire air was injected using a radial injector. The axial furnace position of the OFA injector was varied to vary the reburn zone residence time.

The FEF was fully instrumented for all parameters of interest. Two stainless steel, water cooled panels were installed in the furnace, located at axial distances of 40 and 64 inches from the burner face. Measuring the flow rate and inlet/outlet temperatures of cooling water to each panel allowed panel heat absorption to be measured. Thus the panels could be used to characterize furnace heat release patterns as a function of oxygen enrichment and reburning process parameters.

A suction pyrometer was used to measure furnace gas temperatures. The pyrometer was shielded to minimize impacts of radiation on readings. Refractory temperatures were measured using Type-S thermocouples. Combustion air and cooling water temperatures were measured using Type-K thermocouples.

A IFRF ellipsoidal radiometer was used to measure total radiative flux at the furnace wall collected over a dual angle (hemi-sphere). The instrument consists of a water cooled ellipsoidal cavity with an aperture at one focus and a thermopile at the other. The ellipsoidal cavity focuses all radiation entering the cavity onto the thermopile surface. The surface of the cavity is plated with a gold layer to protect the thermopile and to eliminate convection effects. The ellipsoidal radiometer was mounted at the bottom of the radiant furnace and was aligned directly upward toward the flame.

A continuous emissions monitoring system (CEMS) was used for on-line flue gas analysis. CEMS components included a water cooled sample probe, sample conditioning system (to remove moisture), and gas analyzers. Species analyzed, detection principles, and precision limits were as follows:

- O_2: paramagnetism, 0.1% precision
- NO_x: chemiluminescence, 1 ppm precision
- CO: non-dispersive infrared spectroscopy, 1 ppm precision
- CO_2: non-dispersive infrared spectroscopy, 0.1% precision

High purity dry nitrogen was used to zero each analyzer before and after each test. Certified span gases were used to calibrate and check linearity of the analyzers.

4.3 Oxy-fuel Burner Designs

The primary burner design premise is to maintain flame core stoichiometries which are sufficiently fuel rich and slow mixing to promote sooting to coincidentally lower flame temperatures and increase radiant heat transfer.

4.3.1 Burner I

Two oxy-fuel burner designs were evaluated in the pilot-scale testing. Figure 4-2 shows a conceptual design of burner configuration 1 (Burner I). Burner I design follows the EZ-Fire™ burner design concept of APC. It is best described as a "burner-in-a-burner." The most important design consideration is soot promotion in the oxy-fuel flame to enhance flame radiant heat transfer. This lowers flame temperature and helps control NO_x through fuel rich operation and slow mixing, e.g., low slip velocities between streams. An oxy-fuel burner is installed in the center of the conventional air-fuel burner. This approach provides more efficient heat transfer and available heat benefits of oxy-fuel while maintaining the external flame characteristic similarity of the original air fuel burner. A feature of this design concept is that the air fuel flame provides an envelope around the oxy-fuel flame that protects the furnace refractory and product steel charge from the hotter inner flame. Heat input can be varied between the air-fuel and oxy-fuel components to moderate flame temperature and shape and adjust heat transfer characteristics. Burner stoichiometry can also be varied to change flame characteristics and temperature. Figure 4-2 also shows velocity characteristics of Burner I as a function of oxy-fuel burner heat input at the FEF's full thermal load of 0.8 MMBtu/hr. As seen on this plot, gas velocity of the oxy-fuel burner becomes dominant as heat input to the oxy-fuel burner increases above 37%. Similarly, oxygen velocity increases as heat input to the oxy-fuel burner increases and does not approach that of the air passage until the heat input reaches approximately 80%.

4.3.2 Burner II

Burner II is an APC's second generation burner design. Figure 4-3 shows a conceptual design of Burner II. The burner has three streams instead of four streams, i.e., without the middle gas stream. As seen on the velocity versus oxygen enrichment plot, the burner is designed for lower stream velocities, i.e., highest velocity only reaches 80 ft/s as compared to about 140 ft/s of Burner I. At a constant load, the gas velocity remains constant throughout. Oxygen stream velocity increases while air stream velocity decreases as the degree of oxygen enrichment increases. At approximately 42% oxygen enrichment[1], the three streams have similar velocities, about 50 ft/s,

1 The oxygen enrichment is defined as:

$$\text{Mole Fraction of } O_2 = \frac{\text{Volumetric flow rate of } O_2 \text{ in the oxidizer}}{\text{Total volumetric flow rate of oxidizer}}$$

$$\text{Oxygen enrichment Level} = (\text{Mole Fraction of } O_2 \times 100\%) - 21\%$$

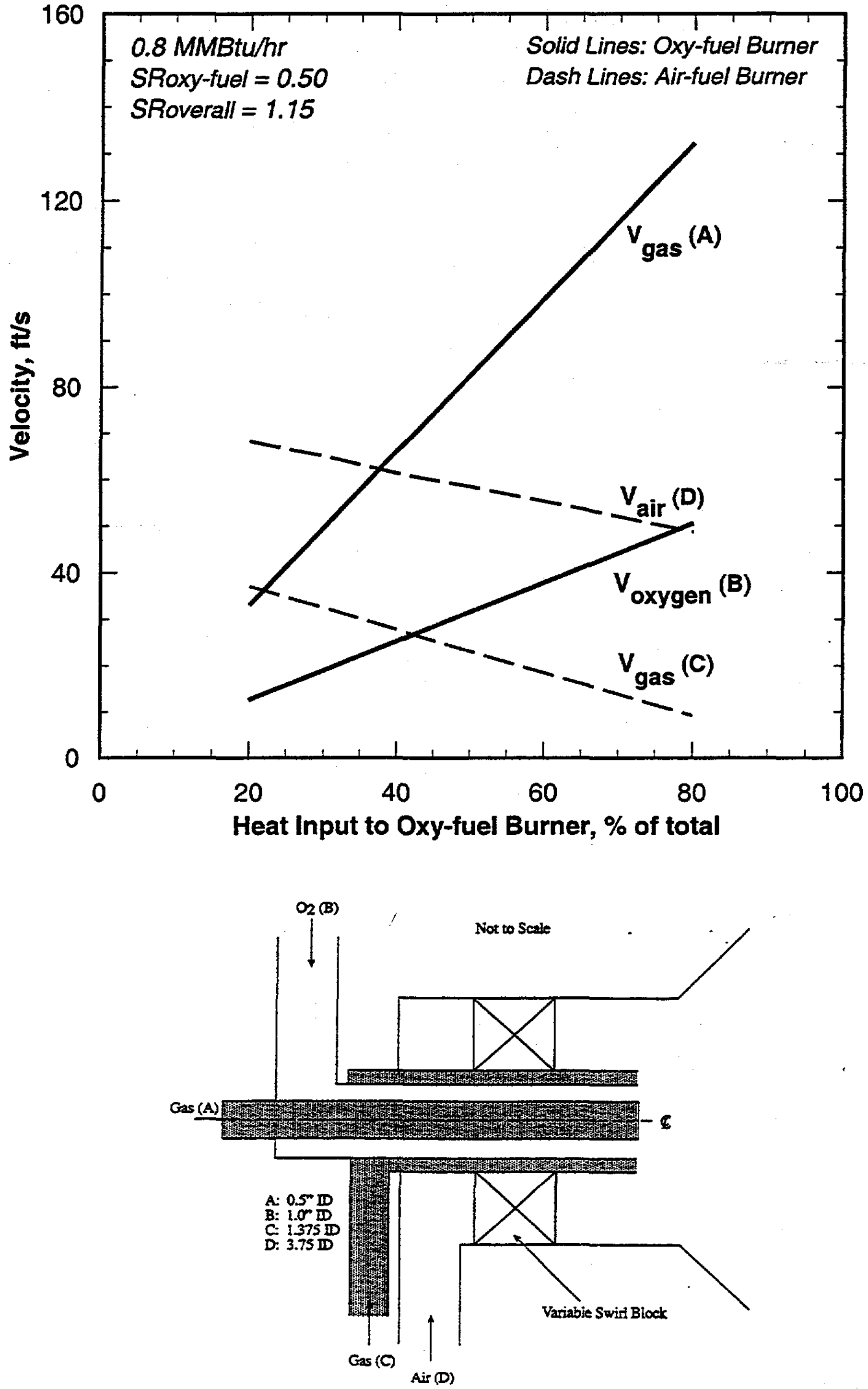
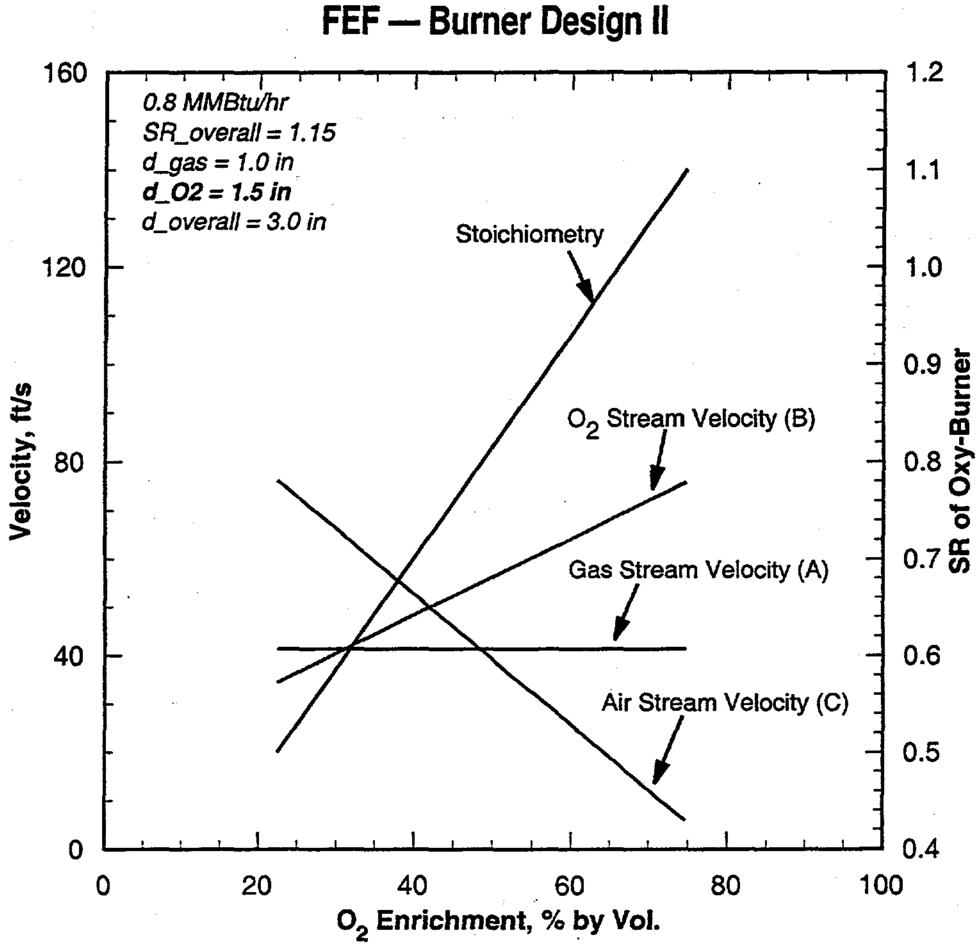


Figure 4-2. Conceptual design of Burner I.



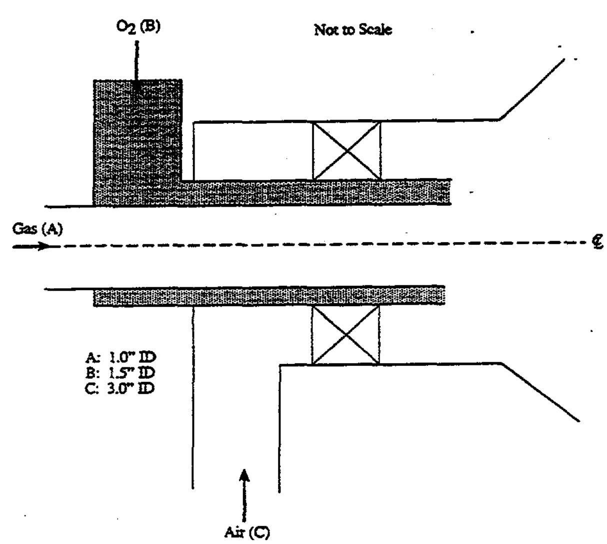


Figure 4-3. Conceptual design of Burner II.

and the corresponding stoichiometry of the oxy-fuel burner is approximately 0.7. The swirl vanes in the air passage were set at zero to reduce turbulent intensity at the burner exit, which results in lower NO_x emissions.

4.4 Test Matrix

The experimental test matrix was designed to parametrically evaluate burner process variables in order to identify conditions of optimum heat transfer and NO_x control. Test variables included the following:

- Burner Configuration: The initially tested configuration (Burner I) had two fuel-oxidant assemblies, one for OEA firing and one for air firing. The second configuration had a single natural gas injector surrounded by concentric oxygen and air injection pipes. With the second configuration, tests were also conducted in which the oxygen was injected down the center pipe with natural gas through the annulus. Other test configurations included premixing the oxygen and natural gas, and reducing the oxygen annulus diameter to increase stream velocity.

- Injector Depth: The axial position of the injector in the quarl was varied over a span of 4 inches to vary flame mixing patterns.

- Oxygen Enrichment Flow Rate: The flow rate of enrichment oxygen was varied such that it comprised between 21% and 40% of the total oxidant stream.

- Burner Load: Firing rate of the primary burner was varied from 200,000 to 800,000 Btu/hr.

- Reburn Process Variables: The heat input of the reburn fuel was varied from 0 to 26%, corresponding to a range of reburn zone stoichiometries of 1.15 to 0.85. Reburn tests were also conducted in which the overfire air was enriched with oxygen.

The test approach was to first vary each parameter individually, followed by combined parameter tests designed to define overall optimum conditions.

4.5 Test Results

This section of the report discusses the results of the pilot-scale tests. The discussion focusses on addressing the impacts of oxygen enrichment on changes in heat absorption by the cooling panels and compares these changes with those of the reference furnace. In addition, OEA impacts on NO_x emissions and reburning for final NO_x emissions control are also presented and discussed.

4.5.1 Oxygen Enriched Heat Transfer

Furnace gas temperatures were measured using a suction pyrometer. Figure 4-4 shows furnace temperature profiles for air firing and oxygen enrichment. At 800,000 Btu/hr heat input, enriching the oxidant by 3.6 and 19% OEA increased furnace peak and average temperatures by approximately 100 and 200°F respectively relative to air only. The results typically bracket the temperature profiles predicted for the model furnace using CFD (Figure 3-9). The triangle symbols shown on the plot were temperature data measured at 400,000 Btu/hr.

Tests were conducted at burner firing rate of 200,000, 400,000 and 800,000 Btu/hr for varying oxygen enrichment levels with the Burner II configuration. Figure 4-5 shows a plot of furnace heat release per unit volume as a function of heat input in the FEF. The reference furnace heat release per unit volume in the heat zones is approximately 11,100 Btu/hr ft^3, which corresponds to about 360,000 Btu/hr heat input in the FEF furnace. Therefore, the results at 400,000 Btu/hr in the FEF are used to predict reference furnace NO_x and heat transfer.

Figure 4-6 shows the impacts of load and oxygen enrichment on cooling panel heat absorption. Cooling panel 1 was located at a higher gas temperature and flame proximity, and absorbed more heat than panel 2 in all cases. At the full load firing condition of 800,000 Btu/hr, heat absorption by each panel increased significantly with increasing oxygen. Panel 1 heat absorption increased by over 50% as oxygen increased from 0% to 18% OEA. The trend was less pronounced at 400,000 Btu/hr. At the low-load firing rate of 200,000 Btu/hr, panel heat absorptions changed minimally with increasing oxygen. At the reference furnace equivalent load of 400,000 Btu/hr, a 20% increase in the combined heat absorption of Panels 1 and 2 occurs at 7% OEA. A cross plot of the heat absorption at 7% OEA (88 lb/MMBtu) as a function of load is also shown. It can be seen that panel heat absorption also increase significantly with the increase in burner heat input.

Similarly, the combined heat absorption change for both Panels 1 and 2 as a function of oxygen enrichment on the basis of lb O_2/MMBtu heat input is shown in Figure 4-7. The project objective of a 20% increase in the combined heat absorption of Panels 1 and 2 at 400,000 and 800,000 Btu/hr occurs at 88 and 60 lb O_2/MMBtu, respectively. Heat absorption improves at 88 lb O_2/MMBtu as firing rate increases, suggesting that furnaces that are fired hard may benefit the most by OEA.

Tests were also conducted at 400,000 Btu/hr with a series of burner configurations, including oxygen through the center pipe, oxygen/natural gas premixing, and a reduced oxygen annulus diameter (from 1.56 in. to 1.35 in., thereby causing a threefold increase in oxygen velocity). Radiative heat flux was measured at each load using an ellipsoidal radiometer. Figure 4-8 shows radiative heat flux as a function of degree of oxygen enrichment for each configuration. Relative to

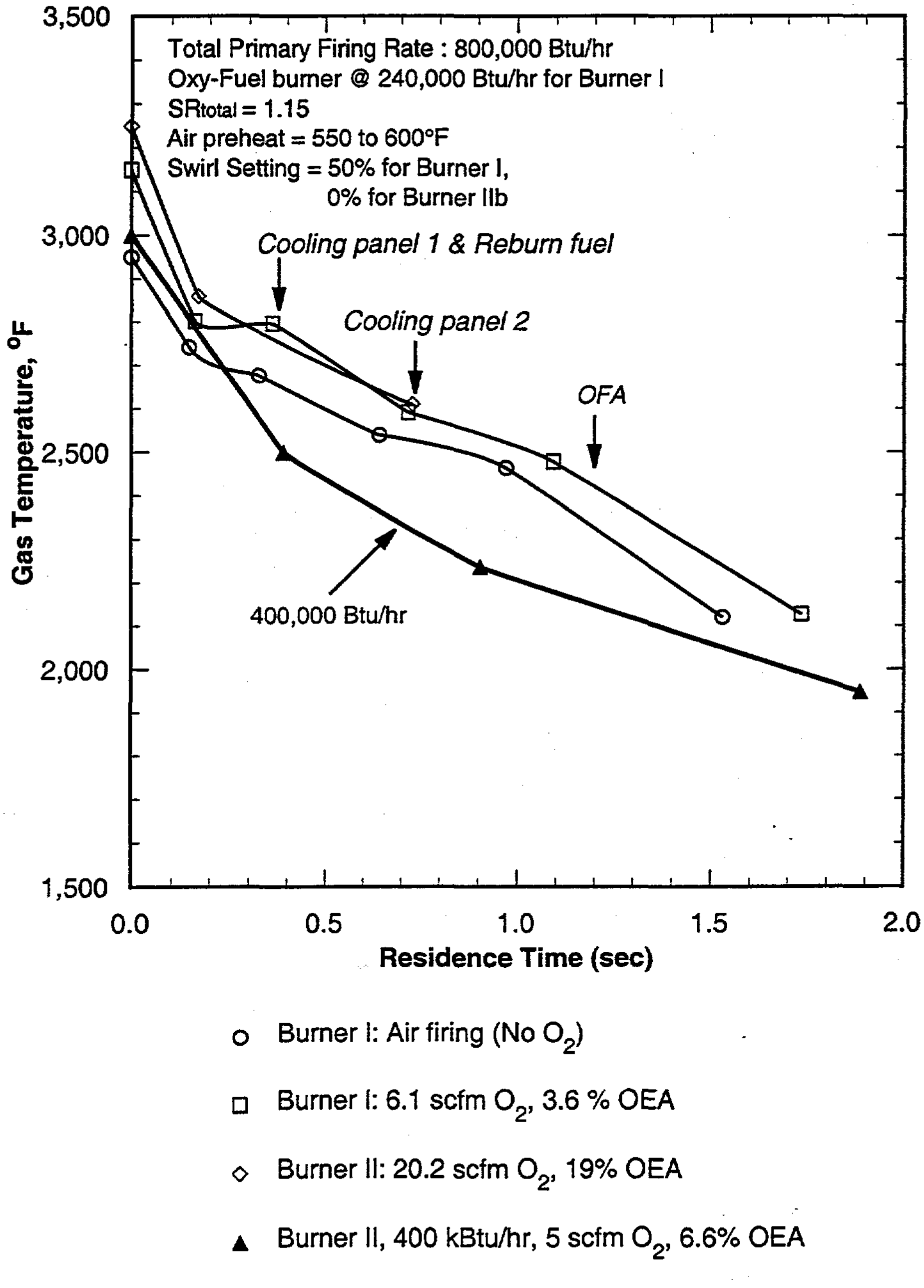


Figure 4-4. FEF steel furnace simulation temperature profiles.

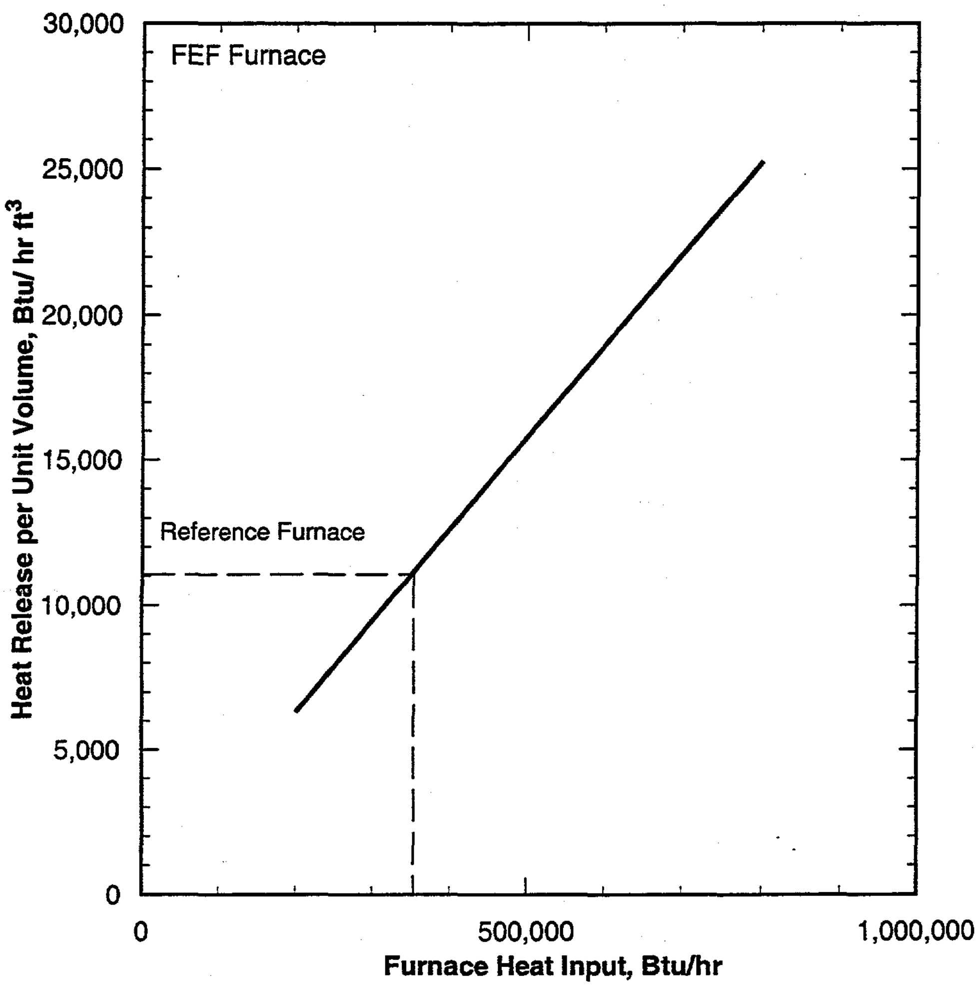


Figure 4-5. Furnace heat release as a function of heat input.

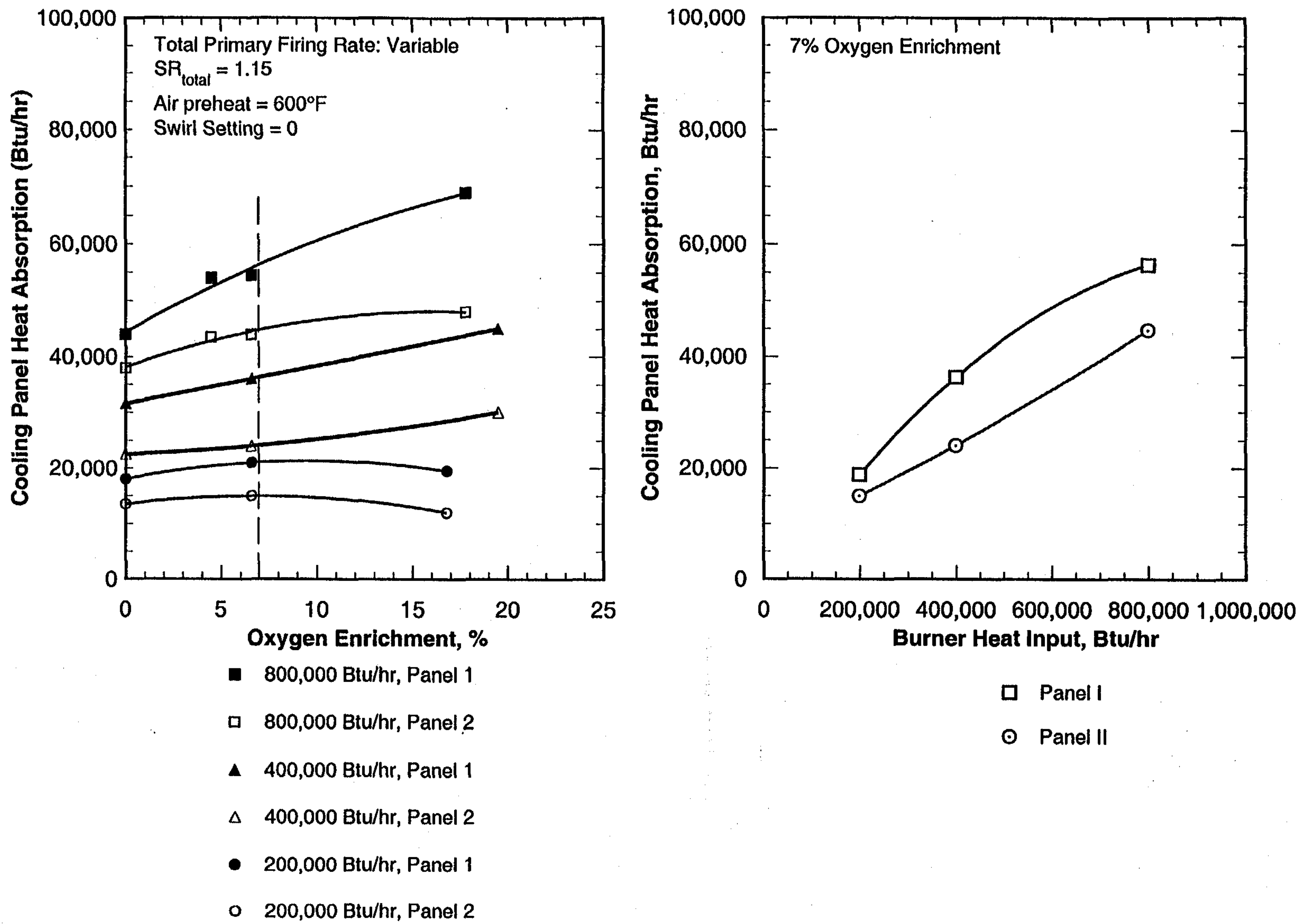


Figure 4-6. Cooling panel heat absorption versus oxygen enrichment and firing rates for Burner II.

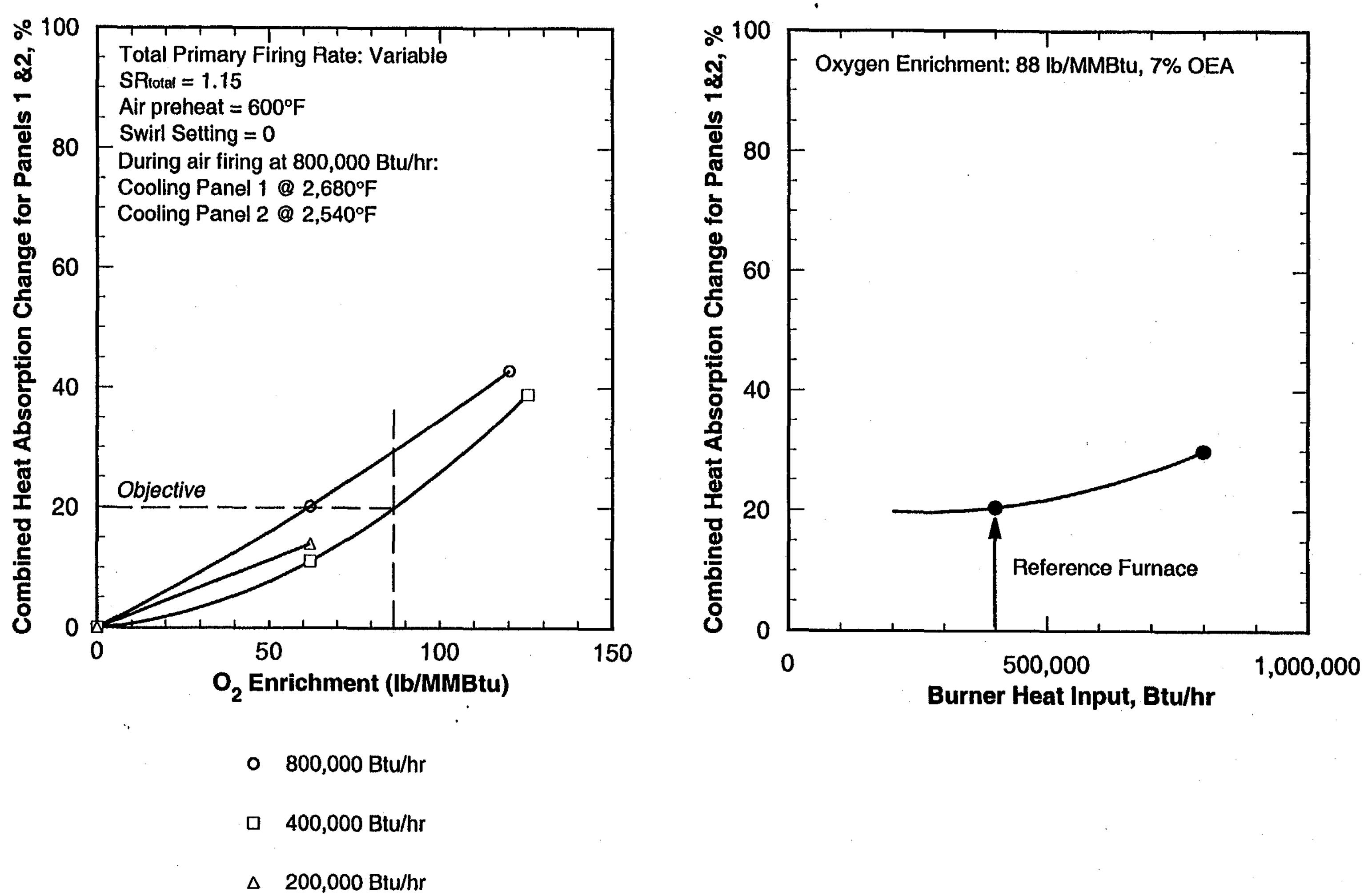


Figure 4-7. Change in combined cooling panel heat absorption versus oxygen enrichment and firing rates for Burner II.

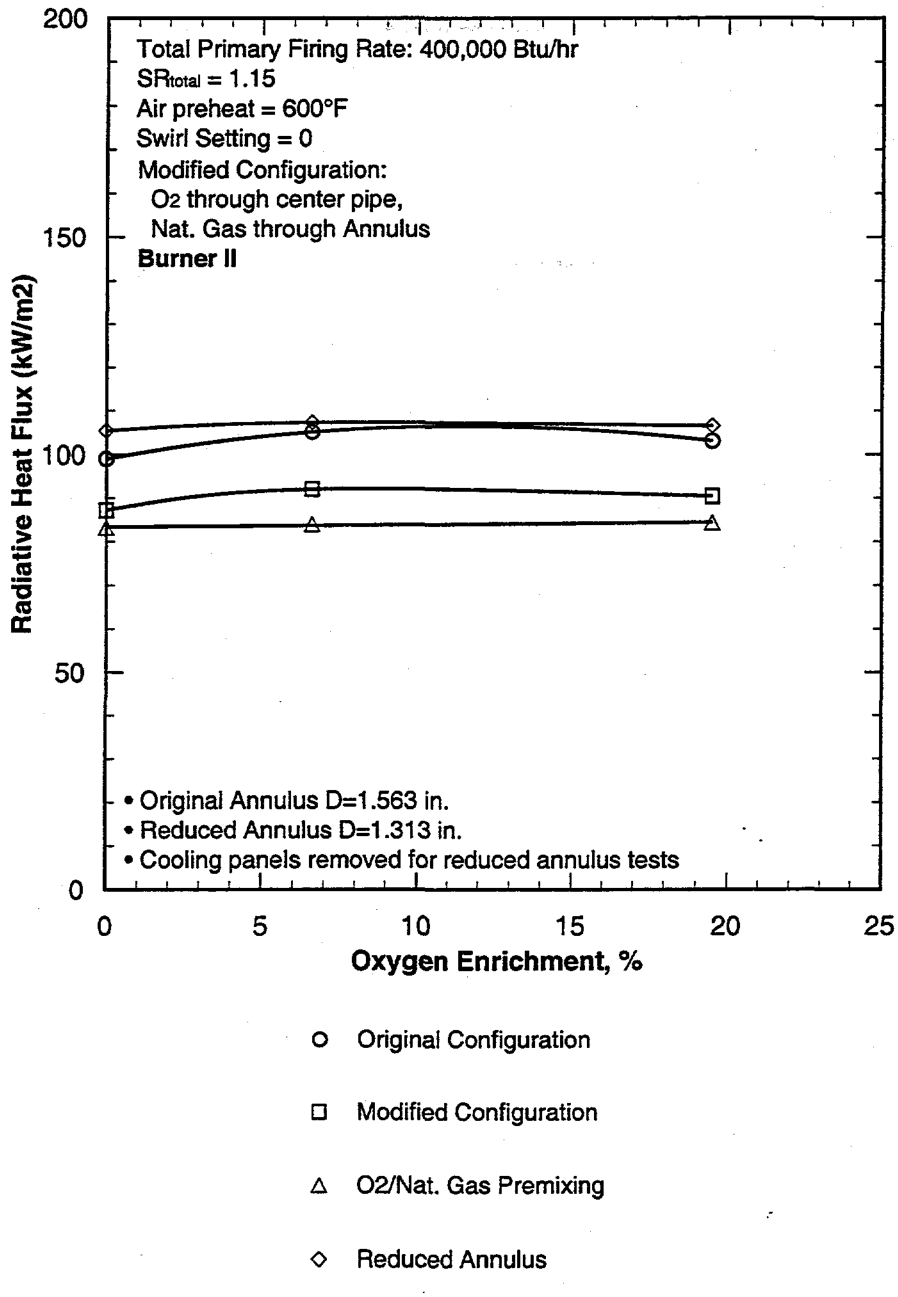


Figure 4-8. Total radiative heat flux versus oxygen enrichment for Burner II at 400,000 Btu/hr.

the baseline configuration, heat flux decreased 10 to 20% with oxygen injected down the center pipe and with natural gas/O_2 premixing. Reducing the annulus diameter had minimal impact on performance.

The two cooling panels were relocated in the reburn zone, upstream of the overfire air to determine the impact of zone stoichiometry on furnace heat absorption. Figure 4-9 shows that heat absorption improvements with oxygen enrichment (O_2/MMBtu) were similar for the reburn cases as for baseline firing, suggesting no net effect of gas reburn on steel heating.

4.5.2 NO_x Emissions

Figure 4-10 shows the relationship between NO_x emissions and oxygen enrichment at different firing rates. In all cases NO_x increased significantly with increasing oxygen. The rate of NO_x increase was greatest at the highest firing rate. At 800,000 Btu/hr, NO_x increased by a factor of 8 as the O_2 flow rate increased from zero to 115 lb/MMBtu, while at 200,000 Btu/hr NO_x increased only by a factor of 4 as the O_2 flow rate increased from zero to 108 lb/MMBtu. At the reference furnace heat input of 400,000 Btu/hr, NO_x increased by a factor of 5 when O_2 flow rate increased from zero to 125 lb/MMBtu. At this load, NO_x emissions were about 0.83 lb/MMBtu at an O_2 flow rate of 88 lb/MMBtu. A plot of NO_x emissions as a function of burner heat input at a constant O_2 flow rate of 88 lb/MMBtu is also shown in this figure.

The four burner configurations were comparatively tested at the reference furnace firing rate of 400,000 Btu/hr. These included the original configuration, oxygen through the center pipe, oxygen/natural gas premixing, and a reduced oxygen annulus diameter (which provided a threefold increase in oxygen velocity). Figure 4-11 shows NO_x emissions as a function of enrichment oxygen for each of these configurations. For the premixing configuration NO_x emissions increased rapidly but then began to level off. With the reduced annulus diameter, NO_x emissions increased linearly with increasing oxygen, and were the highest of any configuration at the highest oxygen concentration. This is attributed to the rapid rate of O_2 entrainment into both the air and fuel jets due to the higher shear velocities. The first Burner II configuration over the range of oxygen enrichment of interest has the lowest NO_x emissions. Interestingly, this is the second best configuration for heat transfer improvement. Clearly, if enrichment is used NO_x must be mitigated with a post combustion approach.

4.5.3 Reburning Tests

Natural gas was used as the reburn fuel and was injected at a gas temperature of 2,800°F. Both nitrogen and air were used as the reburn fuel transport media. Overfire air was injected at 2,480°F. Reburn zone residence time was approximately 0.7 second. Reburn tests were performed at 400,000 (reference furnace condition) and 800,000 Btu/hr burner firing rates. As shown in Figure

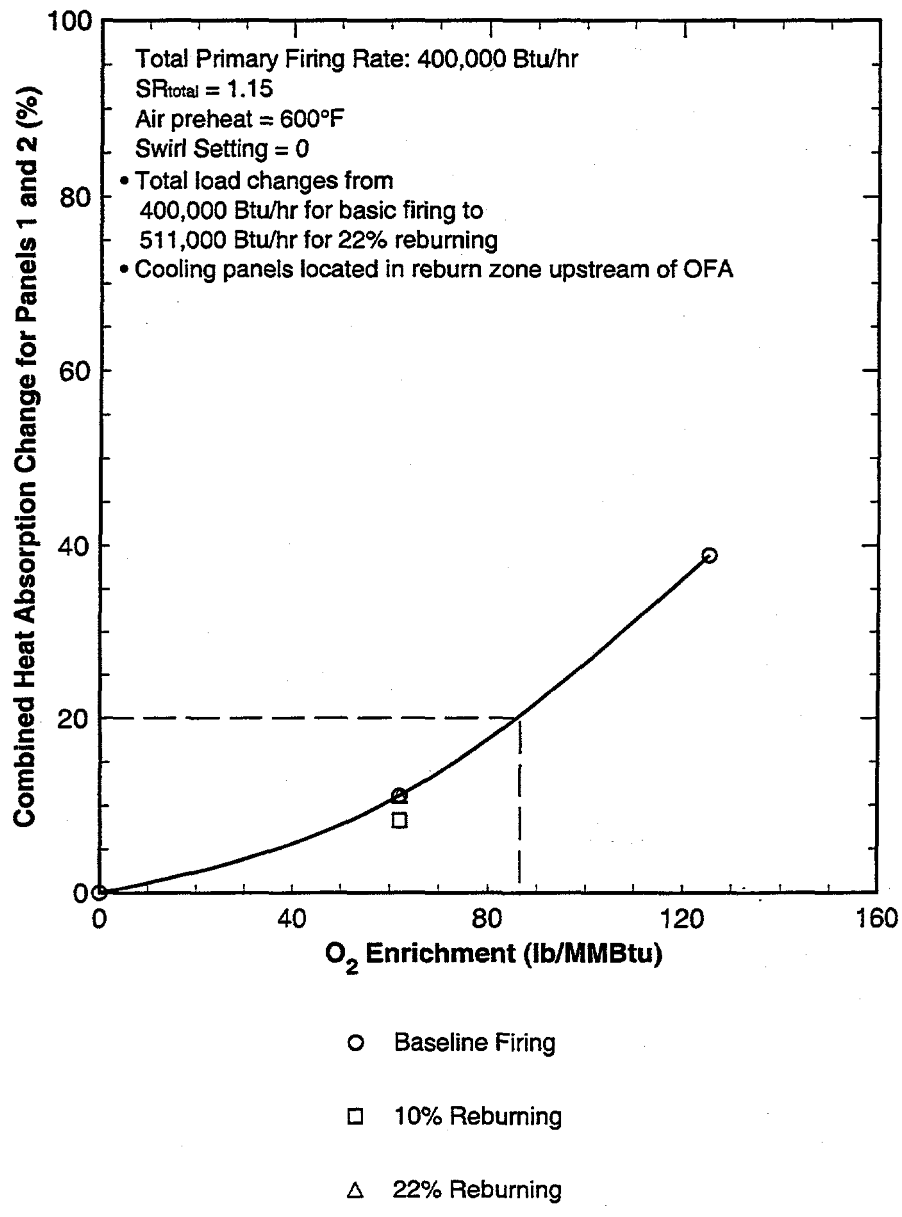


Figure 4-9. Cooling panel heat absorption change versus enrichment oxygen flow rate for Burner II at 400,000 Btu/hr.

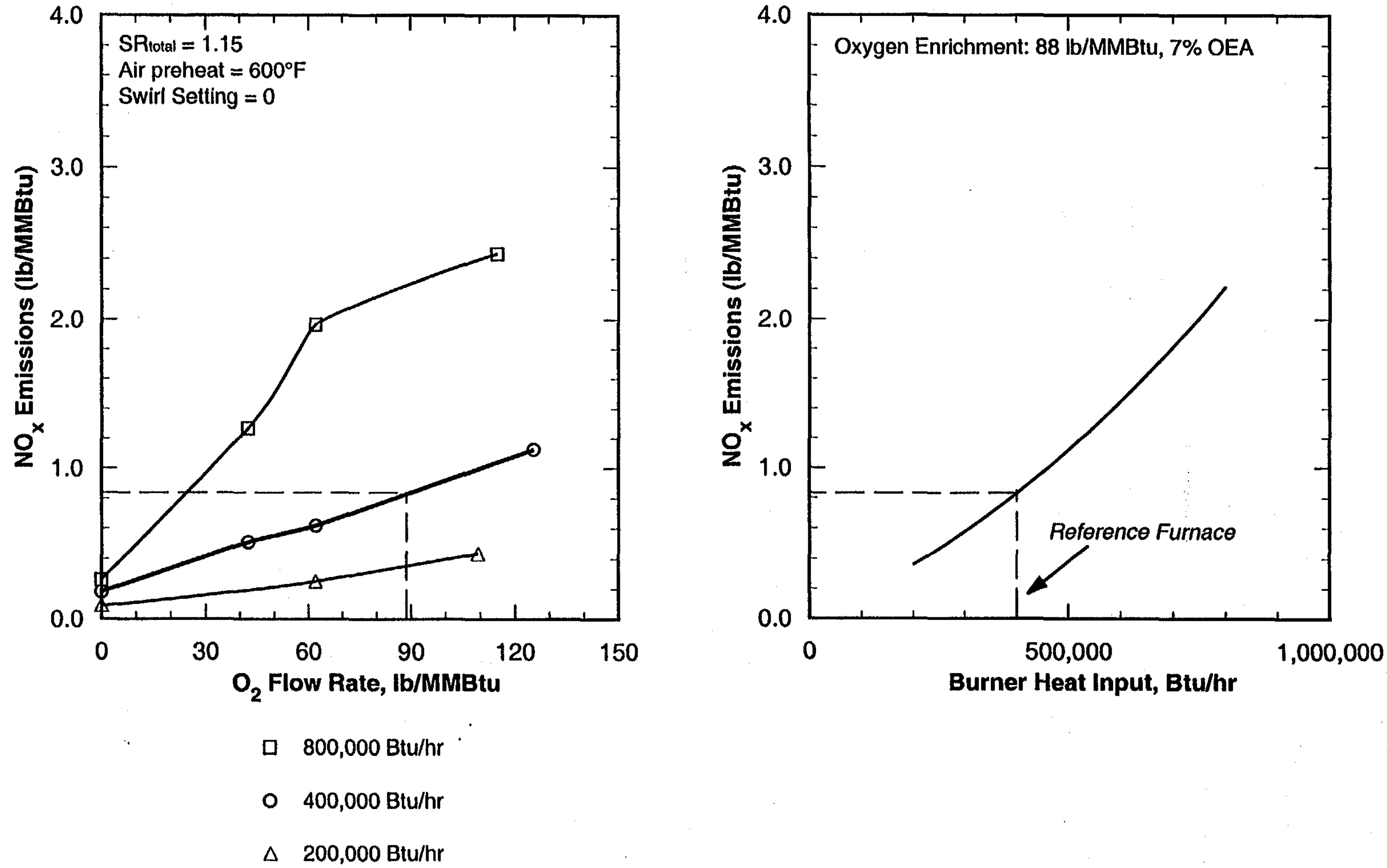


Figure 4-10. NO_x emissions versus oxygen enrichment and heat input for Burner II.

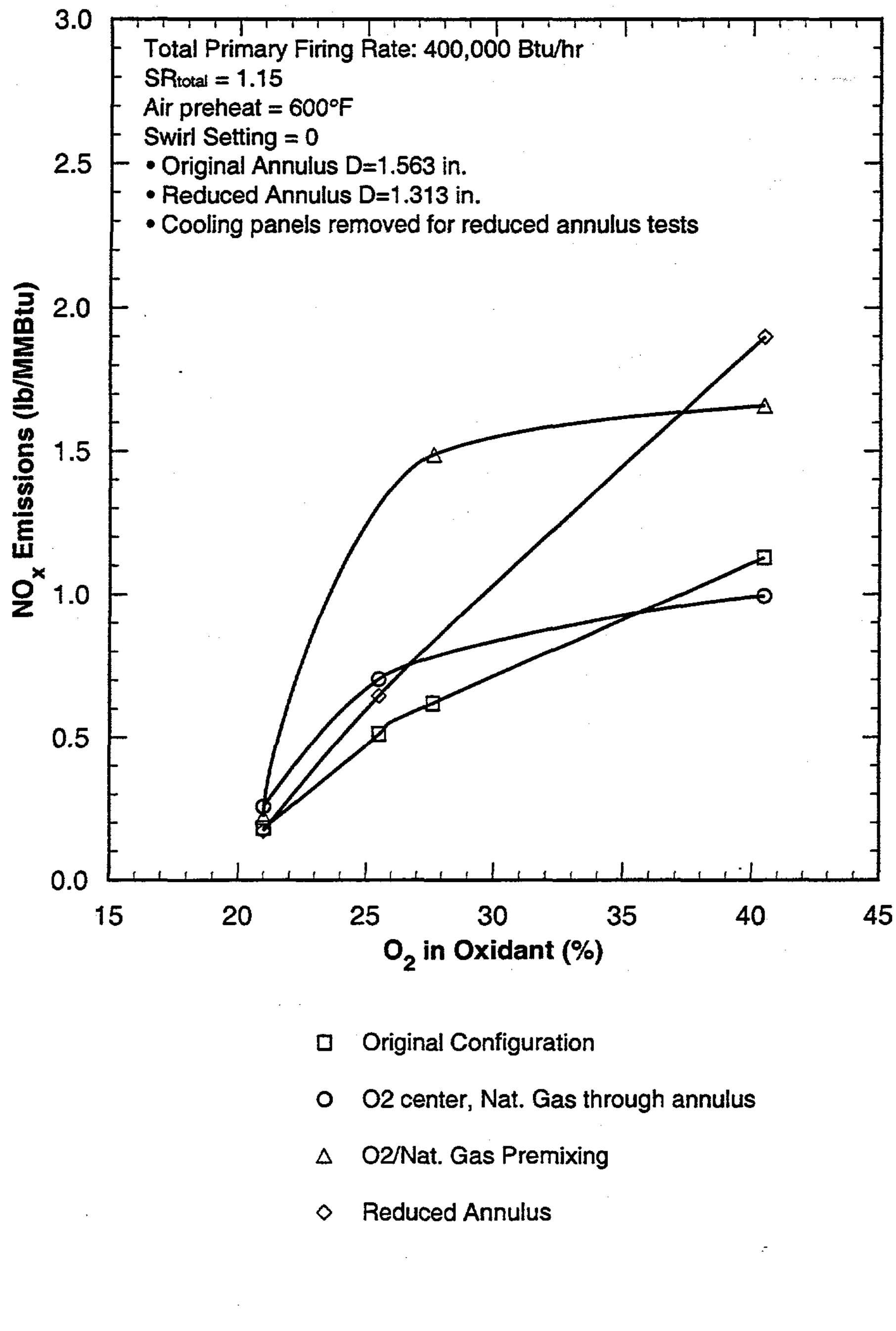


Figure 4-11. NO_x emissions versus enrichment oxygen flow rate for Burner II with different configurations at 400,000 Btu/hr.

4-12, reburn performance was best at reference furnace conditions with nitrogen as the transport gas, likely due to improved furnace mixing. This trend was observed despite the fact that the initial NO_x concentration for the 400,000 Btu/hr condition (0.73 lb/MMBtu) was much lower than that for the 800,000 Btu/hr condition (3.80 lb/MMBtu). At the half load condition, over 70% NO reduction could be achieved. Figure 4-13 presents these results on the basis of lb/MMBtu of NO versus reburn heat input. At the reference furnace condition it was possible to reduce NO emissions to below 0.2 lb/MMBtu.

Figure 4-14 presents stack NO_x emissions as a function of enrichment oxygen flow rate at 400,000 Btu/hr. Baseline NO_x emission with no oxygen enrichment were 0.20 lb/MMBtu. At an oxygen enrichment rate of 60 lb/MMBtu, NO_x emissions increased to 0.62 lb/MMBtu. However, by applying 22% reburning NO_x emissions could be reduced to 0.18 lb/MMBtu. Thus, reburning was able to offset the NO_x emissions increase caused by oxygen enrichment.

4.6 Conclusions

In summary, a series of pilot scale tests was conducted to determine the impacts of oxygen enrichment on steel reheat furnace heat absorption and NO_x emissions. Burner and reburning process parameters were parametrically varied to define the sensitivity of system performance to each variable. Under full-load conditions, it was found that oxygen enrichment substantially increased heat absorption and radiative heat flux. NO_x emissions were found to increase dramatically with increasing enrichment O_2. Other burner process variables, including combustion stoichiometry, air preheat temperature, burner configuration and injector axial position, had a lesser impact on NO_x emissions. Reburning was found to result in significant NO_x reduction. The results may generally be summarized as follows:

- At twice typical reference furnace intensities firing (800,000 Btu/hr), oxygen enrichment increased heat absorption by over 50% as oxygen increased from zero to 18% OEA. The trend was less profound at 400,000 Btu/hr and 200,000 Btu/hr. Calculations have indicated that the FEF temperature profile and combustion intensity at 400,000 Btu/hr were similar to that of the reference steel furnace. The project objective of 20% heat absorption increase occurs at an oxygen flow rate of between 60 and 88 lb/MMBtu or 7% OEA.

- Similarly, radiative heat flux increased with increased oxygen enrichment. At 800,000 Btu/hr, oxygen enrichment increased radiative heat flux by approximately 42% as oxygen increased from zero to 18%. The trend was less profound at firing rates of 400,000 Btu/hr and lower.

- NO_x emissions increased significantly with the increase of oxygen enrichment. As expected, reburning reduced NO_x emissions significantly with and without oxygen enrichment.

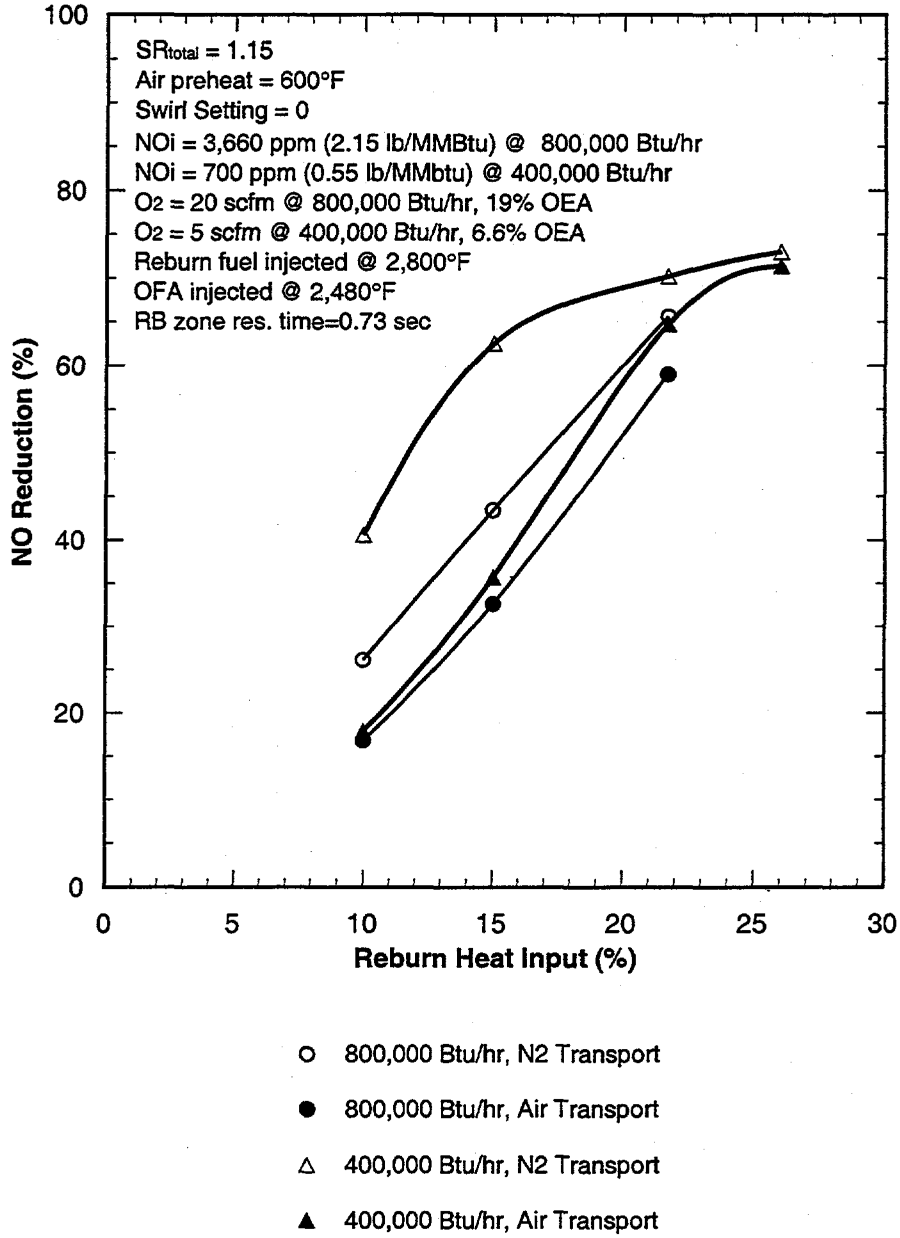


Figure 4-12. NO_x reduction versus reburn heat input during preliminary reburn test with Burner II at different firing rates.

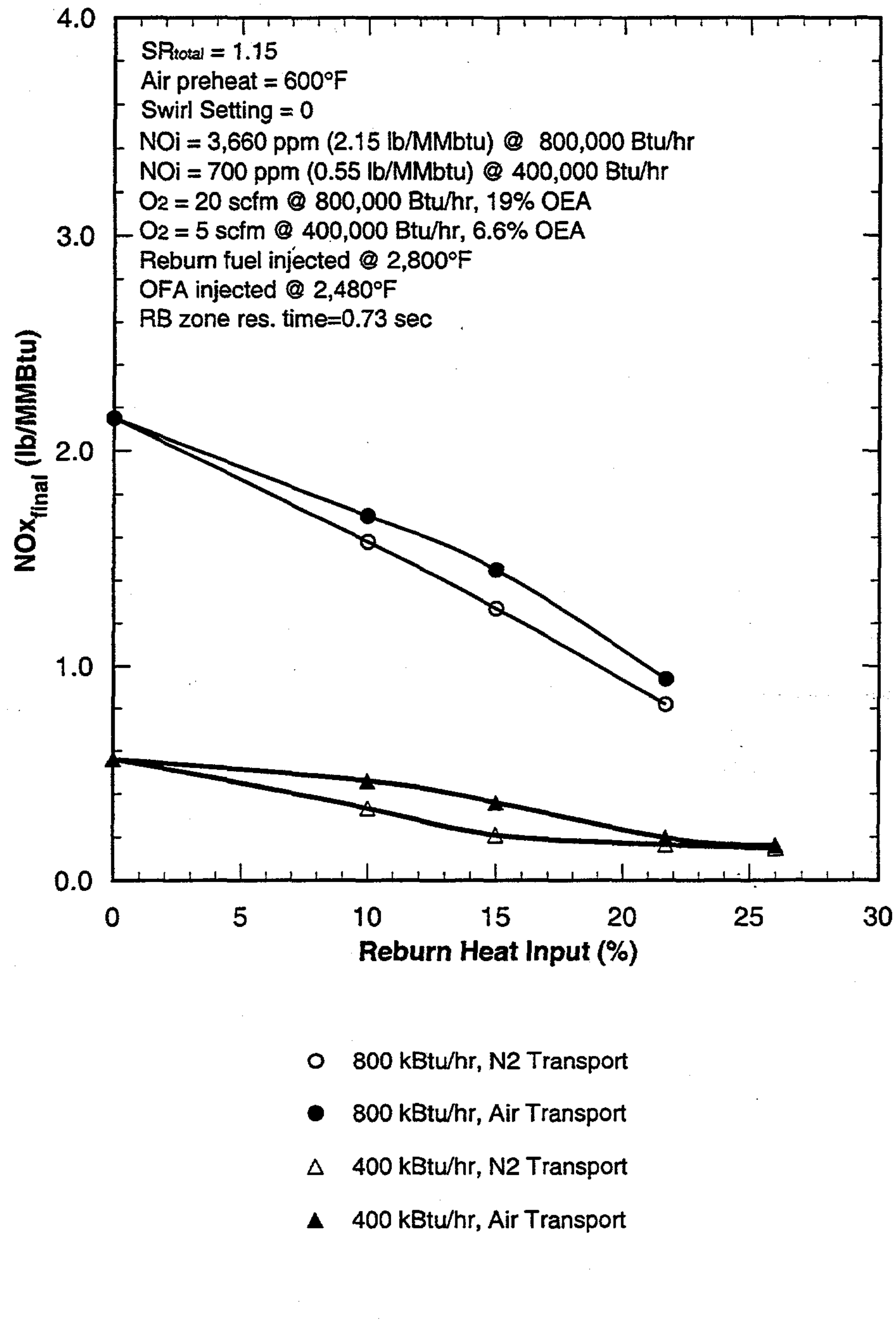


Figure 4-13. NO_x reduction versus reburn heat input during preliminary reburn test with Burner II.

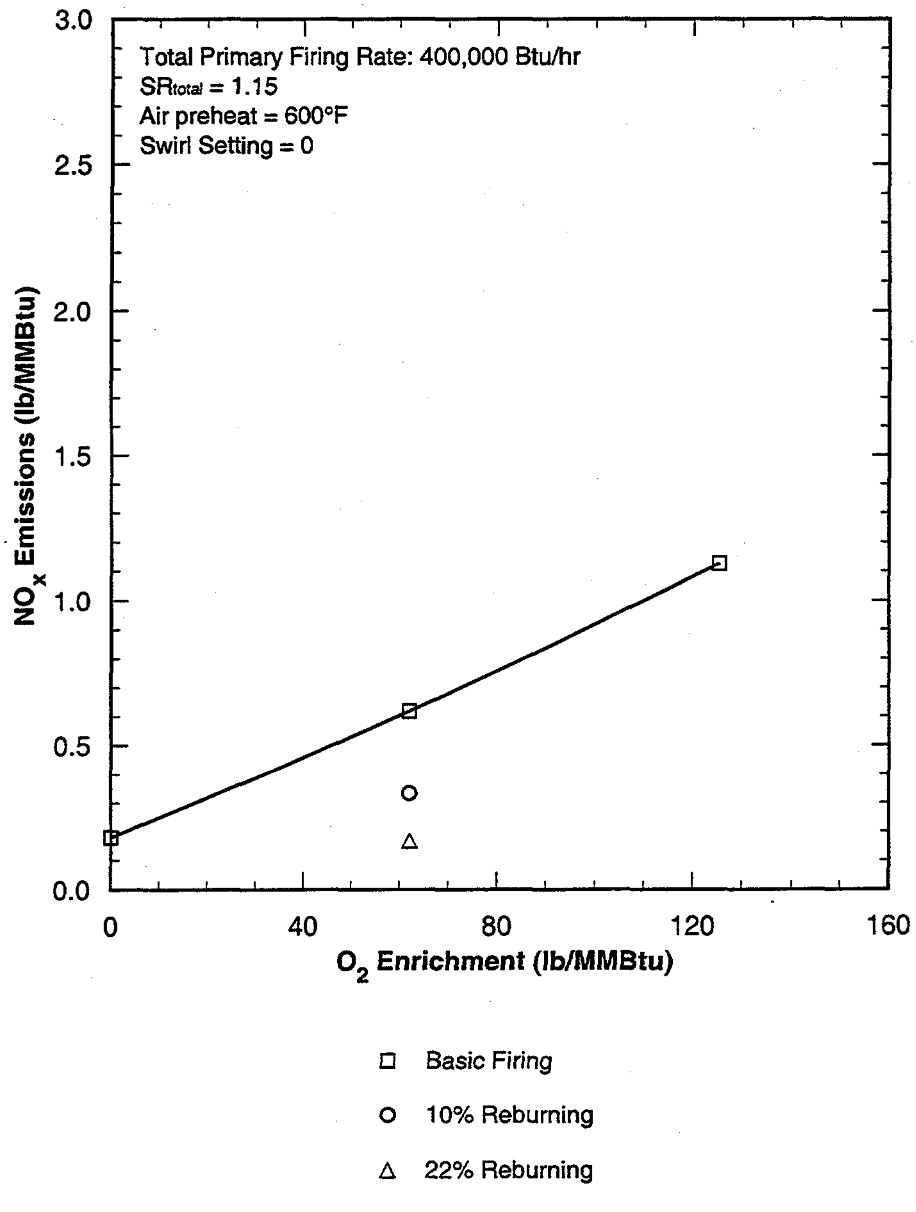


Figure 4-14. NO_x emissions versus enrichment oxygen flow rate for Burner II during reburning tests at 400,000 Btu/hr.

The tests have shown that up to 73% NO_x reduction was achieved with reburning. Thus, reburning was able to largely offset the increase in NO_x emissions caused by oxygen enrichment. For instance, at the reference furnace load of 400,000 Btu/hr NO_x increased from a baseline level of 0.2 lb/MMBtu to 0.62 lb/MMBtu as the oxygen flow rate increased to 60 lb/MMBtu. However, by applying 22% reburning NO_x emissions was reduced to 0.18 lb/MMBtu.

With respect to similarity with the reference furnace and its operating conditions the followings are projected relative to a 20% production improvement and a 0.2 lb NO/MMBtu baseline:

- Oxygen consumption = 60 to 88 lb O_2/MMBtu
- Oxygen enrichment = 7 % O_2
- NO_x after reburn of 0.18 lb/MMBtu slightly below the baseline.

5.0 Proforma Economics

A proforma cost-effectiveness evaluation has been performed for the three cases and compared to the baseline furnace performance.

- Stand-alone gas reburn for NO_x control.
- Stand-alone OEA for production increase.
- Combined technologies.

The figure of merit for the comparisons is as follows:

- *Gas reburn only*: the annualized cost per ton of NO_2 reduced.
- *Gas reburn with OEA*: the net annualized value of incremental steel produced less O&M costs for GR and oxygen (net revenue per ton of steel produced).

5.1 Assumptions

The economics were based on the following assumptions:

- The material and heat balances previously discussed.
- Capital costs of $340,000 and $250,000 for GR and OEA, respectively.
- Cost of oxygen of $30/ton.
- Oxygen consumption, parametrically evaluated.
- Operating hours of 8,000/yr.
- Fuel cost of $2/MMBtu.
- Capital recovery factor identical to the EPA ACT (1994) document, 7% interest and 15 year life
- A twenty percent increase in furnace productivity

5-1. THE ECONOMICS OF ADVANCED STEEL REHEAT PERFORMANCE IMPROVE

	Units	Baseline	Reburn	OEA w/o Reburn	OEA w/ Reburn
Fuel Usage					
Furnace Capacity	tons/hr	115	115	138	138
Fossil Efficiency	mmBtu/ton	**1.20**	**1.24**	**1.04**	**1.04**
Fuel Usage	lb/hr	6,276	6,485	6,527	6,527
Fuel Usage	mmBtu/hr	138.0	142.6	143.5	143.5
Fuel Unit Cost	$/mmBtu	2.00	2.00	2.00	2.00
Fuel Cost	$/hr	276	285	287	287
Cost Increase	$/hr	0	9.20	11.04	11.04
NOx					
Concentration					
Baseline	ppm	245	225	500	460
primary	ppm	245	225	500	460
Reburn Controlled	ppm	245	124	500	184
Per Ton Steel					
Initial	lb/ton	0.303	0.278	0.515	0.474
Controlled	lb/ton	0.303	0.153	0.515	0.190
Per Unit Heat Input					
Initial	lb/mmBtu	0.25	0.22	0.50	0.46
Controlled	lb/mmBtu	0.25	0.12	0.50	0.18
Hourly Emission					
Initial	lb/hr	34.8	32.0	71.1	65.4
Controlled Rel to Baseline	lb/hr	34.8	17.6	71.1	26.2
Total NOx Reduction Rel. to Baseline	lb/hr	0.0	17.2	-36.3	8.7
Operation & Maintenance Costs					
Capital Cost					
Reburning System	$	0	340,000	0	340,000
Air Enriched System	$	0	0	250,000	250,000
Construction	$	0	0	0	0
Additional Technology					
Total Capital Cost	$		340,000	250,000	590,000
Maintenance/Capital Cost	%/yr		2	2	3
Maintenance Cost	$/hr		0.85	0.63	2.21
Oxygen Requirement	lb/hr		0	8,333	8,333
Oxygen Unit Cost	$/ton		30	30	30
Oxygen	$/hr		0	125.0	125.0
Hourly Operating Cost Summary					
Additional Fuel	$/hr		9.20	11.04	11.04
Maintenance	$/hr		0.85	0.63	2.21
Oxygen	$/hr		0.00	125.00	125.00
Total	$/hr		10.05	136.66	138.25
Annual Operating Cost Summary					
Operating Hours	hr		8,000	8,000	8,000
Annual Operating Cost	$/yr		80,400	1,093,280	1,105,980
Annual NOx Reduction	Ton/yr		69	-145	35
Total Annual Costs					
Capital Cost (levelized)					
Interest Rate	%		7	7	7
Life	yrs		15	15	15
Capital Recovery Factor			0.110	0.110	0.110
Annual Capital Cost	$/yr		37,330	27,449	64,779
Annual Operating Cost	$/yr		80,400	1,093,280	1,105,980
Total Annual Cost	$/yr		117,730	1,120,729	1,170,759
Revenue (1)					
Revenue	$/ton			20	20
Total Annual Revenue	$(000)/yr			3,680,000	3,680,000
Cost Effectiveness (2)					
Net Revenue	$/ton inc. steel		0.13	2.318	2.273
Cost Effectiveness of Emission Control	$/ton NO2		1,707		

Notes:

1, Assuming profit of 5% on incremental steel production.

2, Negative values are annual net costs, positive are revenues, divided by the annual steel production.

- Finished steel at $0.22/lb, and a 2.5 and 5% revenue enhancement from production increase

5.2 Cost Effectiveness

The economics of the three concepts relative to baseline performance are detailed in Table 5-1. Gas reburn capital costs have been annualized, $37,330/yr, with a capital recovery factor based on the EPA ACT (1994) assumptions. Fuel efficiency impacts could vary between 0 and $73,600/yr, depending on GR heat release/absorption. The cost-effectiveness of GR was calculated on the basis of annualized cost/ton NO_x removed, and evaluated parametrically as a function of its impact on furnace efficiency, Figure 5-1. The modelling results suggested a slight to some decrease in furnace efficiencies (between 1.22 to 1.25 Btu/ton), resulting in 1,100 to 1,900 $/ton NO_2 reduced, respectively. Gas reburn and low-NO_x burners could be used in combination to achieve control levels approaching 75% reduction, similar to selective catalytic reduction. The importance of recovering the reburn fuel heating value suggests that this should be one of the focuses of the development plan. Specifically, the reburn fuel jets need to be placed well upstream of the exit to the last heating zone and the OFA jets should be close coupled, e.g., providing about 400 milliseconds of mixing/reaction time. For the base case, 90% of the flue gas flow was at a velocity of about 20 ft/s at the injection point, indicating that the reburn fuel and overfire air injectors should be spaced 8 feet apart. Because of the substantially lower flows when oxygen enrichment is used, the distance could be reduced about 30% or to about 5 feet. Thus, there would be sufficient time/temperature to recover a significant amount of the reburn fuel as useful steel heating.

OEA without and with reburn is directed at debottlenecking a production line and are of primary interest in increasing revenues through production increases. The annualized cost per ton of steel increases because of the cost of O_2 (about 0.48 $/ton) and capital, even though there is an off-setting fuel savings of about 0.3 $/ton. The potential revenue enhancement (2.5 to 5% profit) of a 20% production increase (23 TPH) is about $10 to $20/incremental ton for finished steel priced at $440/ton. Thus, there is some considerable advantage to debottlenecking with net savings of up to $3,680,000 on $590,000 of capital, an excellent return of the investment. Figure 5-2 shows net revenue from implementing oxygen enrichment with and without reburning for two levels of net profit increase (2.5 and 5%) on a 20% production increase as a function of oxygen consumption. Net revenue is defined as the before tax profit ($/ton) less capital charges, oxygen and incremental fuel purchases, and operating and maintenance (O&M) costs. Typical estimates of oxygen consumption from the modeling (4.4 TPH) and pilot-scale (5.1 to 7.5 TPH) work are superimposed on these graphs to estimate the most likely range of revenue.

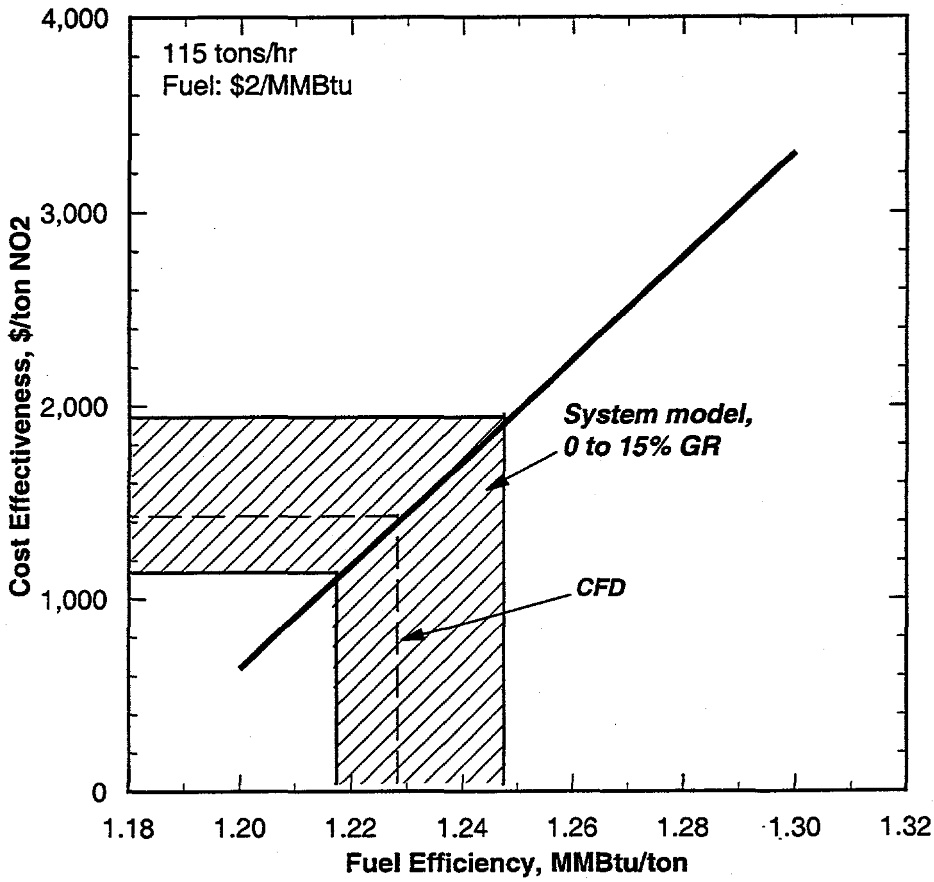


Figure 5-1. Cost effectiveness parameter sensitivity to gas reburn fuel efficiency impact.

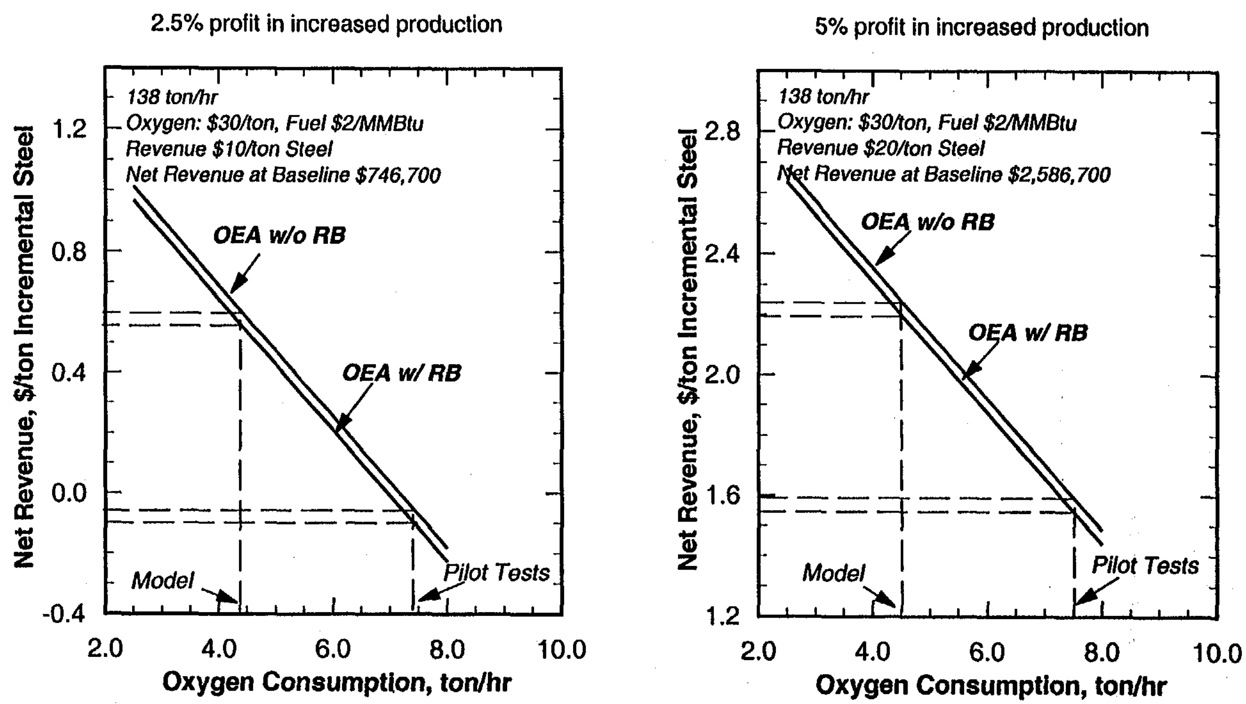


Figure 5-2. Economic sensitivity of amount of oxygen enrichment required for 20% production increase.