A Novel High-Heat Transfer Low-NO_x
Natural Gas Combustion System

Final Technical Report

for

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Prepared by
David M. Rue - Institute of Gas Technology
Dan Wishnick – Eclipse Combustion

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Executive Summary

This report is submitted to the United States Department of Energy in fulfillment of the contractual requirement for a Final Technical Report covering Phases !, II, and III of the project titled, 'A Novel High-Heat Transfer Low-NO_x Natural Gas Combustion System', under co-operative agreement number DE-FC02-95CE41185. The full project is divided into three Phases with go-no go decision points after Phases I and II. The 15-month Phase I of the project, titled Research and Development Definition, focused on acquiring the market needs, modeling, design, and test plan information needed to proceed with Phase II. Phase I was completed on time and within budget, and Phase I was highly successful. The 24-month Phase II, titled Research and Development, focused on design, fabrication, and testing of the high-heat transfer low-NO_x natural gas combustion system on laboratory and pilot scale furnaces. All goals and objectives for Phases I and II have been achieved. The 36-month Phase III, titled Demonstration Testing and Planning for Adoption, focused on commercial demonstration of the high heat transfer low-NOx natural gas combustion system on an Owens Corning fiberglass furnace. All goals and objectives of Phase III have been met. The project was completed on budget.

The project team assembled all elements necessary to develop and demonstrate this novel, innovative technology and to accelerate its commercialization. The Gas Technology Institute (GTI) is a premier industry-supported energy systems and environmental technology development organization. The Institute of Gas Technology (IGT) was the original prime contractor. During this course of this project, IGT combined with the Gas Research Institute (GRI) to form a larger not-for-profit corporation still focused on energy and environmental research and technology development. Combustion Tec (CTI), a division of Eclipse, is a major supplier of advanced natural gas combustion systems to the glass industry. Combustion Tec was an independent company at the start of this project and was purchased during the project period. Combustion Tec now serves as the glass industry combustion system supplier for Eclipse. Owens Corning (OC) is a leading glass industry manufacturer/end-user with a well-established reputation for the introduction of innovative technology. GTI and Combustion Tec have an established track record of successful teaming arrangements over the past fourteen years that has rapidly commercialized innovative technologies in the glass industry. Owens Corning participation ensures development is focused on end-user needs and commercialization barriers are minimized. The strong industrial participation in this project team and the active participation of industrial team members in all Phases and Tasks of the project demonstrates the commitment of industry to develop and commercialize this innovative energy-saving, low emission combustion system.

The key component of the system is an innovative burner technology conceived by GTI. This novel burner capitalizes on GTI's and Combustion Tec's extensive expertise in this area.. This technology, which combines high temperature natural gas preheating with soot formation and subsequent soot burnout in the flame, increases the system's energy efficiency and furnace throughput, while minimizing the furnace air emissions, all without external parasitic systems. The burner will be a highly cost-effective retrofit to existing high temperature furnaces fired with natural gas using oxygen, oxygen-enriched air, or air.

The framework for the project was set in Phase I, the R&D definition phase, which is now completed. The results of Phase I were presented in the Phase I Final Report. Work included identifying industry's needs and constraints, modeling the high luminosity burner system, designing the prototype burner for initial laboratory-scale testing, defining the test plan for Phase II, adapting the GTI burner technology to meet industry needs and constraints, and outlining the

Industrial Adoption Plan. Owens Corning, Combustion Tec and GTI all participated in this phase of the project.

The modeling results produced by the University of Illinois at Chicago (UIC) and Purdue University were very positive. These teams modeled the burner system as consisting of a Fuel Preheat Zone and a Flame Zone. They determined that direct heating in the Fuel Preheat Zone and subsequent soot precursor formation increases the carbon conversion to soot in an oxy-gas flame from 0.1 percent of the feed carbon to 2 percent of the carbon. Flame radiation heat transfer calculations showed this leads to an increase in heat transfer to the load of 25 percent. Only 2 to 9 percent of the feed natural gas must be burned in the Fuel Preheat Zone's Precombustor to achieve this effect, and the residence time needed to generate the soot precursors is as short as 10^{-4} seconds. A Topical Modeling report was prepared and submitted to DOE. The CTI burner design team developed a prototype burner design for laboratory testing which covers the temperature and residence time ranges specified by the modeling results. This design can be readily fabricated by standard practice.

The experimental portion of the program began in Phase II, the Research and Development phase, by engineering and testing at laboratory and pilot scale. Results were presented in the Phase II Final Report. These proof-of-concept tests showed that the burner technology will meet industry's technical and financial needs and constraints. The laboratory-scale testing with three different 0.5 MMBtu/h burners took place in GTI's Applied Combustion Research Facility (ACRF). The pilot-scale testing with a 3 MMBtu/h burner was conducted at Combustion Tec. Combustion Tec constructed all test burners. Test results were analyzed by GTI and Combustion Tec, and Owens Corning reviewed results to ensure performance meets industry needs and constraints.

The results of tests with three prototype laboratory-scale 0.5 MMBtu/h burners were highly positive and confirm the modeling results which calculated a large increase in heat transfer to the glass. Heat transfer increase to the load of more than 12 percent was achieved compared with a commercial Combustion Tec oxy-gas burner. The project team expects to achieve 20 percent increase in heat transfer in an industrial glass melter. Data analysis was completed and the 3 MMBtu/h prototype burner was designed CTI with GTI input. The 3 MMBtu/h prototype burner was approximately 6 inches in diameter and 50 inches long. Testing was conducted in two series at Combustion Tec in Orlando, Florida. Parametric testing of the prototype burner was conducted along with comparison tests with two commercial oxy-gas burners. Variables included different amounts of precombustor gas and oxygen and different ratios between fuel-lean and fuel-rich combustion zones. Analysis showed a 250°F drop in exhaust gas temperature and an increase in heat transfer to the load of 10% with the 3 MMBtu/h burner.

The Phase III full scale demonstration at an Owens Corning facility confirmed the suitability of the burner technology and provided the information necessary to complete the Industrial Adoption Plan. All team members participated in Phase III of the project in which one burner has been replaced on an Owens Corning oxy-gas fiberglass furnace located in Delmar, NY. The burner has performed well after three months of continuous operation. The project team is preparing to complete conversion of all seven burners on the furnace. At that time, full data will be collected to determine the energy savings and NO_x reduction benefits of the high luminosity burner.

Before the prototype 3 MM Btu/h burner was installed at OC, a commercial prototype burner was designed. This burner design and associated CFD modeling results were reviewed by the project team. The project team, with strong input from Owens Corning, concluded that this burner design had significant deficiencies. A second prototype commercial burner was designed and modeled. This design was considered acceptable by all team members and was fabricated by Eclipse. The burner was installed in December, 2001 and has performed well, creating a highly luminous, flat flame.

Demonstration testing of the high luminosity burner was conducted in October, 2002 with all seven burners on the melter changed from conventional Primefire 300 burners to high luminosity burners (designated Primefire 400 burners). With state-of-the-art Primefire 300 burners serving as a baseline, the high luminosity burners were found to decrease NO_x emissions by a dramatic 50 percent on the furnace. One of the seven burners was found to have a longer than desirable flame, and this led to overheating of the exhaust duct and loss of melter efficiency. Even so, the project team measured a decrease in melter energy use of 0.7 percent, equicalent to an increase in burner efficiency of 1.5 percent. After testing was complete, Eclipse engineers changed the burner of concern to one with a shorter flame. This led to a decrease in exhaust duct temperature, and likely to a decrease in energy use. Unfortunately, the data for energy use is not available on a comparable basis of melter pull rate and temperature. Even so, the high luminosity burner is considered a success. Eclipse is now marketing the high luminosity burner under the Primefire 400 tradename.

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Introduction

The two largest problems facing high temperature combustion processes are the consumption of large quantities of fuel and the production of high levels of pollutants. The production of NO_x is of particular concern in high temperature processes because NO_x yield increases as combustion temperature increases. Both problems can be addressed for natural gas combustion by switching from air-gas to either oxygen enriched air-gas or oxygen-gas firing. Combustion with oxygen offers advantages of reduced energy costs, lower NO_x and particulate emissions, and decreased capital and maintenance costs by eliminating the need for flue gas cleaning and heat recovery. Oxy-gas flames burn at a higher temperature, allowing energy savings through more efficient radiant heat transfer and higher energy availability. Low NO_x levels result from the presence of a reduced amount of nitrogen in the flame.

While oxy-gas firing for industrial processes such as glass melting is attractive and has been adopted commercially to some extent, optimization of the process promises large rewards in both energy savings and NO_x reduction. The dominant mode of heat transfer to the load in a process such as glass making is by radiation. Radiative heat transfer is dependent upon both the temperature and emissivity of the heat source. At the high combustion temperatures of an oxy-gas or a high temperature air-gas flame, combustion products are not luminous (low emissivity) which leads to low radiation, poor heat transfer to the batch, a high exit gas temperature, low process efficiency and production rate, high fuel consumption, and poor furnace efficiency. Process and energy efficiency increase for high temperature furnaces. Increasing flame luminosity by seeding the flame with soot particles has been shown to provide significant benefits to oxy-gas combustion.[1,2] Although large gains can be made, commercial application has not occurred due to the complexity and cost of co-burning soot particles with natural gas.

The high-heat transfer low-NO_x natural gas burner system for oxy-gas furnaces produces an improvement in energy efficiency of at least 20% and a significant decrease in NO_x formed per ton of product. In this innovative burner, improvements arise from increased luminosity produced by forming and then consuming soot in the flame. Benefits include:

- Higher heat transfer to the load. Cracking of natural gas generates soot particles that increase luminosity and provide higher heat transfer as well as higher process and energy efficiency.
- Lower flame temperature and exit temperature. Greater heat transfer from a more luminous flame generates a radiative cooling effect.
- Lower NO_x yield. The lower flame temperature and the lower consumption of natural gas lead to less NO_x production

The burner system can be retrofit to existing air-gas fired furnaces minimizing cost and maximizing energy savings, production rate, and NO_x reduction.

The burner being developed in this program, referred to as the GTI high-heat transfer low-NO_x natural gas burner, has direct application in glass melting furnaces and other industrial furnaces. The burner combines a preheating zone and two combustion zones. A conceptual drawing of the burner is presented in Figure 1. The high-heat transfer low-NO_x natural gas burner has the following zones:

- Preheating zone - includes partial combustion and direct preheating of natural gas
- First combustion zone - soot formation, fuel-rich partial combustion
- Second combustion zone - soot burning, high luminosity combustion.

Conventional industrial oxygen-natural gas combustion furnaces offer little, if any, energy efficiency improvement over a glass tank with a high air preheat temperature (2300°F) from a good regenerator.[3] A substantial amount of energy is needed to separate air and produce industrial oxygen. Significant reductions in NO_x production can be realized, but only at the expense of using pure oxygen instead of industrial oxygen with several percent nitrogen. The natural gas must also be free of nitrogen to achieve low NO_x levels. Natural gas often contains large amounts of nitrogen (3 - 10%). To derive the full benefits of oxygen-gas combustion in

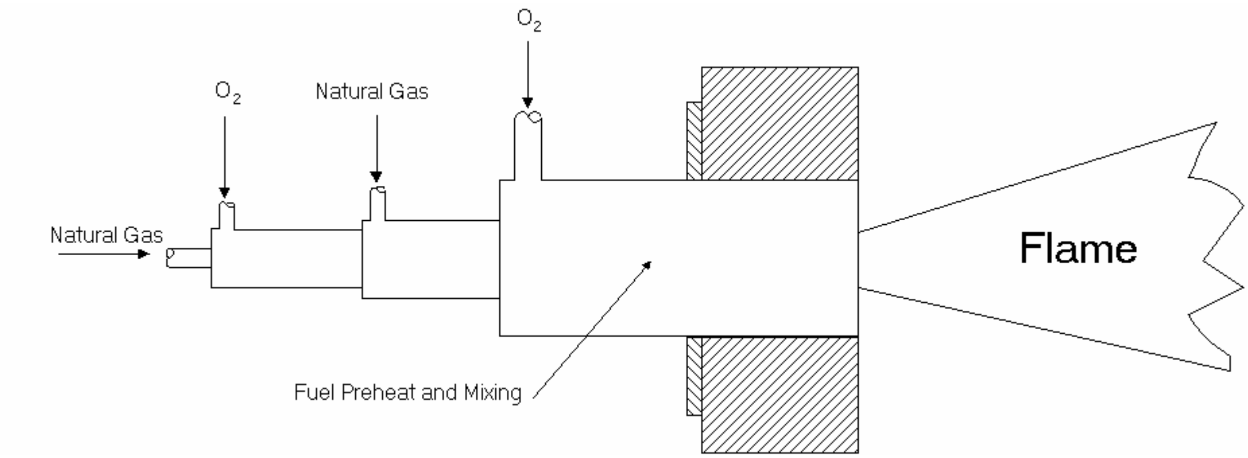


Figure 1. HIGH-HEAT TRANSFER LOW-NO_X NATURAL GAS BURNER CONCEPT

commercial processes, cost effective heat recovery technologies and a means to use industrial oxygen are needed. Energy savings realized by preheating natural gas alone with a recuperator are not cost effective. However, using preheated (and possibly partially reformed) natural gas to generate soot in a first stage of combustion and a highly luminous flame in a second stage of combustion provides additional benefits of lower NO_x emissions, higher heat transfer to the glass, increased productivity, reduced furnace size, and substantially reduced furnace heat losses through the wall.

This technology offers immediate, realistic benefits to industry. These include:

- Applicable to a wide range of furnaces in the materials processing industry, including glass melting, metal melting and treatment, and cement production
- Enables industry to meet emission regulations cost effectively, while also increasing production rate and system thermal efficiency
- Can be retrofit to existing furnaces without major furnace modifications
- Allows utilization of more cost efficient industrial oxygen, instead of pure oxygen, without generating high levels of NO_x.

Particles in a flame are known to cause a flame to burn with greater luminosity than if the particles are not present. Conductive and convective heat transfer raises the particles to a high temperature after which they radiate as nearly perfect black bodies. Soot particles are present in coal and oil combustion but not in less luminous natural gas combustion.

In the high-heat transfer low-NO_x natural gas burner, soot particles are created and burned in the flame. This increases the flame luminosity, and thus the heat transfer to the load, while producing lower NO_x and other air emissions such as CO, CO_2, and unburned total hydrocarbons. The higher heat transfer will lower the flame temperature and decrease the NO_x emissions.

The High-Heat Transfer Low-NO_x Natural Gas burner improves upon GTI's proven oxygen-enriched two-stage low NO_x burner and the Combustion Tec/GTI oxy-natural gas cracker developed and proven by GTI and Combustion Tec to increase the flame luminosity and thus the heat transfer from the flame to the load, thereby increasing the furnace production rate and decreasing NO_x emissions. The involvement of Combustion Tec, Inc., the primary supplier of combustion technology to the U.S. glass industry, in this project assures that the developed technology will be commercialized in the glass and other industries. Owens Corning, the third team member, is a major international producer of fiberglass. Their participation in this project confirms the strong industry interest in the development of this technology.

The original prime contractor for this project was the Institute of Gas Technology (IGT). During the course of this project, IGT combined with the Gas Research Institute (GRI) to form a larger not-for-profit company with an expanded, and continuing, role of energy and environmental research and technology development. All IGT and GRI intellectual property and on-going projects were passed directly to GTI. Also during this project, Combustion Tec was purchased by Eclipse, Inc. Combustion Tec is currently a division of Eclipse, serving the same glass industry market served before the acquisition.

Combustion Tec and GTI previously invented a separate oxy-natural gas cracker which produces soot particles. The particles from the external cracker are transported to a low NO_x burner where they are burned along with the natural gas. Flame luminosity was increased but the system cost was also increased as a result of the cost of the cracker, and system performance was not optimized. GTI has run experiments which show that the heat transfer from the flame is increased when soot particles are present. This can only occur if the flame luminosity is increased by the presence of the particles.

Significant work by GTI and others supports the concept of this innovative GTI burner. Recent work by Factory Mutual indicates methane needs to be preheated to 1000°C (1830°F) and above to create significant amounts of soot in the flame.[4] Figure 2 shows high methane preheat temperature significantly increases flame radiation. Older work of Wolanin indicates the optimum methane preheating temperature is in the range 1150° to 1180°C (2100° to 2160°F).[5] Wolanin shows the heat transfer to the load is increased by 63% when 26.5% of the natural gas is decomposed and the gas is preheated to 1190°C (2174°F). To have a practical high luminosity burner with soot generated in the flame, these results indicate the natural gas must be preheated to between 1000° and 1180°C (1830° and 2160°F) without cracking and then mixed with oxygen. The desired soot should be formed during the oxygen-hot natural gas combustion, and not during the heating of the natural gas. The natural gas needs to be heated very rapidly to form soot precursors. Significant amounts of carbon particles can nucleate and grow into soot when natural gas containing soot precursors is mixed with the oxygen.

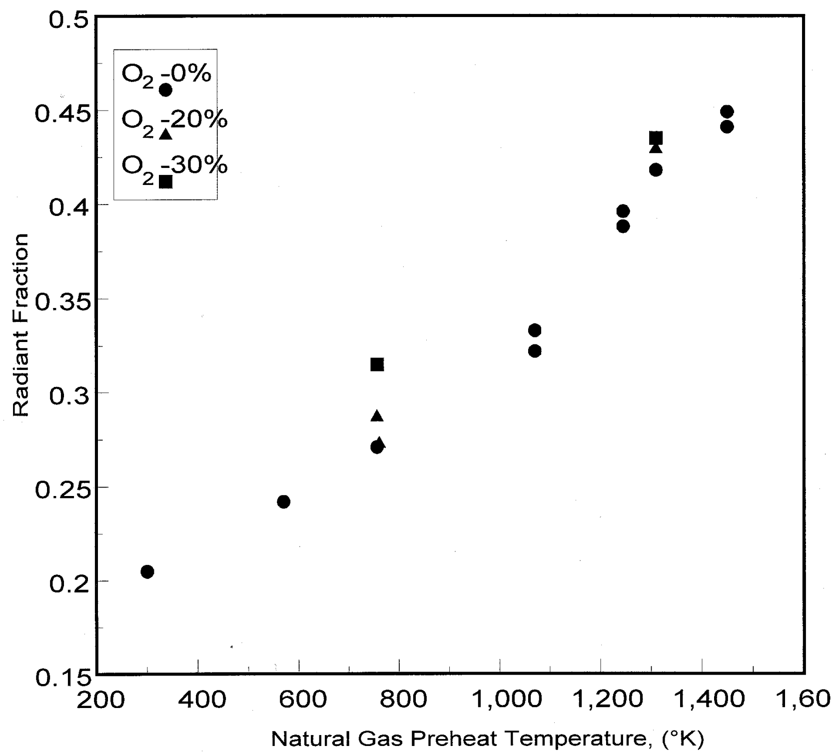


Figure 2. RADIANT FRACTION MEASUREMENTS AS A FUNCTION OF THE FUEL PREHEATING TEMPERATURE AT VARIOUS OXYGEN PREMIXING FRACTIONS

Numerous models of methane combustion exist in the literature. These models range from complex to very simple kinetic models. The complex models include detailed kinetics of all major and minor flame species[8] and typically involve reaction schemes with 75 to 150 reactions and 30 to 50 reaction species. Simple models have typically had 1 to 20 reactions[9-10] and involve <10 of the major flame species (i.e., CO_2, H_2O, H_2, CO, C_2H_2, H, and OH). Both types of models can be employed for predicting major species concentration, temperature profiles, and laminar burning velocities.[6-11] In simplified models, species whose concentrations are not calculated by the kinetics scheme are calculated by assuming thermodynamic equilibrium exists between calculated species and those not calculated. Our efforts focused on selecting and modifying one of the existing simple models such that the model could accurately predict not only the major flame gas and temperature profiles, but also the concentration profile of the soot nucleus and growth species. The selection of a soot nucleus and growth species and their kinetic modeling along with modeling of the radiation heat transfer from the flame constitutes a major contribution of this Phase of the program. A separate Topical Report on modeling has been preparing and includes detailed modeling of the Fuel Preheat and Flame Zones of the high luminosity burner performed by the University of Illinois at Chicago and Purdue University.

High temperature industrial combustion processes often have relatively low energy efficiency and generate high levels of NO_x emissions. These problems are particularly acute in the glass industry which consumes 200 bcf/y of natural gas and is reported to be the fourth largest industrial energy consumer in the U.S. Work in this program addressees the glass industry as a first priority because of the large positive impact the technology would have on the industry, improvement in energy efficiency, and decrease in NO_x production.

Regenerative glass furnaces use extremely high combustion air temperatures (2000° to 2400°F) to improve production rate, product quality, and furnace thermal efficiency. Furnace and flame temperatures - and consequently NO_x generation - are high. NO_x emissions of over 3000 vppm (12 to 15 lb/ton of glass produced) are not uncommon from natural gas-fired glass furnaces.[12,13] There are no current national regulations on NO_x emissions from glass tanks in the U.S., but this could change in light of the 1990 Clean Air Act. These emissions are restricted in some areas - the most stringent being Southern California. The South Coast Air Quality Management District currently restricts NO_x emissions from glass furnaces to 4.0 lb/ton of produced.[14] Even stricter regulations are now being implemented for this region, requiring NO_x reduction to below 0.8 lb/ton in the year 2003. The current 4.0 lb/ton regulations can be approached using relatively simple combustion modification techniques developed by GTI and Combustion Tec (with funding support from GRI and SoCalGas).[13,15] Augmenting the electric boost and increasing the percent cullet in the feed can also decrease NO_x emissions by decreasing the natural gas combusted.

Other technologies have been developed to decrease NO_x emissions from glass furnaces.[16,17] The various methods are listed in Table 1. While some of these methods can remove a large fraction of the NO_x formed, all of them except Oxygen-Enriched Air Staging and oxygen-fuel firing have no affect or decrease the efficiency of the glass making process. Fuel oil does produce some reduction in NO_x formation but at the expense of higher SO_x and particulate emissions, higher fuel costs, higher vanadium and sulfur concentrations, and decreased furnace life because of higher furnace crown temperatures.

The glass industry would benefit greatly from the adoption of the High Luminosity Burner technology since it would be an easily installed process modification which would increase process and energy efficiency by more than 20% while significantly decreasing NO_x emission levels at a relatively low cost. The high-heat transfer low-NO_x natural gas burner can achieve both goals for oxygen-, enriched air-, and air-fired furnaces. The greatest energy efficiency gains will be seen for oxy-gas fired furnaces because current technologies are still far from fully exploiting the potential benefits of oxy-gas combustion in terms of flame luminosity, heat transfer increase, NO_x reduction, and costs. An important feature of the high-heat transfer burner is that it can be used in conjunction with most NO_x reduction techniques including combustion modifications and Oxygen-Enriched Air Staging.

Table 1. COMPARISON OF NO_x REDUCTION TECHNOLOGIES

NO_x Reduction Technology	NO_x Reduction, %	Relative Cost	Efficiency
Cullet Preheating	5	Moderate	Small Increase
Electric Boosting	30	High	Decrease
Selective Non-Catalytic Reduction	30	Moderate	No Change
Fuel Oil Switching	30	Moderate	Small Increase
Fuel Staging	35	Moderate	No Change
Oxygen-Enriched Air Staging	60	None to Low	Small Increase
Reburning	60	Moderate	Decrease
Selective Catalytic Reduction	75	High	No Change
Oxygen-Fuel Firing	80	Moderate	No Change
High-heat Transfer Low-NO_x Burner for Oxy-Fuel Firing	90+	Moderate	Large Increase (> 20%)

Objectives

The objectives of this program are to research, develop, test, and commercialize a novel high-heat transfer low-NO_x natural gas combustion system for oxygen-, oxygen-enriched air, and air-fired furnaces. This technology will improve the process efficiency (productivity and product quality) and the energy efficiency of high-temperature industrial furnaces by at least 20%. GTI's high-heat transfer burner has applications in high-temperature air, oxygen-enriched air, and oxygen furnaces used in the glass, metals, cement, and other industries. Development work in this program is focused on using this burner to improve the energy efficiency and productivity of glass melting furnaces that are major industrial energy consumers. The following specific project objectives are defined to provide a means of achieving the overall project objectives.

- Identify topics to be covered, problems requiring attention, equipment to be used in the program, and test plans to be followed in Phase II and Phase III
- Use existing codes to develop models of gas combustion and soot nucleation and growth as well as a thermodynamic and parametric description of furnace heat transfer issues
- Conduct a parametric study to confirm the increase in process and energy efficiency
- Design and fabricate a high-heat transfer low-NO_x natural gas burners for laboratory, pilot-, and demonstration-scale tests
- Test the high-heat transfer burner in one of GTI's laboratory-scale high-temperature furnaces
- Design and demonstrate the high-heat transfer burner on GTI's unique pilot-scale glass tank simulator
- Complete one long term demonstration test of this burner technology on an Owens Corning full-scale industrial glass melting furnace
- Prepare an Industrial Adoption Plan. This Plan will be updated in each program Phase as additional information becomes available. The Plan will include technical and economic analyses, energy savings and waste reduction predictions, evaluation of environmental effects, and outline issues concerning manufacturing, marketing, and financing. Combustion Tec, Owens Corning, and GTI will all take active roles in defining this Plan.

During Phase I, the first three objectives were addressed and completed along with the design component of the fourth objective. In Phase II, the fabrication component of the fourth objective was completed along with objectives five and six. Results of the Phase I work were reported in the Phase I Final Report and are summarized in this Final Technical Report. Work for Phase II was divided in four specific Tasks. Results of the Phase II work were reported in the Phase II Final Report and are also summarized in this Final Technical Report. No Phase III Final Report was prepared, so this Final Technical Report presents the results of Phase III commercial demonstration efforts. A description of each Task in Phases I, II, and III is presented below.

One significant change was made by the project team during Phase II. The location of pilot-scale testing described in objective six was changed from the GTI glass tank simulator to a burner test facility at Combustion Tec. This change was made to keep costs in line with the project budget and to allow the maximum possible time for testing.

In the program, GTI was the Prime Contractor and is responsible for meeting project schedule, cost and technical objectives and reporting requirements. Project tasks were designed to be highly interactive, ensuring focused development and rapid commercialization of a commercially attractive burner technology.

Project Work Scope

Phase I. Research and Development Definition

In Phase I, current glass industry problems and concepts to improve energy efficiency and increase productivity were characterized. Factors affecting industrial adoption of the high-heat transfer low-NO_x natural gas combustion system were examined and described. Parametric and thermodynamic descriptions of combustion, soot nucleation and growth, and heat transfer issues were developed. The burner for Phase II testing was designed, and the test plans for Phase II and Phase III was prepared. This Phase was originally scheduled to require 6 months to complete after project initiation.

Task 1. Characterization of Process Problems and Improvements

The objective of this Task was to prepare a comprehensive description of efficiency, heat transfer, and emissions problems associated with glass melting furnaces. Work by the project team included literature review, discussions with glass manufacturers, and compilation of data to be used in the Task 2 modeling work. Efforts were directed toward achieving a detailed understanding of problems in glass production. Problems include the need to increase energy efficiency in oxy-natural gas flames by means such as adding soot to increase luminosity and radiative heat transfer, the need to increase production rate while maintaining glass quality, and the need to reduce pollutant emissions, especially NO_x.

Task 2. Furnace Modeling and Burner Design

Work in this task began with development of parametric, heat transfer, and thermodynamic descriptions of the high-heat transfer low-NO_x natural gas burner and the burner as installed in a glass melting furnace. Results of this modeling effort were then used to prepare a design of a high-heat transfer low-NO_x natural gas burner for the laboratory- and pilot-scale tests in Phase II. Parametric studies and modeling work were managed by GTI with active Combustion Tec and Owens Corning participation, and the design was developed by Combustion Tec, Inc. with input from GTI and Owens Corning. A description of the concept behind this innovative burner and the method used to achieve high luminosity by soot formation in the flame is presented in the Introduction. This compact burner can replace the burners traditionally used in glass melting furnaces with little alteration to the furnace. Combustion Tec is the primary burner supplier to the U.S. glass industry with many years of burner manufacturing experience and extensive business contacts throughout the U.S. glass industry. They will modify the high-luminosity burner design in conjunction with GTI and review by Owens Corning. If more cost-effective manufacturing processes or better mixing methods are identified, they will be adopted for actual production.

Commercially available models to describe oxygen-methane combustion and soot formation and growth were purchased and modified. The combination of these models allowed prediction of major combustion species, temperatures, and the conditions and levels of soot formation. The combined combustion and soot formation models were incorporated into more general fluid mechanics and flame radiation models. The parametric and thermodynamic models were solved for mass, species, momentum, and energy balances for turbulent flow and were validated with laboratory- and pilot-scale testing in Phase II. Adjustments based on experimental results was made to the models as necessary to accurately describe the burner and the glass melt furnace.

The effort here is to generate a simple kinetics model of soot formation in gas/oxygen flames. Again, a complex model[6] and simple models[9-10] of soot formation have appeared in the literature. In the complex model, the initial soot nucleus (a radical) is "grown" by a lengthy series of elementary reactions to build the "final soot nucleus" (pyrene or acepyrene). This molecule is assumed to "dimerize", "trimerize", etc., by stacking the pyrene plate-like molecules on top of each other. Concurrent with the polymerization reactions (coagulation), the growing soot particle can be oxidized by OH and O_2 to CO or CO_2 in the flame.

In the simple models, the nucleation steps of soot formation are eliminated and empirical correlations of the soot volume fraction as a function of "mixture strength" are used to obtain the number density of soot particles. Problems with this approach are: 1) the correlation is fuel and oxidizer specific and 2) not all mixture strengths are amenable to a single correlation (e.g., very fuel rich or very fuel lean).

All soot models, simple or complex, embody soot coagulation and oxidation steps to arrive at reasonable soot particle sizes compared with experimental values.[18-23] Therefore, we will concentrate our efforts at developing a model which uses a soot nuclei concentration profile (i.e., C_3H_3+) as input and add a few kinetics steps to produce a large soot nucleus - pyrene or coronene sized. Then, we will add reactions for this larger soot nucleus to coagulate and oxidize. The soot model will be compared to literature data on premixed and diffusion flames of methane/oxygen and methane/air, as well as the experimental data acquired in this project for validation and refinement of the model.

The radiation heat transfer model for an oxygen combustion system will rely on an analysis predicting radiative heat transfer from isothermal gas volumes (planar layers and infinitely long cylinders) and isothermal gas and soot mixtures. Concentrations of CO, CO_2, H_2O, and soot will be assumed, and emissivities will then be calculated for different size systems. The completed model will be prepared with protocols to get approximate radiant heat transfer rates as a function of the concentrations of the radiating species. This work will include a scheme for integration over the spectrum. A solution means will be developed to solve the RTE equations for three dimensional systems and account for the spectral nature of emissions and absorptions of radiation.

Using the results of the modeling efforts, the project team (GTI, Combustion Tec, and Owens Corning) selected an optimum burner design for fabrication and use in Phase II testing. Other designs, however, were prepared in this Task. These other designs were available for use if the initial design did not provide sufficient mixing, soot formation, luminosity increase, or improvement in energy efficiency. As a result, three laboratory-scale burners were developed and tested in Phase II and two versions of a commercial prototype burner were built and tested in Phase III.

Task 3. Phase II and Phase III Research Plan Development

The objective of this Task was to develop the laboratory- and pilot-scale testing plans for Phase II and the demonstration-scale testing plan for Phase III. All of the experimental work in this program was designed to verify the increase in energy efficiency (greater than 20%), the increase in production rate, and the decrease in NO_x production which result from the use of this technology on a glass melt furnace. All tests were to be conducted in oxygen-fired or enriched air-fired furnaces. Testing in an oxygen-fired furnace is preferred because the greatest benefits from this technology will be realized in oxygen-fired furnaces. Laboratory- and pilot-scale tests were to be conducted by the project team in GTI facilities with burner fabrication performed by Combustion Tec. The demonstration test in Phase III was conducted by the project team (GTI, Combustion Tec, Owens Corning) at a commercial glass melting furnace owned by Owens Corning.

Laboratory-scale tests (Phase II) consisted of testing several high-heat transfer low-NO_x natural gas burners on an existing GTI-owned furnace. A series of tests outlined in Task 6 were conducted at various conditions of velocity, temperature, stoichiometric ratio, and flow (natural gas and oxygen). Measurements included pressure, temperatures, furnace load, gas emissions, soot yield and particle size, and radiative and convective heat transfer.

Pilot-scale tests (Phase II) were planned to be conducted in GTI's unique glass tank simulator, but the test location was changed to Combustion Tec's test facility in Orlando, Florida. A series of tests were conducted to confirm the burner operating results of the laboratory-scale tests and to determine the optimum conditions for the Phase III demonstration test. Pilot-scale tests outlined in Task 7 were conducted as an oxygen-fired flame with test variables including velocity, preheat temperature, stoichiometric ratio, and flow (natural gas and oxygen). Gas emissions, heat flux level, furnace temperatures, and flame characteristics were monitored.

The Phase III demonstration-scale test was conducted by the project team on a commercial Owens Corning glass melt furnace in Delmar, NY. The furnace is oxygen-fired and produces borosilicate insulating fiberglass. An oxygen-fired furnace was preferred for testing in order to demonstrate the benefits of this technology against the best available high efficiency/low NO_x technology. Conditions were selected based on the results of laboratory- and pilot-scale tests in Phase II. Independent variables were controlled in the demonstration test to allow detailed determination of the improved energy efficiency, increase in production rate, and decrease in NO_x emissions.

Experimental testing in Phase II and Phase III was conducted in existing GTI and Combustion Tec laboratory- and pilot-scale furnaces and in a commercial Owens Corning glass melting furnace. All project team members took part in planning the test matrices, preparing burners and furnaces for testing, performing tests, and analyzing test results.

Task 4. Industrial Adoption Plan

An outline of an Industrial Adoption Plan for the high-heat transfer low-NO_x natural gas burner was developed in this Task. The objective of developing an adoption plan in Phase I of the program is to provide a structured approach to the commercialization of the technology. Update of the Plan through all three Phases of the program will allow test results, design modifications, and industrial concerns to be recognized and managed in a timely manner. The goal of this program is to develop a technology that increases production, improves energy efficiency by at least 20%, and penetrates a significant fraction of the U.S. glass industry. All members of the team recognize this new technology will not be adopted by industry unless the costs, benefits, and potential risks are known, addressed, and then clearly communicated to the end-users. This is the role of the Industrial Adoption Plan.

The Industrial Adoption Plan will include technical and economic analysis, energy savings and waste reduction predictions, an evaluation of environmental effects, and manufacturing, marketing, and financing options. In this Task only an outline of the Plan was developed.

Further details and a step-by-step adoption Plan will be included as more input becomes available during Phases II and III.

Combustion Tec led in the Industrial Adoption Plan preparation with constant communication and input from the Owens Corning and GTI. In Phase II and III comments received from additional glass makers were incorporated into the Plan in order to address specific concerns and streamline the commercialization process.

Task 5. Project Management

This management task was active throughout Phase I of the program. Management activities included communication between the team members, co-ordination of all project-related activities, and reporting of project results in a timely manner. Reports for this Phase of the project were prepared by all team members and included monthly status reports and a Final report for Phase I. The Final Report was complete and written to provide the reader with an accurate understanding of the state of development of the high-heat transfer low-NO_x burner system. Included in the Final Report were parametric and thermodynamic studies of combustion, soot nucleation and growth, and heat transfer as well as the burner design for laboratory testing. A complete discussion was also included concerning glass industry problems and concepts to resolve these problems and increase energy efficiency and productivity. The initial Industrial Adoption Plan was also included in the Phase I Final Report.

Phase II. Research and Development

Phase II was divided into four Tasks, Tasks 6 through 9, and included laboratory-scale testing of the high luminosity burner system and pilot-scale testing of the high luminosity burner on a burner test stand. Engineering design and prototype testing were incorporated into the laboratory- and pilot-scale testing campaigns. The Industrial Adoption Plan was updated and refined based on the results of testing and design work focused on optimizing energy efficiency and increasing productivity with the least environmental impact. All team members participated in development of test plan matrices, preparations for testing, testing, and analysis of test results. This project Phase required 24 months to complete.

Task 6. Laboratory-Scale Testing

Three prototype High Luminosity Burners were designed by GTI and Combustion Tec during Phase I, fabricated by CTI, delivered to GTI, and installed on a laboratory-scale furnace for testing. The prototype burners had a firing capacity of 0.5 MM Btu/h with a 4:1 turndown ratio. Details of the burner designs are proprietary, but a general description is provided in section 3.1.1, Test Conditions and Burner Design, of this report. Based on test results with the first prototype burner, the project team chose to fabricate and test the second and third, 0.5 MM Btu/h prototype burners.

The furnace used for laboratory-scale testing of the High Luminosity Burner is a well instrumented test furnace located in GTI's combustion laboratory. This flexible test unit has a firing rate of up to 500,000 Btu/h and is fully equipped with controls and measurement devices. A schematic diagram of the unit is presented in Figure 3. Modifications for testing in this program included providing oxygen service, changing burners, piping and metering the natural gas and oxygen, installing and calibrating the gas analysis equipment, and preparing or removing the furnace load as desired. This work was performed by GTI personnel.

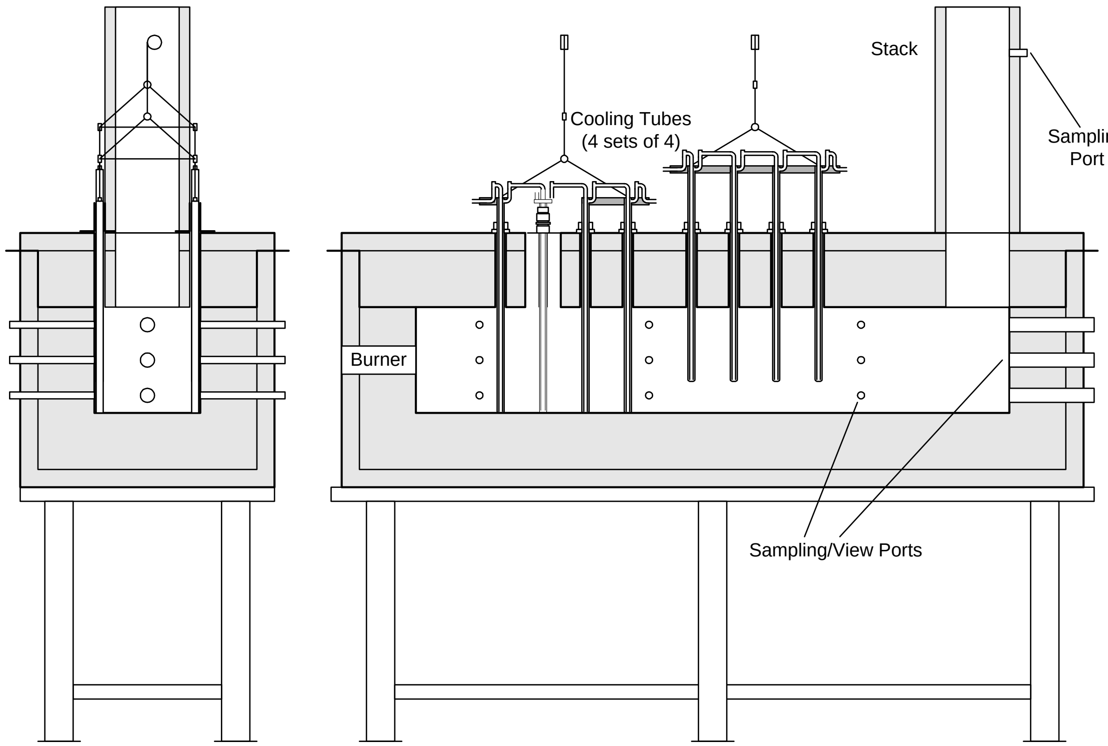


Figure 3. LABORATORY-SCALE TEST FURNACE

The laboratory-scale furnace is 7 feet long with a 15 in. by 15 in. cross section. The furnace is lined with 3000°F fiberboard insulation. Up to sixteen water-cooled tubes can be lowered into the furnace to provide variable loads. An available, electric preheater can be used to preheat the natural gas. Nine ports on both sides of the furnace and three ports at the back end provide for gas sample, temperature, and optical data collection. The front end is removable to allow installation of many types of burners with capacities up to 1 MM Btu/h. The top of the furnace is removable to allow access to the furnace chamber. Natural gas, air, oxygen, and load water flow rates and temperatures are measured. Gas analyzers are available for measuring the NO_x, CO, CO_2, O_2, and THC concentrations in the combustion gases.

Laboratory-scale tests included tests with a standard oxy-gas burner, tests with the High Luminosity Burners with no Fuel Preheating Zone, and tests with the High Luminosity Burners over a range of conditions. All tests were oxygen-fired: no air-fired or enriched air-fired tests were planned or conducted. Natural gas was not preheated before entering the Fuel Preheat Zone of the burners. Several test campaigns were conducted with the commercial burner and the three prototype burners. More than 50 data points were collected for each burner with a total of more than 220 data points collected. Independent test variables and their ranges are outlined in Table 2. Multiple test points were covered in a single test period, and sufficient test duplication (at least 25%) was included to verify the data precision. All instruments were calibrated regularly to assure data accuracy.

Table 2. LABORATORY-SCALE TEST CONDITIONS

Test Burner	Independent Operating Variable	Range of Test Conditions
Standard Burner – Baseline Tests	Firing Rate, Btu/h	125,000 - 500,000
	Overall Excess O_2, %	0 - 10
High Luminosity Burners	Firing Rate, Btu/h	125,000 - 500,000
	Overall Excess O_2, %	0 - 10
	Fuel Preheat Fraction, %	0 – 18
	Preheat Residence Time, sec.	0 - 1 sec.
	Mixing Geometry	Various
	First Stage Combustion O_2/Gas Stoichiometry	0.0 - 0.4
	First Stage Combustion Residence Time, sec.	Various

The first laboratory-scale High Luminosity Burner was designed to have complete flexibility for controlling natural gas and oxygen flows. Varying these flows and changing the mixing section length and geometry allowed study of all independent parameters of concern. Internal thermocouples and a gas sampling port provided data for evaluation of operating results. Test measurements enabled determination of efficiency improvements and NO_x reduction levels related to test conditions. Measured values in the laboratory-scale tests included:

- O_2, CO_2, CO, total hydrocarbons (THC), and NO_x in the flue and at selected points along the flame using water cooled probes and a continuous emissions monitoring system (CEMS)
- Fuel preheat temperature
- Heat flux profile along the furnace length using adjustable water-cooled load and heat flux sensors
- Total heat flux to the load
- Total and radiative heat flux measured by sensors
- Furnace refractory temperatures using embedded thermocouples to obtain a temperature profile.
- Exhaust gas temperature
- Flame luminosity measured optically
- Flame temperature measured with an optical pyrometer
- Burner wall temperatures

- Gas temperatures in the exhaust using suction pyrometers
- Flame length
- Gas composition including soot precursors in the mixing section using grab samples.

The second and third laboratory-scale burners were simplified versions of the first laboratory-scale high luminosity burner. The second burner was simplified by allowing a greater amount of combustion in the precombustion section, fixing the lengths of the premixing and direct mixing sections, and allowing the length of the fuel rich combustion section to be varied. In the third laboratory-scale burner, the precombustion and direct mixing sections were combined. All natural gas and a portion of the oxygen were charged to a stabilization device inside the burner. This provided sufficient combustion to heat the remaining gas and produce the desired degree of direct heating and mixing in an oxygen-free environment.

Data collected in laboratory-scale testing was analyzed to determine optimum burner operating conditions. These conditions include fraction of gas burned in the preheater, preheater residence time and exit temperature, oxygen-natural gas stoichiometric ratio and residence time in the first, fuel rich combustion stage, firing rate, and overall level of excess air for the entire burner. Results of the analysis were used to design and fabricate the larger burner for pilot-scale testing. Information gained from testing the first prototype burner in the laboratory-scale furnace was considered during design and testing of the second and third laboratory-scale burners. All team members participated in data analysis and shared findings, results, and conclusions.

Task 7. Pilot-Scale Testing

A pilot-scale High Luminosity Burner was fabricated by CTI with input from the other team members. The burner was based on the design of the prototype laboratory-scale burner developed in Phase I and test results obtained with the laboratory-scale burner. The pilot-scale burner had a maximum firing rate of 3 MM Btu/h with a 4:1 turndown ratio. All tests were conducted at a firing rate of 2.25 MM Btu/h. This is equivalent to the smallest size of a commercial oxy-gas burner for glass furnaces. A high degree of flexibility was built into the pilot-scale burner to allow adjustments of natural gas (precombustor and main) and oxygen (precombustor, fuel rich zone, and fuel lean zone) flow rates, to permit changes in preheat length to control preheat residence time, and to provide variable first stage combustion oxygen injector geometry to change first stage combustion residence time. A single test burner was fabricated for this project.

The burner was installed and tested on a burner test chamber at CTI. The project team initially planned to conduct the pilot-scale tests on the GTI Glass Tank Simulator. A decision was made to use the CTI test chamber instead so more testing data could be collected at a lower cost. A photograph of the burner test chamber is presented in Figure 4. The refractory-lined steel chamber is 20 feet long with a 4 foot diameter vertical stack. A series of nine ports are located along the side of the chamber to allow insertion of water-cooled tubes as artificial load and probes for total and radiative heat flux measurements. These ports are spaced at one foot intervals beginning at two feet away from the burner inlet to the test chamber. Thermocouples are positioned to measure gas temperatures in the roof of the test chamber and are set at seven and twelve feet from the burner inlet to the test chamber. A thermocouple is positioned in the center of the exhaust stack. A gas probe is also located in the stack. GTI instruments were used to measure CO_2, CO, O_2, and NO_x in the exhaust gas. The burner is mounted in a standard refractory block positioned at the end of the test chamber. Oxygen is supplied from a liquid tank and metered to all burner inlets (precombustor, fuel rich zone, fuel lean zone). Natural gas is metered and supplied to the burner precombustor and direct mixing zones. A coputer-based process control and data acquisition system is used to control all flow rates and collect all flow rate, temperature, pressure, and heat flux information.

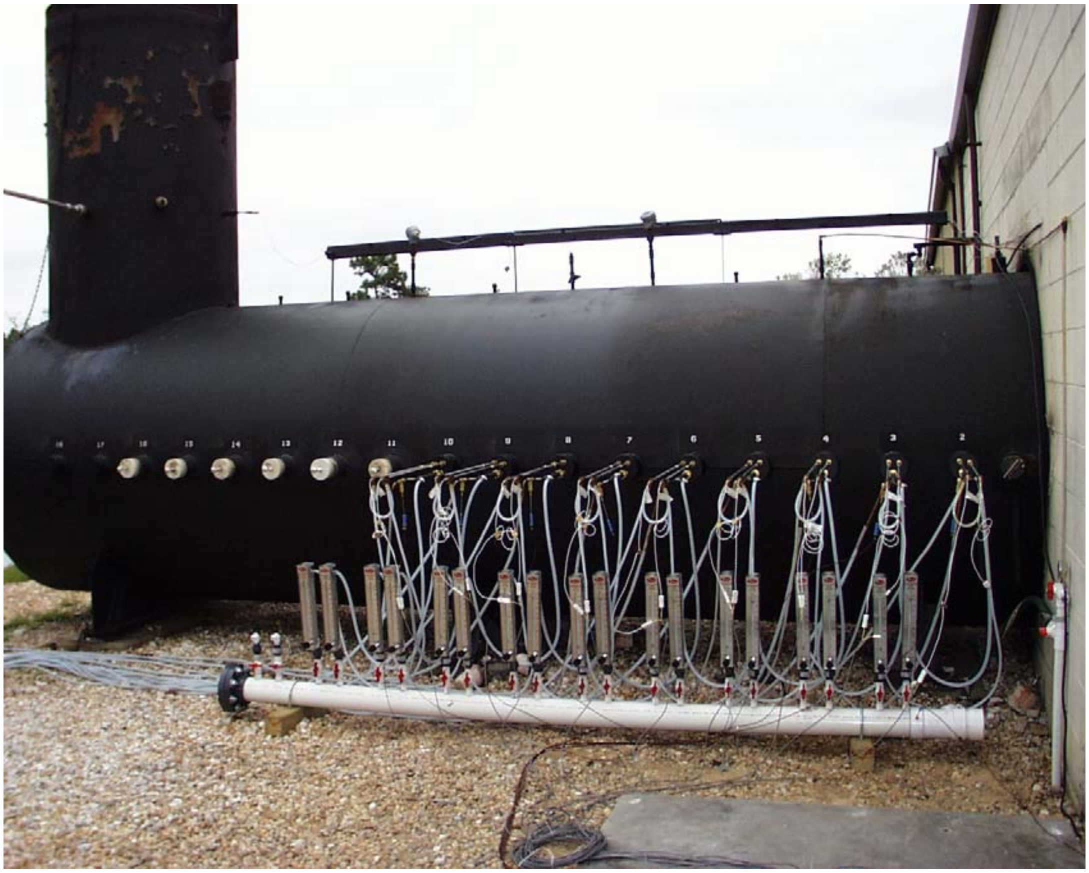


Figure 4. BURNER TEST CHAMBER AT COMBUSTION TEC

Three test series were conducted by GTI and CTI project team staff in the test chamber. The first two test series provided parametric burner testing and data collection along with comparison with two commercial oxy-gas burners fired at similar conditions. The third test series provided an opportunity to collect data for extended burner operation at preferred firing conditions providing high heat transfer.

Pilot-scale tests included baseline tests with a standard burner and a series of tests with the high-heat transfer low-NO_x natural gas burner. Tests with the High Luminosity Burner will included the case in which the Fuel Preheat Zone was not used. The test matrix was completed in the first furnace campaign, but additional tests were conducted in the second and third test series. Oxy-fuel firing was used for all tests. No air-fired or enriched air-fired tests were conducted. Natural gas was not preheated before entering the preheating section of the burner. A total of 80 data points were taken with the pilot-scale High Luminosity burner. These included 41, 12, and 27 points in series 1, 2, and 3, respectively. Commercial burners were tested in series 1 and 2 with 3 data points in series 1 and 18 points in series 2. Duplicate tests were conducted to verify data precision. Ranges of test conditions are summarized in Table 3.

Table 3. PILOT-SCALE TEST CONDITIONS

Test Burner	Independent Operating Variable	Range of Test Conditions
Standard Burner – Baseline Tests	Firing Rate, Btu/h	2.25×10^6
	Overall Excess O_2, %	0 - 10
High Luminosity Burner	Firing Rate, Btu/h	2.25×10^6
	Overall Excess O_2, %	0 - 10
	Fuel Preheat Fraction, %	0 – 20
	Preheat Residence Time, sec.	0 - 1 sec.
	Mixing Geometry	Various
	First Stage Combustion O_2/Gas Stoichiometry	0.7 – 0.9
	First Stage Combustion Residence Time, sec.	Various

Similar test measurements were made for the pilot-scale tests as were made for the laboratory-scale tests in Task 6. Test measurements allowed determination of energy efficiency improvements and NO_x reduction levels related to test conditions. Measured values in the pilot-scale tests will included:

- O_2, CO_2, CO, total hydrocarbons (THC), and NO_x in the flue using water cooled probes and a continuous emissions monitoring system (CEMS)
- Fuel preheat temperature
- Heat flux profile along the test chamber length using adjustable water-cooled load and heat flux sensors
- Total heat flux to the load
- Total and radiative heat flux measured by sensors
- Exhaust gas temperature
- Burner wall temperatures
- Gas temperatures in the test chamber using roof thermocouples
- Flame length
- Gas composition including soot precursors in the mixing section using grab samples.

Project team members analyzed test data and discussed results and conclusions. Data collected from pilot-scale tests included heat transfer to the load, NO_x emissions, and temperatures of the exit gas and in the test chamber. Burner independent variables of natural gas flow and temperature, oxygen flow and temperature, velocity, stoichiometric ratio, etc. were controlled at desired testing levels. Increases in heat transfer and decreases in NO_x emissions with the high-heat transfer low-NO_x natural gas burner were calculated with reference to baseline cases fired under similar conditions using conventional burners. Comparisons of various firing conditions allowed selection of preferred operating conditions for the demonstration test in Phase III.

Task 8. Industrial Adoption Plan

An outline of an Industrial Adoption Plan for the high-heat transfer low-NOx natural gas combustion system was prepared in Phase I and reported in the Phase I Final Report. This outline was updated and developed into a full, preliminary plan in this Task. The objective of developing an Industrial Adoption Plan is to provide a structured approach to the commercialization of the technology. Continual update and refinement of the Plan through all three Phases of the project will allow test results, design modifications, and industrial concerns to be recognized and managed in a timely manner. The goal of this program is to develop a technology that increases production, improves efficiency by at least 20%, and is put into practice by industry. All members of the project team recognize this new technology will not be adopted by industry unless the costs, benefits, and potential risks are known, addressed, and understood and then clearly communicated to the end-users. This is the role of the Industrial Adoption Plan.

The Industrial Adoption Plan includes technical and economic analysis, energy savings and waste reduction predictions, an evaluation of environmental effects, and options for manufacturing, marketing, and financing. In this Task the outline of the Plan developed in Phase I (Task 4) was expanded. Laboratory- and pilot-scale test results and design work completed in this program Phase were used to improve the various analyses. A step-by-step Industrial Adoption Plan will modified as more input becomes available during Phase III of the program.

Combustion Tec led the Industrial Adoption Plan preparation with equal participation from the other team members. In Phases II and III. Comments regarding commercialization will be sought from additional glass makers. Questions and concerns will be addressed, and the Plan will be modified to improve and streamline the commercialization process.

Task 9. Project Management

The management task was active throughout Phase II of the program. Management activities included communication between GTI and other team members, coordination of all project-related activities, and reporting of project results in a timely manner. Communication provides opportunities for needed changes in burner design, test conditions, controls and monitoring, planning for demonstration tests in Phase III, and compilation of inputs for updating the Industrial Adoption Plan. Reports for this Phase of the project were prepared by GTI with input from other team members and included monthly status reports and a Final Report for Phase II. The Final Report will be complete and written to provide the reader with an accurate understanding of the state of development of the high-heat transfer low-NO_x natural gas combustion system. The Final Report will contain results from the laboratory- and pilot-scale testing, the updated Industrial Adoption Plan based on Phase II testing and analysis, and a complete discussion of design and development issues concerning the technology and its implementation.

Phase III. Demonstration Testing and Planning for Adoption

Work in Phase III included preparations for demonstration-scale testing (relying on Phase I and II results), testing of the high-heat transfer low-NO,, natural gas burner system on an operating, full-scale industrial oxygen-natural gas glass melting furnace, and preparation of a final Industrial Adoption Plan based on the results of analysis and testing in Phases 1, II, and III of the program. All team members participated in designing the demonstration-scale test matrix, conducting the tests, and analyzing the data along with developing the final Industrial Adoption Plan. This program Phase was planned to require 18 months to complete. Program funding reductions by DOE caused the project team to shorten the planned amount of testing during Task 11 on the host furnace. The project team met all project objectives, but the DOE funding reduction curtailed some of the intended testing.

Task 10. Preparation for Demonstration

Work was conducted in this task to prepare for the long-term demonstration test in Task I1. Subtasks included subtask 10. 1, System Design, for the specific, host commercial oxy-gas glass melting furnace; subtask 10.2, Burner and Auxiliary System Fabrication; and Subtask 10.3, Baseline Data Acquisition. Project team members worked closely together on all subtasks in this Task.

Subtask 10.1. System Design

System design work was conducted by GTI and CTI with input regarding the furnace from Owens Coming, the host site owner. Work involved determination of burner sizes and capacities, natural gas and oxygen flow rates, piping and valving modifications for the new burners, and instrumentation installation, piping and utilities support.

Subtask 10.2. Burner and Auxiliary System Fabrication

Burners and auxiliary system fabrication was performed by CTI with input from GTI and Owens Coming on final designs. The full-scale burner was based on the modeling work in Phase I, and the laboratory- and pilot-scale testing results in Phase 11. The host furnace has multiple burners, seven in total. New burners will be fabricated to replace all the existing burners. Any modifications to the auxiliary systems to supply gases (oxygen and natural gas) and utilities for the burners were also fabricated in this subtask.

Subtask 10.3. Baseline Data Acquisition

Before the host furnace modifications were made, GTI, CTI, and OC will collected baseline furnace operating results. Temperatures, gas emissions, gas compositions, and flows of natural gas and oxygen provided information on baseline furnace efficiency, heat transfer to the load, and emissions levels (particularly of CO and NO_x,). Calculations in Task 11 were designed to measure the reduction in emissions, increase in production rate, and improvement in energy efficiency.

Task 11. Demonstration-Scale Testing

Demonstration-scale testing was conducted at a host, commercial oxy-gas-fired glass melting furnace in Delmar, NY owned by Owens Coming. All of the burners will be replaced with full-scale high-heat transfer low-NOx natural gas burners. Data will be collected on furnace energy efficiency, energy savings, production rate, and emissions over an extended campaign of at least 18 days. **The original project Statement of Work planned for a 30 day extended campaign, but this campaign has been shortened because of the reduction in available DOE funding.** The furnace operating results will then be compared with baseline data acquired in Task 10 to demonstrate lower NO_x emissions and an energy savings of at least 20%. All team members will actively participate in conducting the demonstration-scale test.

Subtask 11.1. Host Industrial Furnace Modifications

Modifications required for testing the high-heat transfer low-NO_x natural gas burner system on the host commercial furnace owned by Owens Coming were performed in this subtask. Modifications were made by CTI with assistance from GTI and OC. Changes required to conduct the demonstration-scale testing were determined in subtask II.I and included changing burners, adding auxiliary burner gas supply valves and piping, and placing and calibrating temperature, heat flux, and exhaust gas measurement instrumentation. A depiction of a typical oxy-gas glass melting furnace is shown in Figure 5. These furnaces typically have multiple burners that needed to be replaced for the demonstration test.

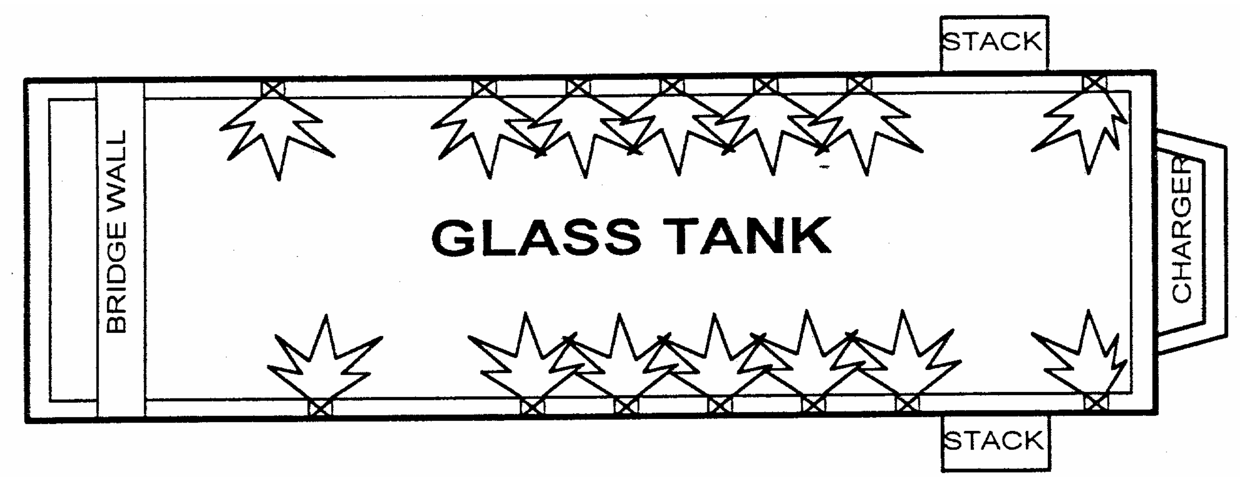


Figure 5. TOP VIEW OF A TYPICAL OXY-GAS FIRED GLASS FURNACE

Subtask 11.2. Demonstration Testing

Demonstration-scale testing was conducted by CTI engineers, GTI engineers, and personnel from the Owens Coming commercial host site. The campaign was to continue for at least 18 days to allow sufficient operating experience for reliable and repeatable results to be acquired. All data will be collected and analyzed in subtask 11.3.

Subtask 11.3. Data Analysis

Data collected from demonstration-scale tests in the OC commercial glass melting furnace included heat transfer to the load, NO_x emissions, and temperatures of the exit gas and in the tank. Burner independent variables of natural gas flow and temperature, oxygen flow and temperature, velocity, stoichiometric ratio, etc. were controlled at desired testing levels.

Increases in heat transfer and decreases in NO_x emissions with the high luminosity burner were calculated with reference to baseline cases fired under similar conditions using conventional burners. All project team members participated in data analysis.

Task 12. Industrial Adoption Plan

The preliminary Industrial Adoption Plan for the high-heat transfer low-NO_x natural gas burner prepared in Phase II was developed into a final Plan in this Task. The objective of developing an adoption plan is to provide a structured approach to the commercialization of the technology. Development of the Plan through all three Phases of-the program will allow test design modifications, and industrial concerns to be recognized and managed in a timely manner. The goal of this program is to develop a technology that increases production, improves efficiency by at least 20%, and actually is put into practice by industry. All members of the team recognize this new technology will not be adopted by industry unless the costs, benefits, and potential risks are known, addressed, and understood and then clearly communicated to the end users. This is the role of the Industrial Adoption Plan.

The Industrial Adoption Plan includes technical and economical analysis, energy savings and waste reduction predictions, an evaluation of environmental effects, and manufacturing, marketing, and financing options. In this Task the preliminary Plan developed in Phase II (Task 8) was expanded into a final Plan. Demonstration-scale test results and design work completed in this program Phase was used to improve the various analyses. A step-by-step adoption Plan was prepared as more input became available during Phase III of the program. The final Plan is a stand-alone document providing a complete commercialization plan and the supporting documentation required to provide support for industrial adoption.

CTI, as a glass industry burner manufacturer, led in preparing the Industrial Adoption Plan with input from the other team members. In Phase III, comments regarding commercialization were sought from additional glass makers. Questions were raised and concerns were addressed and the Plan was modified in order to improve and streamline the commercialization process. After establishing firm burner system costs, an aggressive marketing campaign, led by CTI, will be initiated. Because this technology is a retrofit not requiring the rebuilding of furnaces, marketing will focus on demonstrating cost payback, energy savings, increase in production rate, and decrease in NO_x emissions. Initial marketing efforts will be aimed at the glass industry and operators of oxy-gas fired glass melting furnaces. After demonstration of successful industrial operation, marketing of the burner system will be expanded to glass makers using air-gas and enriched air-gas firing furnaces.

Finally, marketing will be extended to other industries using high temperature oxy-gas (as well as air-gas and enriched air-gas) furnaces. These industries include iron, non-ferrous metals, and cement producers. GTI staff will take the lead in surveying markets other than glass and in preparing a marketing Plan to extend this technology into these markets.

Task 13. Project Management

This management task was active throughout Phase III of the program. Management activities included communication among the team members with an emphasis on continuous, informed discussion with OC, the owner of the host glass melting furnace, coordination of all project-related activities, and reporting of project results in a timely manner. Communication provided opportunities for needed changes in burner design, test conditions, controls, and monitoring and compilation of inputs for updating the Industrial Adoption Plan. Reports for this Phase of the project included monthly status reports and a Final Technical report for Phases I, II, and III from each team member.

This Final Report is complete and written to provide the reader with an accurate understanding of the state of development of the high-heat transfer low-NO_x burner system. The Final Report for Phase III is a stand-alone document providing an overview of the entire project and a detailed approach toward industrial adoption of the technology. The Final Report includes a description of the host industrial glass melt furnace used for demonstration testing, a description of modifications performed, a comparison between baseline efficiency, energy usage (savings), and waste generation, and a complete presentation of test results. The Final Industrial Adoption Plan including technical and economic analyses, energy savings and waste reduction predictions, an evaluation of environmental effects, and a presentation of manufacturing, marketing, and financing issues (and how they are addressed by this technology).

Project History

Overview of Activities

Project objectives and accomplishments in all three Phases are described in detail in this Final Technical Report. The first Phase activities centered on modeling of the high luminosity burner mixing zone and flame zone followed by initial laboratory burner design. Phase II work involved building and testing three laboratory scale test burners and a pilot-scale test burner. All results of testing were analyzed and used for design of the next larger burner, each burner being one step closer to the commercial prototype high luminosity burner. Phase III concentrated on demonstration testing. Work began with building and testing two commercial prototype burners. Later Phase III work involved fabrication, installation, and testing of seven high luminosity burners on an Owens Corning fiberglass melter. Following successful demonstration tests, GTI and Combustion Tec executed a licensing agreement, and Combustion Tec is currently marketing the high luminosity burner to the glass industry.

This project was active from late in 1995 through the end of 2002. While the project was longer that the original 3 year plan, the project objectives, project team, and scope of work did not change throughout the project. The original sponsors, DOE and SMP, continued their funding through all three project Phases, and these sponsors were joined by NYSERDA and GRI for funding of the Phase III demonstration of the high luminosity burner at Owens Corning.

Project Team

Gas Technology Institute (GTI)

GTI was the prime contractor for this project and holds the basic technology patent. GTI led all Tasks in the three Phases and prepared all Technical and Financial reports. Details of project activities and results are presented later in this report. GTI has licensed the technology to Combustion Tec, and Combustion Tec is now marketing, installing, and servicing this new oxy-gas combustion system for glass melters. During the course of this project, the original prime contractor, the Institute of Gas Technology (IGT), joined with the Gas Research Institute (GRI), to form a new company, the Gas Technology Institute (GTI). This new organization retained the full staff and activities of the parents companies, so no change was needed or made in project team staffing, in project objectives, or in the scope of work.

Eclipse / Combustion Tec

Eclipse engineers participated in all three project Phases, but most actively in Phases II and III. In Phase II, Eclipse fabricated all lab and pilot-scale test burners, assisted actively in design, attended meetings with GTI and Owens Corning, participated in DOE project reviews, and assisted with data analysis and interpretation. Eclipse carried out the same role in Phase III, by fabricating and installing the first prototype high luminosity burner as well as the seven revised prototype burners installed at Owens Corning. Eclipse organized all installation and actively participated in testing and analysis. At the end of the project GTI and Eclipse signed a licensing agreement, with Combustion Tec actively initiating marketing of the new technology. A joint GTI-Eclipse patent was filed for the final burner design.

Owens Corning

Owens Corning monitored Phase I progress. During Phase II, OC engineers reviewed results and advised project engineers of specific needs and conditions of glass melters. In Phase III. Owens Corning made a fiberglass melter in Delmar, New York available for retrofit with prototype high luminosity burners. Their staff assisted with installation and initial burner monitoring, all at Owens Corning expense.

University of Illinois at Chicago

A University of Illinois team of faculty and graduate students modeled the fuel pretreatment zone (precombustion, mixing, and preheating) of the high luminosity burner during the first year of the project. An important finding related formation of soot precursors to residence time and temperature in an oxygen-free environment. Results of this work were published in a Topical Report to DOE and were used to design the first lab-scale test burners.

Purdue University

A Purdue University team of faculty and graduate students modeled the high luminosity burner flame zone during the first year of the project. This work included heat transfer models along with the impact of increased soot and high luminosity on heat transfer. Results were published in a Topical Report to DOE and were used to design the first lab-scale test burners.

Sponsors

There were six sponsors of this overall project. Four sponsors provided monetary support, and two sponsors provided in-kind support during the project. Sponsor support is summarized below.

U.S. Department of Energy (DOE) Office of Industrial Technology (OIT)

The U.S. Department of Energy (DOE) Office of Industrial Technology (OIT) provided constant and majority support of all three Phases of this project. DOE support was substantial from concept modeling and inception through final demonstration testing of prototype commercial high luminosity burners at Owens Corning.

Gas Research Institute

GRI has a long history of providing support for research projects of interest to the domestic gas industry. GRI support of Phase III of this project helped the project team to complete the full scope of work and demonstrate the high luminosity burner.

GTI Sustaining Membership Program (SMP)

The GTI Sustaining Membership Program (SMP) is a co-funding entity composed from gas industry funds supporting mid-range research of interest to the gas industry. The SMP is administered by GTI, and SMP managers are responsible for choosing projects to support. All three Phases of this project were co-funded by SMP. SMP was the only sponsor, along with DOE, to monetarily support the full project. Cost sharing from SMP was critical in meeting cost-sharing requirements specified by DOE>

New York State Energy Research and Development Authority (NYSERDA)

NYSERDA provided critical financial support for demonstration testing at Owens Corning in Phase III of the project. This support enabled the project team to install all seven burners on the OC furnace and to conduct tests of combustion system and burner performance.

Eclipse

Eclipse, through their Combustion Tec division, participated in all three project Phases. In Phase I, Combustion Tec fabricated the 0.5 MMBtu/h test burners and assisted GTI researchers with mounting and testing. Phase II testing was carried out at Combustion Tec's Orlando, FL facilities, and Combustion Tec built the 3 MMBtu/h pilot-scale high luminosity burner. In Phase III, Combustion Tec built one prototype 3 MMBtu/h burner and made Eclipse testing facilities in Rockford, IL available for testing. The prototype high luminosity burner was re-engineering, and then built by Eclipse, followed by additional testing in the Rockford, IL test chamber. Eclipse built the seven prototype burners installed in the Owens Corning furnace in Delmar, NY. Eclipse provided in-kind cost sharing in this project by reducing labor costs by 20 percent

Owens Corning

Owens Corning was not actively involved in Phase I of the project except to review activities and results. In Phase II, OC reviewed testing results and held meetings with other team members. In Phase III, OC worked with the project team to design and installed seven burners and burner blocks on their oxy-gas fiberglass melter in Delmar, NY. OC personnel helped with installation and testing as well as with hands-on support of demonstration testing activities. All Owens Corning support and access to the fiberglass melting furnace was in-kind support. No money was paid to Owens Corning to support their project activities.

Discussion

Characterization of Process Problems and Improvements

A project review meeting was held at GTI's Energy Development Center on April 18, 1996. Prior to this meeting, GTI and CTI conducted a review of glass furnace operation and characterized process problems and improvements. The results of this review were presented in written and oral form to DOE personnel at this meeting. A summary of the information presented at that project review meeting is presented below.

A review of current technology revealed that the largest problems facing high temperature combustion processes are low productivity, high fuel consumption, and production of high levels of pollutants such as NO_x. All of these issues can be addressed by switching from air-gas firing to oxy-gas firing. However, in most industrial applications, oxy-gas firing is not economically attractive because of the added cost of oxygen. An oxy-gas flame in a hot furnace tends to be non-luminous and provide low radiation heat transfer to the load. The use of oxygen significantly lovers NO_x production, but NO_x is still generated from nitrogen present in the fuel or oxidant or through infiltration.

The solution to the deficiencies with oxy-fuel combustion can be addressed by developing an economical, easily-operated combustion system which increases radiative heat transfer and lowers NO_x emissions. This can be accomplished by seeding the flame with soot particles to generate a highly luminous flame. Higher luminosity increases radiative heat transfer and decreases flame temperature. Lowering the flame temperature lowers the production of NO_x. Increased radiative heat transfer to the load improves the thermal efficiency of the burner and reduces the fuel and oxidant requirements per ton of product melted. This improves the economics of oxy-gas combustion.

The High Luminosity Burner being developed in this project addresses all of the deficiencies identified with oxy-gas combustion. The project team believes that development and application of this new burner will hasten the adoption of oxy-gas firing for high temperature combustion processes. Compared with current oxy-gas combustion systems, the High Luminosity Burner offers higher production rate, an efficiency improvement of a least 20 percent, lower fuel and oxygen consumption, and a significant reduction in NO_x emissions.

Air-gas fired glass furnaces typically rely on regenerators to recover much of the process heat leaving the furnace with the exhaust gas. The amount of exhaust gas is reduced by more than 70 percent by switching to oxy-gas firing. Oxy-gas fired glass furnaces typically do not rely on regenerators to recover process heat. Ideal combustion, with methane representing natural gas, can be described as follows:

Air-Gas Combustion	$CH_4 + 2O_2 + 7.52N_2 \rightarrow CO_2 + 2H_2O + 7.52N_2$ 10.52 moles product gas / mole of CH_4 79% of product gas is N_2
Oxy-Gas Combustion	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ 3 moles of product gas / mole of CH_4 0% of product gas in N_2

Air-gas combustion has several advantages including:

- air is free
- air is safer and simpler to handle
- air-gas combustion processes are well understood with a long record of industrial use

There are also a number of disadvantages associated with air-gas combustion. These include:

- high heat loss with heated nitrogen
- regenerators are needed for heat recovery
- gas velocities are high
- particulate carry-over can be high
- high levels of NO_x formation
- large fans, ducts, and gas cleaning equipment are needed.

The use of regenerators to recover heat from air-gas combustion exhaust gases provides a significant increase in thermal efficiency for these furnaces. A major drawback of the use of regenerators is an increase in NO_x emissions. Figure 6 shows the general air-gas combustion trend for NO_x emissions as a function of combustion air temperature. NO_x emissions increase at a more than linear rate as combustion air temperature increases. This relationship does not affect oxy-gas combustion because the oxygen is not preheated and because there is a low nitrogen concentration in the oxidant.

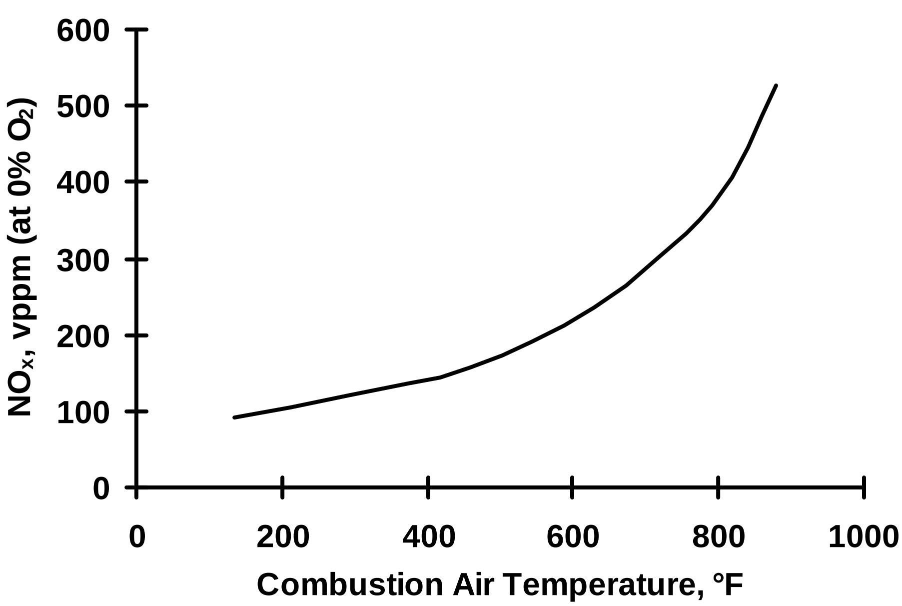


Figure 6. THE GENERAL EFFECT OF AIR PREHEATING ON NO_x EMISSIONS

Some of the major advantages of oxy-gas combustion are:

- higher combustion temperature
- reduced flue gas volume and velocity
- lower particulates carry-over
- reduced flue gas cleaning costs
- regenerators are not needed for heat recovery
- lower fuel gas consumption
- lower NO_x production
- smaller fans and ducts are required
- water content in glass can be increased

Figure 7 shows the general effect of oxygen enrichment on the process efficiency for a glass furnace. Values will vary from furnace to furnace to the two illustrated trends always hold true. First, increasing the oxygen concentration, at any given flue gas temperature, produces an increase in process efficiency. Second, the impact of flue gas temperature decreases with increasing oxygen enrichment. This figure illustrates the large increase in efficiency provided by regenerators for air-gas fired furnaces. However, as the amount of nitrogen in the gas decreases, the benefit gained with regenerators also declines. For oxy-gas combustion, a regenerator does not provide a very large increase in process efficiency.

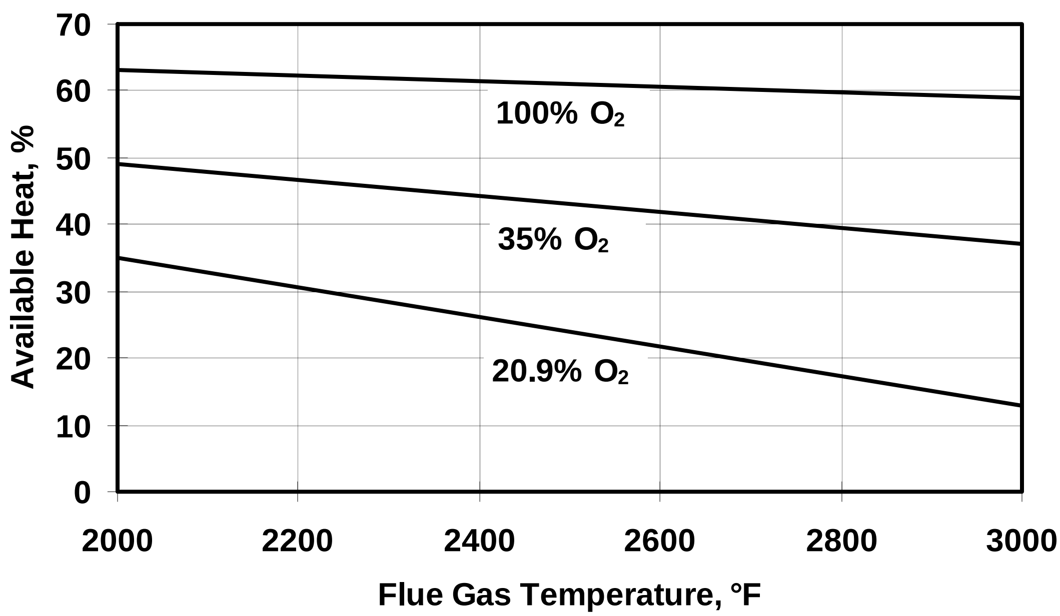


Figure 7. THE EFFECT OF OXYGEN ENRICHMENT ON PROCESS EFFICIENCY

In the effort to improve process efficiency and lower NO_x emissions without increasing process expense, the use of oxygen-enriched air as an oxidant has been considered. There is, unfortunately, a large NO_x production penalty realized when oxygen-enriched air is used. Figure 8 shows the general effect of increasing oxygen concentration on NO_x emissions. Enriching the oxidant with oxygen produces higher combustion temperatures. This leads to higher NO_x

production as long as large amounts of nitrogen are available for oxidation. Oxygen concentration must be raised to more than 90 percent to achieve the low NO_x production benefits of oxy-gas combustion.

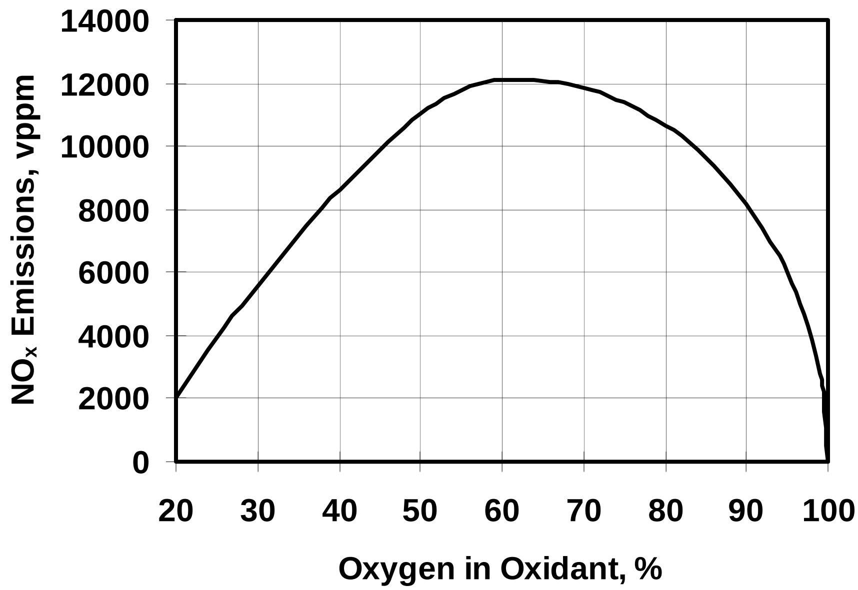


Figure 8. THE EFFECT OF OXYGEN ENRICHMENT ON NO_x EMISSIONS

The High Luminosity Burner being developed and demonstrated in this project is expected to produce significantly lower levels of NO_x than other oxy-gas burners. This is because the High Luminosity Burner will have a significantly lower flame temperature and will therefore generate less NO_x at the same oxygen concentration concentration in the oxidant. This will translate into a cost savings for the High Luminosity Burner because this burner will generate low NO_x using low cost PSA or VPSA oxygen containing 90 to 92 percent oxygen. Other oxy-gas burners will produce higher levels of NO_x, or they must use much more expensive pure oxygen to achieve the same low NO_x emission level.

The temperature and radiant heat flux profiles for air-gas and oxy-gas burners are significantly different. Figure 9 shows that the profiles for air-gas burners are flatter and less peaked than for typical oxy-gas burners. Oxy-gas burners, with high combustion temperatures and peaked profiles, have the potential to provide poor heat distribution and to create hot spots on the furnace crown. The High Luminosity Burner being developed in this program will have a reduced flame temperature and less peaked temperature and radiant heat flux profiles compared with current oxy-gas burners. Also, because the High Luminosity Burner is more efficient than other oxy-gas burners, the amount of fuel and oxygen can be reduced for the same load. This will create even lower temperature and radiant heat flux peaks. These results have been confirmed by the modeled conducted during Phase I of this project. Detailed results of this modeling are presented in the Topical Report on Modeling.

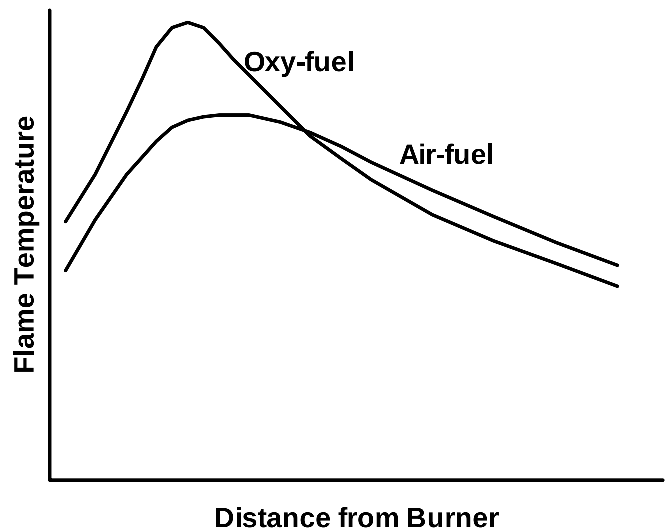


Figure 9. TEMPERATURE PROFILE COMPARISON FOR AIR-GAS AND OXY-GAS COMBUSTION

A general comparison of some characteristics of oxy-gas and air-gas combustion is presented in Table 4. Oxy-gas combustion has a significantly higher adiabatic flame temperature and a faster normal flame velocity. The speed of oxy-gas combustion initiation is shown by its lower induction time. The higher adiabatic flame temperature leads a decrease in the Arrhenius group (E/RT) and thereby increases the reaction rate coefficient k, equal to exp (-E/RT).

Table 4. COMPARISON OF OXY-GAS AND AIR-GAS COMBUSTION

Characteristic	Oxy-Gas / Air-Gas
Adiabatic Flame Temperature	1.4
Reaction Rate Coefficient	1.35
Flame Induction Time	0.75
Normal Flame Velocity	1.16

Oxy-gas combustion has a number of advantages over air-gas combustion and has been partially implemented in a number of industries. Some industries using oxy-gas combustion are:

- glass melting
- hearth furnaces (steel industry)
- ladle heating
- aluminum sintering furnaces
- magnesia sintering furnaces
- specialty ceramic production

In all applications, oxy-gas combustion requires special considerations. Specific burners must be designed and used to handle and utilize the characteristics of oxy-gas combustion. For example, burners must operate properly when the laminar gas phase viscosity is higher for oxy-gas combustion while turbulent mixing in the flame is reduced. The oxy-gas conversions in the glass industry have reported 25 to 49 percent reductions in gas usage. Considering the overall cost of glass melting with oxy-gas (including oxygen production), the cost of oxy-gas combustion is no better, and often not as good, as the cost of air-gas combustion with a good regenerator.

The glass industry in the United States was reviewed to assess the possible market for the High Luminosity Burner. Data was taken from an IUPAG report to GRI in Feb. 1995 and from CTI business data. Major points concerning the U.S. glass industry can be summarized by:

- total U.S. glass production in 1992 was more than 81,000 ton/day,
- major segments of the glass industry include container, flat, wool fiber, textile fiber, lighting/TV, press and blown, and sodium silicate,
- container glass represents 55 percent of total glass produced and flat glass represents 20 percent of glass,
- in 1992, 10 percent of the 490 U.S. glass melting furnaces were oxy-gas fired,
- natural gas supplies more than 80 percent of the energy for glass melting,
- natural gas consumption for glass melting is approximately 200 BCF/year,
- NO_x production varies widely between 2 and 15 lb/ton of glass.

A breakdown of glass furnaces by market segment and furnace type is provided in Table 5.

Table 5. COMMERCIAL GLASS MANUFACTURING IN THE UNITED STATES IN 1992

	No. of Plants	Tons per day	Furnace	Regen. Sidepor	Regen. Endport	Unit Furnace	Oxy/Fu	All Electric
Container	68	48,000	154	68	66	--	13	7
Flat	29	19,000	38	36	--	--	1	1
Wool Fiber	24	1,400	58	--	--	16	5	37
Textile	12	2,100	60	--	--	47	6	7
TV/lighting	19	3,000	60	19	--	30	9	2
Press and Blown	31	3,400	95	32	10	33	11	9
Sodium Silicate	24	4,500	25	20	--	5	--	--
Total	207	81,400	490	175	76	131	45	63

CTI is the leading supplier of burners and combustion systems to the U.S. glass industry. They have been involved in the trend toward oxy-gas combustion and are actively seeking new products to introduce to the market. The move toward oxy-gas combustion is expected to continue and accelerate when improved combustion system such as the High Luminosity Burner become available. CTI has observed and participated in the conversion to oxy-gas combustion and has observed the following historical trend:

- 1970s
  - Oxygen enrichment was used for productivity increase on some furnaces.
  - Some small, specialty glass furnaces (less than 50 ton/day) were converted to oxy-gas
- 1980s
  - Some fiberglass furnaces converted to oxy-gas.
  - A few container glass furnaces converted to oxy-gas.
- 1990s.
  - Most fiberglass and specialty glass furnaces converted to oxy-gas.
  - Half of container glass furnaces converted to oxy-gas.
  - All TV/lighting glass furnaces converted to oxy-gas.
  - One or two flat glass furnaces converted to oxy-gas.
- 2000
  - Approximately 20 percent of all glass furnaces will be converted to oxy-gas.

CTI has converted furnaces in the container, fiberglass, frit, TV, lighting, and tubing markets from air-gas firing to oxy-gas firing. These conversions have been completed for more than sixteen companies and total more than forty furnaces. Different industrial situations lead to various reasons to adopt oxy-gas combustion in a glass furnace. Figure 7 shows the leading reasons for conversion from air-gas to oxy-gas firing. A reduction in NO_x emissions is clearly the dominant reason for switching from air to oxygen. Other important reasons include a reduction in capital costs, fuel savings, an increase in production, and a decrease in particulates. Several other reasons that apply to a few furnaces include an increase in glass quality, the ability to reduce electric boost and save on the electricity costs, and a savings on batch to the furnace.

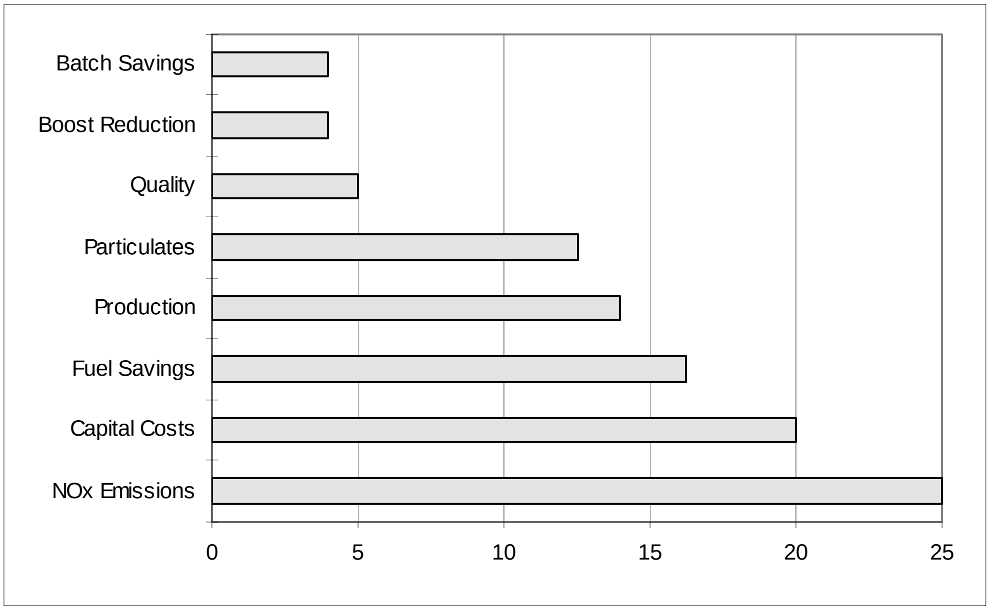


Figure 10. REASONS FOR CONVERTING GLASS FURNACES TO OXY-GAS FIRING, PERCENT OF FURNACES

Figure 10 confirms that the dominant reason to convert a furnace to oxy-gas combustion or to build a new oxy-gas furnace is to reduce NO_x emissions. Conversion rates have been low because glass makers have not had compelling economic reasons to convert to oxy-gas firing. Figures 11 and 12 demonstrate that the economics of oxy-gas combustion are improving. Over a four year period from 1991 to 1995, natural gas prices have oscillated and electricity costs have remained unchanged. During this same period, oxygen production technology has improved, and oxygen costs have decreased by as much as 30 percent. Also during this time, a number of oxy-gas conversions were completed, and industry became more familiar and comfortable with this new melting technology. Oxygen companies and burner companies (such as CTI) have aggressively marketed oxy-gas combustion systems to the glass industry.

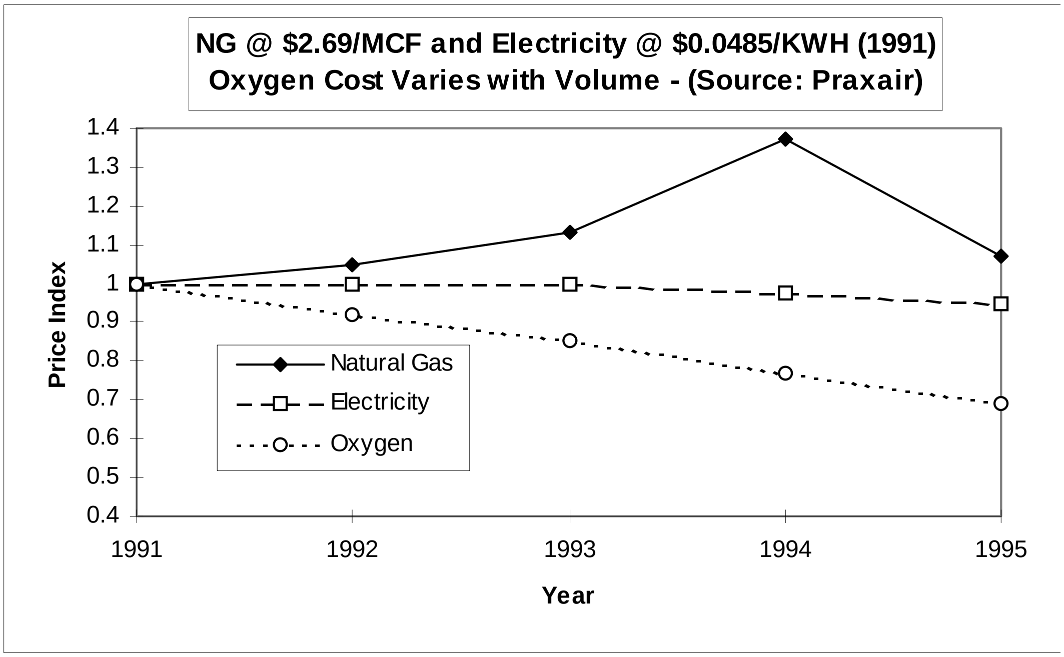


Figure 11. CHANGES IN ENERGY AND OXYGEN PRICES

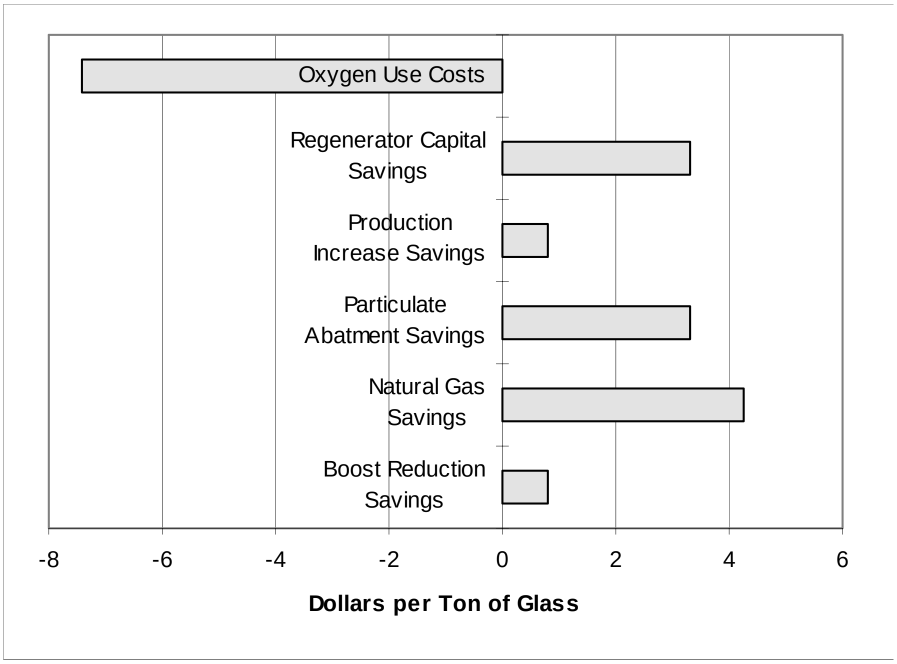


Figure 12. OXY-FUEL COSTS AND BENEFITS BASED ON A 300 TON/DAY CONTAINER GLASS FURNACE REBUILD

The cost analysis in Figure 9 is a general breakdown for the rebuild of a large container glass furnace. The analysis shows oxygen cost outweighs any single benefit of the conversion. However, when all the benefits are considered, they can outweigh the cost of oxygen. Also, as the cost of oxygen decreases, this cost-benefit analysis looks more attractive to the glass maker.

The project team studied the commercial oxy-gas burners that are currently available. All of these burners use one of the following methods to achieve low NO_x emissions.

- reducing the peak flame temperature
  - temperature can be reduced by entraining furnace gases
  - delayed mixing can also reduce temperature
- increasing flame area
  - a low momentum flame covers more area
  - a flat flame, with greater width than height, also covers more area
- increasing flame luminosity
  - staging combustion can increase luminosity
  - soot burnout increase luminosity. Precombustion can be used to generate soot.

Table 6 provides a list of the commercially available high luminosity, low NO_x oxy-gas burners for glass furnaces. All manufacturers claim their burners provide high heat transfer and low NO_x emissions. Operating characteristics, however, vary widely among the commercial burners, and the High Luminosity burner is expected to provide at least 20 percent higher heat transfer to the load than the best currently available burner while producing less NO_x.

Table 6. COMMERCIAL OXY-GAS BURNERS CLAIMING HIGH LUMINOSITY AND LOW NO_X

Company	Burner	Method
AGA	OXY-GAS	low velocity (momentum)
Air Products	CLEANFIRE	cracking via precombustion, delayed mixing
BOC Gases	Flat Jet	low initial mixing rates allow fuel pyrolysis and soot particle nucleation; flame stabilized close to burner to obtain laminar fuel flow; rectangular flow
Combustion Tec, Inc.	Primefire 100	low momentum, precombustion for soot formation
Combustion Tec, Inc.	Primefire 300	low momentum, precombustion for soot formation, flat flame
Maxon Corp.	LE	staged O_2 with holes through burner block to achieve low NO_x
Union Carbide	'A' Burner	dilution of oxygen via aspiration of furnace gases to reduce peak flame temperature; smaller oxygen flow to annulus around natural gas for stability
Xothermic	--	conventional oxy-gas burner

A number of other oxy-gas burners have also been identified. A list of these burners is presented in Table 7. These burners are either older models or not as well known as the burners described in Table 6.

Table 7. OTHER OXY-FUEL BURNERS

Company	Burner	Claim
Air Liquide	ALGLASS	Low NO_x
Airco	--	--
Air Products and Combustion Tec	KT-3	--
Empco	--	--
Kaiser Marquardt	--	high luminosity
Korf	--	--
Maxon Corp.	Kinemax	low NO_x
Maxon Corp.	OXY-THERM	low momentum bushy flame
North American	--	high luminosity
Praxair, Inc.	--	high luminosity

The characterization study was conducted by CTI with input from GTI. The conclusion is that a sizable, and growing, market exists for the High Luminosity Burner, being developed in the program. Strong demand, based on economics and emissions savings, is anticipated in the glass industry and in other markets. During Phase II, laboratory and pilot-scale High Luminosity Burner prototypes will be tested and evaluated relative to the best commercial oxy-gas burners.

Modeling

A Topical Report presenting modeling study results for the novel high-heat transfer low-NO_x natural gas combustion system being developed, tested, and demonstrated in this program has been prepared. This Topical Report on Modeling was submitted to DOE in partial fulfillment of the Phase I contractual requirements. Before construction and testing of prototype burners, the Novel High-Heat Transfer, Low-NO_x Natural Gas Combustion System was mathematically modeled to verify the predicted improvements in heat transfer and lower NO_x compared with conventional burner systems. The burner system, referred to as the High Luminosity Burner, is described by the modelers as being composed of a Fuel Preheating Zone and a Flame Zone. The Fuel Preheating Zone was modeled by a group at the University of Illinois at Chicago headed by Prof. Alexander Fridman, and the Flame Zone was modeled by a team at Purdue University headed by Prof. Raymond Viskanta.

Modeling was conducted for the High Luminosity Burner system firing into an oxy-gas glass melting furnace. This application of the burner will be demonstrated in Phase III of the project. Many other oxy-gas and air-gas fired applications of this burner system have been identified by the project team but have not yet been modeled. This work is important to the development of the High Luminosity Burner but is outside the scope of the current project.

The Topical Report on Modeling includes the results from both modeling teams. A Summary is provided along with Appendices presenting reports from the modeling teams with detailed results for both the Fuel Preheating Zone and the Flame Zone of the High Luminosity Burner. The Summary includes the High Luminosity Burner concept, the modeling strategy, results and discussion of modeling efforts, and conclusions. The Fuel Preheating Zone modeling discussion covers natural gas preheating; pyrolysis and oxidation reactions and reaction pathways; and soot precursor and soot nucleation, growth, coagulation, and oxidation in a laminar, preheated methane-oxygen flame. Results are in Appendix 1 of the Topical Report.

Modeling of the Flame Zone began with development of an idealized, one dimensional (1-D) model for predicting temperatures and radiation heat transfer to the load from non-luminous flames and from flames containing soot. The impact of axial heat transfer was then determined through the development of a quasi-two dimensional (quasi 2-D) model of the Flame Zone and combustion space. Results obtained using the quasi 2-D model are consistent with the 1-D modeling results and are presented in Appendix 2 of the Topical Report. The Appendix describes and discusses parametric calculations which show the increase in radiation heat transfer to the load resulting from the presence of soot in the products of combustion.

Kinetic, heat transfer, and thermodynamic modeling of both Zones, Fuel Preheat and Combustion, of the High Luminosity Burner system were completed. The modeling results for the Fuel Preheat Zone were provided as an input to the Combustion Zone modeling. Results were extremely encouraging for the High Luminosity Burner concept. Major conclusions of the modeling studies are:

- Only 2 to 9% of the feed natural gas must be combusted to provide heat for soot formation.
- Short residence times are required (10^{-2} to 1 seconds at 1300 K and 10^{-4} to 10^{-2} seconds at 1600 K) to produce soot precursors and soot.

- Soot concentration increase from 0.1 to 2.0 volume percent when optimum concentrations of soot precursors are formed in the Fuel Preheat Zone.
- Soot concentrations in the fuel and at the furnace inlet are important parameters affecting furnace thermal performance.
- At high enough soot concentrations, the thermal efficiency of luminous flames can be increased by 25% with no changes in other parameters.
- Flames covering a larger fraction of the glass surface enhance the thermal performance of the furnace.
- Short flames are undesirable because they produce highly peaked and non-uniform profiles at the glass surface and create high gas and refractory temperatures.
- Increasing soot concentration lowers gas temperature and expected to lower NO_x formation.
- Crown temperatures are determined to increase slightly with the addition of soot to an oxy-gas flame.

The results of the modeling effort have been incorporated into the design of the prototype High Luminosity Burner which will be fabricated and tested during Phase II of this DOE program. During Phase II, testing results will be compared with the modeling predictions. Any discrepancies between modeling and practice will be examined before proceeding to the next level of testing. Phase III work will involve demonstration of the burner system on a commercial oxy-gas glass furnace.

Burner Design

After the modeling work was completed, engineers at CTI designed a prototype High Luminosity Burner for laboratory testing on an GTI furnace. Complete CAD drawings of the first prototype burner have been prepared along with instructions for fabrication. The design team included all components of the burner system in the Fuel Preheat Zone and the Flame Zone. The sections included in the two furnace Zones are:

- Fuel Preheat Zone
  - Precombustor
  - Indirect natural gas heating
  - Direct natural gas heating
  - Mixing
- Flame Zone
  - Fuel-rich combustion
  - Fuel-lean combustion

The first prototype burner was designed to operate at a maximum capacity of 0.5 MM Btu/h with a 4:1 turndown. A large amount of flexibility was designed into this burner to allow for variations in temperatures, residence times, mixing characteristics, and flame section distributions and oxygen/fuel ratios. The burner was equipped with test ports to allow collection of gas samples for analysis, to measure temperatures, and to observe the flame. The burner concept is proprietary to GTI. Detailed discussions of the exact burner configuration are outside the project scope. Therefore, drawings and detailed descriptions are not included in this report.

During Phase II of this project, a prototype burner was fabricated by CTI from the design developed in Phase I. This burner was tested by GTI, and changes and improvements will be incorporated in a new design. This new design will be used to fabricate a 3 MM Btu/h High

Luminosity Burner that will be tested on an GTI pilot-scale furnace. This second burner will be used to compare the High Luminosity Burner system with commercial oxy-gas burners. After completing this testing in Phase II, the project team will fabricate full-scale burners (at CTI) and demonstrate the new combustion system on a commercial Owens Corning oxy-gas glass furnace.

Laboratory and pilot scale testing was conducted with several high luminosity burners fabricated by Combustion Tec. Laboratory testing with three high luminosity burners and a Combustion Tec Primefire 100 burner was conducted at GTI. Pilot scale testing was conducted at Combustion Tec with one pilot scale high luminosity burner and commercial Combustion Tec burners. The commercial Combustion Tec burners evaluated for comparisons with the high luminosity burner were the conical Primefire 100, the flat flame Primefire 300, and the Primefire 300 with a precombustion zone added.

Laboratory-Scale Testing

Laboratory testing was conducted in the GTI Combustion Laboratory with 0.5 MMBtu/h lab-scale burners. All tests were conducted by mounting burners in AZS burner blocks and firing them into a fully instrumented test furnace.

Test Conditions and Burner Design

Figure 13 shows a schematic diagram of the GTI test furnace used for laboratory testing.. The furnace has a firing capacity of more than 500,000 Btu/h and is fully instrumented. Furnace system modifications for this test program included changing burner and burner blocks in and out, providing metered oxygen service, piping and metering separate natural gas lines, and calibrating the emissions monitoring equipment. Four thermocouples, two in the chamber roof and two in the exhaust gas stream, were monitored. Their positions are shown on the diagram.

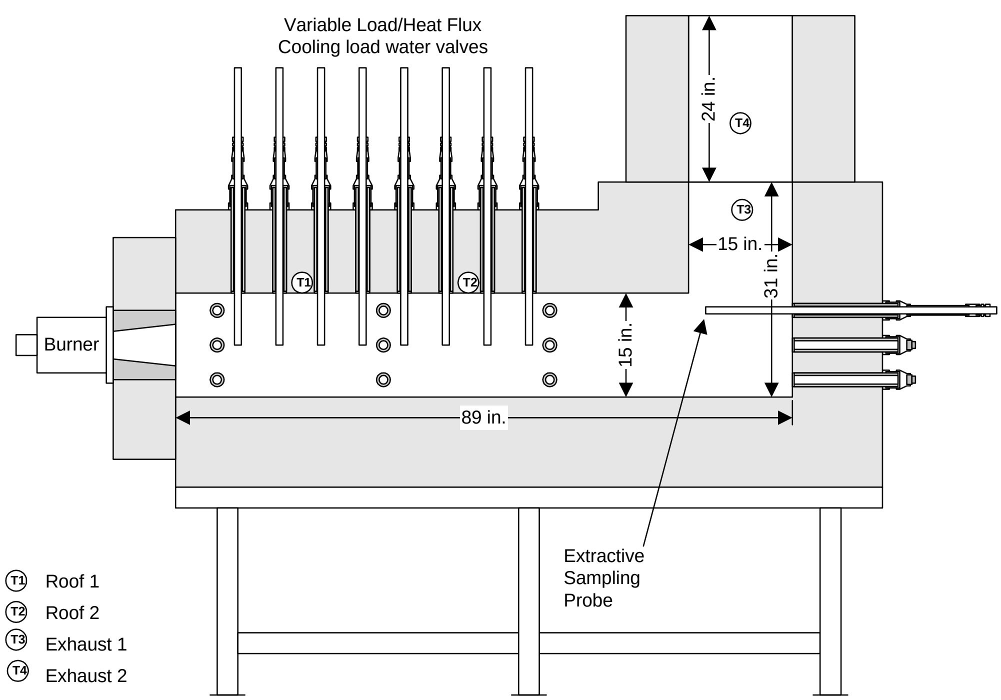


Figure 13. LABORATORY SCALE TEST FURNACE

The laboratory scale furnace is 7 feet long with a 15 x 15 in. cross section. The furnace is lined with 3000°F fiber board insulation. Up to sixteen water-cooled tubes can be lowered into the furnace to provide variable loads. In this program, the tubes were fully inserted at all times. Electric preheat of the natural gas and air preheat of up to 1100°F are available but were not used in this program. Nine ports on both sides of the furnace and three ports at the back end provide for gas sample, temperature, and optical data collection. The front end is removable to allow installation of many types of burners with capacities of up to approximately 1×10^6 Btu/h. The top of the furnace is removable to allow access to the furnace chamber. Air, natural gas, oxygen, and load water flow rates and temperatures are measured. Gas analyzers were used to measure NO_x, CO, CO_2, O_2, and THC concentrations in the furnace exhaust gas.

Tests were conducted with three versions of a 0.5 MMBtu/h high luminosity burner. A commercial 0.5 MMBtu/y Combustion Tec Primefire 100 conical burner was also tested to provide baseline results for a typical oxy-gas burner. All tests were oxy-fired. No air or enriched air tests were conducted. Approximately 200 data points were taken with the three laboratory scale high luminosity burners. Independent variables and measurements are presented in Table 8 below.

Table 8. RANGES OF LABORATORY TEST CONDITIONS

Test Burner	Independent Test Variable	Independent Variable Range
Primefire 100 commercial conical oxy-gas burner	Overall Excess O_2 Firing Rate	3% and 13% 0.25, 0.35, 0.50 MMBtu/h
High-Heat Transfer Low-NO_x Burners (high luminosity burners)	Overall Excess O_2 Firing Rate Mixed Gas Temperature Precombustion Residence Time Direct Mixing Residence Time O_2 split – Precombustion, Fuel-rich Combustion, Fuel-lean Combustion Fuel-rich Combustion Residence Time	3% and 13% 0.25, 0.35, 0.50 MMBtu/h up to 2000°F 0 – 0.16 s 0.015 – 0.14 s 0 - 20%, 0 - 20%, 65 - 95% 0 – 0.15 s

All three laboratory high luminosity burners were designed by GTI and Combustion Tec, fabricated by Combustion Tec, and tested at GTI. The burners progressed from completely flexible to adjustable on specific independent variables. All zones of burner 1 had adjustable lengths. After testing was completed with this burner, and second burner was fabricated with fixed precombustion and direct mixing section lengths and an adjustable fuel-rich combustion zone length. Also, in the second burner, residence time was significantly longer in the fuel-rich combustion zone to provide time for soot formation. The third burner was designed to test a method of combining the precombustion and direct mixing sections. An internal precombustor enabled all the gas and only the precombustion oxygen to be introduced to the back of the burner. The products of the precombustion zone then heated the majority of the natural gas. In the third burner, the direct mixing section was adjustable and no fuel-rich combustion zone was included. A summary of the three laboratory burner characteristics is presented in Table 9.

Table 9. LABORATORY-SCALE HIGH LUMINOSITY BURNER CHARACTERISTICS

	Burner 1	Burner 2	Burner 3
Precombustion zone, in.	0 – 9	0 - 12	0 – 6
Direct Mxing Zone, in.	6 (fixed)	9 (fixed)	0 – 9
Fuel-rich Combustion Zone, in.	none	0 - 14	None
Data Points	59	79	84

Photographs of the three laboratory high luminosity burners are shown in Figures 2 through 4. The burners varied in length and complexity depending on the amount of adjustments build into them for parametric testing. All burners were conical (round) in shape and made from standard stainless 304 and Inconel pipe.

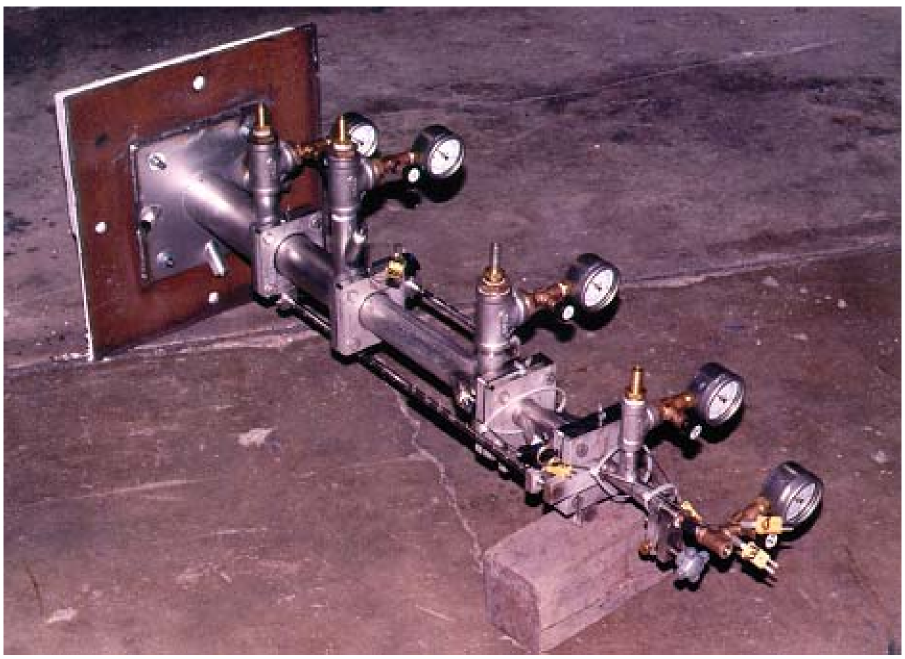


Figure 14. LAB-SCALE HIGH LUMINOSITY BURNER (VERSION 1)

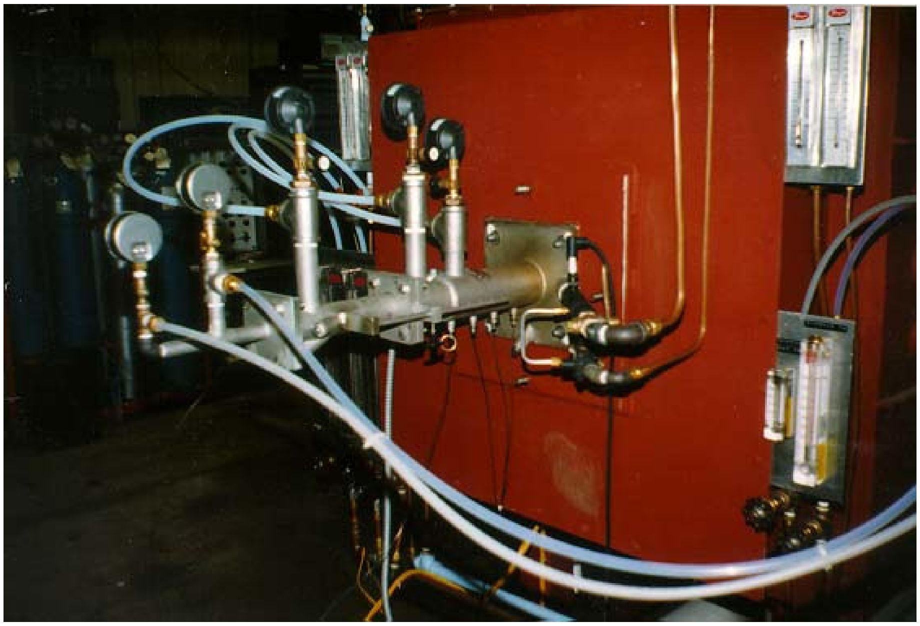


Figure 15. LAB-SCALE HIGH LUMINOSITY BURNER (VERSION 2)

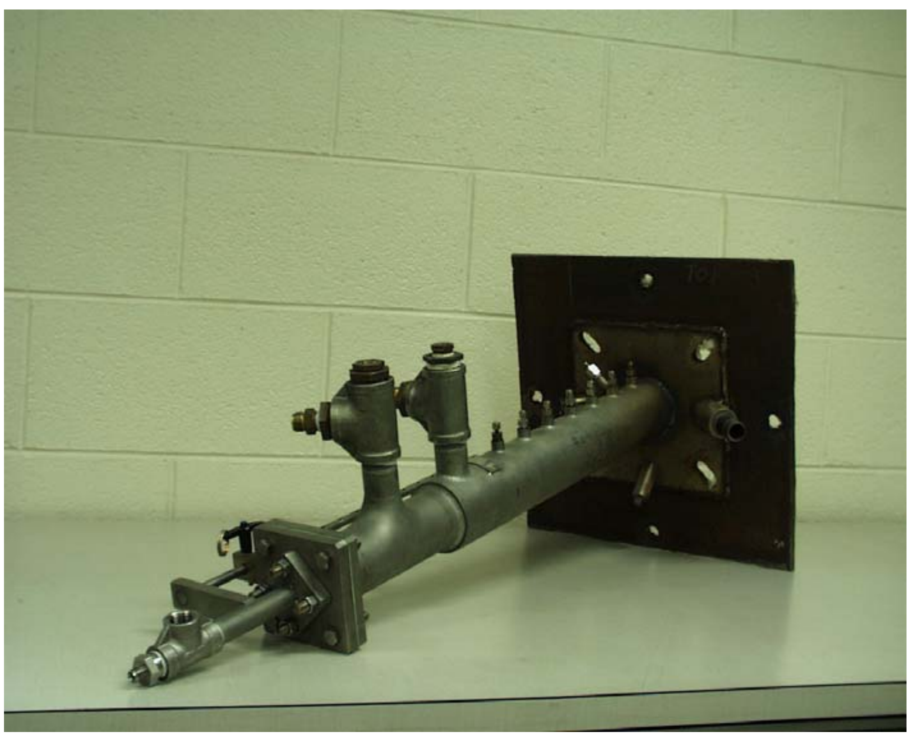


Figure 16. LAB-SCALE HIGH LUMINOSITY BURNER (VERSION 3)

Laboratory-Scale Testing Results

The first tests were conducted to determine the desired exhaust gas composition. Figure 17 shows heat transfer is consistently higher with 3% oxygen in the exhaust gas compared with 13% oxygen in the exhaust gas. To eliminate this variable from impacting other test results, the project team conducted all later tests with 3% oxygen in the exhaust gas. Natural gas flow was set, and oxygen flow was then adjusted to produce 3% oxygen in the exhaust gas.

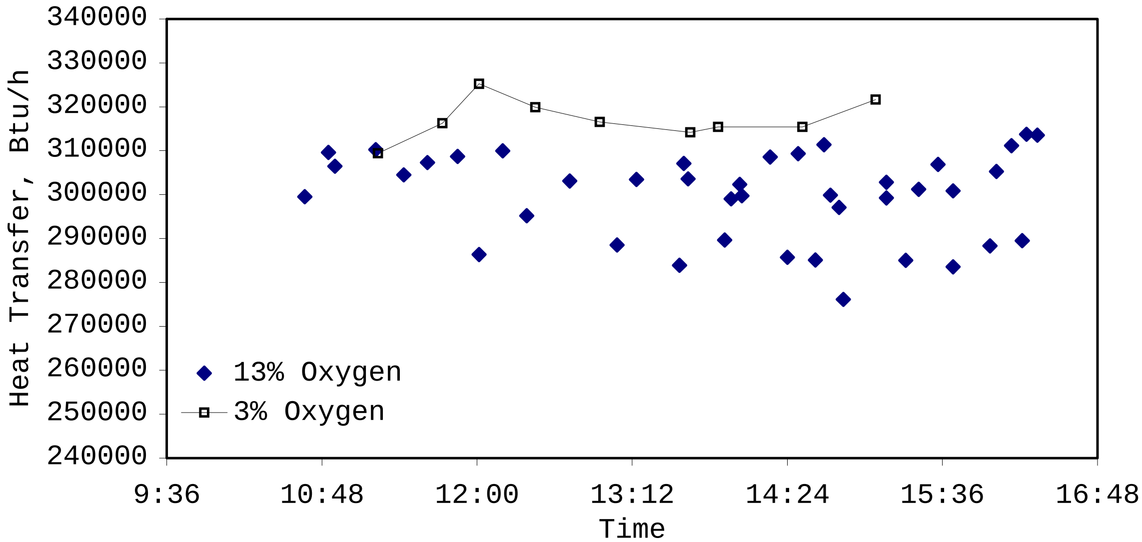


Figure 17. BURNER 1 HEAT TRANSFER WITH 3% AND 13% OXYGEN IN EXHAUST

At a constant firing rate of 0.5 MMBtu/h and 3% oxygen in the exhaust gas, the first high luminosity burner showed higher heat transfer, higher roof temperatures, and significantly lower exhaust gas temperatures than the Primefire 100 burner. Figure 18 shows heat transfer to the artificial load was approximately 10 % greater, at 309,000 Btu/h compared with 281,000 Btu/h. Results varied as various burner firing conditions were changed, but the result was consistent for all high luminosity burner firing conditions.

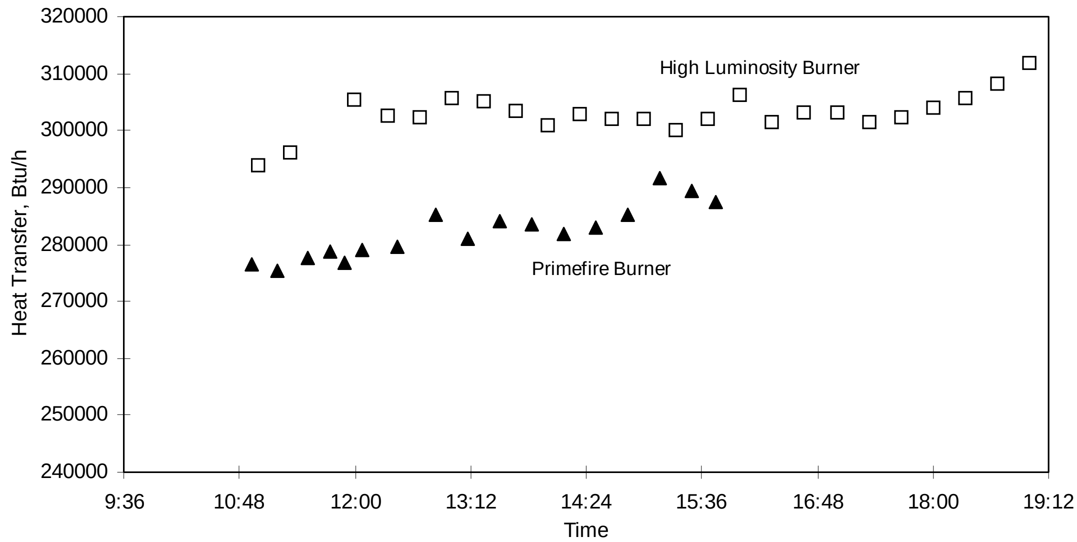


Figure 18. HEAT TRANSFER FOR BURNER 1 AND THE PRIMEFIRE 100 BURNER

The two roof thermocouples had similar temperatures (only 100°F apart) with the first high luminosity burner. Roof temperatures were more than 400°F apart with the commercial burner. This indicates the flame is more spread out and both temperature and heat transfer profiles are more uniform for the high luminosity burner. A comparison of the temperatures of these two thermocouples over several days of testing and many conditions is shown in Figures 19 and 20. If increased heat is transferred to the load, the exhaust gas must carry less heat. A check of exhaust gas temperatures in Figure 21 confirms a temperature decrease of over 100°F when firing the first high luminosity burner compared with the commercial Primefire burner.

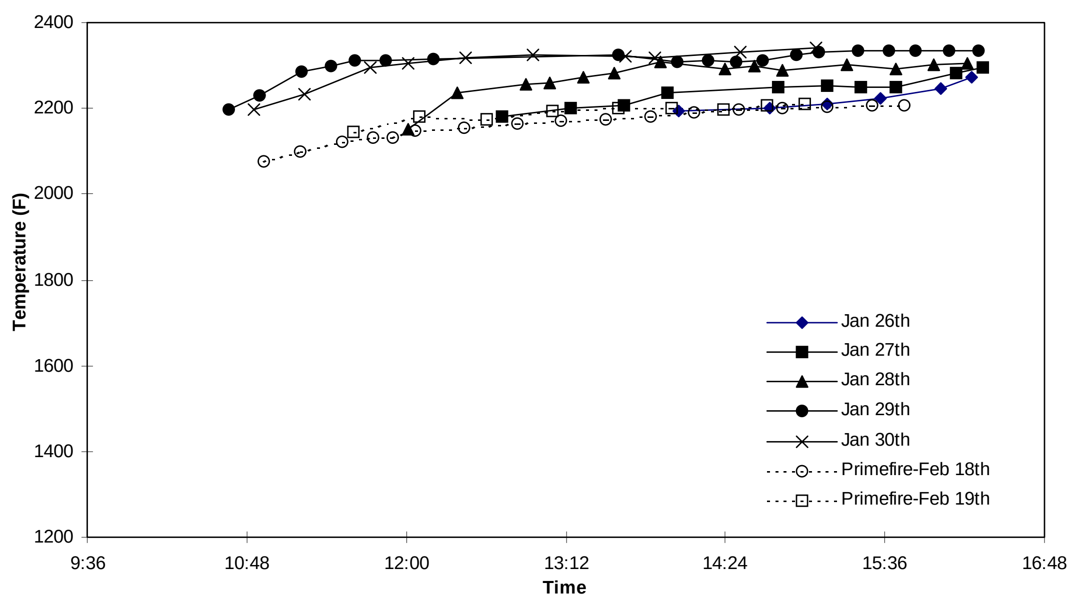


Figure 19. ROOF 1 TEMPERATURE FOR BURNER 1 AND THE PRIMEFIRE 100 BURNER

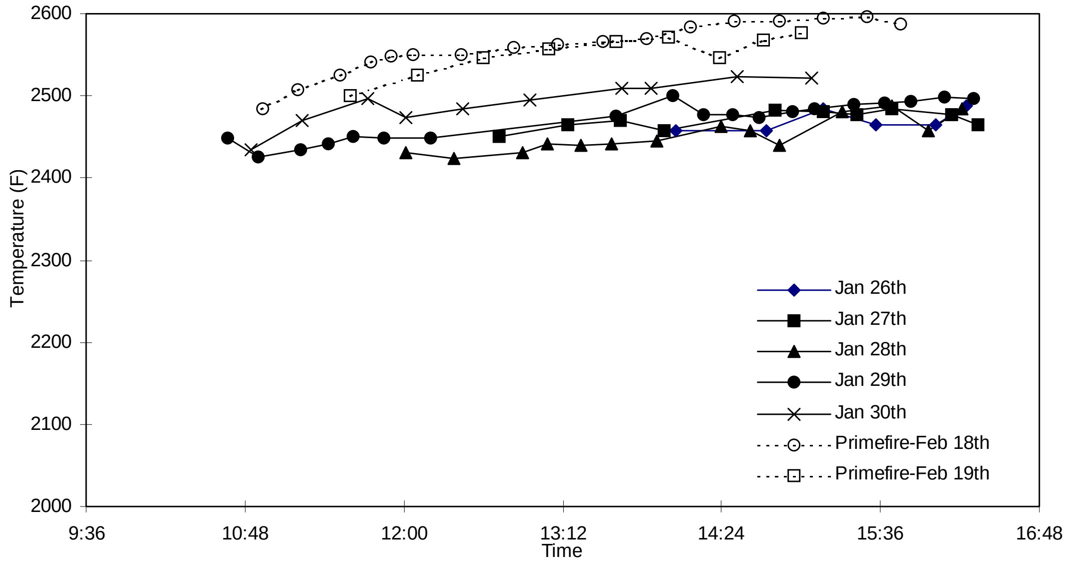


Figure 20. ROOF 2 TEMPERATURE FOR BURNER 1 AND THE PRIMEFIRE 100 BURNER

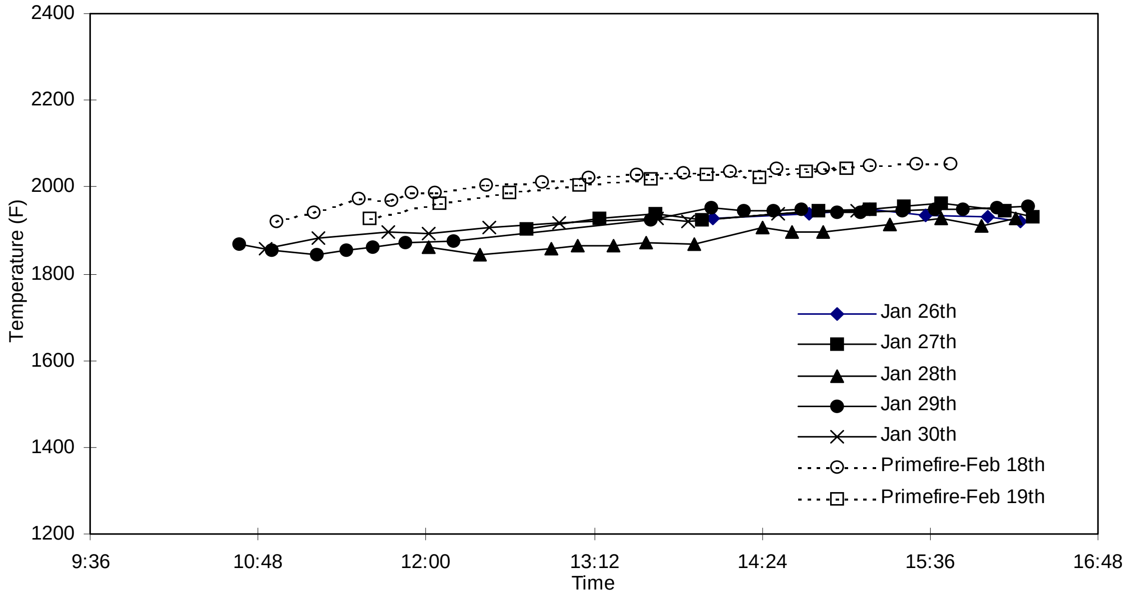


Figure 21. EXHAUST GAS 1 TEMPERATURE FOR BURNER 1 AND THE PRIMEFIRE 100 BURNER

The first laboratory burner was designed to allow testing with different lengths of the precombustion zone, the direct mixing zone, and the fuel-rich combustion zone. A series of tests was conducted over several days to determine the effects of these zone lengths and the subsequent residence times on heat transfer to the artificial load. The precombustion zone length was found to have no effect on heat transfer. So long as sufficient space was provided for the precombustor to operate, no lengthening of this zone had any noticeable effects on heat transfer or temperature. The direct mixing zone length did affect the heat transfer to the artificial load. Figures 22 and 23 show that increasing the length of the direct mixing zone from 6 to 10 inches increased the heat transfer to the load by 3 to 5 percent. The scatter in the figures is from the adjustment of other variables during this parametric testing.

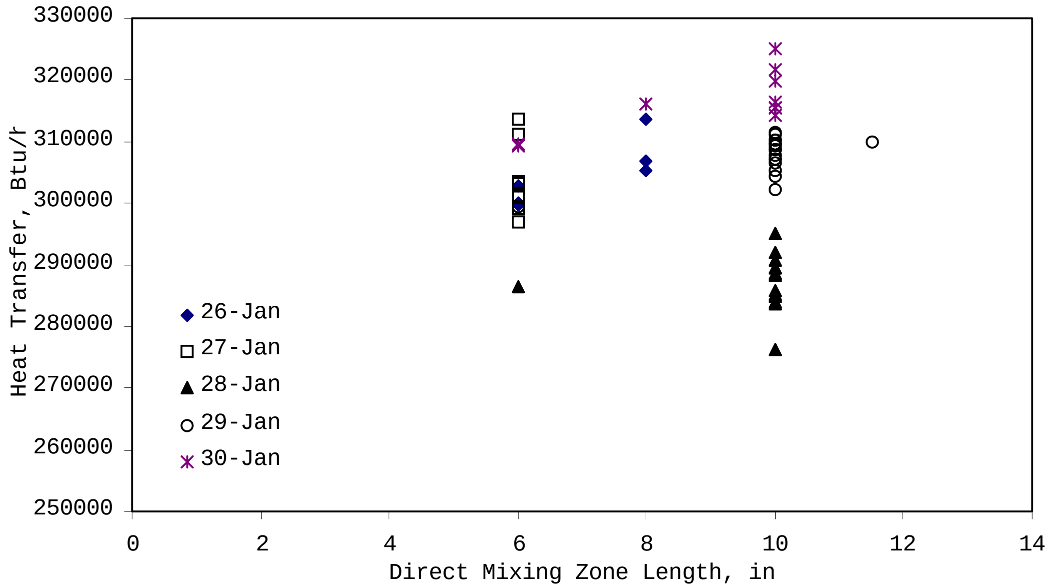


Figure 22. INCREASED DIRECT MIXING ZONE LENGTH RAISES HEAT TRANSFER

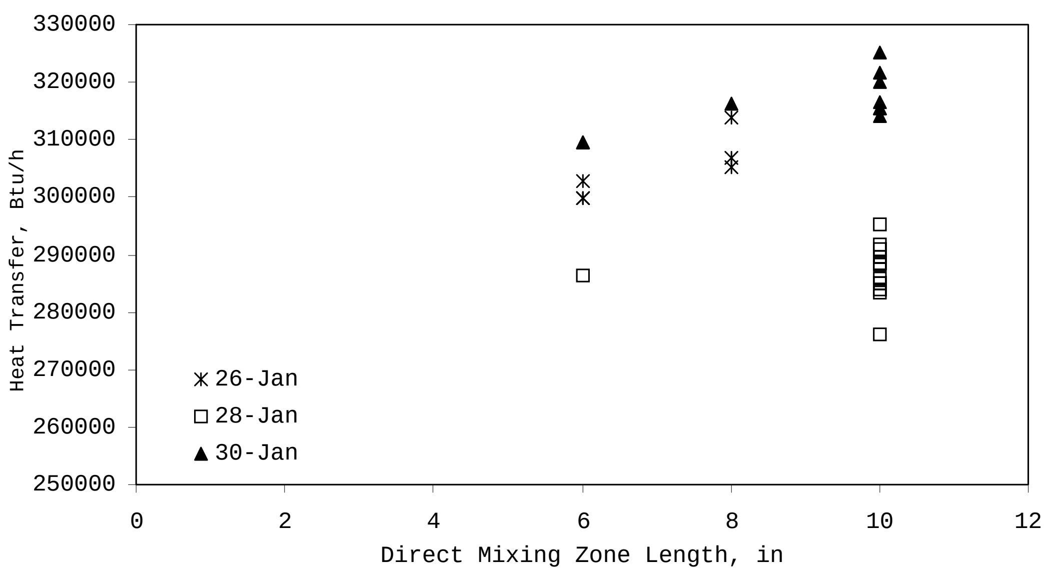


Figure 23. HEAT TRANSFER IS INCREASED 3 TO 5% WITH LONGER DIRECT MIXING ZONE LENGTH

A series of tests was made to determine the effect of the fuel-rich combustion zone length on heat transfer. Figure 24 shows that the length of this zone had no effect on heat transfer to the artificial load under any conditions tested. The fuel-rich combustion is fast enough and hot enough to produce all the needed soot for flame luminosity in an extremely short residence time.

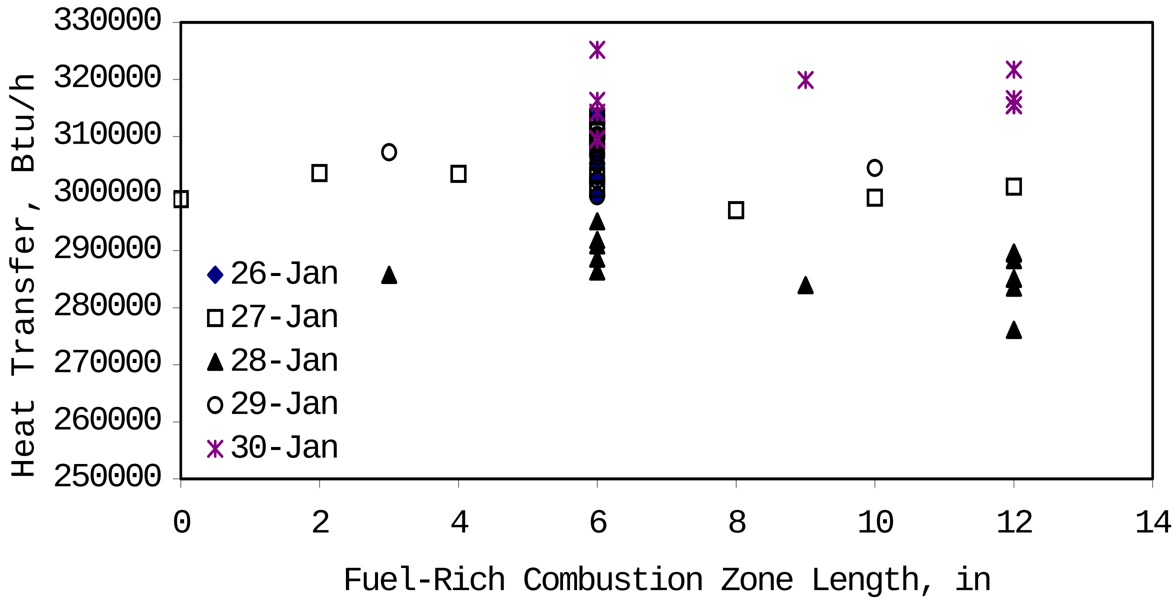


Figure 24. HEAT TRANSFER IS NOT AFFECTED BY FUEL-RICH COMBUSTION ZONE LENGTH FOR LABORATORY HIGH LUMINOSITY BURNER 1

Other tests were made with the first laboratory high luminosity burner to determine the effects of oxygen split between precombustion, fuel-rich combustion, and fuel-lean combustion. Figures 25, 26 and 27 show that little change in heat transfer was seen over the ranges of oxygen examined. The primary reason for this was the low amount of oxygen sent to the precombustor. In most tests a maximum of 10 percent oxygen was sent to the precombustor. Calculations and temperature measurements showed this is insufficient to achieve the 1800°F needed to create soot precursors. Tests with the second laboratory burner were conducted with higher fractions of the oxygen for precombustion to generate soot precursors and increase flame luminosity.

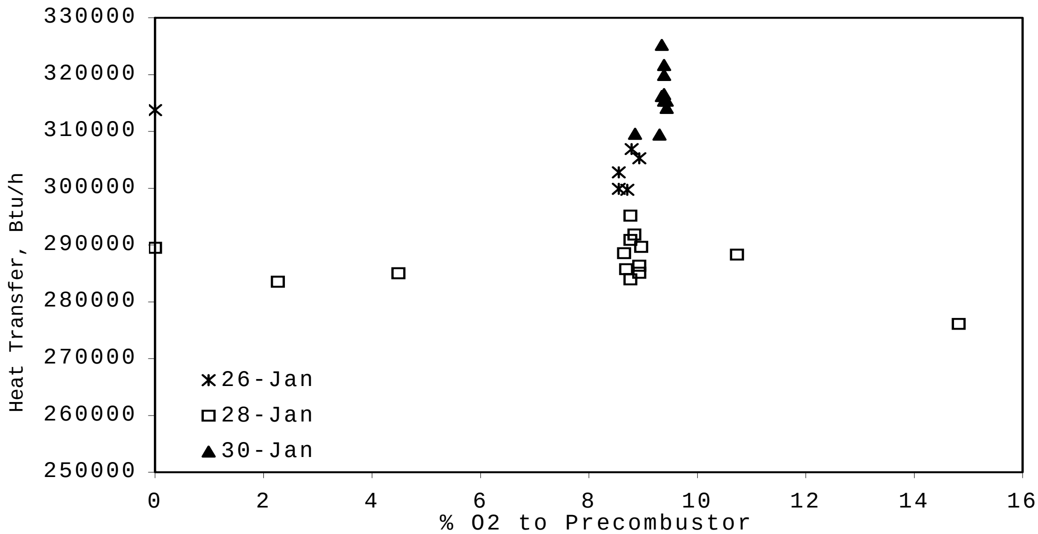


Figure 25. FRACTION OF OXYGEN SENT TO THE PRECOMBUSTOR FOR BURNER 1 WAS TOO LOW TO GENERATE SOOT PRECURSORS

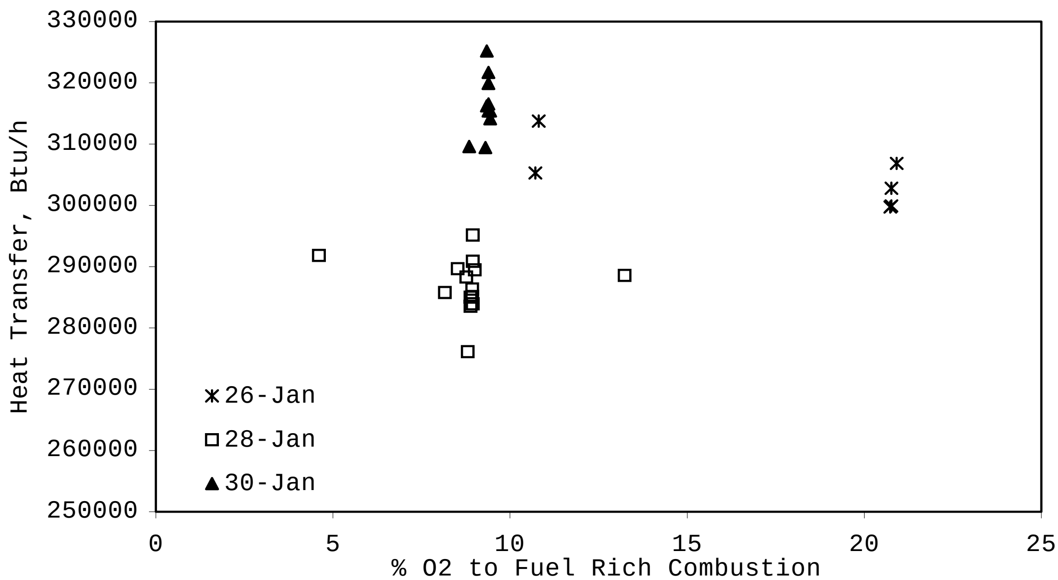


Figure 26. CHANGING FRACTION OF FUEL-RICH OXYGEN HAD LITTLE EFFECT ON HEAT TRANSFER FOR BURNER 1

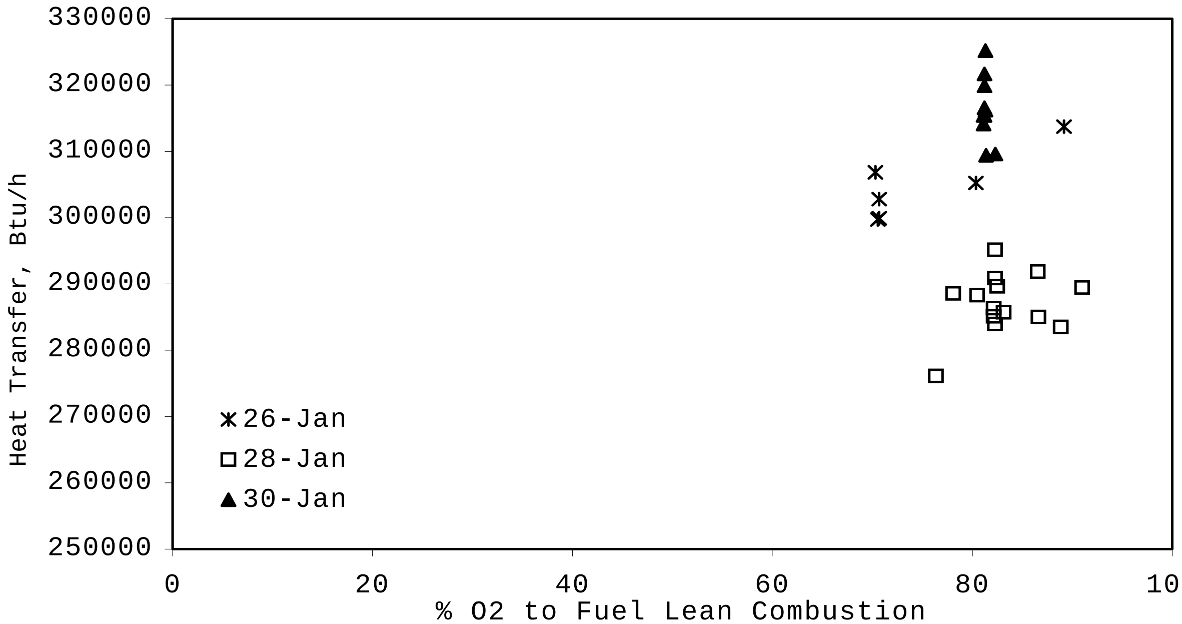


Figure 27. CHANGING FRACTION OF FUEL-LEAN OXYGEN HAD LITTLE EFFECT ON HEAT TRANSFER FOR BURNER 1

The final series of tests with the first laboratory high luminosity burner was at a range of firing rates. Figures 28,29, 30, and 31 show the effect of firing rate on the two roof thermocouples and on the two exhaust gas temperatures. The firing rates tested were 500,000, 375,000, and 250,000 Btu/h. Decreasing the firing rate from 0.5 to 0.25 MMBtu/h lowered the first roof temperature by approximately 300°F and lowered the second roof temperature by approximately 500°F. This confirms the expected decrease in flame length and radiative heat transfer at the lower firing rate. The two exhaust gas temperatures both decreased approximately 600°F when the firing rate was reduced by half. Since both exhaust gas temperatures decreased by the same amount, the project team was assured that the exhaust thermocouples are reading gas temperatures and are not influenced by radiation from the flame.

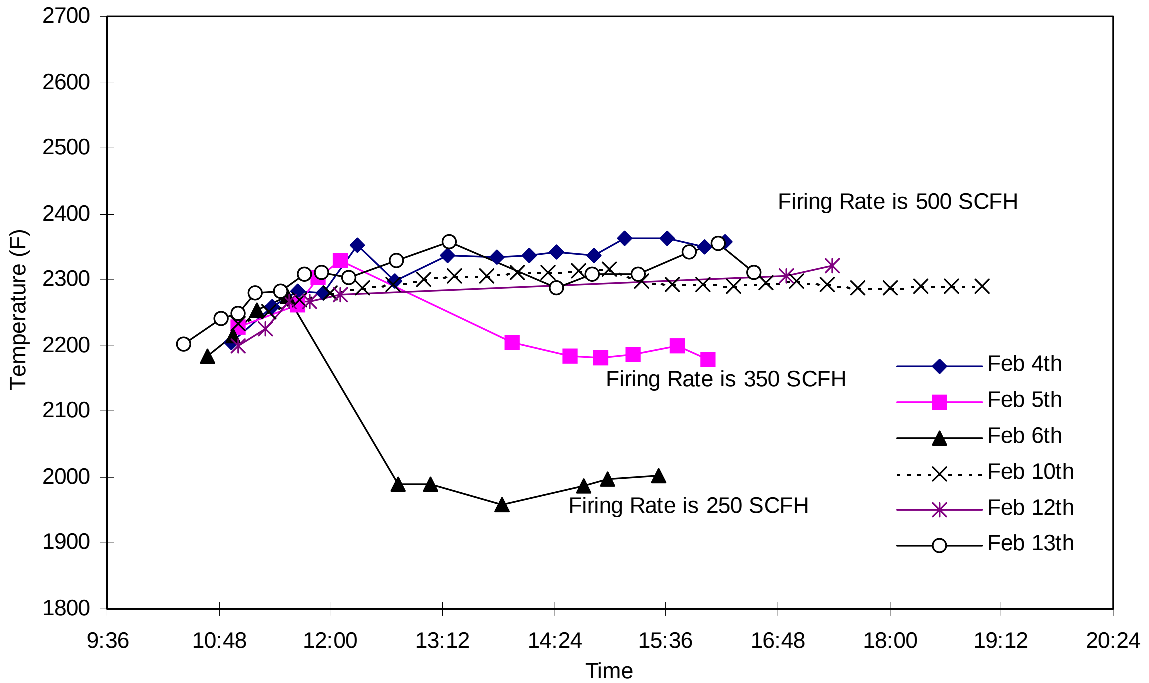


Figure 28. ROOF 1 TEMPERATURE AT VARIOUS FIRING RATES WITH BURNER 1

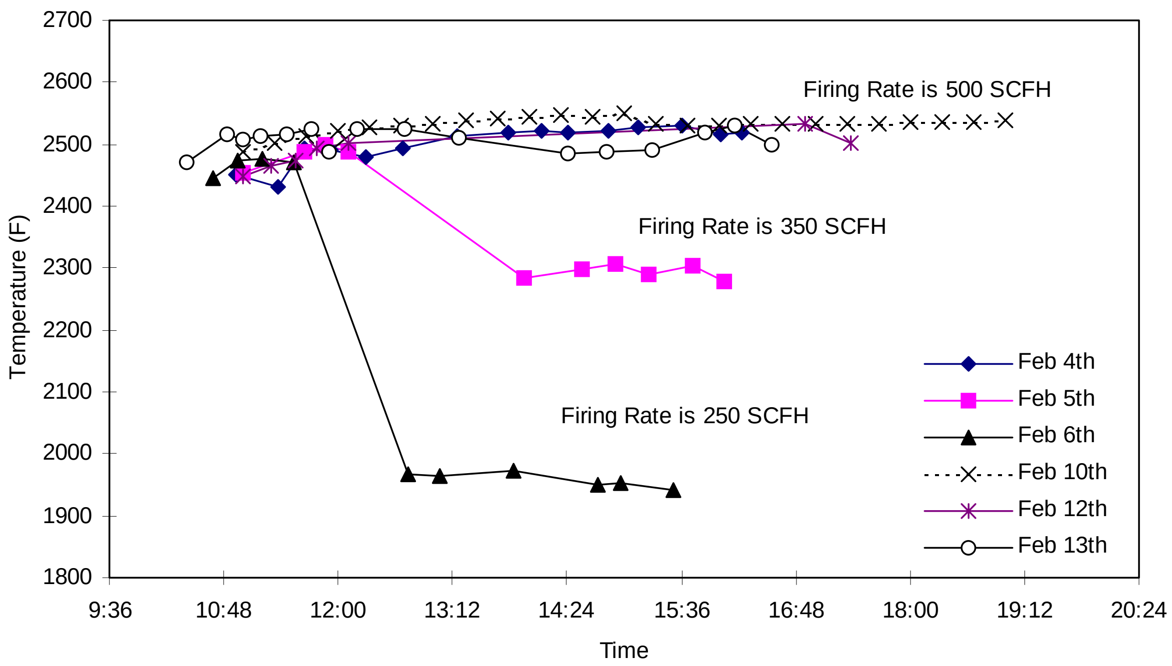


Figure 29. ROOF 2 TEMPERATURE AT VARIOUS FIRING RATES WITH BURNER 1

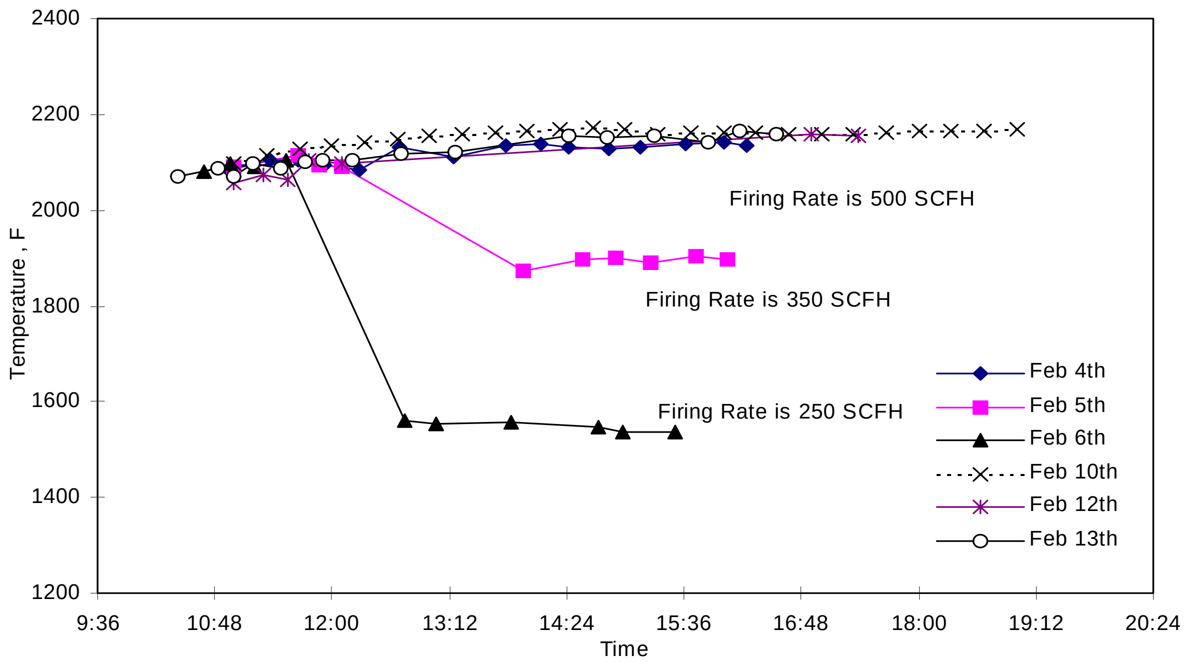


Figure 30. EXHAUST 1 TEMPERATURE AT VARIOUS FIRING RATES WITH BURNER 1

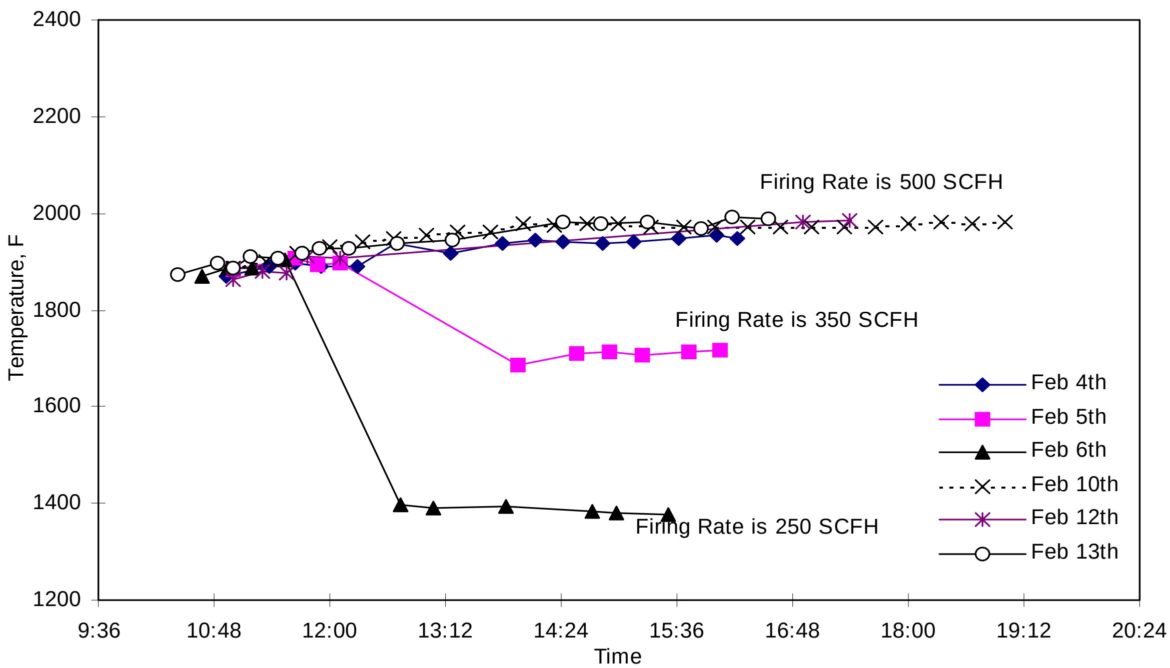


Figure 31. EXHAUST 2 TEMPERATURE AT VARIOUS FIRING RATES WITH BURNER 1

The second laboratory high luminosity burner was built to allow the project team to increase the amount of precombustion and to vary the length of the fuel-rich combustion zone. Tests were conducted with 5 to 20 percent of the oxygen sent to the precombustor so the main natural gas would be heated to 2000°F and generate the desired soot precursors by pyrolysis for soot formation. Other tests evaluated the effect of fuel-rich combustion residence time on heat transfer by varying the length of the fuel-rich combustion zone between 0 and 9 inches.

Figure 32 shows the effect of changing the fuel-rich combustion zone length on heat transfer to the artificial load. The figure indicates that heat transfer is highest at an optimum length of 9 inches. At shorter lengths and residence times, insufficient precursors are expected to form. At a longer length, soot formation may b decreasing the overall heat transfer from the flame. Heat transfer is approximately 4 percent greater at 9 inches than at either 0 (no fuel-rich combustion zone) or 12 inches. Also, because enough precombustion takes place in the second burner, the maximum heat transfer to the artificial load increased to 330,000 Btu/h for the second burner compared with 315,000 Btu/h for the first burner and 290,000 Btu/h for the commercial Primefire 100 conical burner. The second burner showed an increase in heat transfer of 14 percent compared with the commercial burner and an increase of 4.7 percent compared with the first laboratory high luminosity burner.

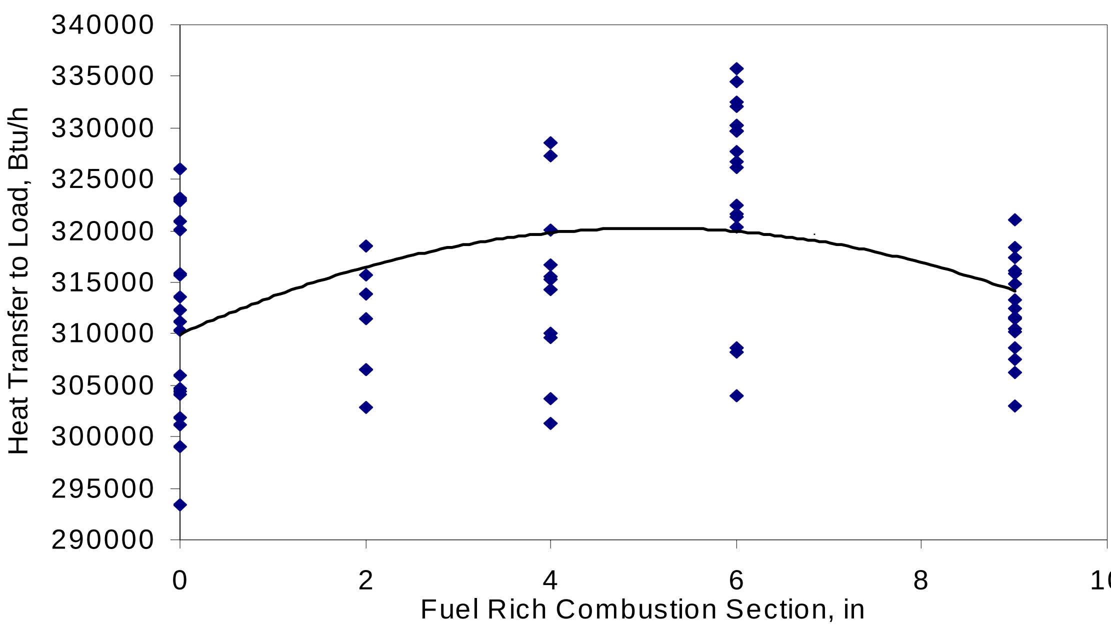


Figure 32. BURNER 2 SHOWS HIGHEST HEAT TRANSFER WITH A 9 INCH FUEL-RICH COMBUSTION ZONE

A comparison of the heat transfer from the second burner with different fractions of oxygen sent to the precombustor is shown in Figure 33. The figure clearly shows that as the amount of oxygen is increased from 5 to 10 and then to 15 percent, the amount of heat trasfer to the artificial load increases. However, 15 percent oxygen to the precombustor appears to be an optimum value. At 20 percent precombustion oxygen, the heat transfer decreases slightly. This is in agreement with the fuel-rich combustion zone length experiments that showed too much residence time decreases heat transfer. Apparently, too much precombustion leads to high syngas (CO and H_2) formation. High CO production decreases available methane for soot formation by pyrolysis. Even if the temperature of the heated natural gas is high (over 2000ºF), sufficient methane must be present to form soot precursors.

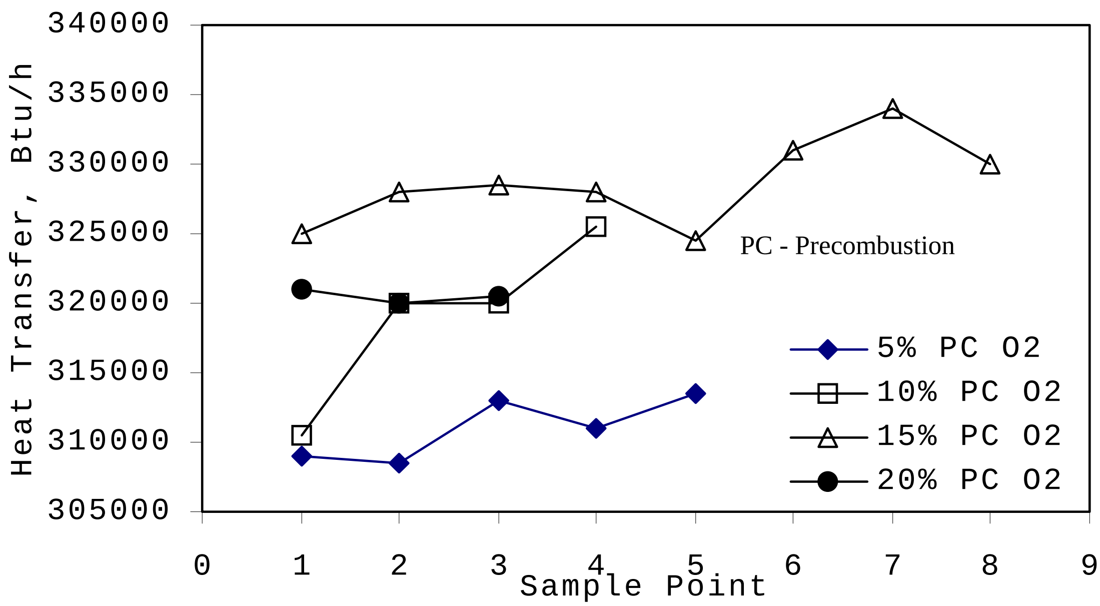


Figure 33. EFFECT OF AMOUNT OF PRECOMBUSTION OXYGEN ON HEAT TRANSFER FOR BURNER 2

The third 0.5 MMBtu/h laboratory high luminosity burner was built to evaluate the effects of several burner simplifications. The precombustor and direct mixing zone were combined by installing an internal ‘cup’ with holes along the sides. The precombustion oxygen was introduced to a ‘cup’ and all of the natural gas flowed along the outside of this cup. The precombustion occurred at the cup and the hot product gases heated the main natural gas stream. Three different cups (small, medium, and large) were evaluated for stability and effects on temperatures and heat transfer. This simplification allowed the two natural gas inlets of the first two burners to be reduced to one natural gas inlet.

Test series were conducted with each of the three cups inside the third laboratory high luminosity burner. One day of testing was conducted with each of the large and small cups, and three days of testing were completed using the middle sized cup. Heat transfer from this burner was again found to be higher than for the conventional burner, but this burner showed the lowest heat transfer of the three high luminosity burners. Heat transfer was approximately 6 percent higher than for the Primefire 100 burner. Figure 34 shows the heat transfer for the third high luminosity burner with the three sizes of cups installed. Although the large cup showed the highest heat transfer, the range was not large.

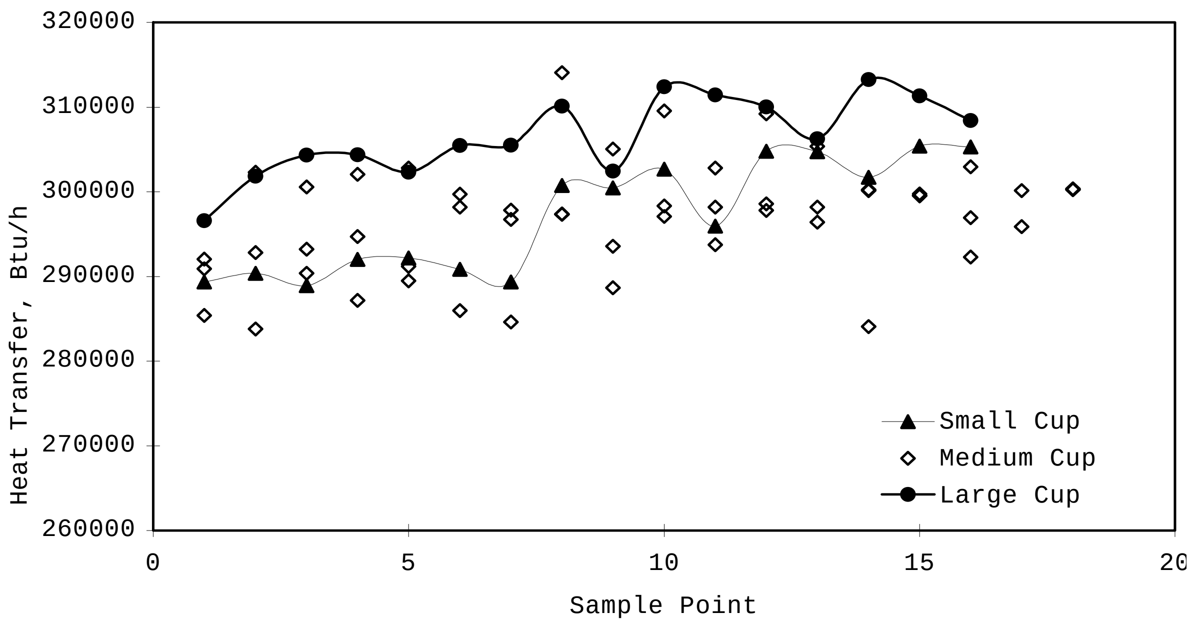


Figure 34. HEAT TRANSFER FOR THE THIRD LABORATORY HIGH LUMINOSITY BURNER

While the third high luminosity burner showed the lowest heat transfer, the second high luminosity burner showed the highest heat transfer. Figure 35 shows range of heat transfer for both burners over a typical day of testing. The major differences between these burners were removing the fuel-rich combustion zone in the third burner and combining the precumbustor and direct mixing zone with the ‘cup’ in the third burner. Earlier testing with the second burner showed the importance to heat transfer of having a fuel-rich combustion zone. The data from the third burner support the need for a fuel-rich combustion zone, and the lower heat transfer from this burner appeared to be caused by removing this zone.

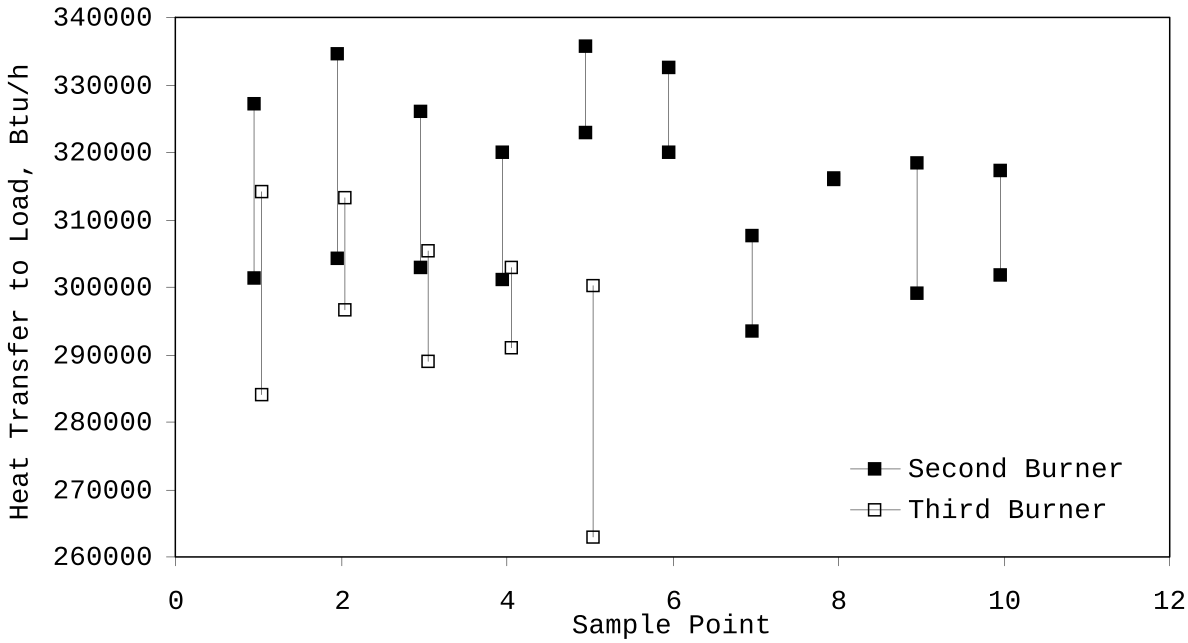


Figure 35. AVERAGE HEAT TRANSFER FOR THE SECOND AND THIRD LABORATORY HIGH LUMINOSITY BURNERS

Temperatures measured by the two roof thermocouples and the two exhaust gas thermocouples for the third burner are shown in Figures 36 through 39. Roof temperatures were approximately 100°F lowering than for similar firing conditions with the first high luminosity burner. This indicates lower radiation heat transfer and confirms the need for a fuel-rich combustion zone to create soot in the flame. The exhaust gas temperatures were similar to temperatures measured at similar firing rates for the first high luminosity burner. The largest cup provided the highest heat transfer to the simulated load, but no pattern is seen between cup size and roof or exhaust gas temperature. The flame was very stable in the third burner and the heat was well distributed. This made for a cooler burner and a much simpler burner design. Based on the results of laboratory testing, a design was developed for the pilot scale burner that included both a precombustion zone and a fuel-rich combustion zone.

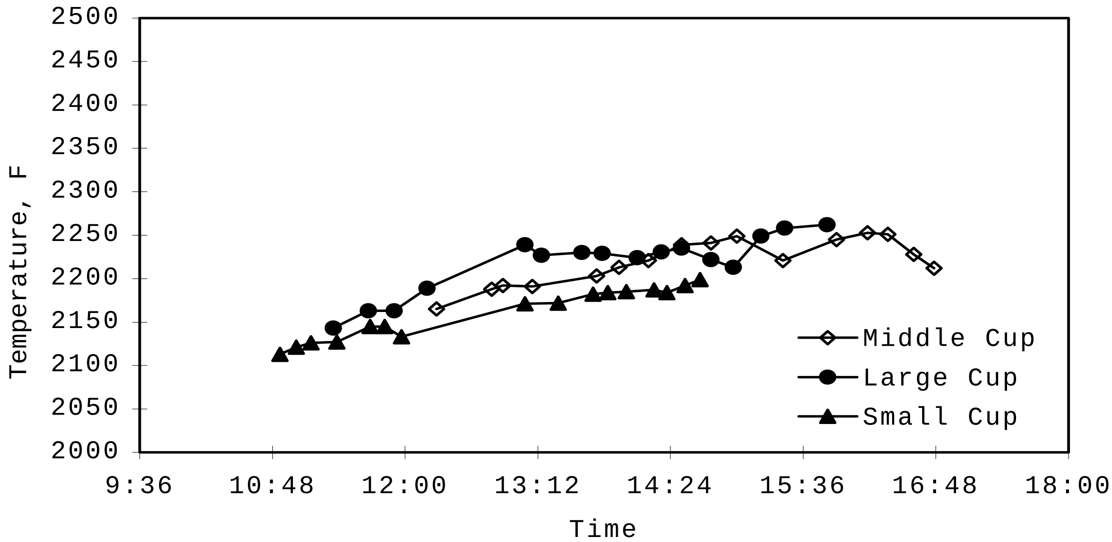


Figure 36. ROOF 1 TEMPERATURE FOR THE THIRD LABORATORY HIGH LUMINOSITY BURNER

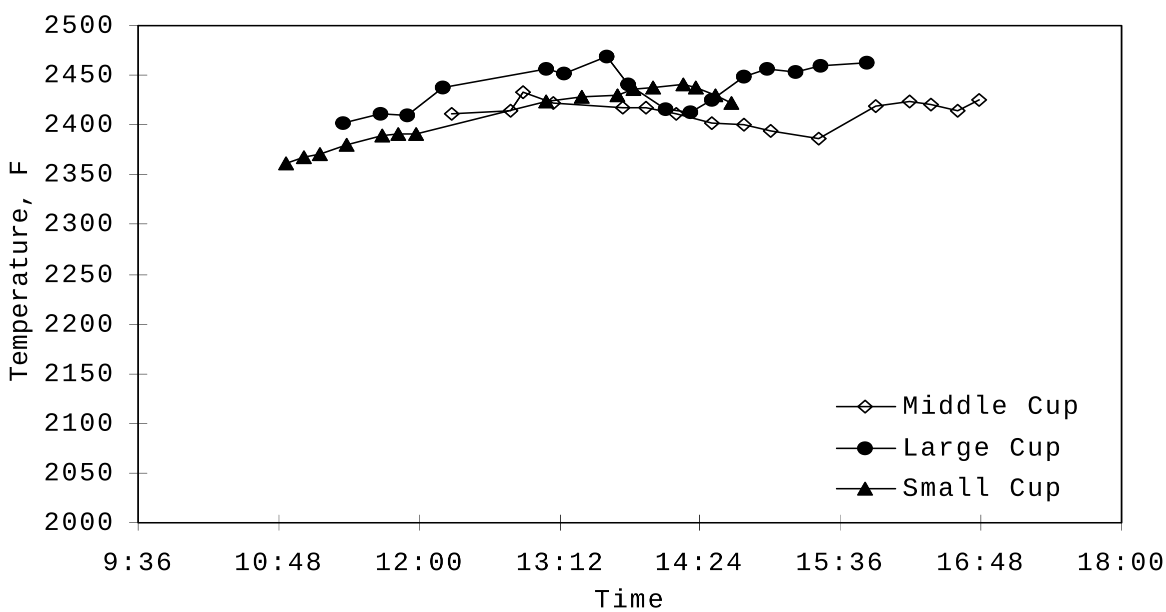


Figure 37. ROOF 2 TEMPERATURE FOR THE THIRD LABORATORY HIGH LUMINOSITY BURNER

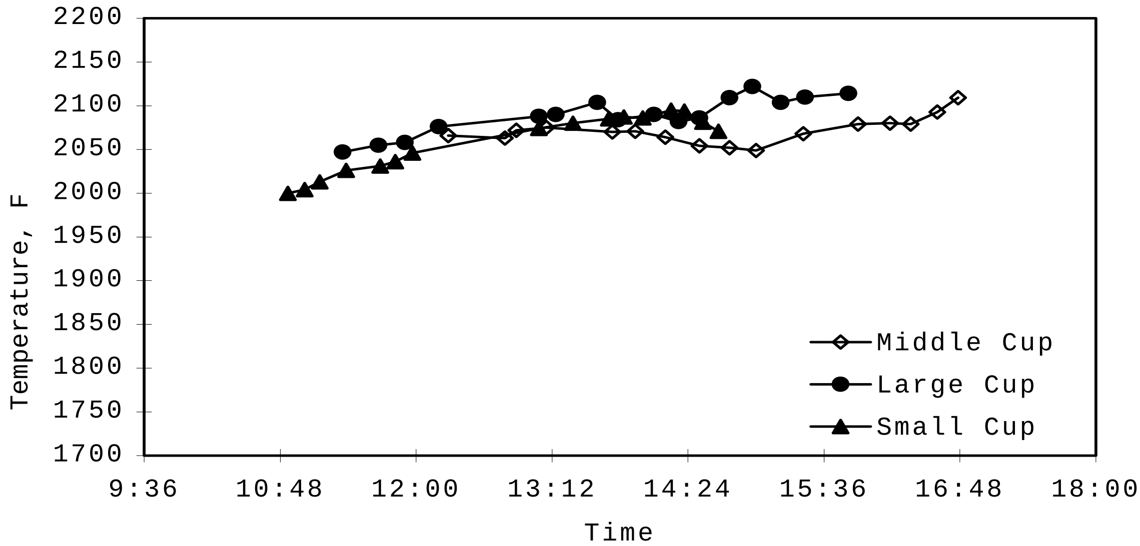


Figure 38. EXHAUST 1 TEMPERATURE FOR THE THIRD LABORATORY HIGH LUMINOSITY BURNER

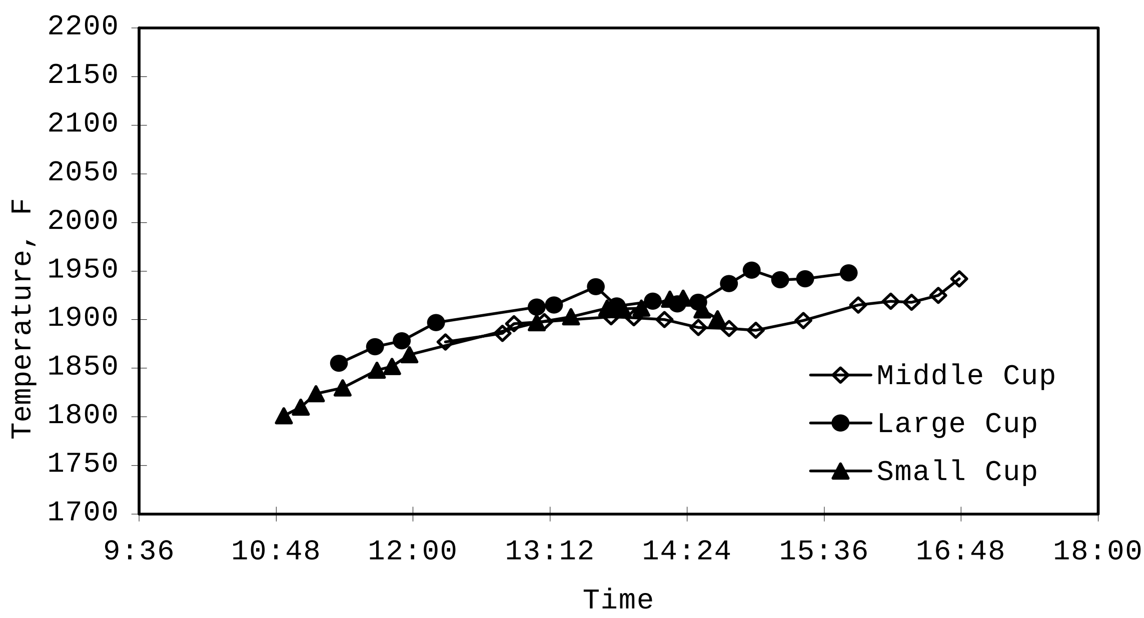


Figure 39. EXHAUST 2 TEMPERATURE FOR THE THIRD LABORATORY HIGH LUMINOSITY BURNER

Pilot-Scale Testing

Pilot-scale testing included designing and fabricating a 3 MMBtu/h pilot-scale high luminosity burner, testing this burner, testing commercial oxy-gas burners with the same firing capacity, and reviewing and comparing test results.

Test Conditions and Burner Design

After successful completion of the lab-testing program, the project team designed a pilot-scale high luminosity burner. The objective of this design was to maintain much of the flexibility of the lab-scale burners while increasing firing capacity to 3 MMBtu/h. This is within the typical 2 to 8 MMBtu/h firing range of oxy-gas burners used on industrial glass furnaces. Design was completed by Combustion Tec and GTI personnel, and Combustion Tec fabricated the pilot-scale burner. All pilot-scale tests were conducted on a test chamber located at Combustion Tec in Orlando, Florida.

A photograph of the pilot-scale high luminosity burner is shown in Figure 40. The pilot-scale burner had a pre-combustion section with an adjustable length of 16 to 28 inches. Controlled flows of up to 20 percent of the oxygen and natural gas were sent to the pre-combustion section. The remaining natural gas was charged to an annulus around the pre-combustion zone and then mixed with the hot combustion gases. A 16 inch long direct mixing zone was maintained for all tests. This enabled the mixture of natural gas and hot combustion products to reach temperatures of over 2000°F. Oxygen for fuel-rich combustion was introduced to an annulus surrounding the direct mixing zone. The flow of cold oxygen kept the tube temperature within a manageable range. The fuel-rich oxygen was charged to the heated natural gas exiting the direct mixing zone. A fuel-lean combustion zone was established through the 15 inch thick block and into the combustion chamber. Fuel-rich oxygen was injected through four holes set around the burner at 90° through the block. This allowed the burner to establish and maintain a stable fuel-rich combustion zone entirely inside the combustion chamber. The fuel-rich combustion section inside the AZS block was 5.5 inches in diameter. The burner section diameters decreased moving toward the back of the burner, with the pre-combustion section having a 4 inch diameter.

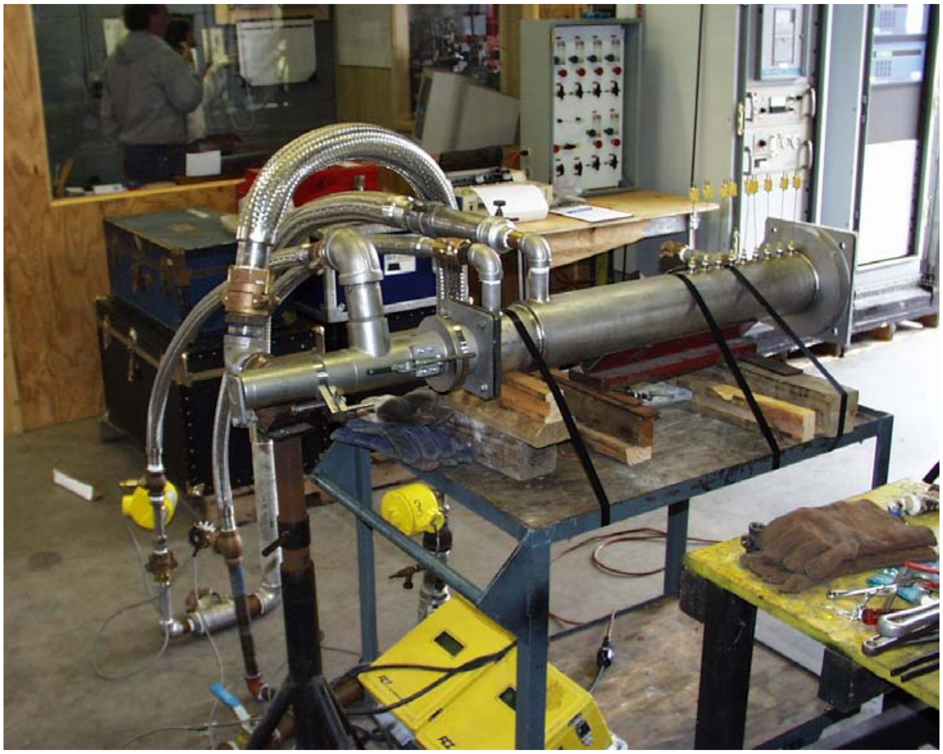


Figure 40. PILOT-SCALE HIGH LUMINOSITY BURNER

The Combustion Tec test chamber used for all pilot-scale tests was a horizontal cylinder with a 5 ft. diameter and a length of 20 ft. This refractory-lined chamber was equipped with two roof thermocouples, a stack thermocouple, and a stack sample port for exhaust gas measurements. Nine ports were located on one side of the chamber allowing insertion of radiation and total heat flux sensors as well as water-cooled probes acting as an artificial load. A schematic diagram of this test chamber is shown in Figure 41. The heat transferred to the water-cooled tubes was calculated from measurements of the water flow rate and the temperature rise. This chamber was insulated but was not as well insulated as a glass furnace or as completely as the GTI test furnace used for lab-scale high luminosity burner testing. Therefore, a significant amount of heat was lost through the chamber walls in all tests. A photograph of the instrumented Combustion Tec test chamber is shown in Figure 4 in an early section.

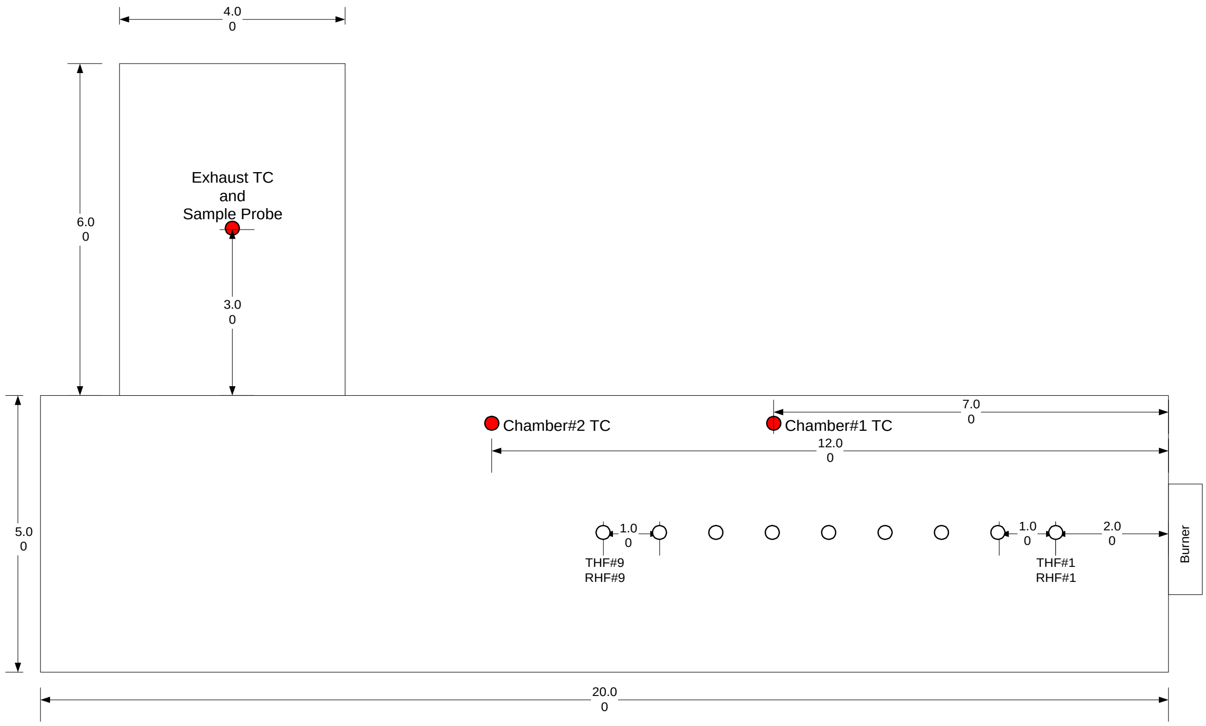


Figure 41. SCHEMATIC DIAGRAM OF THE TEST CHAMBER USED FOR PILOT SCALE HIGH LUMINOSITY BURNER TESTS

The burners were mounted in burner blocks positioned in the center of the end face of the test chamber. Connections were made for all natural gas and oxygen flows. Oxygen was provided from liquid oxygen storage provided specifically for these tests. A computer control and data collection system was used to control and monitor the flow of natural gas and oxygen to the pre-combustion, fuel-lean, and fuel-rich zones of the burner(s). All flow settings and temperature data were stored every minute during testing, along with data from the heat flux probes. The data included the burner skin temperatures as well as the combustion chamber roof and exhaust gas temperatures. Manual measurements were made of the temperature of the gas inside the burner at the end of the direct mixing section. This data was recorded by hand.

GTI stack analysis equipment was shipped to Combustion Tec for the pilot-scale tests. This rack mounted instrumentation includes calibrated O_2, CO, CO_2, and NO_x analyzers. The oxygen analyzer was used to maintain 3 percent O_2 in the exhaust gas for most tests in order to provide a basis for test result comparisons. Oxygen rates were controlled during testing to maintain 3 volume percent O_2 in the exhaust gas. The primary emissions gas analyses were for CO and NO_x.

Pilot-Scale Testing Results

Pilot-scale testing was conducted in three test groups. The great majority of testing was conducted with the pilot-scale high luminosity burner. A number of the other tests were conducted with a commercial Primefire 100 (round or so-called conical) burner for comparison of results. A smaller number of tests were conducted for data comparison using a Combustion Tec Primetfire 300 (flat flame) burner and with the Primefire 300 burner using oxygen preheat.

In the laboratory tests, temperatures were measured at two positions on the furnace roof and at two points in the exhaust gas duct. For the pilot-scale tests, temperatures were measured at two positions in the chamber roof and one position in the exhaust gas flue. Also, one temperature is reported for the inside of the burner at the end of the direct mixing zone. This thermocouple indicated the temperature of the preheated and mixed natural gas before introduction of the fuel-rich oxygen for the first stage of combustion. The goal was to achieve and maintain the 2000°F temperature needed to produce soot precursors. The outside shell of the pilot-scale burner was cooled by the oxygen used for fuel-rich and fuel-lean combustion. Surface temperatures became high (1000°F or higher) when more than 15 percent of the oxygen was sent to the precombustion zone.

The large test chamber used for the pilot testing was not as well insulated as the laboratory furnace and was not as easy to hold at a constant temperature. Testing showed that the most uniform temperature profiles could be maintained when firing all burners at 2.25 MBtu/h, and this firing rate was used for all tests, even though the burners were each rated for 3 MBtu/h. Water cooled probes were used in the pilot tests to provide a simulated load, just in the laboratory furnace. However, the size of the chamber was much larger, and this resulted in only a small fraction of the heat released to be absorbed by the water cooled probes. For this reason, the most accurate measurement of changed heat transfer to the load from the pilot scale burner was determined to be the exhaust gas temperature.

A range of parametric conditions was evaluated with the pilot high luminosity burner during this test series. All pilot-scale tests with the high luminosity burners and the Primefire burners were conducted with a firing rate of 2.25 MMBtu/h. The overall oxygen to fuel ratio was set to provide 3 percent O_2 in the exhaust gas. The precombustor was operated at an oxygen to gas stoichiometric ratio of 1.0 for all tests. Tests in December, 1998 and February, 1999 with a range of oxygen distributions between the precumbustor, the fuel-rich combustion zone, and the fuel-lean combustion zone. These ranges were:

O_2 to precombustion zone	10 – 21 percent
O_2 to fuel-rich combustion zone	10 – 50 percent
O_2 to fuel-lean combustion zone	30 – 80 percent

The temperature of the natural gas at the exit of the direct mixing zone (just before the fuel-rich combustion zone) increased linearly with temperature. The preheated natural gas was 1600°F when 10 percent of the oxygen was sent to the precombustor and 2250°F when 21 percent of the oxygen was sent to the precombustor. This linear trend covering data collected in the December and February test series is presented in Figure 42.

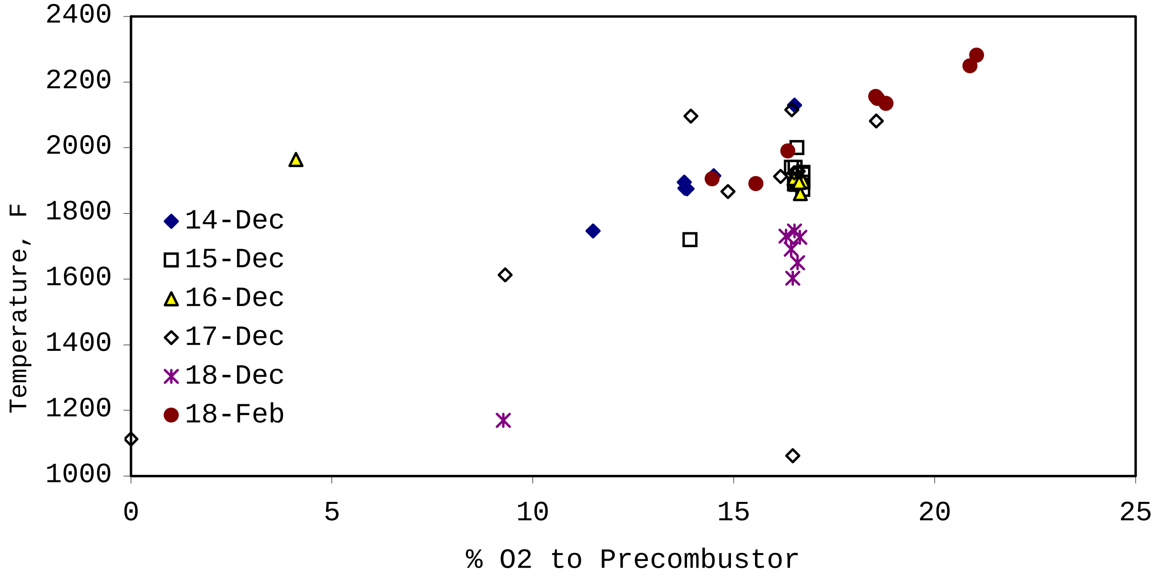


Figure 42. PREHEATED NATURAL GAS TEMPERATURE INCREASES LINEARLY WITH INCREASING PRECOMBUSTION

Heat transfer to the artificial load increased with increasing oxygen sent to the precombustor. Little effect of heat transfer was seen below 15 percent O_2 to the precombustor, suggesting that the natural gas was not heated enough to generate soot precursors. Small increases in heat transfer were seen at 15 to 18 percent oxygen to the precombustor. The largest heat transfer to the load was found at the highest oxygen to the precumbustor of 18 to 21 percent. Results were unchanged at 20 to 21 percent oxygen to the precumbustor, suggesting the natural gas was heated to a high enough temperature to form the maximum amount of soot precursors needed to increase flame luminosity. The test data is shown in Figure 43. The data show the heat transfer to load is increased from 600,000 Btu/h for the Primefire burner to 620,000 Btu/h for the high luminosity burner at less than 15 percent oxygen to the precombustor. This is an increase in heat transfer of approximately 3 percent to load. At 21 percent of the oxygen to the precumbustor, the high luminosity heat transfer to the artificial load was 675,000 Btu/h. This is an increase in heat transfer of nearly 12 percent compared with the Primefire burner.

In the first pilot scale test series, the high luminosity burner was compared with a conventional Primefire 100 burner. Figures 44 and 45 show temperatures measured with these burners at similar firing conditions during the first testing period in December. The Primefire burner maintained an average temperature of 1800°F in the exhaust and temperatures of 2200° and 2360°F at the chamber 1 and 2 thermocouples. The high luminosity burner had a lower exhaust gas temperature of 1550°F and chamber 1 and 2 temperatures of 2200°F. The more uniform chamber roof temperatures indicates the high luminosity burner decreases the roof hot spot and provides a longer and more uniform flame. This was predicted by modeling work and confirmed by visual observation. The flame with the Primefire burner was approximately 2.5 feet in length while the high luminosity burner flame was approximately 3.5 feet long. The 250°F lower exhaust gas temperature shows 6 percent less of the total fuel value is lost to the exhaust. Since heat lost through the chamber walls is constant, this correlates to an increase in heat transfer to the load of approximately 10 percent for the high luminosity burner.

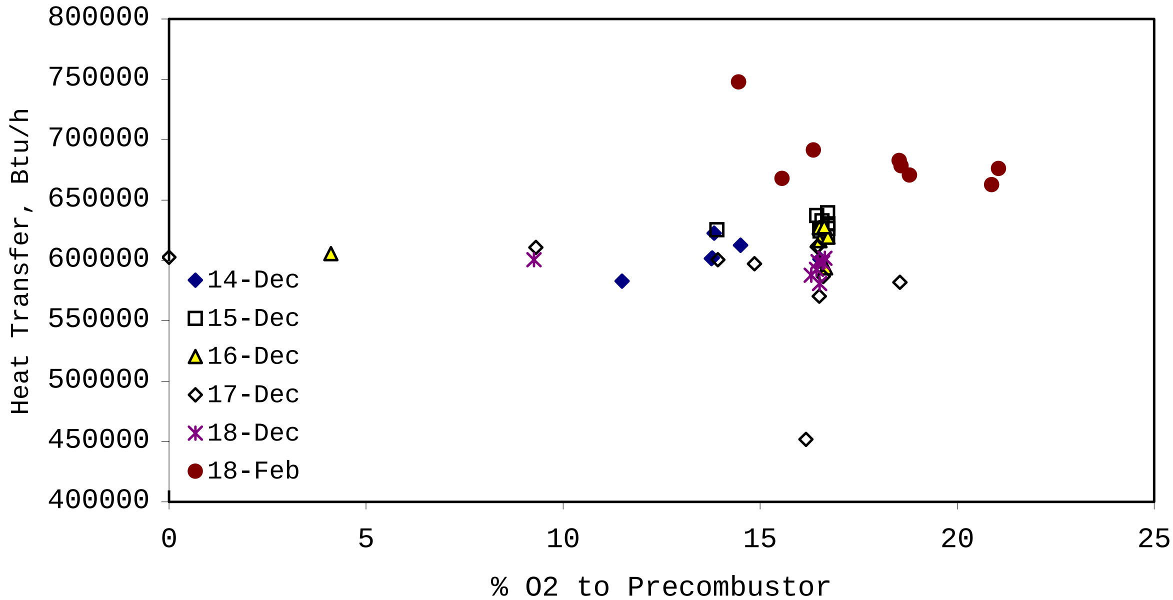


Figure 43. HEAT TRANSFER TO ARTIFICIAL LOAD INCREASES MORE THAN 12 PERCENT WITH MORE THAN 20 PERCENT OXYGEN TO THE PRECOMBUSTOR

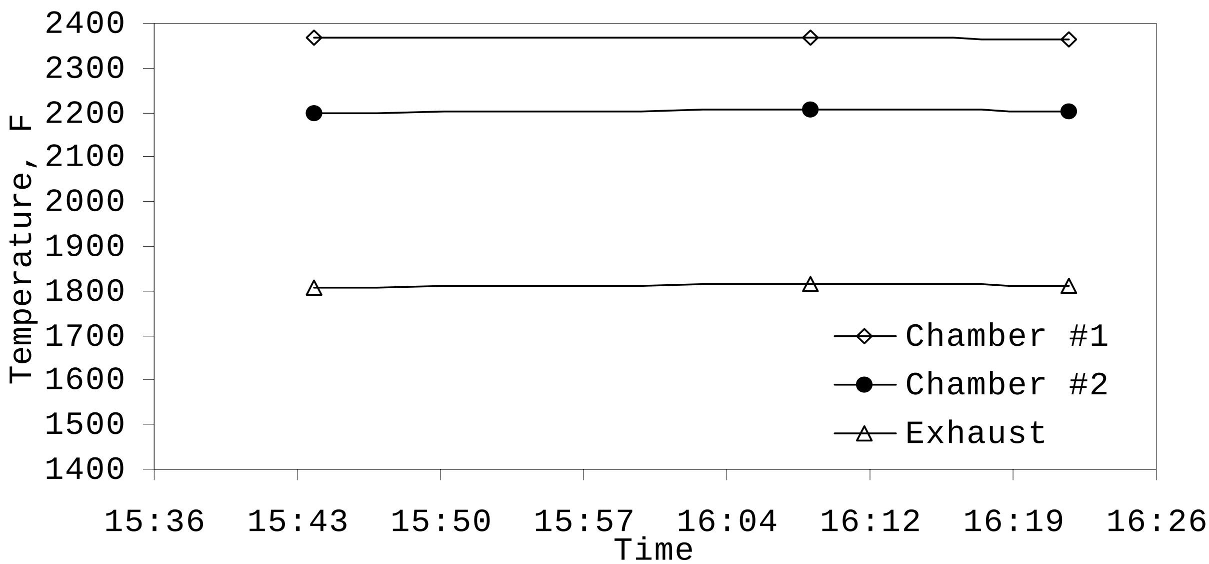


Figure 44. CHAMBER AND EXHAUST GAS TEMPERATURES FOR THE PRIMEFIRE 100 PILOT SCALE BURNER

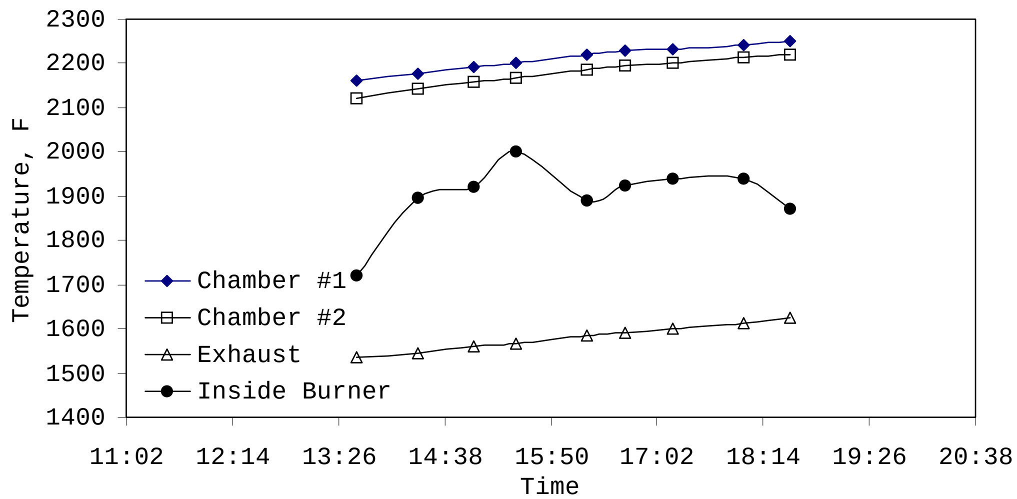


Figure 45. CHAMBER AND EXHAUST GAS TEMPERATURES FOR THE HIGH LUMINOSITY PILOT SCALE BURNER

Heat transfer to the artificial load and NO_x emissions are shown in Figures 46 and 47 for the pilot-scale Primefire and high luminosity burners during the first test period in December. NOx emissions were approximately 20 percent lower for the high luminosity burner compared with the Primefire burner (700 vppm vs. 900 vppm). Heat transfer to the load averaged 630,000 Btu/h for the high luminosity burner and 600,000 Btu/h for the Primefire burner. The heat transfer to load increased approximately 5 percent. This number was shown to be lower than the optimum heat transfer increase because the fraction of oxygen to the precumbustor did not exceed 15 percent in this test series. Greater heat transfer increases were found in later testing with the percentage of total oxygen to the precumbustor raised to 20 and 21 percent.

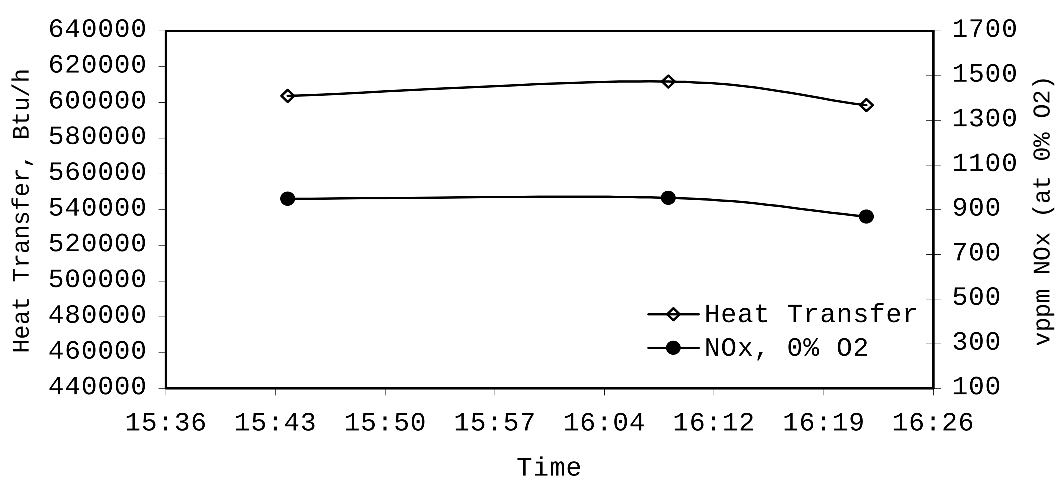


Figure 46. HEAT TRANSFER TO ARTIFICIAL LOAD AND NO_x EMISSIONS FOR THE PRIMEFIRE 100 PILOT SCALE BURNER

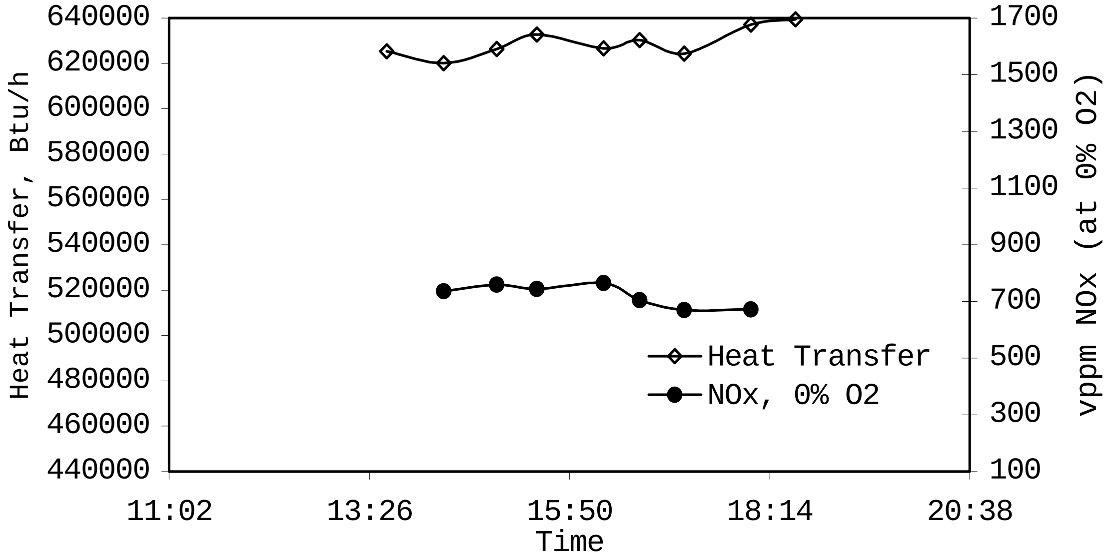


Figure 47. HEAT TRANSFER TO ARTIFICIAL LOAD AND NO_x EMISSIONS FOR THE HIGH LUMINOSITY PILOT SCALE BURNER

Tests were conducted in the December test period to determine whether introducing the main natural gas into the hot precombustor product gases in a straight (parallel flow) or swirl (tangential flow) arrangement had strong effects on temperatures and heat transfer. Figures 48 and 49 compare the heat transfer to artificial load and the gas temperature at the end of the direct mixing zone (just before the fuel-rich combustion zone) for the pilot-scale high luminosity burner with straight and swirl main gas introduction. Tests reported were conducted under similar velocity and oxygen distribution conditions. The results show that the straight flow pattern produced higher heat transfer to the load (greater radiation heat transfer) and a higher direct mixing zone exit temperature. The lower degree of mixing from the straight flow arrangement likely created a hotter mixed natural gas stream containing more hydrocarbon soot precursors. This led to a more luminous flame and higher heat transfer to the artificial load.

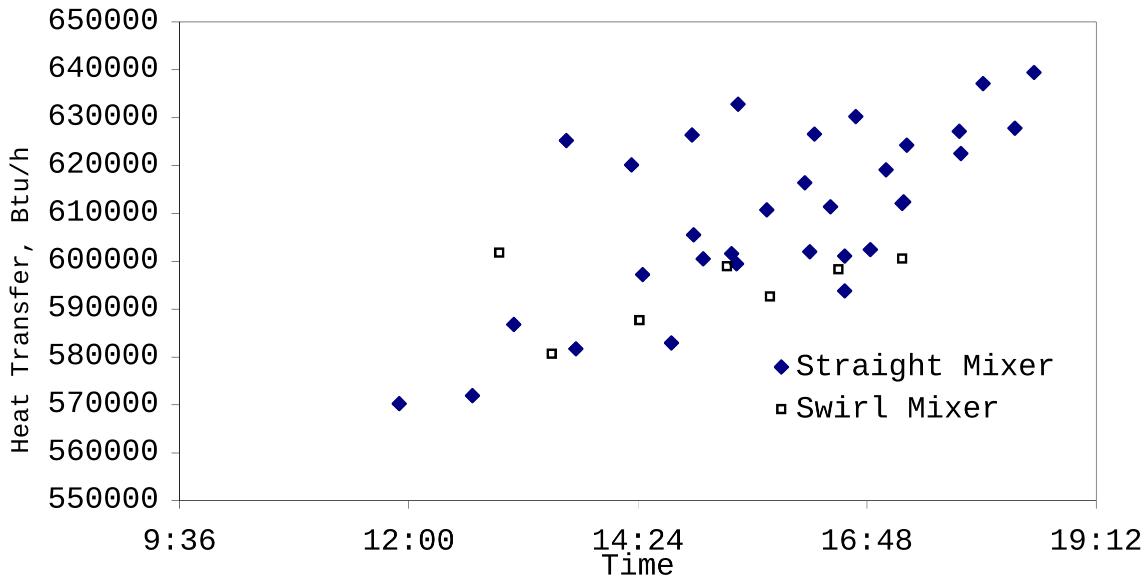


Figure 48. STRAIGHT AND SWIRLED INTRODUCTION OF NATURAL GAS IMPACT ON HEAT TRANSFER WITH THE PILOT SCALE HIGH LUMINOSITY BURNER

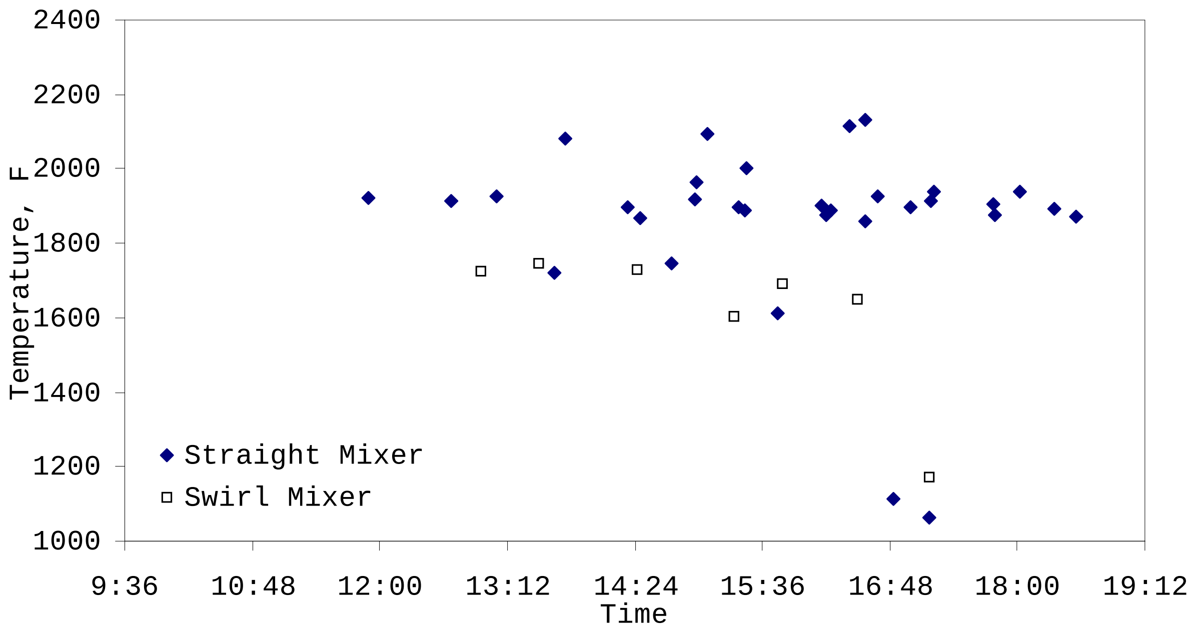


Figure 49. STRAIGHT AND SWIRLED INTRODUCTION OF NATURAL GAS IMPACT ON GAS TEMPERATURE AT THE END OF THE DIRECT MXING ZONE WITH THE PILOT SCALE HIGH LUMINOSITY BURNER

During the February test period, heat transfer to the artificial load was measured for the pilot-scale high luminosity burner, the conical Primefire 100 burner, the flat flame Primefire 300 burner, and the Primefire 300 burner with preheated oxygen. The results of tests at similar firing rates, velocities, and oxygen distributions are shown in Figure 50. The high luminosity burner clearly showed higher heat transfer than the conical burner. The flat flame burner, with and without preheated oxygen, showed higher heat transfer than the conical burner. The high luminosity burner had higher heat transfer than the conventional flat flame burner and similar heat transfer to the flat flame burner with preheated oxygen included.

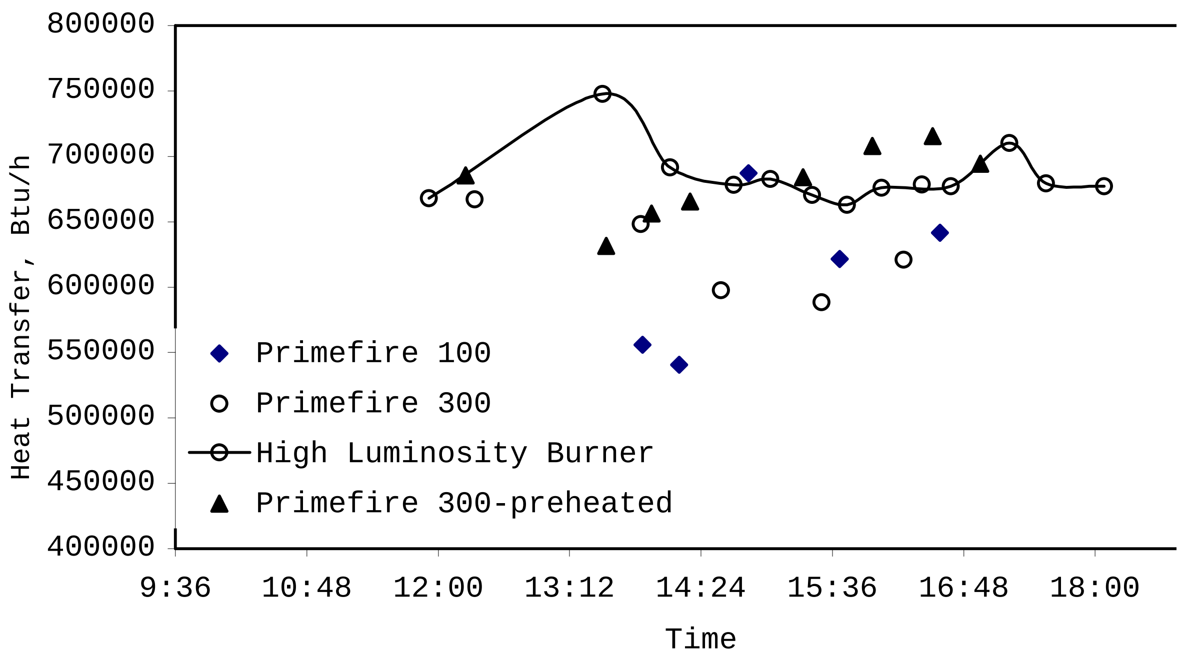


Figure 50. HEAT TRANSFER TO LOAD FOR PILOT-SCALE HIGH LUMINOSITY BURNER AND VERSIONS OF COMMERCIAL CONICAL AND FLAT FLAME BURNERS

Commercial Demonstration

Phase III of this project covered a 36-month period from Jan. 1999 through Dec. 2001. Work focused on designing, fabricating, installing, and testing a commercial prototype of the high luminosity burner. Test results from the laboratory- and pilot-scale testing was encouraging, and the project team agreed to move forward with the commercial demonstration phase of the project by installing high luminosity burners on an Owens Corning fiberglass furnace.

The selected host site was one of two borosilicate, insulating fiberglass furnaces operated by Owens Corning in their Delmar, NY production facility. Furnace details are proprietary to Owens Corning. However, the furnace operates continuously using seven burners, each burning between 1 and 8 MMBtu/hr. The plan was to install one burner initially and evaluate its performance long enough to assure desired operation. At that point, the remaining six burners were to be replaced. With all burners replaced, furnace testing would be conducted to determine energy savings and emissions reductions benefits of the high luminosity burner. At the conclusion of this project, the first burner was installed (in Dec. 2001) and operating flawlessly. The remaining burners will be installed and tested using funds from the other project sponsors. The Industrial Adoption Plan developed in Phase II of the project was reviewed and modified slightly by the project team. Eclipse and Combustion Tec plan to initiate commercial sales of the burner under the trade name Primefire 400 in 2002.

Commercial Prototype 'A'

Pilot-scale testing confirmed the importance of having both a direct mixing zone to allow time for soot precursors to form and to have fuel-rich and fuel-lean combustion zones in the flame. The pilot-scale burner was, however, longer than desired for a commercial burner, and the pilot-scale burner had too many oxygen and gas inlet ports. The intention of the project team was to reduce inlets to one for oxygen and one for natural gas as in other commercial oxy-gas burners. Also, the team sought to convert the conical or round flame pilot-scale burner to a flat flame design for commercial usage.

The needed changed were made through a number of modifications of the pilot-scale burner design. The length of the burner was reduced by combined the burner block with the burner. This combination allowed the direct mixing zone to begin just outside the burner block and to continue through the block to the hot face of the burner. Design of the burner block also addressed issues of creating fuel-rich and fuel-lean flame zones and forming a 'flat' flame. The primary and secondary oxygen were directed through the burner block in channels separated from the preheated-oxygen-free natural gas. Also, the channel shapes changed from round to oval in passing through the block to create the flat flame at the hot face. The center channel on the hot face contained the preheated natural gas. Below the fuel port was the oxygen to create the fuel-rich zone. Further away, and above the fuel port was the final oxygen inlet to create the fuel lean zone of the flame. Diagrams of the block side view and hot face view are shown in Figure 51.

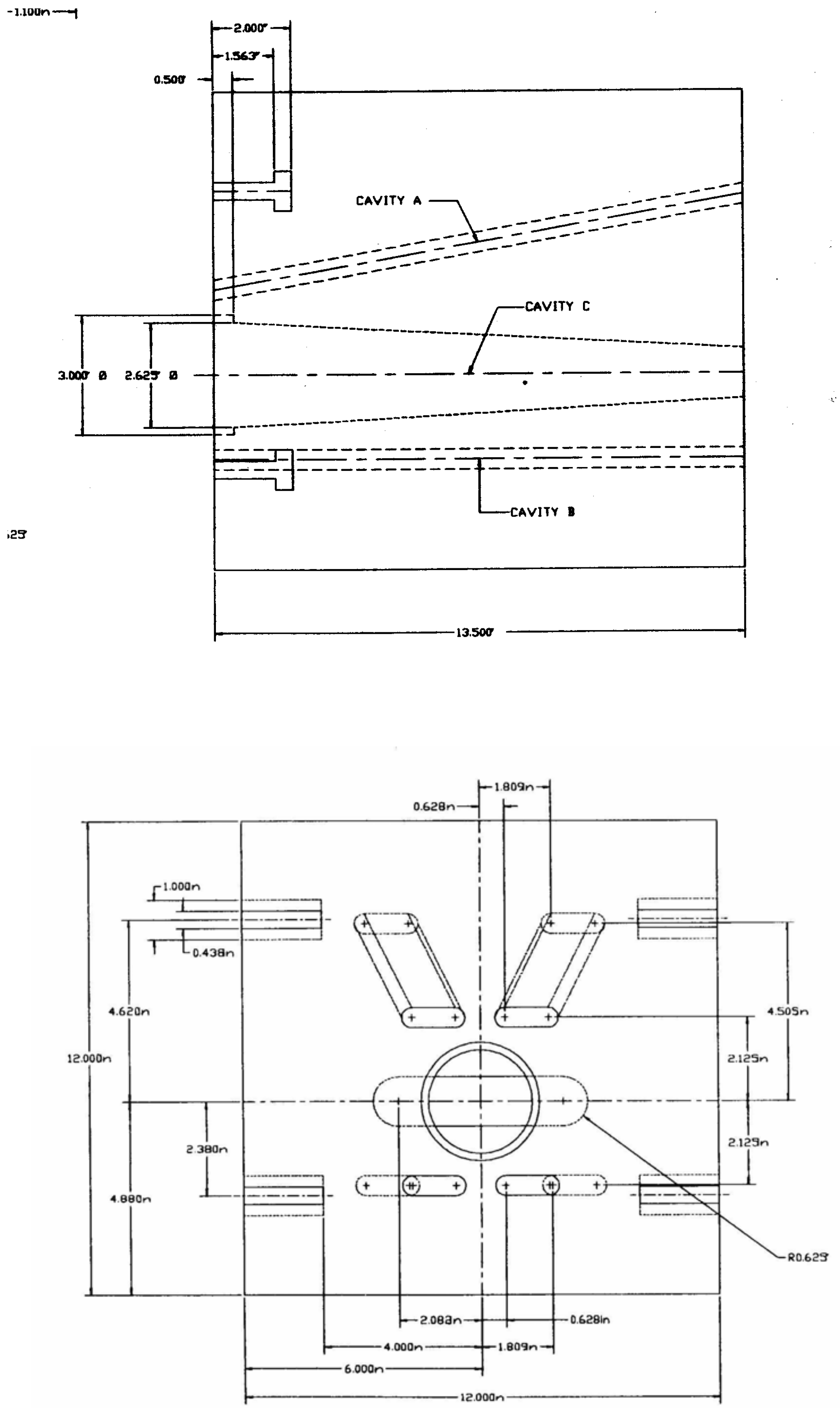


Figure 51. BLOCK DIAGRAMS FOR THE HIGH LUMINOSITY COMMERCIAL PROTOTYPE 'A' BURNER

The final change for the prototype ‘A’ burner was the reduction of inlet ports to one for oxygen and one for natural gas. Pilot-scale testing had confirmed the appropriate division of oxygen to different zones, and the burner was set to the appropriate oxygen splits. The amount of gas needed to be burned for precombustion, less than 10 percent, was also learned during pilot-scale testing. The natural gas was split between the precombustion and the direct mixing sections.

The ‘A’ version of the commercial prototype high luminosity burner was designed by GTI and Eclipse and fabricated by Eclipse. A photo of this 3 MMBtu/h burner installed in a burner test facility at Eclipse in Rockford, IL is shown in Figure 52. The burner length was shortened to be acceptable for industrial use. The distribution of oxygen and natural gas can still be adjusted on this burner. In the commercial version of the burner the flow valves will not be present on the top of the burner.

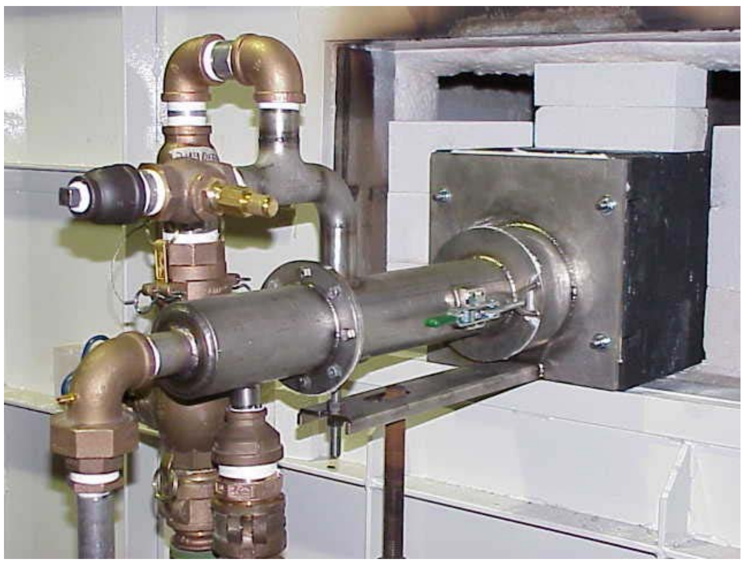
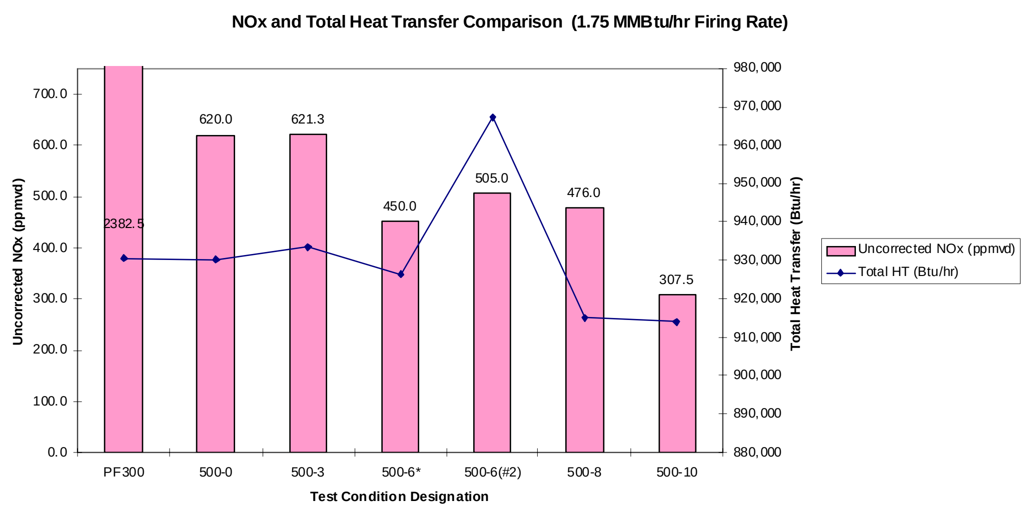


Figure 52. THE HIGH LUMINOSITY COMMERCIAL PROTOYPE BURNER ‘A’

A series of tests was conducted with the high luminosity ‘A’ burner in the Eclipse test chamber. This chamber is approximately 15 feet long with a 3 x 3 foot cross sectional area. Twelve water cooled tubes are used to simulate a load. Measurement included roof and exhaust gas temperatures and components of the exhaust gas (NO_x, CO, CO_2, O_2). The burner is mounted in the center of the wall at one end of the chamber, and the exhaust leaves from the roof at the far end of the chamber. Tests were conducted with the high luminosity ‘A’ burner and a commercial Primefire 300 at the same firing rate.

The high luminosity ‘A’ burner created a brighter flame than the Primefire 300. The flame was the same width but longer (80 to 90) compared with 45 to 60 inches for the Primefire Heat transfer was pushed away from the furnace wall toward the center of the furnace. The NO_x generated was significantly lower for the high luminosity ‘A’ burner (by up to 80 percent), and the NOx decreased with increased oxygen to the precumbustor. The NO_x values are, however, questionable because the burners were firing into an air filled chamber as opposed to a combustion exhaust gas environment in a glass furnace. Optimum flame appearance was achieved with 4 to 6 percent oxygen to the precumbustor. Below 3 percent oxygen increases flame lifting, and oxygen of more than 10 percent to the precumbustor led to a 'clear' flmae and sputtering.

Heat transfer to tubes and NO_x production for the two burners at firing rates of 1.75 and 2.25 MMBtu/h are presented in Figure 53. Heat transfer was similar at the lower firing rate and lower at the higher firing rate for the high luminosity burner. Tubes have low surface area compared with a molten glass surface. Since the high luminosity burner produced a much brighter and larger flame, the heat transfer to a glass load is expected to be significantly higher with the high luminosity burner. NO_x production was much lower with the high luminosity burner and decreased slightly with increasing oxygen to the precumbustor. The NO_x production in a glass furnace will be different because of the much lower oxygen content in the combustion space of a glass furnace. Despite these differences, the NO_x levels are expected to be significantly lower with the high luminosity burner.



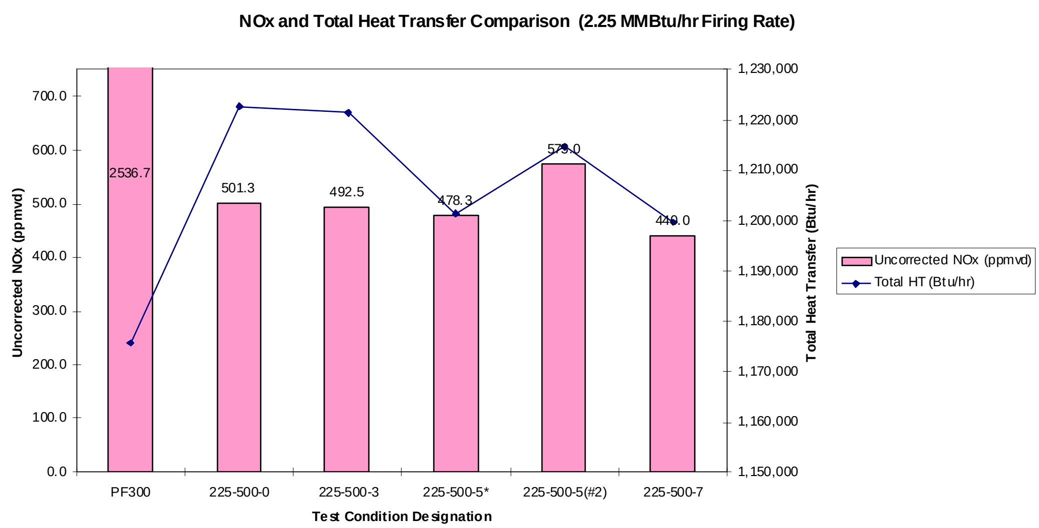
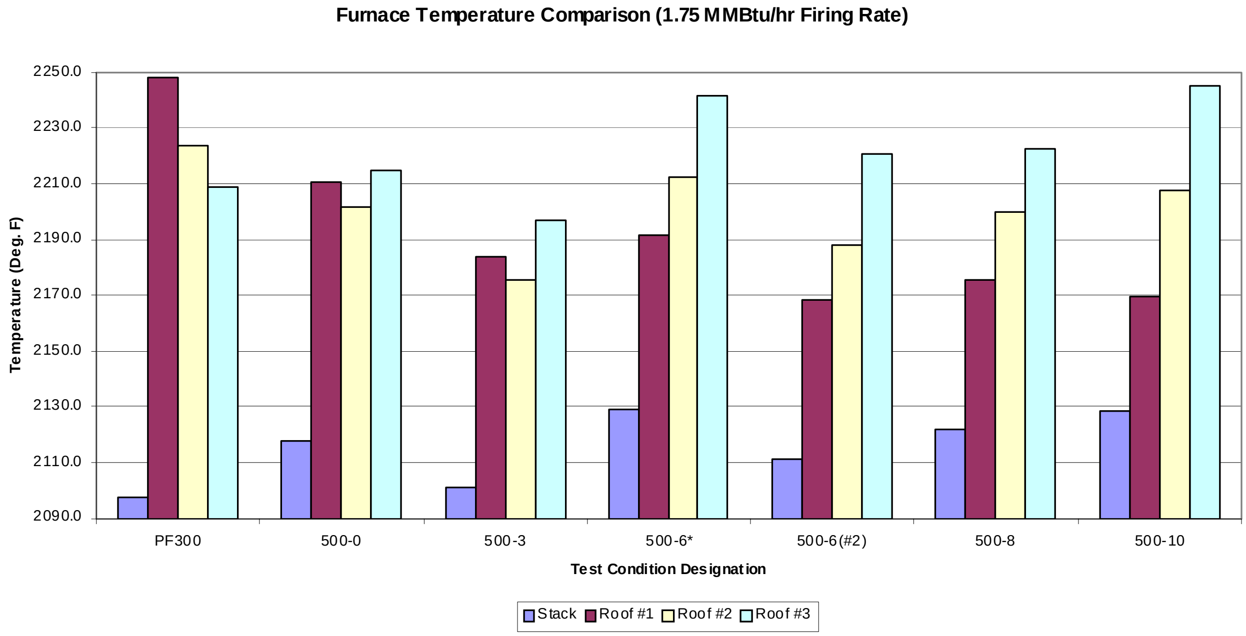


Figure 53. NO_x AND HEAT TRANSFER FOR HIGH LUMINOSITY 'A' AND PRIMEFIRE 300 BURNERS AT 1.75 AND 2.25 MMBtu/h

The longer flame length of the high luminosity ’A’ burner is shown in Figure 54. At both 1.75 and 2.25 MMBtu/h, the temperature was measured at three roof points and in the exhaust. Roof 1 was closest to the burner and Roof 3 was closest to the exhaust. The longer flame is evident by the higher temperatures of Roof 3 and lower temperatures of Roof 1 for the high luminosity burner. Exhaust gas temperatures also rose for the high luminosity burner. This result reflects the longer flame length and not a higher heat loss to the exhaust.

Heat transfer to the twelve water cooled tubes spaced along the side of the combustion chamber also showed the increased length of the flame from the high luminosity burner. Tubes were numbered 1 to 12, starting nearest the burner. Figure 55 shows the heat transfer to the tubes at 1.75 and 2.25 MMBtu/h for the Primefire 300 burner and for several different levels of oxygen to the precumbustor for the high luminosity ‘A’ burner. The best overall results (or highest heat transfer to the tubes) for the high luminosity burner were achieved at 5 percent oxygen to the precumbustor. The heat transfer was higher for the high luminosity burner at both firing rates, but the increase was higher at 2.25 MMBtu/h.

The heat transfer increase to the water cooled probes was quantified at a firing rate of 2.25 MMBtu/h, and the results are plotted in Figure 56. With no oxygen to the precumbustor, the heat transfer for the Primefire and high luminosity burners was the same. At 4 and 8 percent oxygen to the precumbustor, heat transfer to the artificial load increased by an average of 4.5 percent. This is a significant increase in heat transfer because it reflects the amount of fuel that can be decreased under normal glass furnace operation. Also, the actual glass furnace heat transfer increase is expected to be larger because the load surface is so much larger.



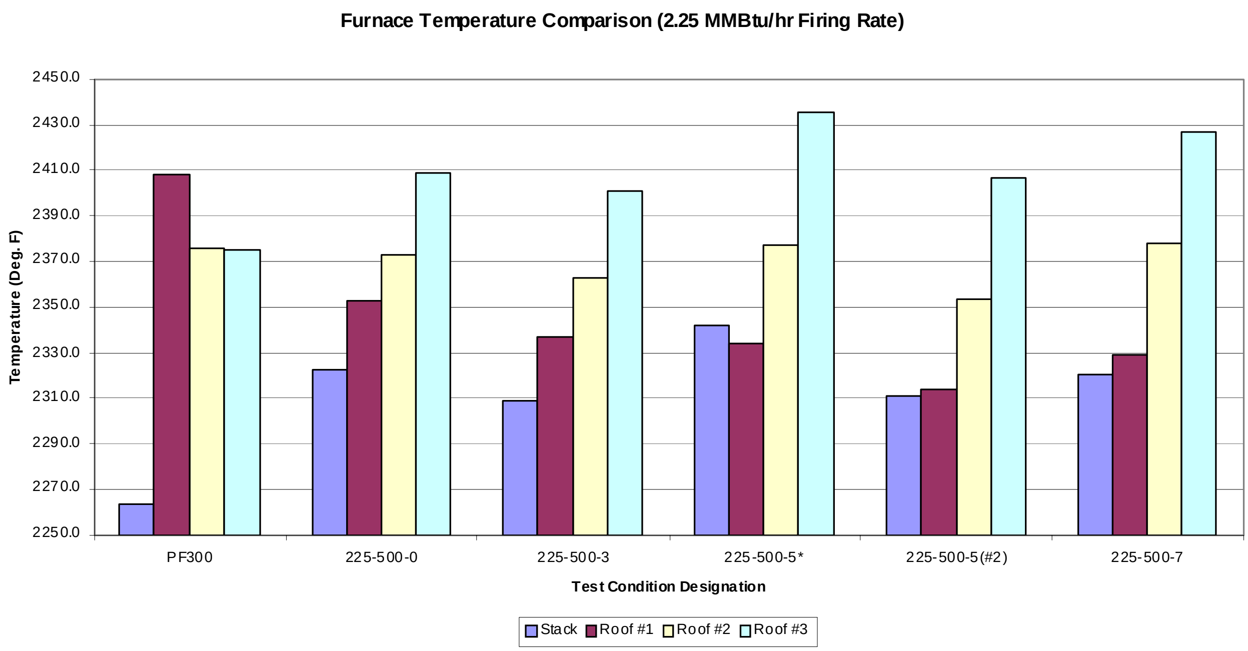
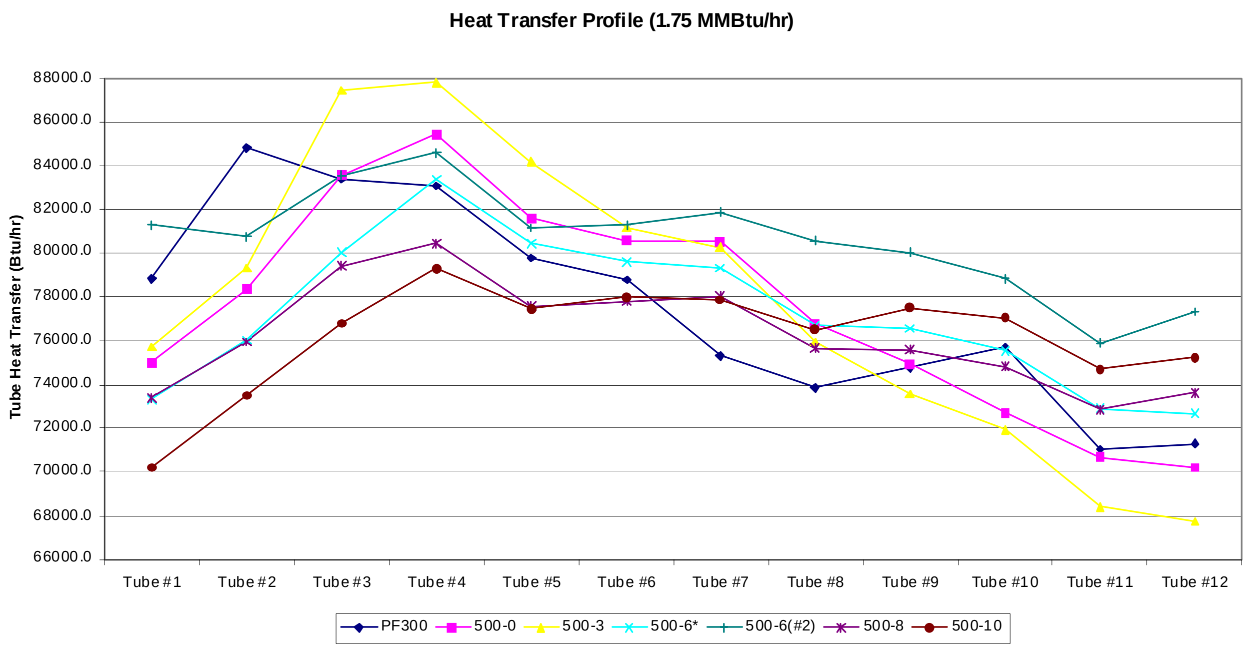


Figure 54. ROOF AND EXHAUST GAS TEMPERATURES FOR HIGH LUMINOSITY 'A' AND PRIMEFIRE 300 BURNERS AT 1.75 AND 2.25 MMBtu/h



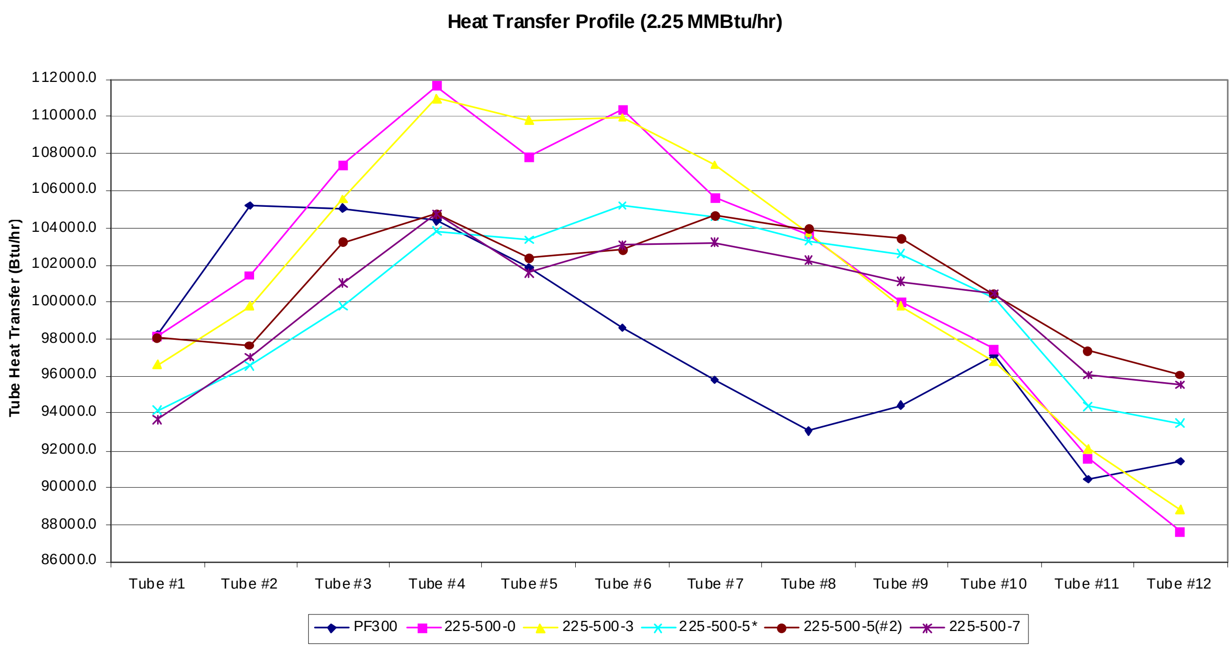


Figure 55. HEAT TRANSFER TO WATER COOLED TUBES FOR HIGH LUMINOSITY 'A' AND PRIMEFIRE 300 BURNERS AT 1.75 AND 2.25 MMBtu/h

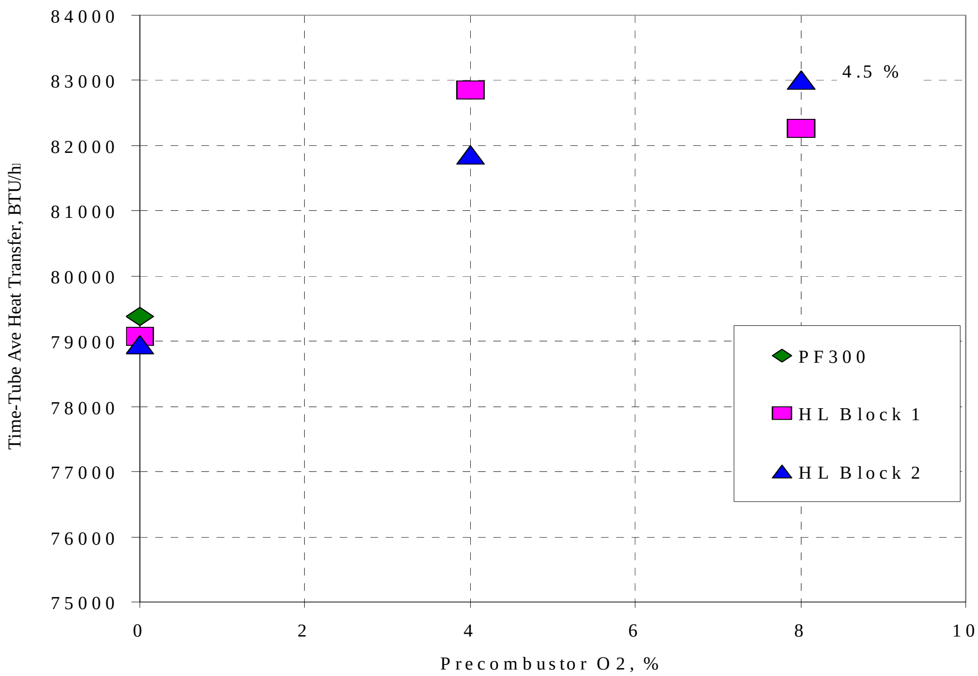


Figure 56. HEAT TRANSFER INCREASE WITH HIGH LUMINOSITY BURNER

Test results with the 'A' version of the high luminosity commercial prototype burner, but the project team had several concerns. First, the burner appears to generate a small amount of soot. The soot, however, was very fine and did not appear to build up on the inner walls of the burner. The project team feels this will not be a problem during industrial operation of the high luminosity burner. The other concern was production of the desired shape of flame with desired fuel rich and fuel lean combustion zones. A CFD modeling effort was conducted at GTI to determine flame behavior of an industrial burner.

Modeling of Commercial Prototype 'A'

CFD modeling requires development of a grid to conduct energy and material balances as well as chemical reactions. The tighter the grid and higher the number of cells or nodes in the model, the more accurate the model can be. Usually, a non-uniform gird is prepared in which smaller cells are used in areas with high energy and concentration gradients. Computing time is a limitation in CFD modeling, so efforts are always made to compromise between using enough cells to provide a reliable model and keeping the cell count low enough to complete calculations in a reasonable amount of time. Modeling was conducted first in two dimensions to establish inputs for later modeling of the burner in three dimensions. Figure 57 shows the 2-D and 3-D gird pattern developed to model the high luminosity 'A' burner.

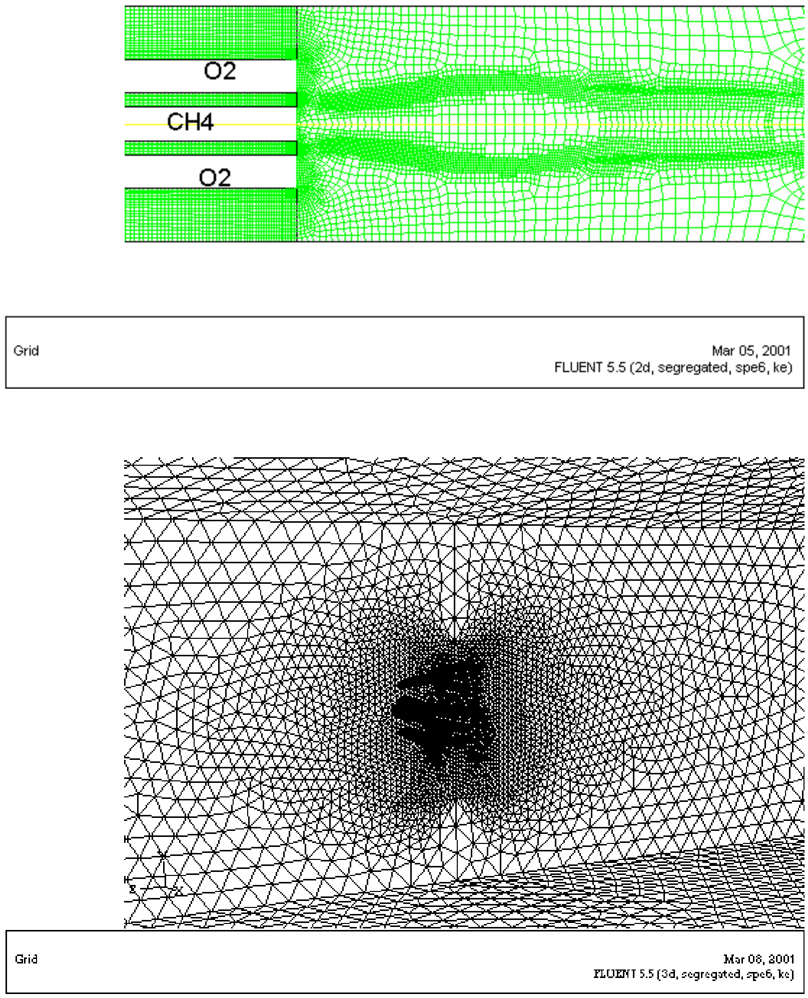


Figure 57. 2-D AND 3-D MODEL GRID PATTERNS FOR HIGH LUMINOSITY BUNER ‘A’

Two dimensional CFD modeling showed increases in temperature and velocity of the flame when preheated was used. Figure 58 shows a sample of that set of calculations where no preheating, and then preheating of natural gas, is employed. Note that flame temperature profile is significantly changed. This demonstrates the formation of fuel rich and fuel lean combustion zones. The overall flame is actually not as hot with preheating because the flame is lengthened and radiative cooling occurs with a brighter flame. Precombustion also leads to a hotter block face temperature.

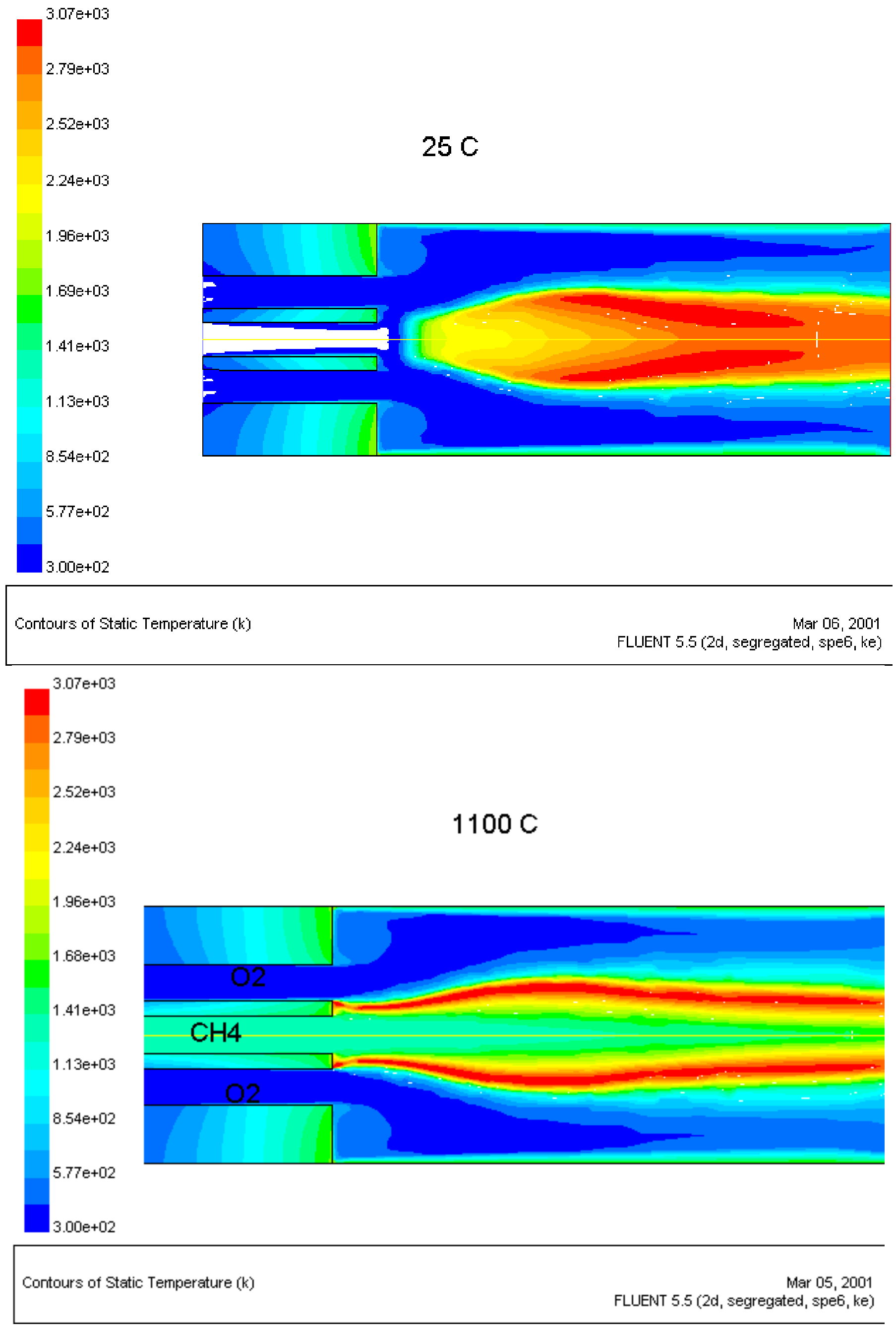


Figure 58. 2-D MODELING OF HIGH LUMINOSITY 'A' TEMPERATURES WITH NO PRECOMBUSTION AND WITH 1100°C PREHEATING

Figure 59 shows that flame species is increased when precomubustion is used to preheat the natural gas in the burner. This lengthens the flame and leads to formation of the fuel rich and fuel lean combustion zones.

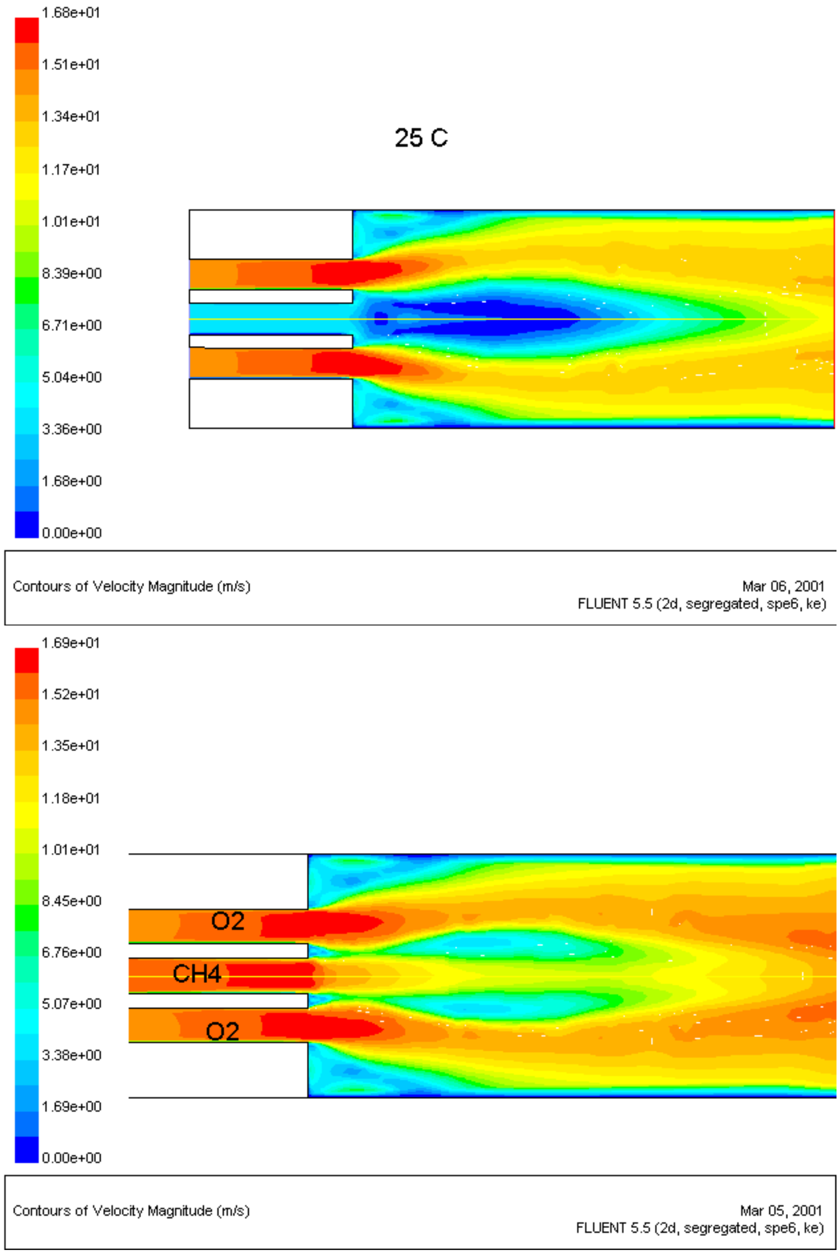


Figure 59. 2-D MODELING OF HIGH LUMINOSITY 'A' FLAME VELOCITIES WITH NO PRECOMBUSTION AND WITH 1100°C PREHEATING

The temperature profiles through the nozzles from cold face to hot face were also calculated in the 2-D modeling. Those results, shown in Figure 60, indicate only a small increase in nozzle wall temperatures when no precombusion is taking place. With precombustion, the direct mixing zone wall temperature rises quickly, but the oxygen nozzle wall temperatures only rise to high temperatures very close to the burner's hot face.

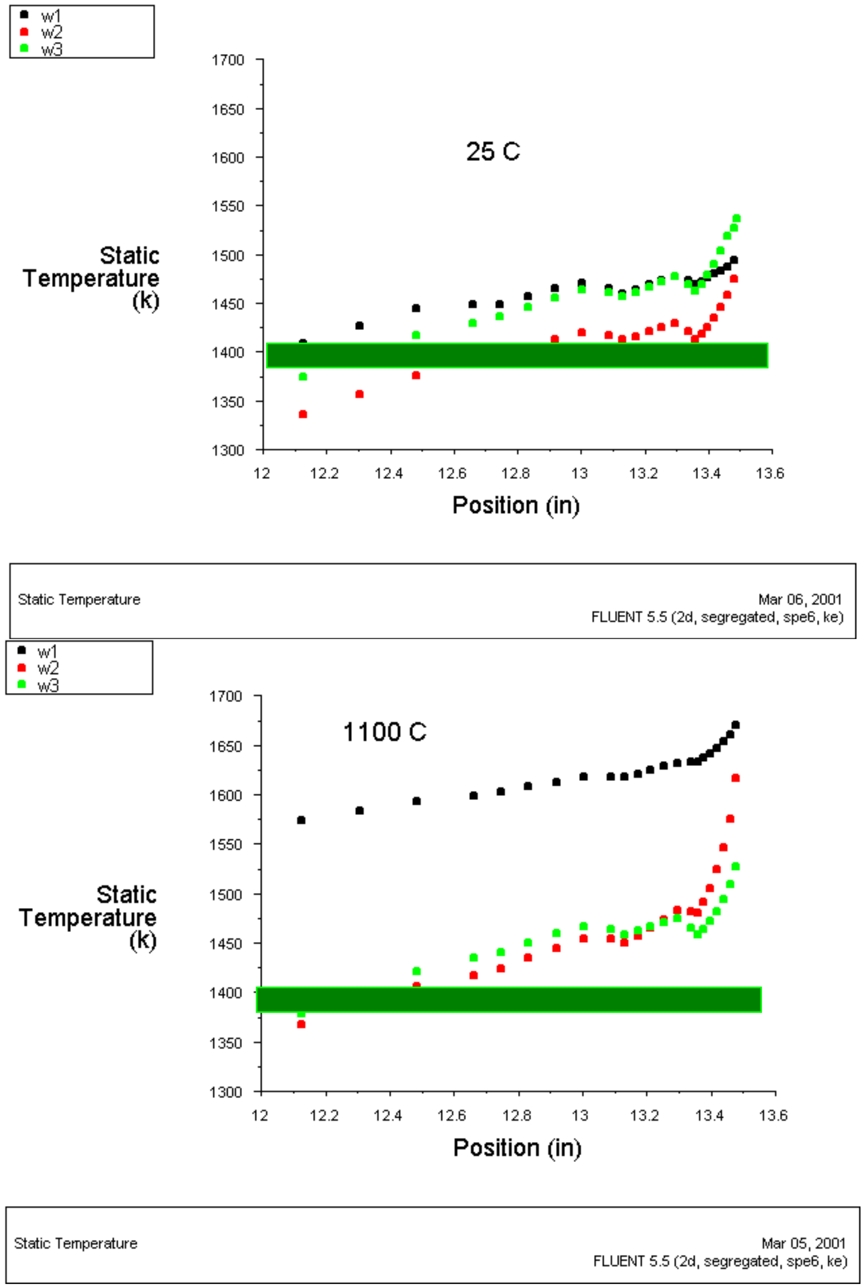


Figure 60. 2-D MODELING OF HIGH LUMINOSITY ‘A’ NOZZLE TEMPERATURES WITH NO PRECOMBUSTION AND WITH 1100°C PREHEATING

The 2-D modeling suggested improvements in flame shape, heat transfer, and temperatures of the block. The project team decided more detailed modeling would reveal more information and conducted a 3-D modeling effort for the high luminosity ‘A’ burner. The same modeling results presented for the 2-D were calculated in three dimensions. Figure 61 confirms the 2-D result for velocity and clearly shows a longer flame with well established fuel rich and fuel lean combustion zones.

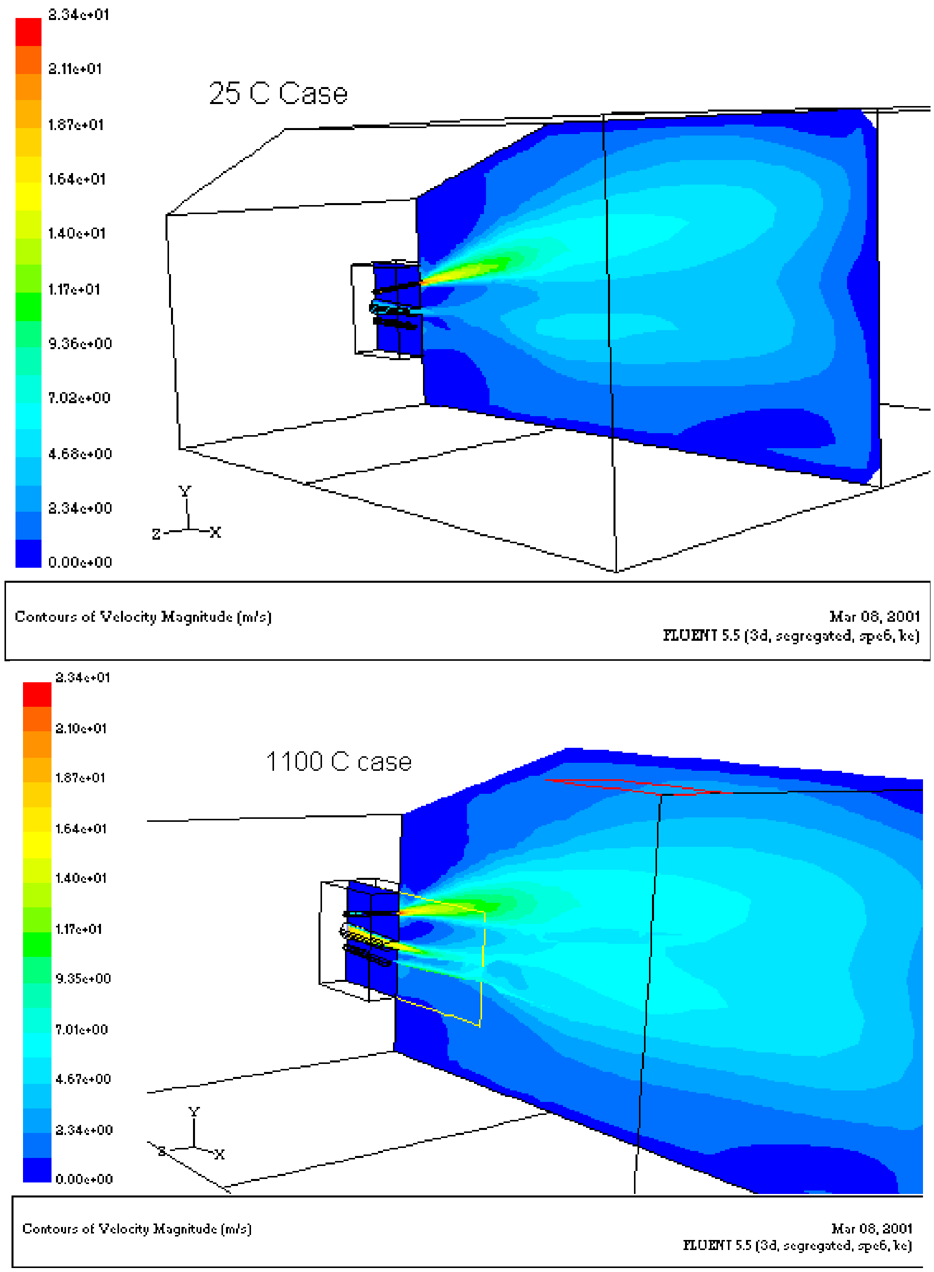


Figure 61. 3-D MODELING OF HIGH LUMINOSITY ‘A’ FLAME VELOCITIES WITH NO PRECOMBUSTION AND WITH 1100°C PREHEATING

Preheating of the natural gas led to a longer flame, a flame with more even temperature distribution, and clear fuel rich and fuel lean combustion zones. Figure 62 shows the effect of high fuel precumbustion temperature on flame shape and mixing.

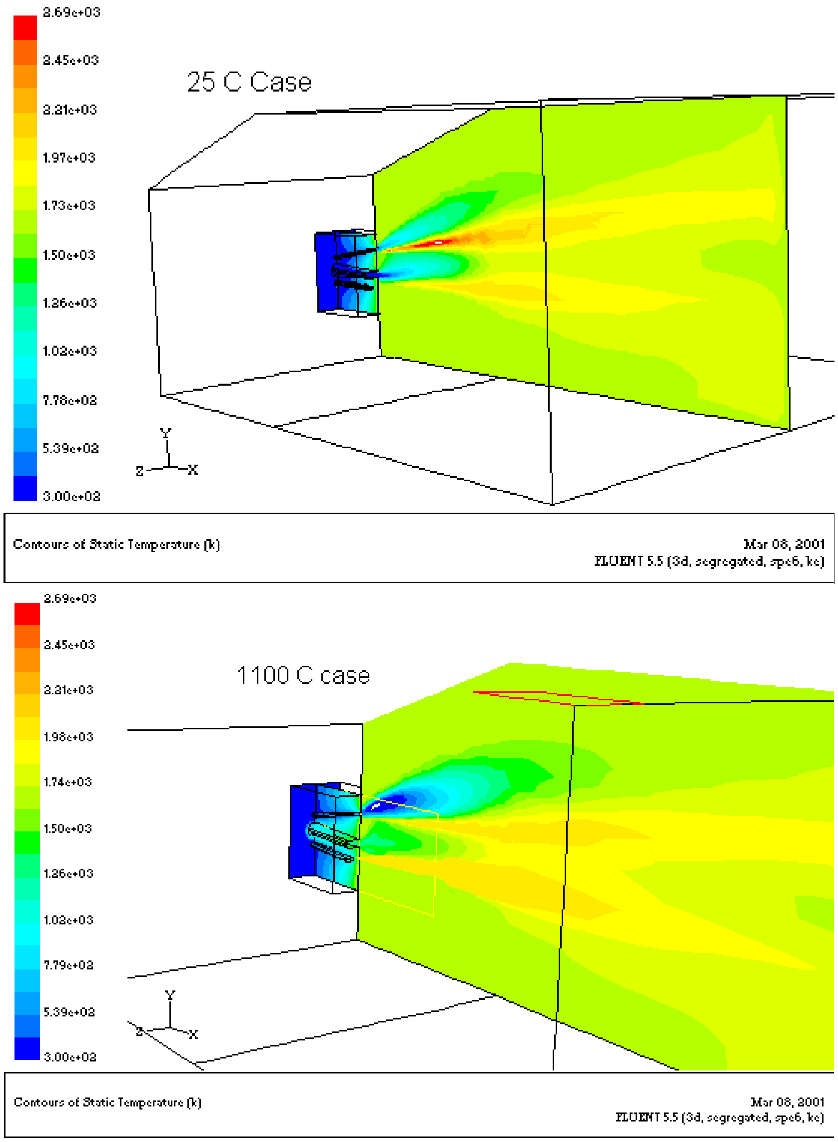


Figure 62. 3-D MODELING OF HIGH LUMINOSITY ‘A’ FLAME TEMPERATURES WITH NO PRECOMBUSTION AND WITH 1100°C PREHEATING

The temperatures profiles of the nozzles in the block were also determined for the 3-D cases. These are shown in Figure 63. Again, the precombustion process led to high nozzle wall temperatures for the fuel gas. Nozzle temperatures were much lower with no precumbustion and only reached high temperatures close to the hot face of the burner. Radiation from the flame is believed to be the main source of heating the nozzles when no precumbustion is used.

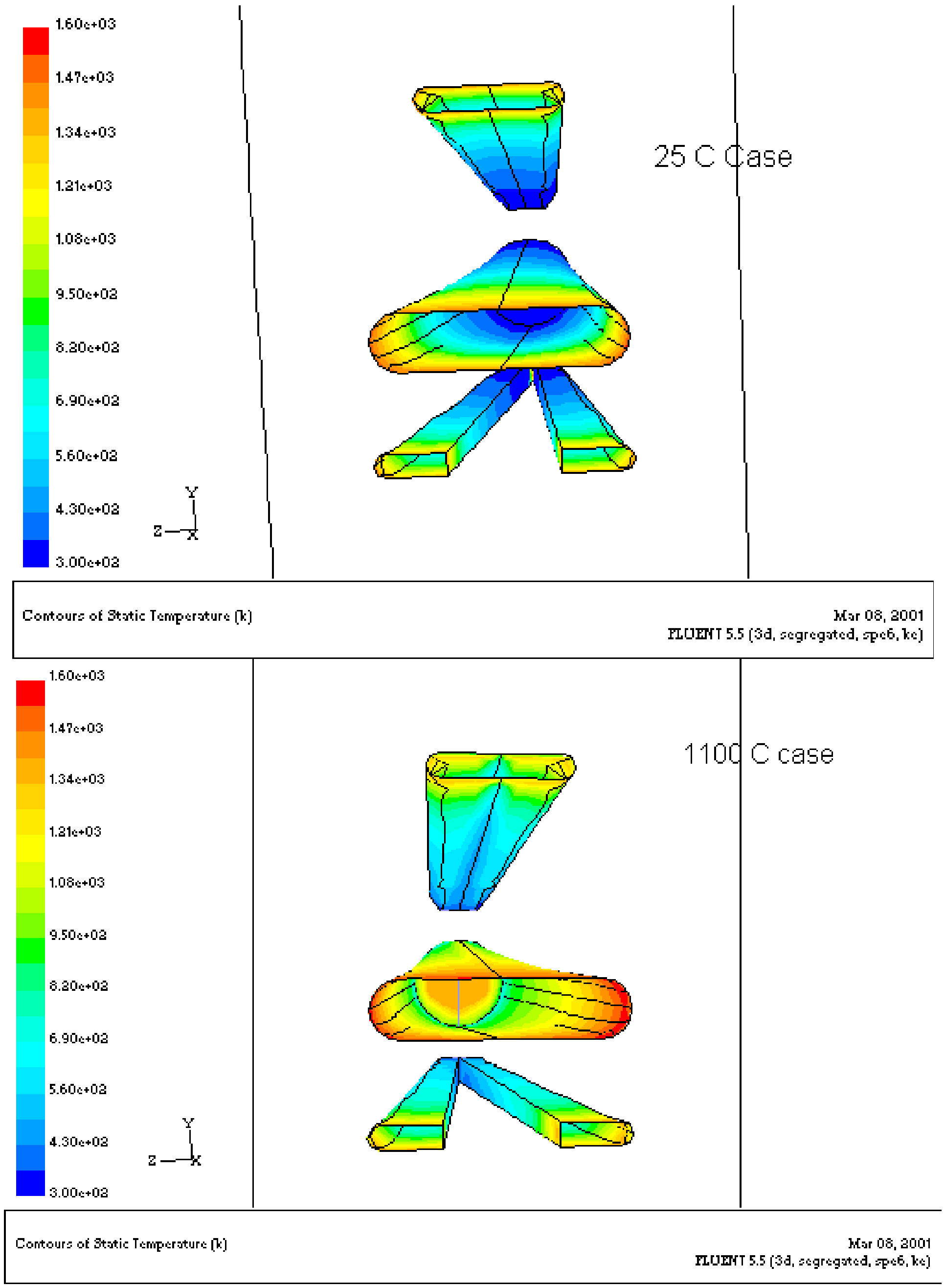


Figure 63. 3-D MODELING OF HIGH LUMINOSITY 'A' NOZZLE TEMPERATURES WITH NO PRECOMBUSTION AND WITH 1100°C PREHEATING

The nozzle wall temperatures are plotted in Figure 64 for the same cases with no preheating and with precombustion. The temperatures show a steadier increase in temperature increase than in the 2-D modeling, but the overall trend is the same. Preheating heats the fuel nozzle and through block conduction leads to higher oxygen nozzle temperatures. However, the largest oxygen nozzle temperature increases are near the hot face of the block.

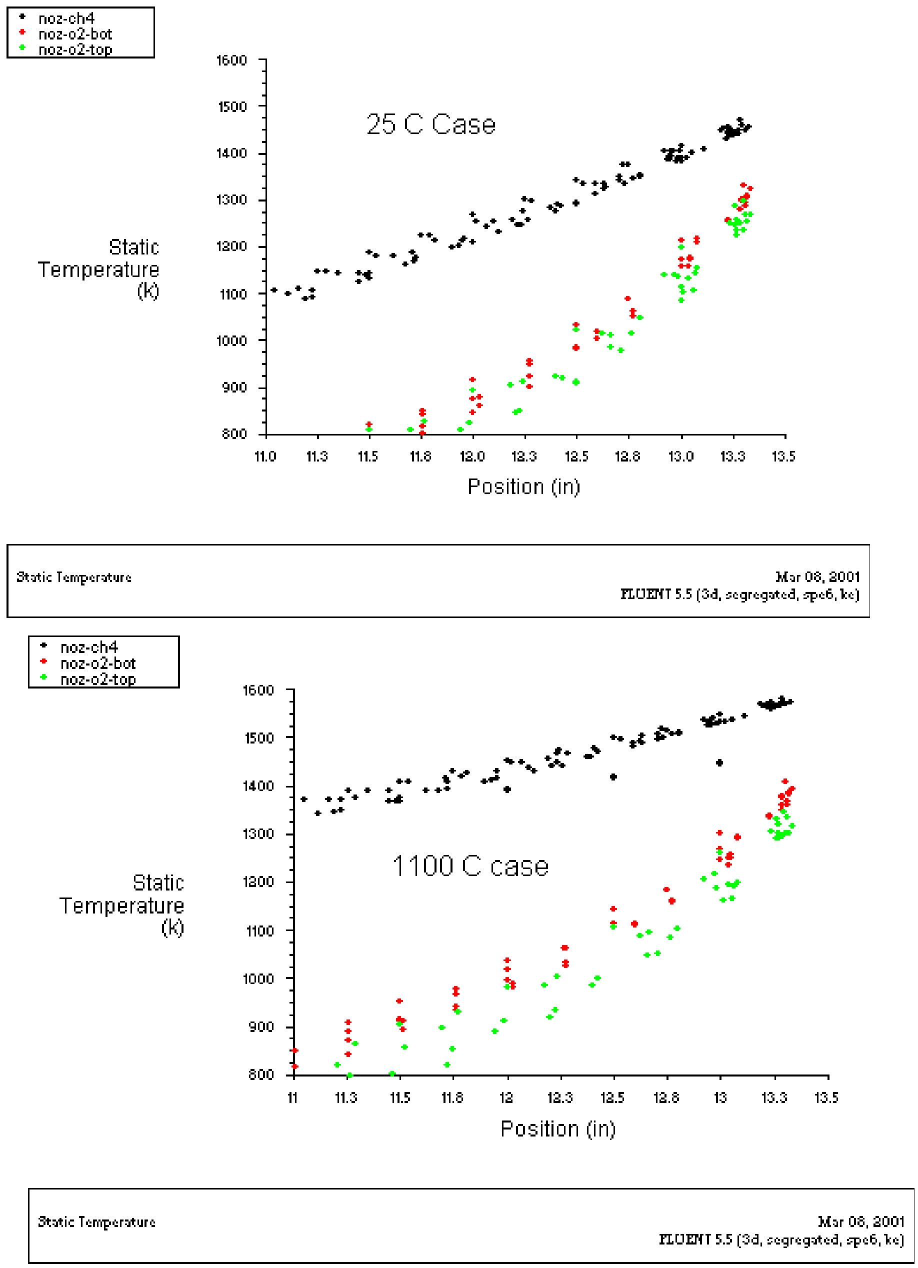


Figure 64. 3-D MODELING OF HIGH LUMINOSITY ‘A’ NOZZLE WALL TEMPERATURES WITH NO PRECOMBUSTION AND WITH 1100°C PREHEATING

The final 3-D modeling determination was of the burner hot face (figure 65). As was suggested by the 2-D modeling, flame radiation and precumbustion led to higher block face temperatures and a more uniform block face temperature profile. Note the temperatures right around the edges of the nozzles. Precombustion strongly increased fuel nozzle edge temperatures and also increased oxygen nozzle edge temperatures. The cold oxygen, however, even in the precombustion case had edge nozzle edge temperatures of approximately 1400 K (2050°F).

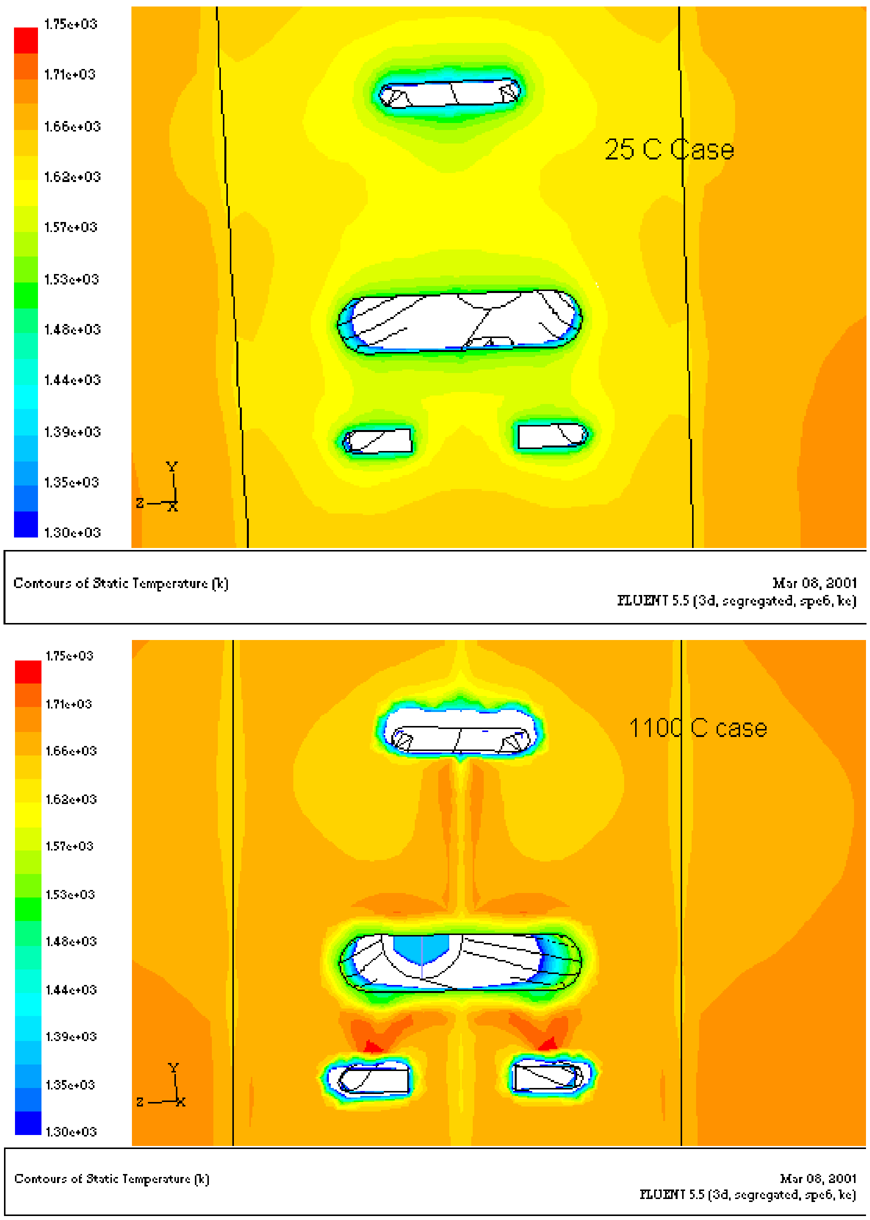


Figure 65. 3-D MODELING OF HIGH LUMINOSITY ‘A’ HOT FACE TEMPERATURES WITH NO PRECOMBUSTION AND WITH 1100°C PREHEATING

Commercial Prototype ‘B’

The project team of GTI, Eclipse, and Owens Corning met and reviewed the high luminosity ‘A’ prototype testing and modeling results. In general, the team was pleased with the burner improvements and simplifications. Several important concerns were raised. The first was the complexity of the burner block. The more holes in a burner block, the more difficult that block is to fabricate and maintain. The second concern was with the heating of the block. Because the block will not be at constant temperature, the team was concerned about the potential for microfractures of the ceramic material. This phenomenon can lead to mixing of oxygen and preheated fuel gas and decrease both performance and block service life. Suggestions to add metal sleeves and isolate the nozzle as much as possible were proposed, but no completely acceptable solution was offered.

The largest concern about the block was the temperature of the hot face. The demonstration test was planned for an Owens Corning borosilicate insulating fiberglass furnace. Borosilicate furnaces have a particularly harsh environment in the combustion space. Sodium borate vapor is known to attack any surfaces that are cool enough to condense the gas. The team felt the preheated natural gas came very close to keeping the burner hot face at a temperature high enough to prevent condensation and attack by sodium borate. However, the temperature around the oxygen nozzles was low enough to be a real concern. GTI and Eclipse engineers reviewed this information and decided to revise the burner block design based on this input. The revision led to design of the high luminosity 'B' prototype commercial burner.

The concerns about multiple nozzles and cooler temperatures around the edges of the multiple nozzles at the hot face of the burner were addressed by changing the block design. The block was redesigned to have a single nozzle. In this nozzle the precombustor product gases are mixed with the natural gas. As before, the natural gas is preheated, using the same precumbustor, while passing through the burner block. Oxygen is introduced to the same channel along the walls, surrounding the natural gas. The nozzle expands into a slot in passing from the cold face to the hot face. This expanding jet prevents significant fuel and oxygen mixing inside the burner block. This change enabled the block design to be greatly simplified, kept the nozzle walls temperatures hot but not overheated, and eliminated concerns about the nozzle edge temperatures not being hot enough. The flame is directly in front of the nozzle in the 'B' design, and this eliminates concerns about any condensation around the nozzle slot. Side and front views of the high luminosity 'B' block design are shown in Figure 66.

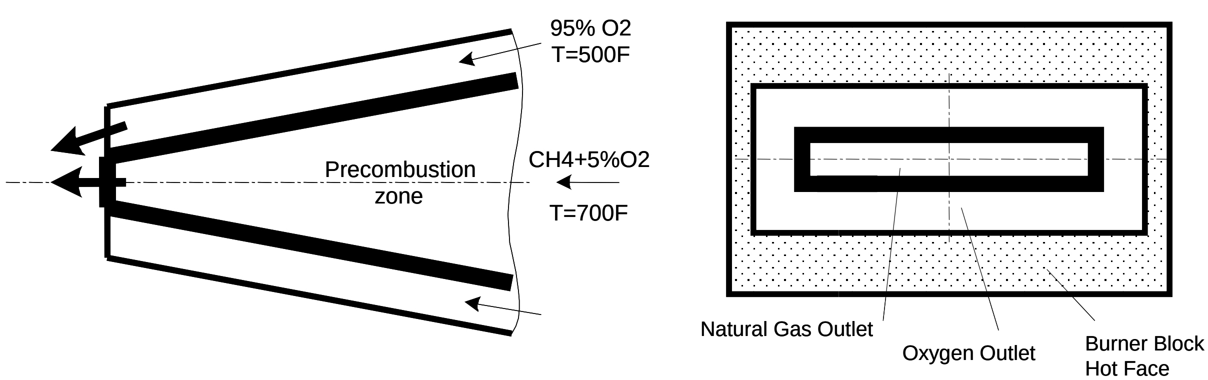


Figure 66. HIGH LUMINOSITY 'B' BURNER BLOCK – SIDE VIEW AND FRONT VIEW

A 1 to 4 MMBtu/h commercial prototype version of the high luminosity 'B' burner was fabricated by Eclipse and tested in the Eclipse burner test chamber by Eclipse and GTI personnel. Burner performance was excellent. The flame luminosity was similar to the high luminosity 'A' burner and superior in shape. Figure 67 shows front views of the flame from the Primefire 300 burner, high luminosity 'A' burner, and high luminosity 'B' burner firing at 2.25 to 3 MMBtu/h in the Eclipse test chamber.

Primefire 300
1.75 MMBtu/h

High Luminosity 'A'
1.75 MMBtu/h
8% O_2 to precombustor

High Luminosity 'B'
3 MM Btu/h
5% O_2 to precombustor

Figure 67. FLAME IMAGES DURING TESTING

Roof temperatures were measured for the Primefire 300 and high luminosity 'B' burners at firing rates of 1, 2, and 3 MMBtu/h. Figure 68 shows the roof temperatures were similar for the Primefire and 'B' burner when no precombustion was used. With 5 percent oxygen to the precumbustor the roof temperature was significantly higher for the 'B' burner. This indicates higher heat transfer and suggests the same temperature can be maintained at a lower firing rate with the 'B' burner.

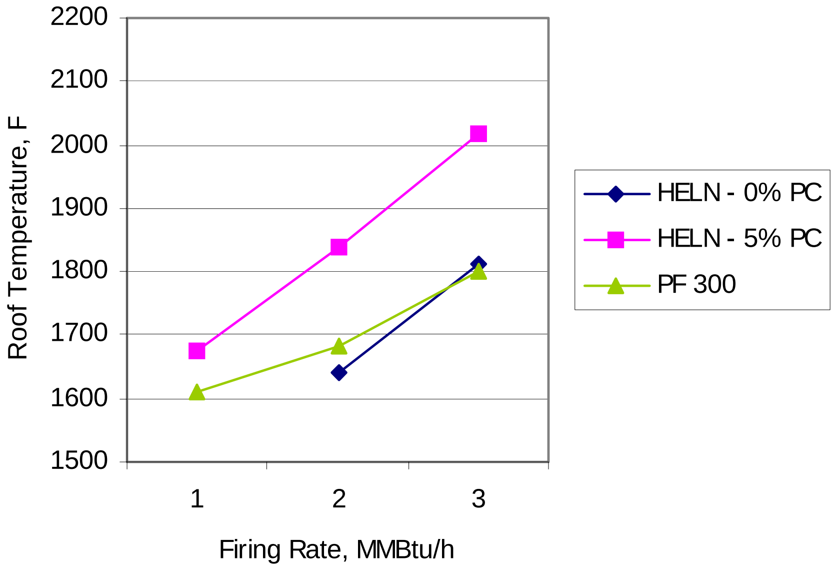


Figure 68. TEST CHAMBER ROOF TEMPERATURE WITH PRIMEFIRE 300 AND HIGH LUMINOSITY 'B' BURNERS

Total radiation from the Primefire 300 and high luminosity 'B' burners was also measured at firing rates of 1, 2, and3 MMBtu/h. These results paralleled the roof thermocouple readings. Figure 69 shows the heat transfer is similar for the Primefire burner and for the 'B' burner firing with no precumbustion. With 5 percent oxygen to the precumbustor, the measured radiant heat flux was 1.5 to 2 times higher for the high luminosity 'B' burner compared with the Primefire 300. Total heat transferred is by convection and radiation, so only testing in a glass furnace will provide total heat transfer data. The burner 'B' performance with no precumbustion matched the Primefire 300 performance.

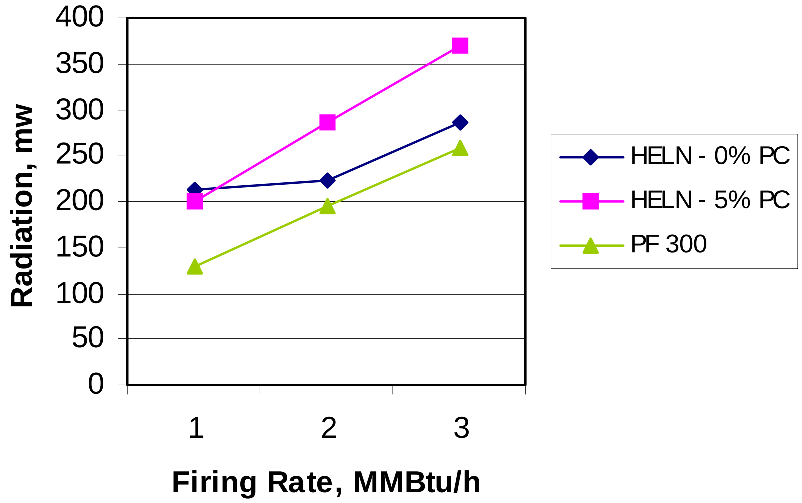


Figure 69. TEST CHAMBER MEASAUED FLAME RADIATION WITH PRIMEFIRE 300 AND HIGH LUMINOSITY 'B' BURNERS

Demonstration Testing of Commercial Prototype 'B'

The project team was pleased with the performance of the high luminosity 'B' prototype burner and the ways concerns about the 'A' prototype burner were addressed. A 1 to 4 MMBtu/h prototype of the high luminosity 'B' burner was fabricated by Ecl8ipse and installed in the Owens Corning insulating fiberglass furnace in Delmar, NY in December, 2001.

The project team monitored burner performance for several days and collected performance data. Because only one out of seven burners was changed, reliable information of heat transfer increases and temperature profiles was not acquired. The prototype burner was designed to be operated with and without the precombustor operating. The flame was significantly brighter with the precumbustor in operation. The burner was left operating in the furnace for a long term evaluation before changing out the remaining six burners. Operation was smooth except a small amount of carbon buildup occurred during steady operation. This problem was resolved in February, 2002 by changing the amount of oxygen sent to the precumbustor. The team was pleased with burner performance and scheduled full demonstration. Eclipse fabricated the burners and the six additional burner blocks were ordered. The full field test will be conducted when blocks and burners are all available. Photographs of the high luminosity 'B' burner mounted on the OC furnace and the flame produced by the burner are shown in Figure 70.

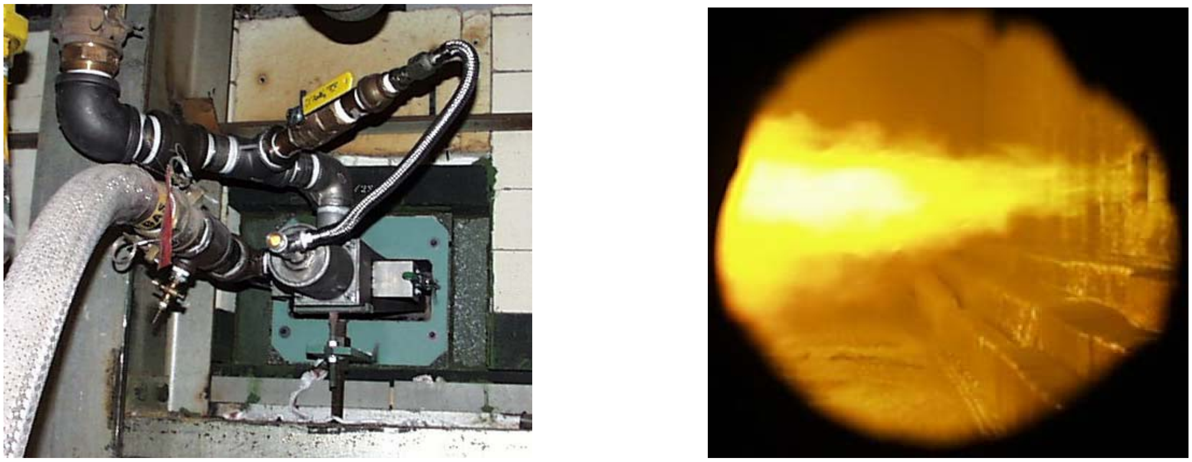


Figure 70. HIGH LUMINOSITY 'B' BURNER MOUNTED ON HOST FURNACE AND THE FLAME PRODUCED

This project was funded by DOE, the Gas Research Institute (GRI), the GTI Sustaining Membership Program (SMP), and the New York State Research and Development Authority (NYSERDA). The final field test will be supported by funds from the other sponsors. This field testing was conducted at the end of October, 2002. Eclipse, through the Combustion Tec division, will market this burner under the trade name of Primefire 400. Sales are scheduled to begin in late 2002, after completion of the field test at Owens Corning.

The Owens Corning furnace used for field testing is one of two similar furnaces located at OC's plant in Delmar, NY. The furnace operates with seven burners each firing between 1 and 7 MMBtu/h or natural gas. The furnace has a single exhaust port. Details of furnace design, operation, control, and pull rate are proprietary to Owens Corning. Testing results presented below are from a sample location in the exhaust duct well before the stack. Data is shown in measured concentrations but not corrected to pounds of emissions per ton since tonnage cannot be reported. Test methods involved collection with a cooled stainless steel probe, sample conditioning (cooling and drying), and analysis for components (CO, CO_2, O_2, and NO_x) using a calibrated Horiba analyzer. Sample handling is reliable and repeatable but cannot be directly related to standard EPA testing methods.

Testing was conducted over a five day period. The furnace was initially operated with seven Primefire 300 burners. Baseline measurements were made with the Primefire 300 burners operating. As the seven burners were removed and replaced with seven high luminosity burners (Primefire 400 burners), the same exhaust gas measurements were made. Data was also collected on gas and oxygen usage throughout this period. Once the furnace was stabilized with the new burners operating, testing was continued long enough to ensure stable, comparable operation. Fortunately, furnace pull rate and temperatures were held constant, within normal operating limits, throughout the testing period. Installing the burners took several days because the burner blocks needed to be preheated on the hot face to avoid cracking from thermal shock. This was accomplished in a small external kiln operated by Owens Corning staff. Blocks were heated for approximately one day and then installed by the hot repair team. All seven blocks were successfully installed with no cracks or failures.

Furnace Emissions. Furnace operating conditions (pull rate, temperatures, firing rate, etc.) were relatively constant throughout the five days of testing. The burners on the furnace are operated at a range of firing rates with the burners in the center of each side having the highest firing rates. There are three burners on side of the furnace and four on the other side. Because of changes in flows during the days of testing, the exhaust gas oxygen content varied between approximately 1.0 and 2.5 percent. There was no regular pattern to these changes. The project team assumed these changes were random and that the furnace is operated in a slightly oxidizing mode. To understand changes resulting from use of the high luminosity burners, the NO_x and CO concentrations measured in the exhaust are presented below on a 0 % oxygen basis.

Table 10. DEMONSTRATION TESTING SUMMARY EMISSIONS

Test Date	PF 300 Burners	PF 400 Burners	Ave. NOx, ppmv	NOx Change, %	Ave. CO, ppmv	CO Change, %
10-28-02	7	0	1237	--	1109	--
10-29-02	6	1	851	-31	1218	10
10-30-02	4	3	667	-46	3770	240
10-31-02	0	7	589	-52	2945	166
11-01-02	0	7	619	-50	3538	219

NOx and CO readings corrected to 0 % oxygen

As the number of substituted burners increased, the measured NO_x steadily declined. All burners did not appear to equally contribute to the formation of NO_x. With All seven burners changed to high luminosity burners, the measured NO_x was approximately 50 percent lower than the level with the Primefire 300 burners. The Primefire 300 is a state of the art burner, so this reduction is a dramatic decrease over levels that can be obtained by the best current practice.

Carbon monoxide levels were found to actually increase with the switch to high luminosity burners. Initially the project team was concerned that this signaled incomplete combustion in one or more burners. On examination of the furnace, the team learned that flame lengths were somewhat longer for several high luminosity burners relative to the Primefire 300 burners that had been operating in the same positions. This meant that part of the combustion process was found to be occurring in the exhaust duct, with some combustion likely occurring after the sampling location. This is not a desired operating mode, and Eclipse engineers will replace the burners with longer flames with burners that will complete the combustion process in the furnace over the glass surface. After noting this behavior, the project team was assured that the high luminosity burners are not leading to an increase in CO emissions from the overall furnace.

Energy Use. The longer flames noted by the testing team caused a small portion of the combustion process to take place outside the furnace. This caused an undesirable increase in exhaust duct temperature and a loss in overall glass melter efficiency. These problems were resolved after the testing program when Eclipse engineers substituted a new burner with a shorter flame length to replace the high luminosity burner in burner position number one. With the loss of heat from the furnace, the measured energy savings on the melter during testing are definitely lower than will be experienced during normal operation. Also, on a glass melter, longer term operation is needed to accurately determine energy use and energy savings. With this understood, the project team measured a decrease in energy use of 0.7 percent for the full melter. Considering the melter thermal efficiency of 50 percent, the increase in thermal efficiency for the burners is measured at 1.5%. This result, while encouraging, is assumed to be low compared to results achieved during correct and normal melter operation.

Industrial Adoption Plan

The following Industrial Adoption Plan lists pertinent information necessary for the successful marketing of a new burner. This information has been obtained or generated as a result of the High Efficiency Low NO_x (HELN@) Burner Development program. Combustion Tec (a division of Eclipse, Inc.), with the aid of GTI and Owens Corning, will assemble the information into technical product brochures, sales brochures, and presentations. Technical brochures will be supplied to present oxygen-gas glass furnace operators. Technical brochures and presentations will be made to new prospective customers of the technology. Other marketing efforts will include advertisements in trade magazines and presentations at trade shows.

Combustion Tec, Inc. has in the past offered new products on a limited trial basis to increase sales and market penetration. The industrial adoption plan may also include a field demo burner(s) and flow control equipment that can be installed at any oxygen-gas fired furnace for the trial period.

I. Technical Information

A. Burner Operating Theory and Principle - A high temperature natural gas preheating burner with soot precursor formation and subsequent soot burnout in the flame, increasing the burners energy efficiency and furnace throughput, while minimizing the furnace air emissions.

B. Burner Firing Capacity (MM Btu/hr) - Three commercial models are planned with firing capacities of 1 to 4, 2 to 8, and 5 to 20 MM Btu/hr. Other capacity ranges can be built per market requirements as necessary.

C. Burner Turn Down Ratio/Range of Burner Firing Capacity - The optimum burner design will offer at least a four to one (4:1) turn down, yielding a minimum firing rate of 0.75 MM Btu/hr.

D. Operating Velocities (ft/s) - The commercial burner will offer flexible firing velocities in the range of 50 - 180 ft/s with interchangeable parts for easy replacement and evaluation. These velocity adjustments will be used for fuel oxidation, indirect heating of natural gas, direct heating of natural gas, fuel rich combustion, and remaining oxygen requirements.

E. <u>Operating Temperatures (F)</u> - The temperatures for optimum performance will be varied during for best possible results in the mechanism of soot formation. This is accomplished by varying the preheat oxygen flow rate.

F. <u>Operating Pressures, Gas and Oxygen (PSIG, IWC)</u> - Operating pressures are expected to be in the range of 5 IWC to a maximum of 4.5 PSIG. This operating data will be laboratory verified.

II. Burner Selection

A. <u>Burner Description</u> - The commercial design of the HELN burner consists of one gas inlet and one oxygen inlet. All the natural gas enters the rear of the burner. A portion of the fuel is oxidized with a predetermined amount of oxygen. This oxygen is referred to as the preheat oxygen and is bled off from the main oxygen inlet through an orifice. The heat release from the partial combustion of the natural gas elevates the temperature of the remaining natural gas so that pyrolysis reactions dominate. The remaining oxygen is introduced along the walls of the preheated fuel nozzle. Because of limited mixing during nozzle expansion through the burner block, the rate of oxygen mixing with the preheated natural gas is delayed. This slows the combustion process and creates a fuel rich combustion region and a fuel lean combustion region. Soot precursors have time to produce soot in the flame, and this soot is burned out in this flame. The presence of soot in the flame leads to high luminosity and high radiant heat transfer to the glass

B. <u>Burner Block</u> - The burner block or precombustor tile will use material selections that have been successfully used with Combustion Tec's Primefire series burners.

III. Operation

A. <u>Installation and Mounting</u> - Installation and mounting methods will be developed based upon Combustion Tec's Primefire series and traditional air fuel methods.

B. <u>Hose Connections</u> - Quick coupler devices with safety locks will be used to provide easy successful connections to the burner.

C. <u>Flow Controls and Adjustments</u> - Flow control equipment will be designed and sized according to supply and usage applications.

D. <u>Velocity Adjustments</u> - Burner velocity adjustments will be made through the use of adjusting lead screws from Combustion Tec's adjustable orifice designs.

E. <u>Optimizing Burner Performance</u> - Throughout the development phase all project partners participated in optimizing the engineered product.

IV. Manufacturing

A. Materials - Material selection can be broken down into:

i. Burner - Will consist of stainless steels primarily 304, 316, 330, 446, as well as some Inconel 600.

ii. Seals - Will consist of viton o-rings or another oxygen compatible material. Temperature will also play an important role in this selection process.

iii. Burner Block (Precombustor) - Will consist of AZS bonded material.

B. Construction Methods - Standard machine shop and design practices will be used in the manufacturing, machining and welding of the burner. Quality checking of each individual part will be done to assure manufacturing tolerances are maintained.

C. Assembly - Two methods will be employed; the first method is to properly oxygen clean the entire burner assembly and the second method is to assemble using oxygen compatible lubricants and seals.

V. Maintenance

A. Cleaning - Maintenance will be evaluated throughout the development phase and will continue during early sales phases. Build up of soot deposits within the burner itself is a consideration that has been addressed in demonstration testing but will continue to be monitored. For a successful marketed product, low maintenance costs and time and required.

B. Replacement Parts - Spare parts are always considered when designing a product, for such places where expected wear may take place, or where interchangeability is needed for adaptation.

VI Base Line Comparisons

A. Air/Fuel - Traditional air/fuel burners may want to be studied to make comparisons.

B. Oxy/Fuel - Testing of the Primefire series burners would offer a comparison between today's technology and tomorrow's ultra-low NO_x efforts.

VII. Economic Analysis

A. Furnace Efficiency / Improvement - An on-going analysis will be required but preliminary information suggests the following:

Improvements can be quantified in terms of heat energy required to melt a unit ton of glass. In Table 11, a typical regenerative furnace melting efficiency is compared with the current oxy-gas furnace and predictions are made for the HELN burner on the same furnace.

Table 11: MELTING EFFICIENCY COMPARISON

Type of Furnace	MM BTU/Ton	% Change
Regenerative (Sideport)	4.5	------
Oxy-Fuel (Current)	3.8	15
HELN Oxy-Fuel (Proposed)	3.0	34

Notes:
1. A 300 tons/day container glass furnace is considered for analysis.
2. All furnaces use electric boost for maintaining glass quality.
3. HELN burners provide a 20% improvement in melting efficiency over the current oxy-fuel furnaces.

Table 10 shows that overall efficiency improvement of the HELN Oxy-fuel furnace over the regenerative furnace is significant (~34%).

B. Cost Comparisons - This will require on going analysis throughout the development early sales stages to refine the information available. Preliminary information suggests the following:

Table 12 compares relative melting costs of the furnaces described in Table 10 translated in cost savings per unit weight of glass produced.

Table 12: MELTING COST COMPARISONS

Type of Furnace	Fuel (SCFH)	Oxygen (SCFH)	Costs ($/Ton)			% Change
			Fuel	O_2	Total	
Regenerative (Sideport)	45,000	---	10.80	---	10.80	---
Oxy-Fuel (Current)	38,000	76,000	9.12	9.12	18.24	+69
HELN Oxy-Fuel (Proposed)	30,000	60,000	7.20	7.20	14.40	+33

Notes:
1. A 300 tons/day container glass furnace is considered for analysis.
2. Fuel is natural gas @ $3.00/MCF and oxygen is at $0.15/CCF.

3. Electric boost costs are not considered.
4. HELN Oxy-fuel is considered to be 20% more fuel efficient than current oxy-fuel.

Table 11 shows HELN burners will provide large savings in both fuel and oxygen costs per ton glass basis. For example, HELN Oxy-fuel burners will provide annual fuel and oxygen savings in the amount of $420,480. This would pay for HELN burner hardware in just one year.

C. Return On Investment - Additional advantages of the HELN Oxy-fuel burner include use of lower purity oxygen (such as VPSA oxygen), which would allow glass producers to purchase oxygen at a lower cost and further reduce melting costs. Current VPSA systems produce oxygen at 92% purity, however, the HELN burner would allow “Equivalent” operation (both in heat output and emissions), at much lower purity. This number can be lowered to 75% purity, by enhancing the radiative heat output and reducing NO_x formation in the primary flame region. The above mentioned data shows lower operating costs for HELN as opposed to traditional oxy-fuel. Capital cost for oxy-fuel technology is significantly less than air-fuel technology, while operating cost increases. The net result is a savings.

VIII. Emission Data

A. NO_x - The benefits of the HELN Oxy-fuel burner in emission control are significant. This can be shown by NO_x abatement costs as computed in Table 13.

Table 13. NO_X ABATEMENT COSTS

Type of Furnace	**Typical NO_x Emissions (Lb./Ton)**	**NO_x Regulation (Lb./Ton)**	**Annual NO_x Abatement Costs @ \$3,000/Ton NO_x**
Regenerative (Sideport)	5.5	0.5	$821,250
Oxy-Fuel (current)	1.5	0.5	$164,250
HELN Oxy-Fuel (proposed)	0.5	0.5	0

Notes:
1. A 300 tons/day container glass furnace is considered for analysis.
2. NO_x regulation is set at 0.5 lb./ton for the purpose of example only.
3. NO_x abatement cost is assumed at $3,000/ton NO_x for all three cases.

Table 12 shows that the regenerative furnace would require significant expenditure in the form of NO_x abatement costs every year to comply with the NO_x regulations. On the other hand, the HELN Oxy-fuel furnace operating at ultra-low NO_x can accumulate NO_x credits (in the non-attainment area) for future use or outright sale to other energy intensive industries.

B. CO - Further studies as to the products of combustion will be developed throughout the tests with early commercial burners.

C. CO$_2$ - Further studies as to the products of combustion will be developed throughout the tests with early commercial burners.

IX. Financing

A. Selling Price – The burner design has been improved to make the HELN burner easily fabricated by current practices. The burner has only a few more components than the Primefire family of burners. Therefore, HELN commercial burners will be somewhat higher in cost than other oxy-gas burners, but that small cost increase will be more than offset by gas and oxygen savings.

B. Lease - A lease option may be considered as a cost effective alternative.

X. Intended Market and Commercialization Plans

Upon successful demonstration of the HELN burner it will be introduced to the glass industry through marketing brochures, advertisements and articles in industry magazines, and papers given at industry conferences. The HELN burner, with the planned trade name of Primefire 400, will be targeted to both new and existing users of oxy-gas combustion in the glass industry. Initially the burner will be demonstrated to potential customers at our lab furnace and possibly at the host furnace where the field demonstrations occurred. As with many of Combustion Tec's burners, the HELN burner could be offered to existing oxy-fuel users on a trial basis for their evaluation.

Combustion Tec presently has over 70 oxygen-gas furnaces operating with our burners and increases this amount by about 6 furnaces per year. This equates to nearly 600 Combustion Tec oxy-gas burners in use today. A successful HELN burner which provides 15-20% better furnace efficiencies and 60% lower NO_x would likely replace these burners and enable us to increase our market share by displacing our competitions burners. All indications from demonstration testing are that the HELN burner performance exceeds the performance of all Combusion Tec burners and all competitive oxy-gas burners from other manufacturers currently used in the glass industry.

Summary Conclusions, and Recommendations

The high heat-transfer low-NO_x natural gas combustion system, also known as the high luminosity burner, has been developed from concept from commercial demonstration. Modeling was conducted on both the preheating sections of the burner and the flame zones. Modeling results confirmed the promise of the high luminosity burner to decrease energy consumption and reduce NO_x emissions. Three lab-scale burners, firing 0.5 MMBtu/h, and a pilot-scale burner, firing 3 MMBtu/h, were desgined, fabricated and tested. Results with all burners confirmed an increase in flme luminosity, higher heat transfer, and decreased NO_x production. Two prototype commercial burners firing 3 MMBtu/h were designed, built, and tested. The 'B' prototype burner proved highly successful and was installed for demonstration testing on an Owens Corning borosilicate fiberglass furnace in Delmar, NY. The demonstration test went smoothly with the burner performing with no interruptions for several months. The flame was more luminous than the replaced Primefire 300 burner. An Industrial Adoption Plan has been prepared and involves commercial sale of the high luminosity burner, with trade name Primefire 400, by Combustion Tec starting in late 2002. A full demonstration of the high luminosity burner will be conducted on the Owens Corning furnace in the summer of 2002. The demonstration test was delayed to allow time to confirm desired operation of the first burner and to give block and burner fabricators sufficient time to provide needed blocks and burners. All burners are fabricated by Eclipse.

The project has proven successful and has led to a commercial oxy-gas burner that has performance characteristics superior to all available oxy-gas burners for glass furnaces. Combustion Tec, a division of Eclipse, Inc., will market sell, install, and service this burner after completion of the demonstration testing in the summer of 2002. DOE funds have been completed used in completing this work through initial demonstration. Funds from other sponsors, GRI, SMP, and NYSERDA, will be used to complete demonstration testing and data processing. Detailed results of the demonstration testing will be presented at the DOE project review meeting scheduled for Sept. 2002 and in a paper to be presented at the Oct., 2002 Glass Problems Conference.

List of Acronyms

Btu, MMBtu	British thermal units, million British thermal units
CFD	computational fluid dynamics, used for burner and combustion system modeling
CO	Carbon monoxide
CO_2	Carbon dioxide
CT	Combustion Tec
direct mixing	zone where precumbustor product gases are mixed with remaining natural gas
DOE	U.S. Department of Energy
efficiency	or thermal efficiency, percentage of total fuel energy transferred to the glass
efficiency improvement	percentage improvement in energy transferred to the glass
flame zone	the burner flame inside the furnace consisting of rich and lean combustion zones
ft^3	cubic feet
GRI	Gas Research Institute
GTI	Gas Technology Institute
HELN	High-Efficiency low-NO_x burner, the high luminosity burner
IGT	Institute of Gas Technology
NO_x	Nitrogen oxides (in NO_2)
NYSERDA	New York State Energy Research and Development Authority
OC	Owens Corning
PF 300	Conventional oxy-gas burner initially operating on the Owens Corning furnace
PF 400	Designation of the commercial version of the high luminosity burner
ppm, ppmv	parts per million, parts per million by volume
precombustor	first burner zone, where a portion of natural gas is used to preheat natural gas
radiation	portion of heat transfer by radiation
SCF	Standard cubic feet (at 1 atm. and 60ºF)
SCFH	Standard cubic feet per hour
soot	solid carbon particles, general C_{16} and greater
soot precursor	hydrocarbons of C_{12} and greater

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