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ADVANCED STEEL REHEAT FURNACE

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Authors
D. Moyeda, M. Sheldon, R. Koppang
Energy and Environmental Research Corp.
Irvine, CA, 92618

M. Lanyi, X. Li, B. Eleazer, Air Products and Chemicals, Inc.
Allentown, PA 18195

Abstract

Energy and Environmental Research Corp. (EER) under a contract from the Department of Energy[1] is pursuing the development and demonstration of an Advanced Steel Reheating Furnace. This paper reports the results of Phase I, Research, which has evaluated an advanced furnace concept incorporating two proven and commercialized technologies previously applied to other high temperature combustion applications:

- EER's gas reburn technology (GR) for post combustion NOx control
- Air Product's oxy-fuel enrichment air (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 NOx emissions
- better control over the furnace atmosphere, whether oxidizing or reducing, leading to better control over surface finish.

Introduction

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 commonly by-product and natural gas with heat inputs ranging from 50 to 400 MMBtu/hr. Because high temperature steel (<2200 °F) is produced, furnace efficiencies tend to be low (30 to 60 %), even when 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 is a required is a technology which can address the issues of NO reduction and capacity expansion singularly or in combination.

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:

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- *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 NOx 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 fuel-rich, NOx reduction zone. The input NOx 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 NOx 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 1600°F to insure good CO burnout without significantly increasing thermally generated NOx. 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.

Market Drivers and Objectives

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 NOx (>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 25 %, without major structural or combustion system modifications. Using gas reburn, NOx reductions using of order 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 underutilized 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.

Approach

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 NOx and furnace gas temperature changes 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 Development Definition (Study)
- Phase II, Design and Development
- Phase III, Field Demonstration

This paper reports on the status of the Phase I Study. Activities include a) an evaluation of USA furnace demographics which led to the development of a model furnace specification, b) computational modelling of the model furnace to select and quantify heat transfer and performance improvements, and c) conceptual design to establish capital and operating costs and benefits. The American Iron and Steel Institute is supporting this activity by providing peer review through their Energy and Environmental Committee. Air Products has developed a computational fluid dynamic (CFD) model to support the analysis of oxygen enhancing heat zone combustion to preferentially improve heat transfer to the steel. The CFD modelling results (flow field structure, temperatures, and species composition) are used as boundary conditions (see Figure 1) for three other computational models:

- computational (jets in cross flow) and physical 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
- one dimensional (multi stream tube) chemical kinetic model for NO reduction and CO oxidation control

- 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.

Concepts

Background

Oxygen-enrichment (OEA) concepts are 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. Newly developed O_2 injection methods for the iron cupola have shown significant reductions in % 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 NO emissions.

Gas reburn technologies for NOx control are being commercially offered for large boilers and MSW incinerators. In a study for the Gas Research Institute [GRI] (Pearson, Moyeda & Koppang, 1994) the feasibility and effectiveness of applying gas reburning technology to industrial equipment was established for the pyroprocessing industries, and specifically, steel reheat furnaces.

The combined technologies should obtain the following attractive features:

- greater production throughput with associated furnace efficiency improvements;
- low NOx emissions, particularly when raw off-gases contain fuel N or OEA increases gas path temperatures;
- better control over scale formation.

Concept Implementation

Continuous 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 2. It is common for reheat furnaces to have multiple heating zones or banks of burners. Zone flue gas, with temperatures ranging from 2150°F to 2650°F, is ultimately exhausted through a recuperator to the stack at 700 to 1200°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. Three concepts shown in Figure 3 are under evaluation: 1) oxygen lancing into fuel rich combustion zones, 2) oxygen enrichment into the primary burner combustion air, and 3) additional oxy-fuel boost burners strategically placed in the heat zones.

Chemical equilibrium calculations at adiabatic conditions indicate that the furnace gas temperatures in these zones are sufficiently elevated to produce higher levels of NOx, as shown in Figure 4, as well as to increase the exiting flue gas temperatures. In reality, the process is far from adiabatic due to the highly stratified, radiating flames developed through burner modifications. These increases will result in initial conditions that are more favorable for gas reburning, e.g., greater than 2200°F and NOx levels approaching 600 ppmv, as shown in the experimental data (Energy and Environmental Research Corp. [EER], 1996) presented in Figure 5.

Figure 5 also shows a block diagram for implementation of the gas reburn process to be implemented in the steel reheat furnace. 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 GR, Over Fire 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 NOx reduction by maximizing reburn zone residence times subject to constraints of complete combustion and furnace efficiency. In upcoming program tasks, CFD modelling will be used to locate these positions for both baseline and OEA conditions.

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 proforma 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 1.

Table 1. Typical and Model Furnace Descriptions

Parameter	Slab	Boom/Billet	Model
Hearth, width/length	32/110	25/60	30/65
Charged Steel	9"x60"x28'	6"sqx22'	5.5" sqx28"
Production, TPH	250	100	115
Efficiency, MMB/hr	1.8	1.5	1.2
Residence Time,hr	2.4	1.6	1.8
Zones	4	3	3
NOx, #/MMBtu	0.4	0.3	0.3

Process Analysis

The current status of the process analysis activity is described below. To date two models based on the model furnace specification have been developed and refined:

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

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

Furnace Process Modelling

The costs and benefits of applying the proposed technologies is under evaluation. This preliminary assessment is 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

- A parametric study of the effects (heat transfer and thermally efficiency improvement and the resulting NOx increase due to high temperature operation) of oxygen enrichment or oxy-fuel boost burner use applied to the heat zones

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

Reference Furnace

A 115 TPH reference billet furnace has been defined which is typical of furnaces found in both mini-mill and integrated steel. The model furnace is of modern design and high efficiency (about 1.2 MMBtu/ton continuous or about 1.5 MMBtu/ton average with mill down time of about 25%). The recuperated furnace preheats combustion air to 1000°F and exhausts flue gas at 1600°F. Two applications using gas reburning and/or oxygen as shown in Figure 6, have been studied:

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

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

Computational Fluid Dynamic (CFD) Model

The CFD modeling is 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 is sufficiently wide to be modeled as two dimensional (2D). This implies that the heat loss from the side walls can be neglected. This is reasonable since losses account for about 4% of the gross fuel energy input, and the side walls are small as compared to the roof and bottom walls. Another implication is the amount of energy distribution by radiation as a result of the side walls. Since the refractory walls have very little heat loss, they are close to perfectly reflective walls of the third coordinate direction as assumed in the 2D model. Therefore, the 2D result will be representative of the true situation except, perhaps, in a small steel volume immediately next to the side walls. The bottom zone is assumed to have no radiative communication with the top heat zone except through the steel, and their flue gas flows are assumed not to merge until the flows are vertically directed. In reality, the furnace width increases under the chimney, a feature known as "ears" in the industry. The ears allow flue gas from the bottom zone to join the rest of the flue and leave 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.

The fuel consists of 90% CH_4, 5% C_2H_6 and 5% N_2 by volume. The molecular weight is 17.3. Its gross heating value (HHV) is 1001 Btu/scf, and requires 15.76 lb. of air per lb. of gas. These fuel characteristics were used consistently in both the CFD model and the process model.

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

The governing equations for the conservation of mass, momentum, energy and chemical species are solved with the FLUENT software package (FLUENT User's Guide, 1996). It uses a control volume based finite difference scheme where nonlinear variations are included inside each control volume, similar to the concept of a shape function in a finite element scheme. This method is a variation of the original approach by Patankar (1980). This formulation ensures 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 showed that the results were independent of further grid refinement. To further assure the accuracy of the solution, a second order discretization scheme (Leonard, 1979) is used. The solution is allowed to iterate until the residuals are reduced by at least 5 orders of magnitude. More importantly, field variables are monitored to ensure they do not vary with further iterations, and the overall mass, species, and energy balances are satisfied. The overall error in the energy balance is 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 (HHV 140 MMBtu/hr) is absorbed by the steel to reach an average discharge temperature of 2120 °F. Water cooling amounts to 11% loss, and refractory loss is 4%. At an average exhaust temperature of 1725 °F, flue loss amounts to 27% of total input. The flue temperature is in reasonable agreement with the recuperator design inlet temperature of 1600 °F. The average gas velocity at the nose is 9.8 ft/s, and the average gas temperature is 2166 °F. Axial furnace temperatures at baseline, Figure 7, show upper zone peak flame and bulk temperatures at around 3700 and 3200 °F, repectively. Temperatures are sufficiently high mid way along the top heat zone, about 2800 °F, to inject reburn fuel. The model also predicts primary combustion to be substantially complete at this location, e.g., CO<200 ppmv. The velocity profiles are shown in Figure 8. Note that the velocity at the point of reburn fuel and OFA injection is approximately 30 ft/s. Jet velocities are selected to penetrate at least 70% through the bulk gas at these locations.

The second case primarily evaluates the impact of increasing furnace production by 20% through oxygen enrichment. Oxygen enrichment is implemented by premixing it into the air supply duct for the top zone only. Furthermore, suppose 75% (10.5 MMBtu/hr) of the reburn fuel energy is recovered inside the furnace. Iterative calculations predict the need for the top zone combustion air to be enriched to 50% oxygen. The CFD model shows that the average steel discharge temperature is 2159 °F, and that the average exhaust flue temperature is 1640 °F, all within expectations.

At the nose, the average velocity is 10 ft/s, and the average gas temperature is 2213 °F. Since the soak zone firing pattern has not changed, the increase in temperature is solely due to radiation from the top zone. The slight velocity increase is due to the increased temperature. The temperature distribution is compared to the baseline in Figure 9. Although the peak flame temperature is considerably higher by 460 °F, the peak ceiling refractory temperature increases more modestly from 2822 °F to 2950 °F (128 °F). Examination of the steel temperature profile indicates that the heat transfer rate in the top zone with oxygen enrichment is higher, since the temperature curve has a larger slope and crosses that of the baseline case. The velocity profiles are similar to the base case. Fuel efficiency, at 1.014 MMBtu/ton, has 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.

Zoned System Model

The Zoned System Model provides a simple mass and energy balance calculation which may be used to evaluate the primary impacts of changes in operating conditions such as variation in gas reburn or oxygen enrichment parameters. The model divides the furnace into distinct zones. A simplified, zero dimensional radiative and convective heat transfer model is applied to each zone. Gas radiative properties are 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 is no direct heat transfer between zones except for the carryover of sensible heat as furnace gases pass from one zone to another, and through interaction with the steel which passes through each zone. Because the steel moves counter to the gas flow direction, the steel heat transfer is 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 are used to refine the model.

This decoupled zone approach allows for quicker evaluation of performance impacts than is possible with a full CFD simulation. Since the impact of Oxygen Enrichment based on CFD has been presented above, only Zone System Model predictions of the impacts of Gas Reburn by itself are included here.

For the model of Gas Reburning applied to the top Heat Zone alone, the model furnace is divided into four zones: Soak, Bottom, and a subdivision of the top Heat Zones into an upstream and downstream part. The two Upper Heat zones are separated by a vertical plane coincident with the burner wall of the bottom zone, which is about the location where reburn fuel is to be injected in the top zone. OFA is also assumed to follow shortly after in the second top Heat Zone, so that the zone may be considered to operate at the burnout stoichiometry. Figure 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.)

Gases from the bottom zone bypass the upper heat zone entirely and are mixed with the flue gases from the top before entering the recuperator. The ducts leading from the heat zones to the recuperator are not modeled separately but are implicitly included in the regenerator calculation.

Heat losses in these ducts and the recuperator are neglected but are 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 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 is incorporated into the model. The calcuation is based on the effectiveness method, assuming that the value of NTU (Number of Transfer Units), established initially at baseline conditions, is constant at all other conditions. Heat removal from the steel skids (by cooling water flow) is included in the furnace model, and is assumed to be the same (15 MMBTU/hr) in all cases presented here.

Figure 11 shows baseline mass and energy parameters of interest. Reburning in the top heat zone is 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 upper heat zone. This effectively moves the heat release in this zone downstream.

Figure 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 is a reduction in overall furnace efficiency of about 2.3%. One way of viewing this is that only about (2.3/15) or about 16% of the reburn fuel heat input is lost, implying 84% heat recovery of the reburn fuel.

Some of the heat recovery is direct heat transfer to the steel within the heat zone. Some of the heat initially escapes the furnace in the form of a higher furnace exit temperature, but is partially recaptured in the recuperator in the form of higher preheat temperatures. This temperature impact is shown as a function of the amount of reburn fuel in Figure 13. At 15% reburning, the additional air preheat energy accounts for about 1.2% of the 140 MMBTU/hr fuel heat input. This implies that most of the reburn fuel heat input is recovered directly in the furnace, and is supplemented by air preheat recovery. Indirect heat recovery in the recuperator is less efficient and thus less desirable than direct heat transfer to steel, but does represent an additional mitigation of the heat loss due to delayed combustion of reburn fuel.

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 establish the fuel injection location, e.g., just downstream of the CO<200 ppmv contour (complete combustion) and at the highest bulk furnace temperature, T>2400 °F. The zoned system model was then used to determine the impact of these locations on the amount of the reburn fuel heat that is usefully recovered, i.e., in the steel and recuperator. For purposes of the proforma economic analysis the furnace baseline NOx emission is assumed to be 0.3 lb/MMBtu.

The mass balance for Case 2 with gas reburn only, differs only slightly from normal operation. Since the gas reburn incorporates a final afterburning zone with the injection of OFA, all high temperature heating zones will be operated close to stoichiometric subject to current practice in scale control e.g., any low levels of CO will be burned out in the last stage of the process. Lower excess air should result in a 10 to 20 % NOx reduction and some fuel efficiency improvement. Gas reburn fuel is then added through jets in the furnace ceiling, bottom and walls at a location about midway along the heating zones where bulk temperatures are about 2600 °F. This should result in an additional 50 to 55% NOx control. Note that the area immediately adjacent to the steel can be kept relatively oxidizing downstream of the fuel injection point to avoid carburizing if required by controlling the penetration distance of the reburn fuel jet. OFA is introduced in the top and bottom zones about 0.4 seconds (about 8 ft downstream) at a point where the process gas temperature is still >>1600°F to complete combustion. Thus, only a very small steel surface area in the treated zones is exposed to the reburn reducing environment. The released heat is substantially recovered (70 to 85%) in the preheat zone and the recuperator. Overall, the gas reburn process is expected to be nearly fuel efficiency neutral. Gas reburn NO control effectiveness is estimated from Figure 5 at 50 % or 0.15 lb/MMBtu. If less NOx control is required, only the top zone would be treated.

Case 3 incorporates the combined GR/OEA technologies to obtain high radiant heat in the top heat zone using about 4.2 TPH of oxygen enrichment (50% O_2). This amount was previously shown to achieve about a 20% efficiency improvement without significantly impacting furnace refractory temperatures and does not result in local steel surface melting. The process conditions have now moved to a more favorable condition, high NOx (about 0.51 lb/MMBtu), but injection temperatures similar to the baseline reburn case (2600°F), improving the gas reburn performance. NOx reductions of about 60%, as shown in Figure 5, result in a NOx emission of about 0.18 lb/MMBtu, or 40% less than baseline.

In reality, actual furnace design, site and regional requirements will dictate the level of enrichment; only sufficient O_2 will be introduced to meet the new production requirements and only enough gas reburn to meet the regulatory requirements. The potential effects on furnace efficiency due to gas reburn heat input to the top heat zone is shown in Figure 12.

Thus, the approach is seen as a tailorable technology for an evolving and changing set of performance requirements. For example, during periods of extended production delays due to mill problems O_2 enrichment would not be necessary or cost effective, and could result in unwanted steel oxidation. Long mill delays increase the potential for steel carburization in the reburn zone where the furnace environment is more reducing due to the injection of the reburn fuel. Under full reburn conditions at a stoichiometric ratio of about 0.93, the process gas between the GR and OFA injection points will typically be composed of about 0.025 and 0.08 mole percents of CO and CO_2, respectively. The carbon potential for this mixture has been estimated and indicates that even at low stoichiometries the potential is several orders of magnitude lower than that used for 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.

Proforma Economics and Market Potential

A proforma cost-effectiveness evaluation has been performed for the two cases and compared to the baseline furnace performance. The figure of merit for the comparisons is as follows:

- *Gas reburn only*: the annualized cost per ton of NO_2 reduced, absolute and as compared to other technologies
- *Gas reburn with OEA*: the net annualized value of incremental steel

produced less O&M costs for GR and oxygen (cost per ton of steel produced)

The economics are 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
- 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 yr life
- A twenty percent increase in furnace productivity
- Finished steel at \$0.22/lb, and a 1.2, 2.5 and 5 % revenue enhancement from production increase

The economics of the three concepts relative to base line performance are detailed in Table 2. GR 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 is calculated on the basis of annualized cost/ton NOx removed, and evaluated parametrically as a function of its impact on furnace efficiency shown in Figure 14. The modelling results currently suggest slight to some decrease in furnace efficiencies (between 1.22 to 1.25 Btu/ton), resulting in 1100 to 1900 \$/ton NO_2 reduced, respectively. GR and LNB's 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 ms of mixing/reaction time. For the base case 90% of the flue gas flow is at a velocity of about 20 fps at the injection point, indicating that the injectors should be spaced 8 ft apart. Because of the substantially lower flows when oxygen enrichment is used, the distance could be reduced about 30% or to about 5 ft. Thus there is sufficient time/temperature to recover a significant amout 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 due to 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 value (2.5 to 5 % incremental value) of a 20% production increase (23 TPH) is about \$10 to 20/ton for finished steel priced at \$440/ton. Thus, there is some considerable advantage to debottlenecking with net savings of over \$600,000 on \$ 590,000 of capital, an excellent return of the investment. Figure 15 shows the cost of implementing oxygen enrichment with and without reburning for different levels of revenue increase. The importance of maximizing the flame radiation to minimize O_2 consumption is suggested and is the other major focus of the development plan.

Summary

Initial results from the Phase I work have been reported as work in progress. 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. The significant economic benefit of increased production was demonstrated along with the relatively minor impact of adding gas reburn to achieve off-set NO control.

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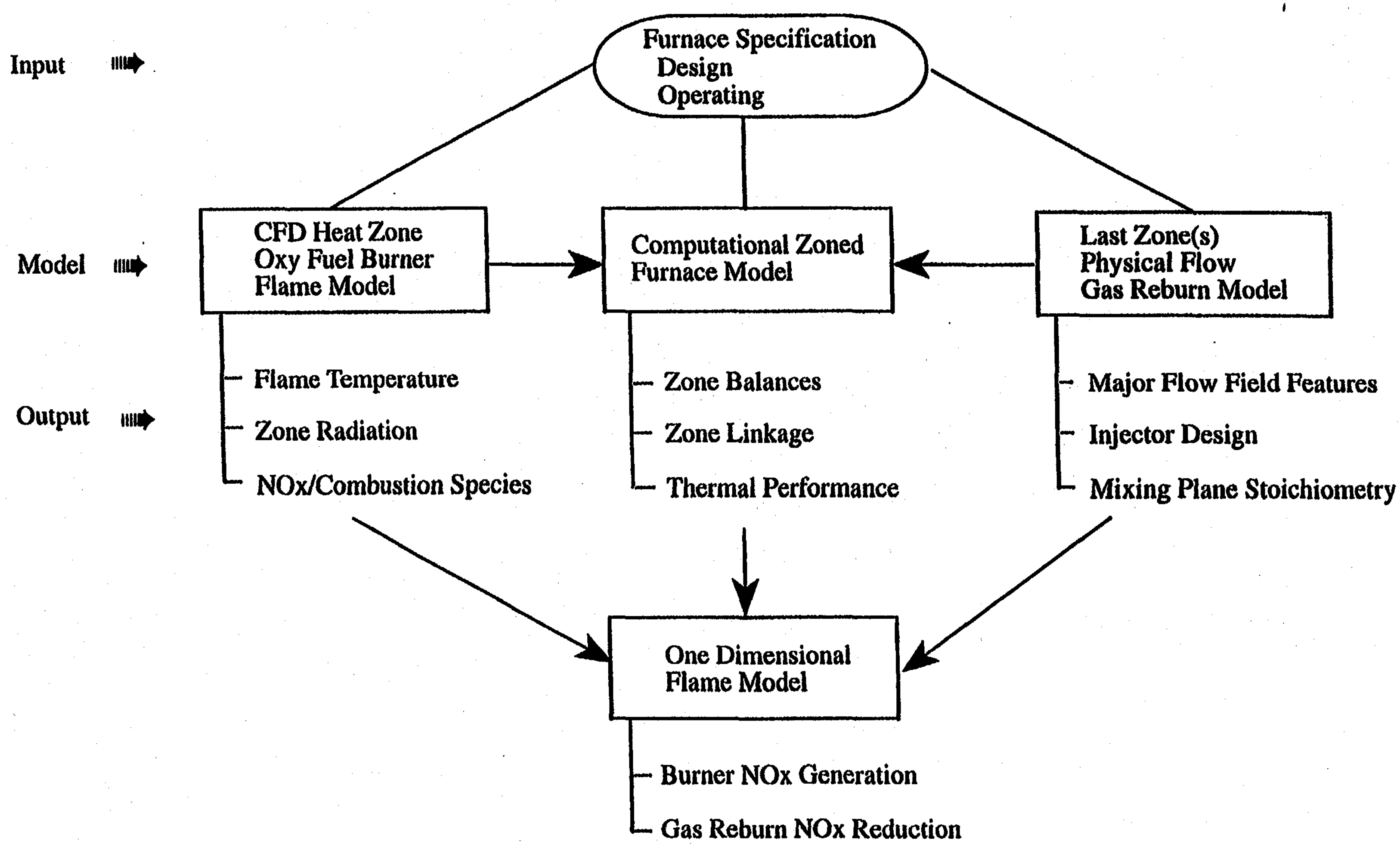


Figure 1. Phase I model development and linkage.

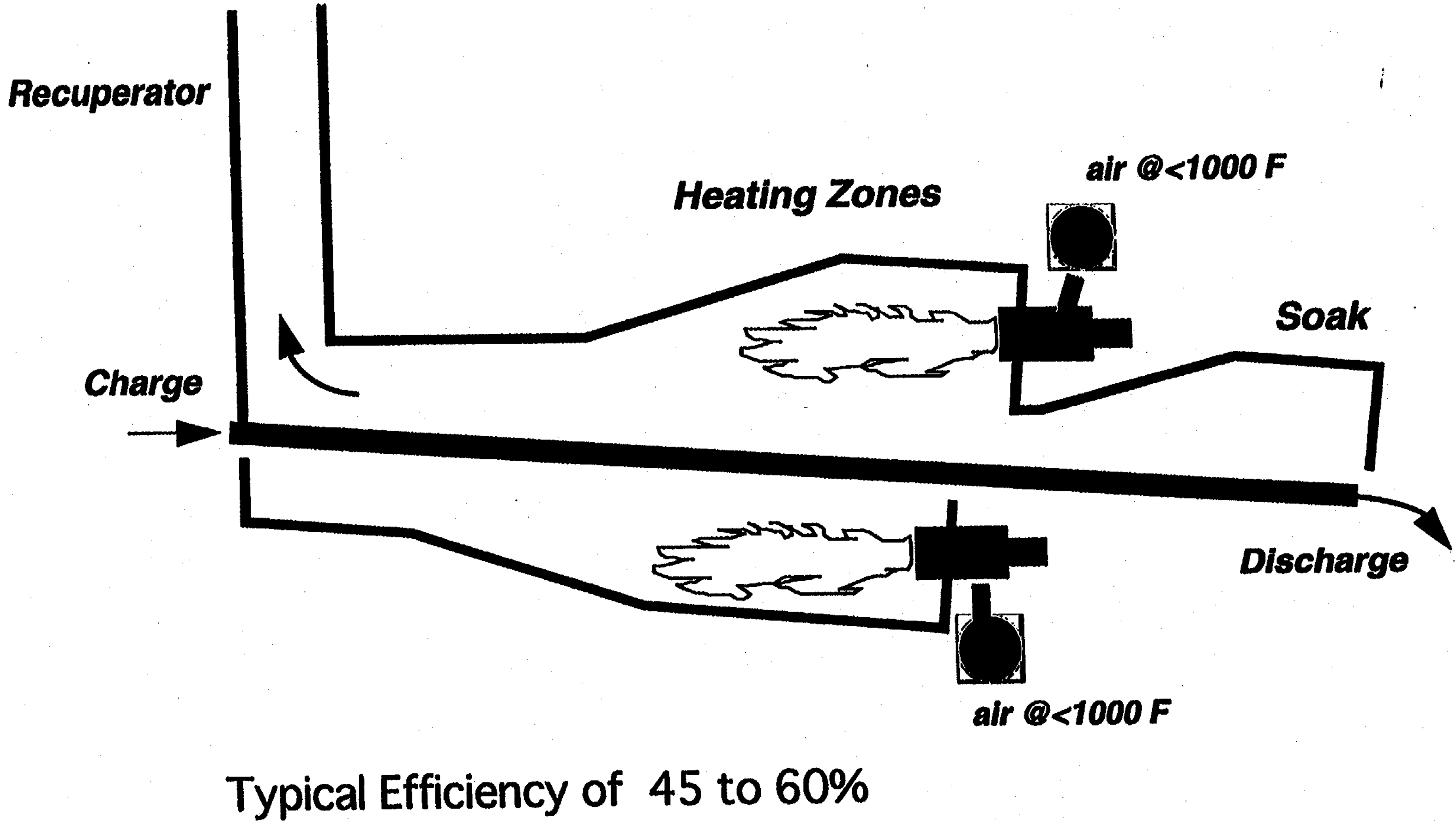


Figure 2. Typical pusher reheat furnace with 3 separately controlled combustion zones.

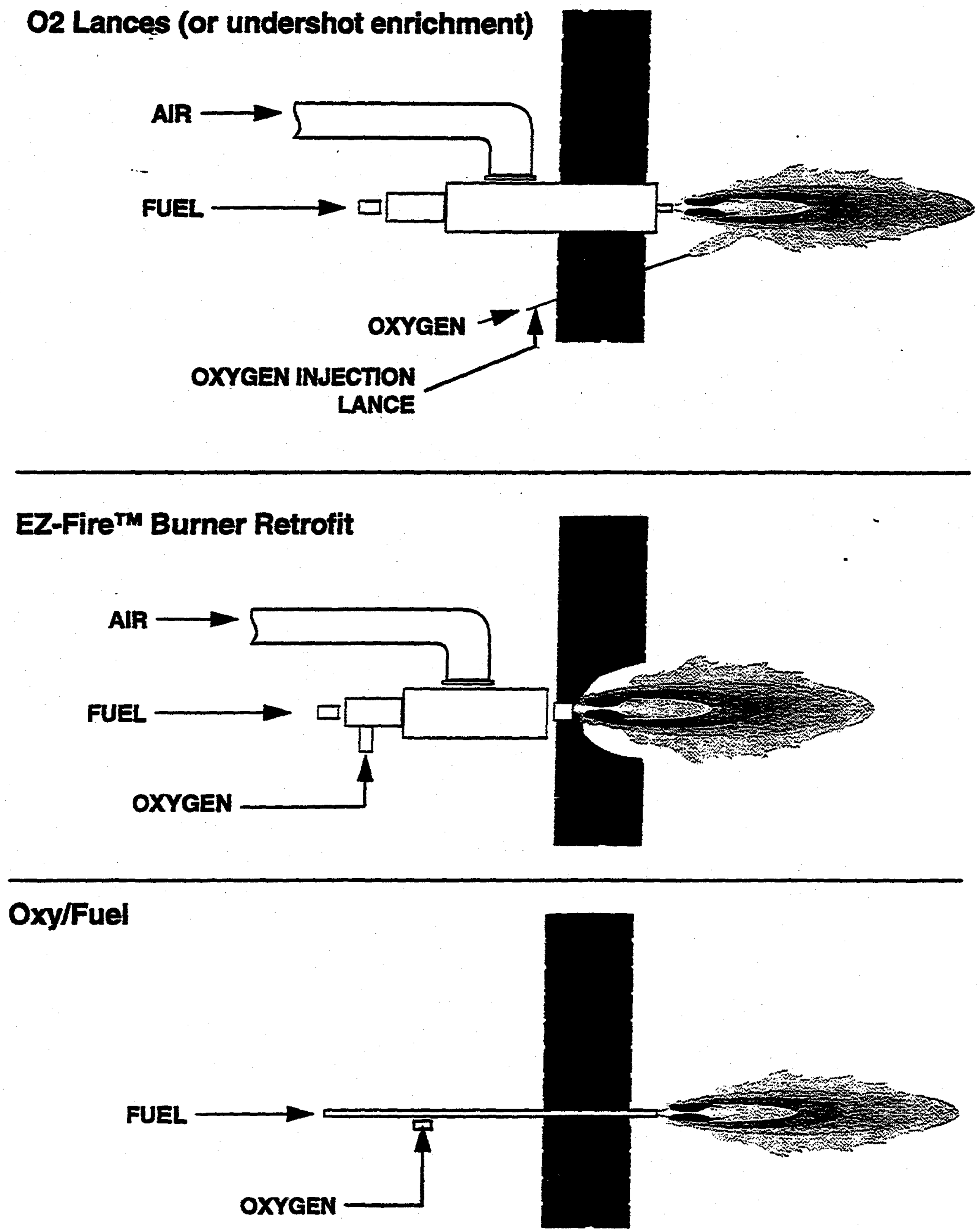


Figure 3. Oxygen enrichment concepts.

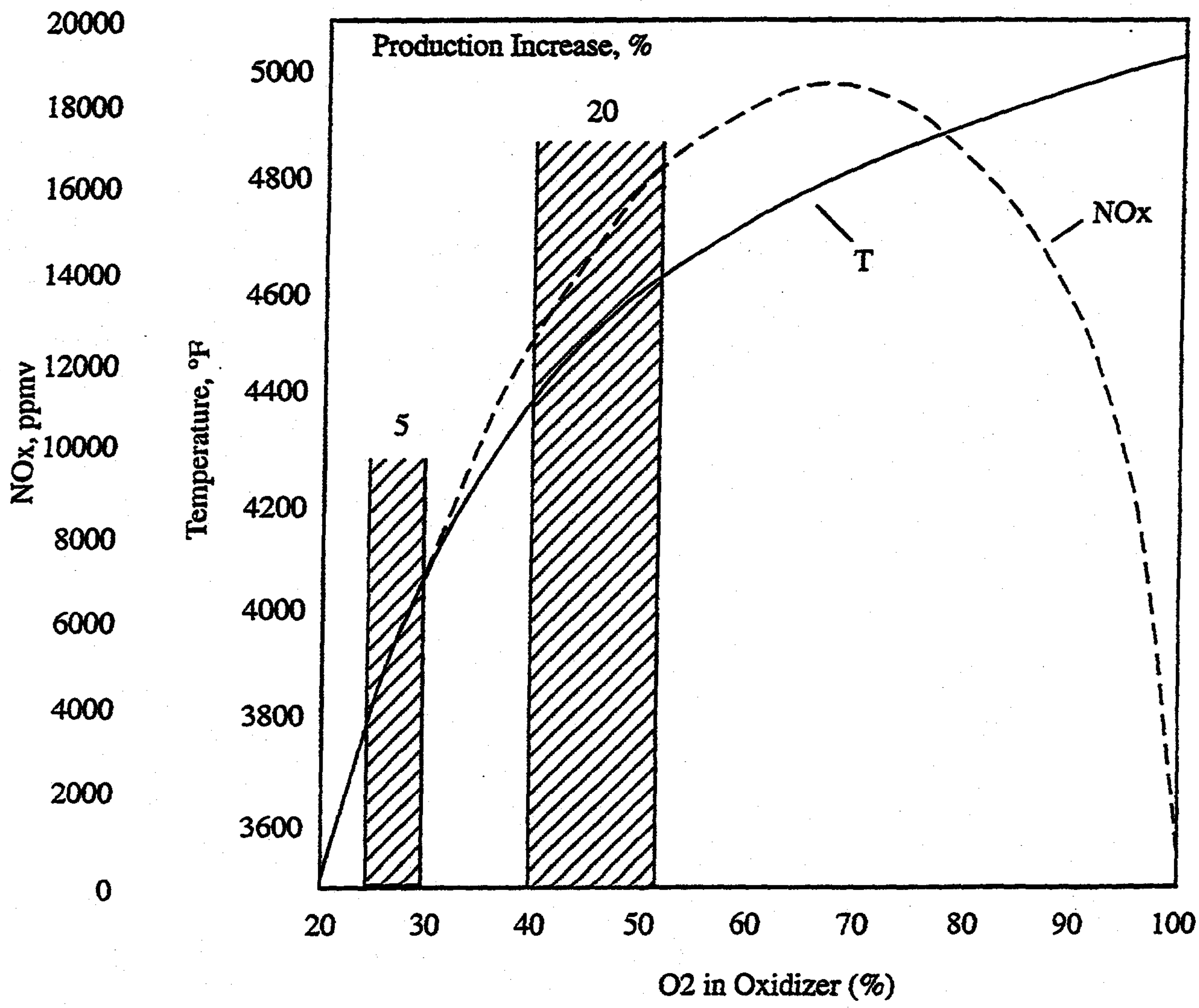
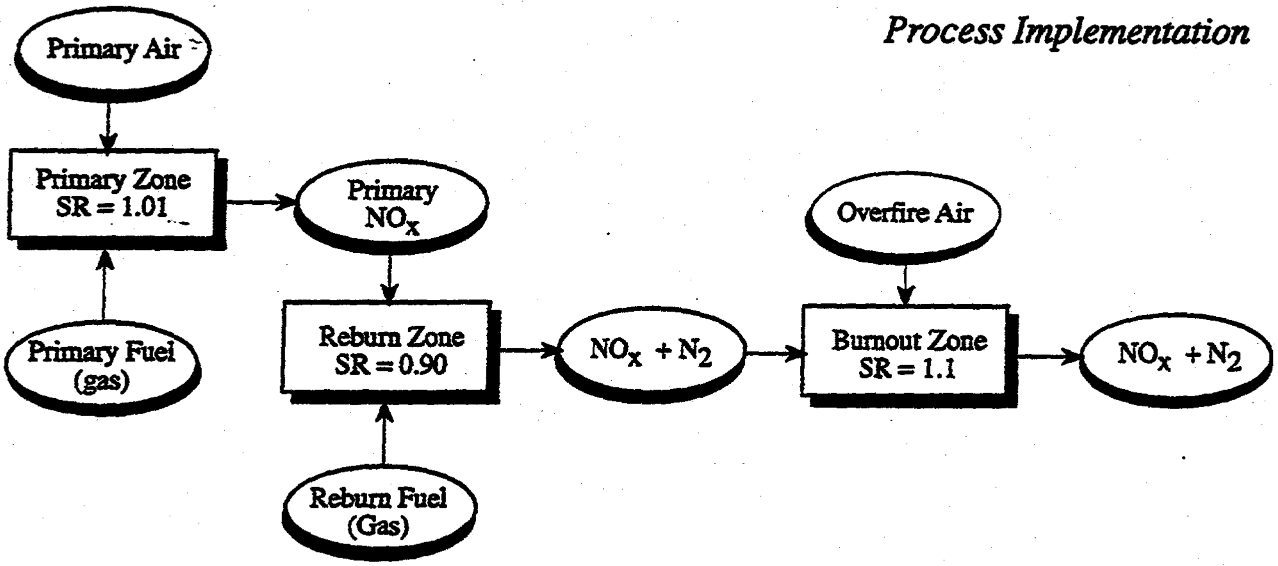


Figure 4. Oxygen enriched theoretical flame temperatures and NO emissions.



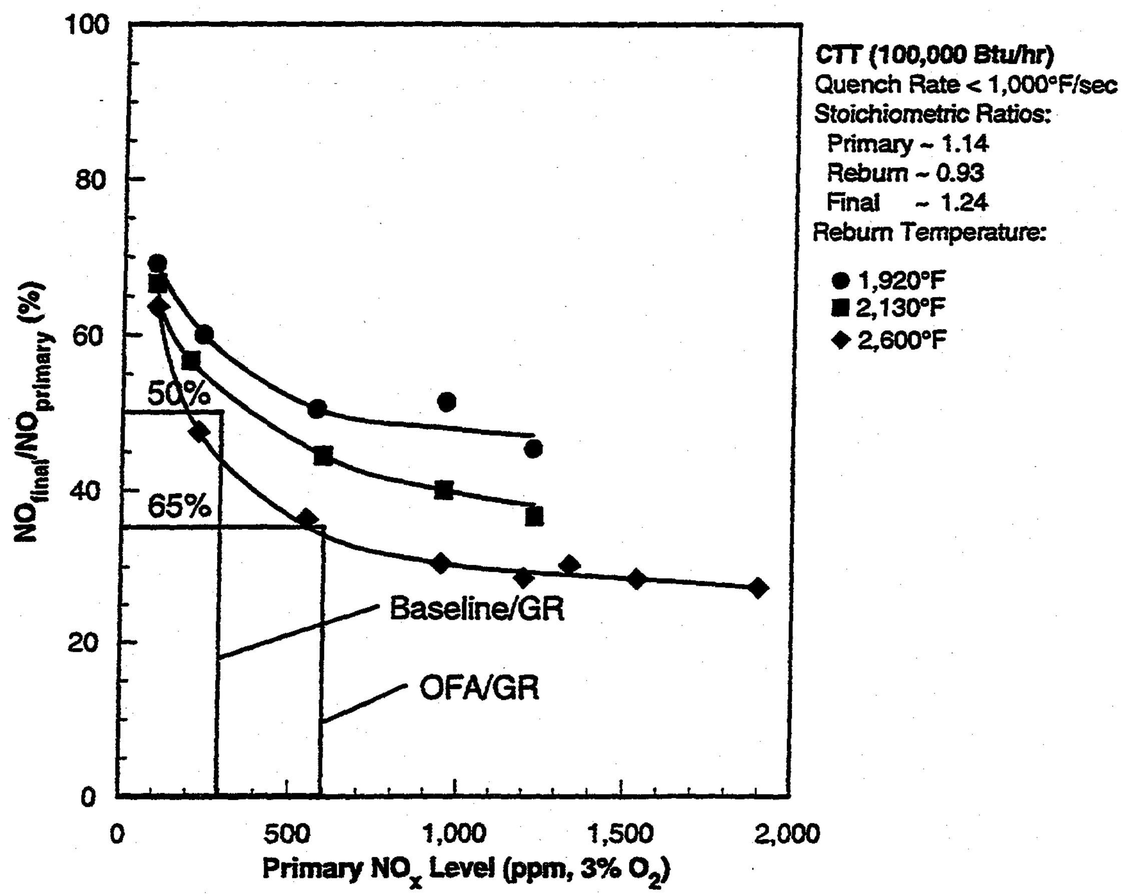


Figure 5. Gas reburn process conditions and pilot scale NO_x performance.

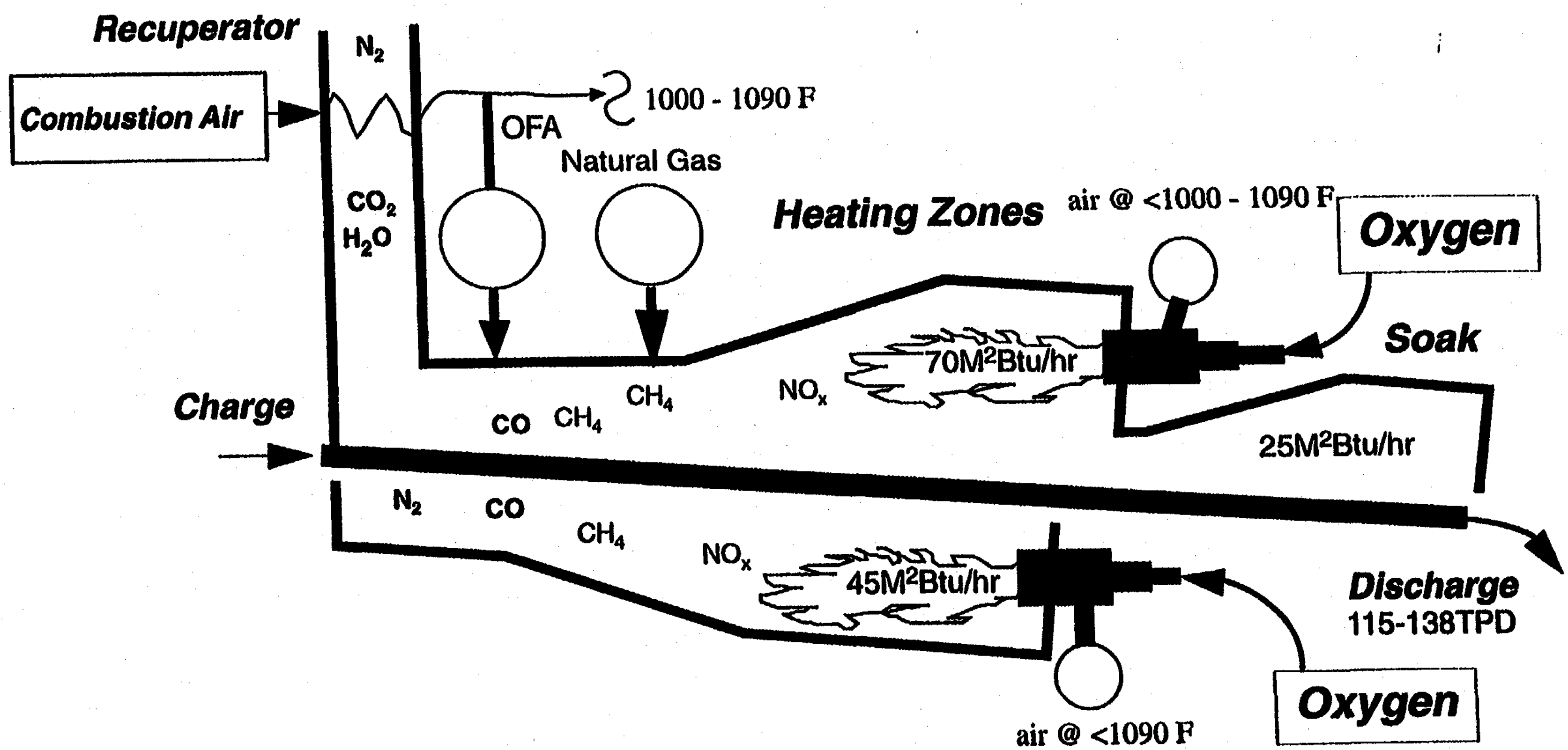


Figure 6. Typical reheat furnace modified for heat zone oxygen enrichment and gas reburn.

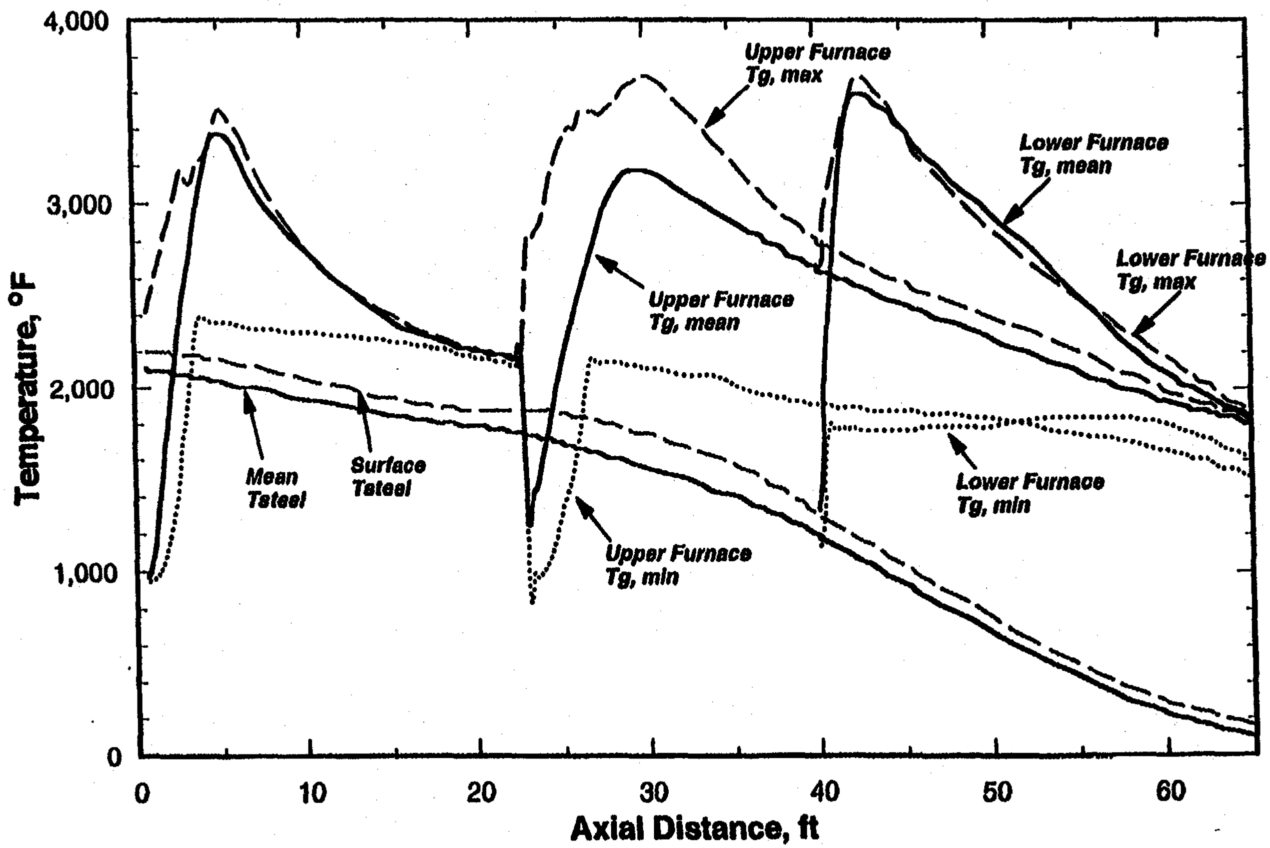


Figure 7. Baseline axial flue gas and steel temperatures.

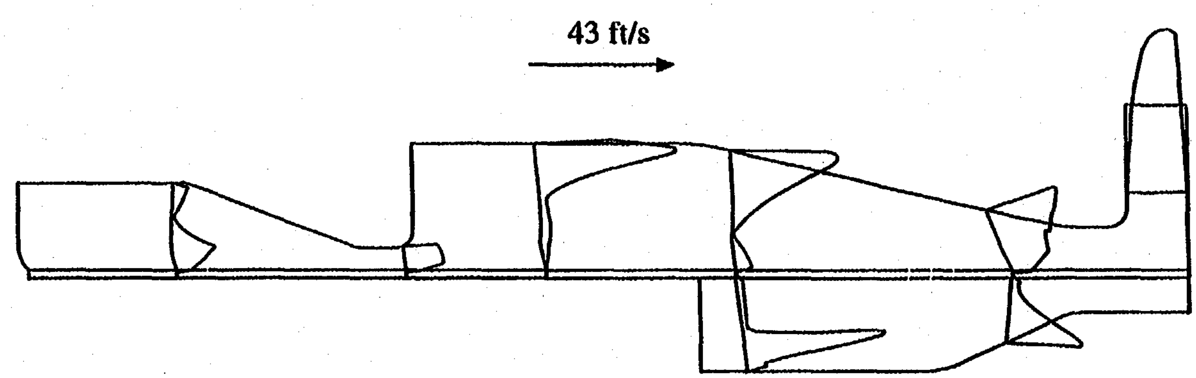


Figure 8. Velocity profiles at various furnace cross sections.

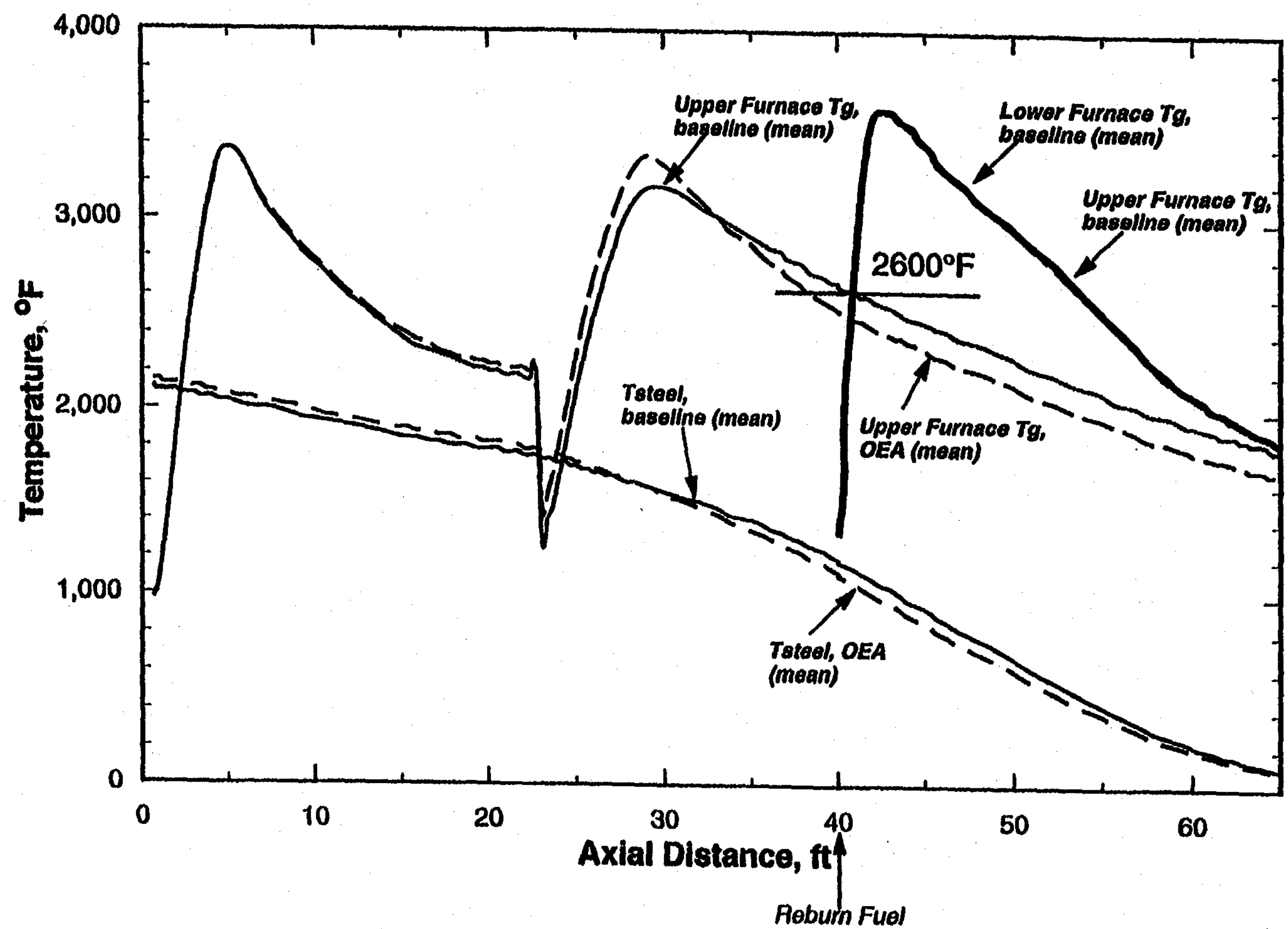


Figure 9. Axial flue gas and steel temperatures at baseline and oxygen enriched conditions.

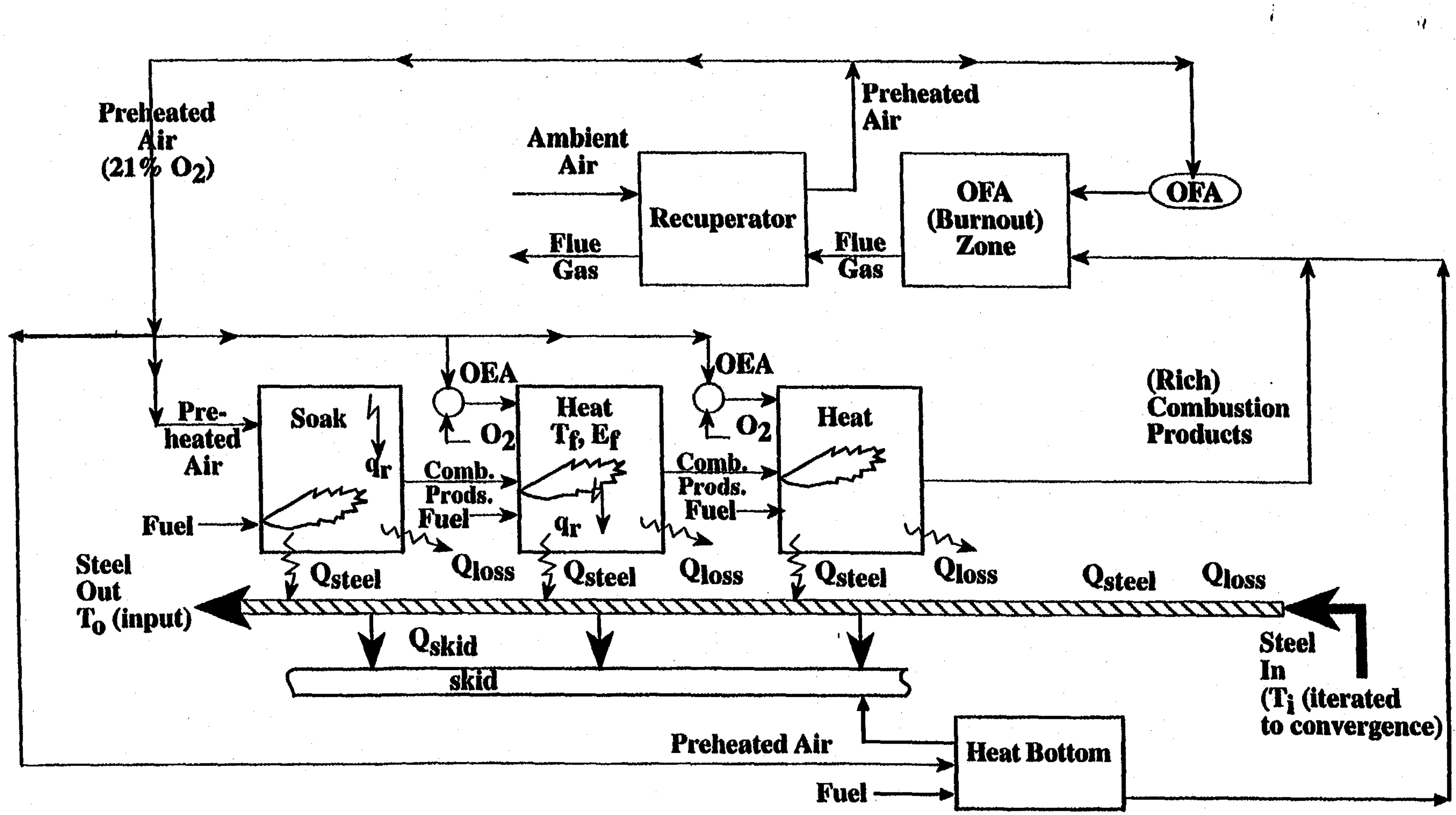


Figure 10. Schematic of mass and heat balance in steel reheat furnace.

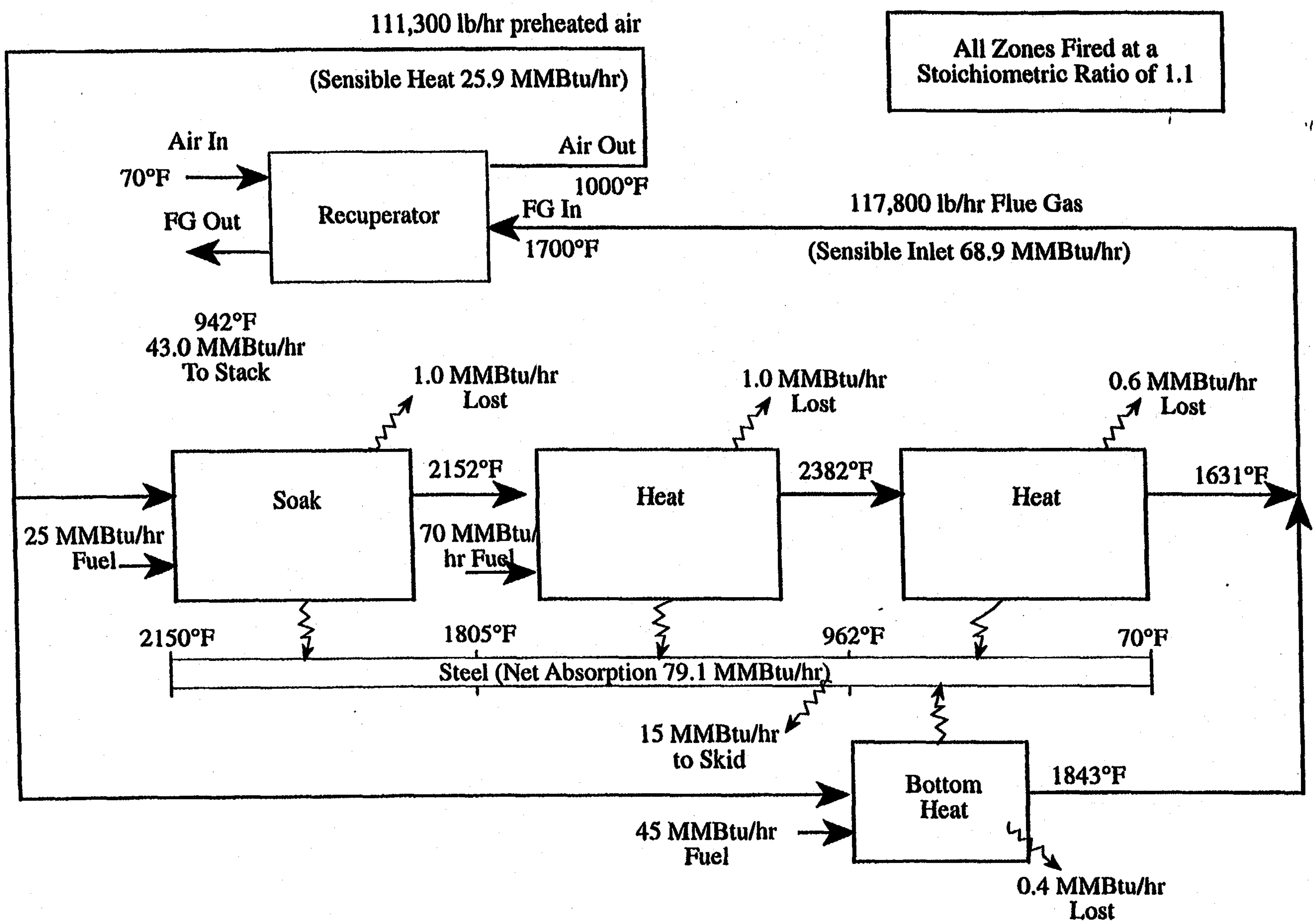


Figure 11. Heat and mass balance for baseline conditions.

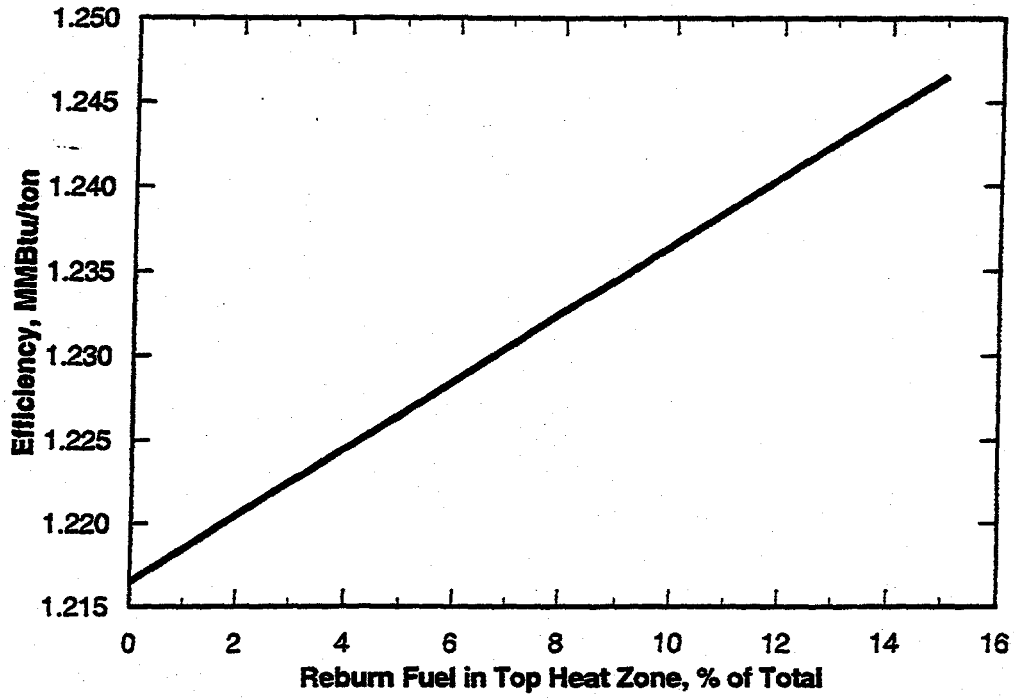


Figure 12. Impact of gas reburn on fuel requirements.

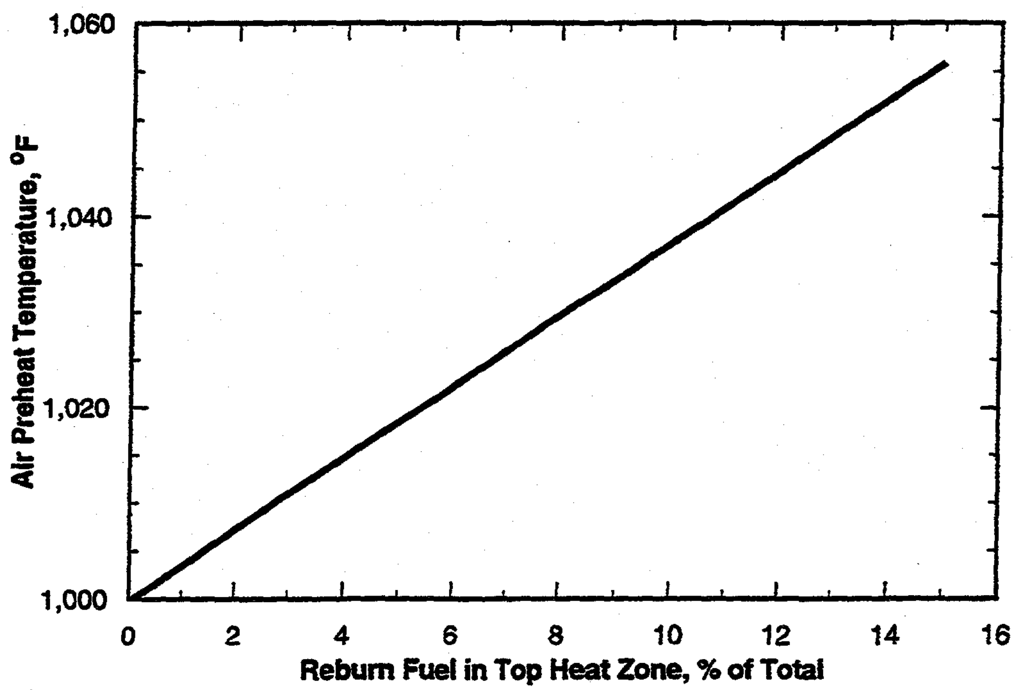


Figure 13. Impact of gas reburn on air preheat temperature.

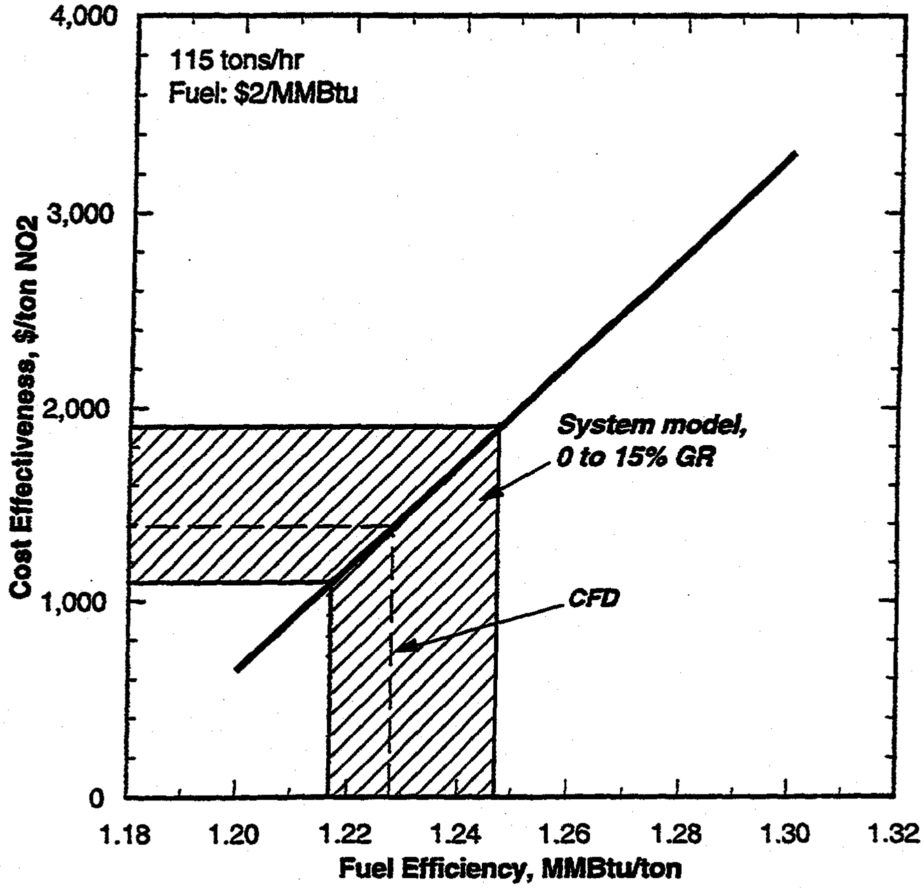


Figure 14. Cost effectiveness parameter sensitivity to gas reburn fuel efficiency impact.

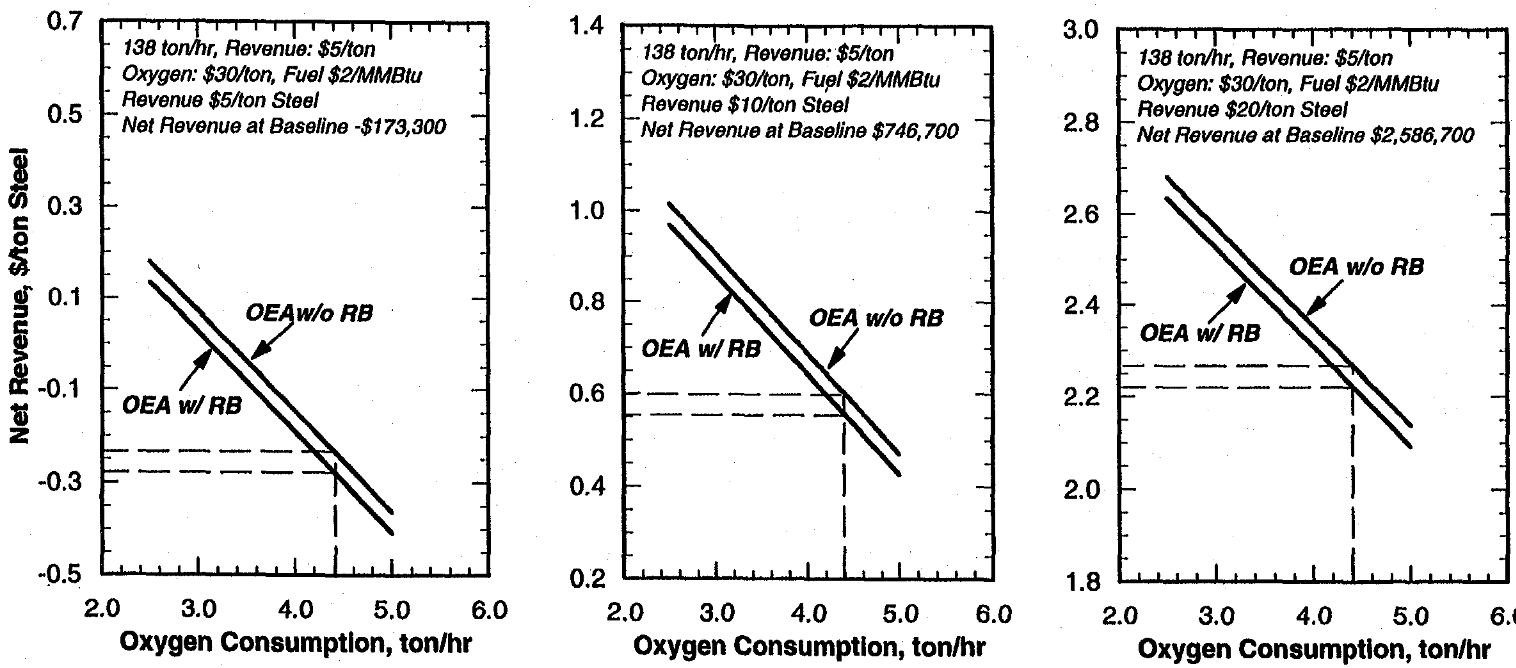


Figure 15. Economic sensitivity of amount of oxygen enrichment required for 20% production increase.