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OXYGEN ENRICHED AIR/NATURAL GAS BURNER SYSTEM DEVELOPMENT

FINAL REPORT
(July 1984—September 1989)

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FINAL REPORT

(July 1984 - September 1989)

Prepared by

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For

GAS RESEARCH INSTITUTE

Contract No. 5083-231-0932

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ABSTRACT

In order to remain competitive in the global market, energy intensive combustion processes must reduce costs. Air-natural gas combustion is used in many of these processes including heating and melting of glass and metals. These applications are summarized with respect to natural gas consumption and energy efficiency. Oxygen enrichment can increase furnace productivity and reduce operating costs through improved energy efficiency.

Commercial air-natural gas burners were shown to be generally limited to 30% enrichment. Since the maximum benefits of oxygen enrichment (high flame temperature and NOx minimization) are achieved with 100% oxygen, a simple retrofit technology was developed to convert air-natural gas burners to fire oxy-fuel. This technology was tested in a ladle preheating process and a glass melting furnace where increased production and fuel savings were observed. In the glass furnace, burner survivability was improved through water cooling.

NOx emissions from heating and melting processes have become a significant environmental issue. A computer-based mathematical model was developed to predict the effect of burner firing conditions on NOx levels. The model currently predicts values higher than experimentally observed, but the trend is correct. The data show that conversion of a furnace to 100% oxygen-natural gas can dramatically reduce NOx emissions to well within existing regulations.

RESEARCH SUMMARY

Title	Oxygen-Enriched Air/Natural Gas Burner System Development
Contractor	Air Products and Chemicals, Inc.
	GRI Contract Number: 5083-231-0932 with Amendments
Principal Investigator	A. I. Dalton
Report Period	July 1984 - September 1989
Objective	Develop, evaluate, and field test a simple, cost-effective natural gas burner system which uses high concentrations of oxygen for combustion in industrial applications. In addition, a mathematical model will be developed to predict NO_x levels in oxygen-enriched, natural gas fired systems.
Technical Perspective	Since addition of oxygen to combustion processes can increase temperature and available heat while reducing inert nitrogen, oxygen enrichment is gaining wide acceptance as a heating and melting method of energy conservation and cost reduction. By using pure oxygen instead of air for combustion, energy savings of up to 70% can be achieved. Developing a new burner system for high levels of oxygen enrichment will minimize undesirable effects of enrichment such as short flame length, excessive temperatures, and material compatibility, while maximizing desirable effects such as increased fuel efficiency, increased productivity, reduced total emissions, and reduced production costs.
Results	Oxygen enrichment of air/natural gas combustion processes can make natural gas more competitive by providing a low cost alternative for increasing production, increasing energy conservation, and reducing particulates and total volume of gaseous emissions. The greatest benefit is achieved at high levels of enrichment approaching 100% oxygen (oxy-fuel) where all the combustion air and the contained nitrogen are replaced with pure oxygen. Fuel savings of 50-70% and flue gas volume reductions approaching 90% can be realized.
	Six commercially available air-natural gas burners were evaluated over a range of oxygen enrichment levels. The results indicate that conventional air-natural gas burners are capable of using oxygen-enriched air at oxygen concentrations below 30%. Above this level burner performance was adversely affected by the decrease in volumetric flow rates which resulted in shorter flames and burner deterioration. Two of the intermediate performing nozzle mix burners, one with a high degree of swirl, were successfully modified to fire 100% oxygen and produce flame

patterns and temperature uniformity similar to the unmodified air-fuel burner at constant available heat. The key parameters relate to oxidant-fuel mixing. The proprietary modification technology is easily retrofitted to existing air-fuel burners in a furnace.

Air-fuel burners in a frit glass furnace and a foundry's ladle preheater were modified to fire oxy-fuel. Faster heat-up times, desired higher ladle temperatures, and fuel savings were observed in the ladle. After six months operation, there were no signs of burner deterioration. In the frit furnace, a concurrent 27% production increase and 60% fuel savings was obtained. However, water-cooling of the burner was required to maintain burner life.

A computer-based NOx preheater model was developed that incorporates fluid dynamics, heat transfer, and combustion and NO_x kinetics. The model, which requires several hours cpu time, predicts higher NO_x levels than experimentally observed, but the correct trend. On the basis of this data, it is projected that furnaces fully converted to oxy-fuel will reduce NO_x emissions to well within current and anticipated NO_x regulations.

Technical Approach

The basic approach included five core tasks:

- Assessment of the market opportunity for oxygen enriched air-natural gas burner technology,
- Evaluation of the impact of oxygen enrichment on the performance of selected, commercially available air-natural gas burners,
- Selection of one or two of the above burners to modify for firing at high levels of oxygen enrichment,
- Conducting field tests of the burner modification technology in heating and/or melting applications within the glass and metals industry, and
- Developing an experimentally verified model to predict NO_x formation.

Project Implications

Oxygen enrichment of combustion air can be an effective way to improve furnace productivity, reduce energy consumption, and control pollutant emissions. For high temperature industrial processes, combustion with oxygen is an energy conservation alternative to combustion air preheating. While conventional high temperature combustion schemes result in the production of an unacceptably high NO_x concentration in the exhaust gas, oxy-fuel burners can be configured to minimize NO_x formation without a loss in furnace performance.

The completed work has illuminated these advantages of combusting natural gas with oxygen and has identified important markets for oxygen-natural gas burners. The application of oxygen-natural gas burner systems is dependent upon the relative prices of oxygen and natural gas, the furnace operator's need for increased production, and air pollution regulations. GRI plans to continue investigations of oxygen enrichment and other combustion modification techniques to control NO_x in high temperature industrial processes.

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Michael A. Lukasiewicz
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APPENDICES

1. INTRODUCTION

In order to remain competitive in the global market, energy intensive commodity processes must reduce costs. Air-natural gas combustion is used in many industrial heating, melting, calcining, and refining processes. Additionally, in this environmentally conscious age, increasingly more stringent regulations are being placed on these processes to limit discharges to the atmosphere of pollutants such as nitrogen oxides (NO, NO_2) which result from these high temperature, natural gas-fired processes. At the beginning of this project, natural gas pricing had reached its peak after some dramatic increases. Many expect similar increases to reoccur in the early 1990's. Both environmental forces and high natural gas costs can make alternative energy sources such as electricity more attractive than natural gas in these heating and melting applications.

Since addition of oxygen to natural gas combustion processes decreases nitrogen content and flue gas volume while increasing flame temperature and available heat, oxygen enrichment can be used not only to increase production, but also to make natural gas more competitive by decreasing NOx emissions and energy consumption. High levels of oxygen enrichment provide the greatest benefit to air-natural gas combustion processes.

The objective of this project was to develop, evaluate, and field test a cost effective gas burner system that is capable of using high levels of oxygen enriched combustion air in industrial heating and melting processes. The specific goal was to develop burner technology to minimize the undesirable effects of enriched air such as short and intense flames, skewed heat release patterns, excessively high flame temperatures, material compatibility, and NOx generation, while at the same time maximizing the desirable effects such as increased fuel efficiency, increased productivity, reduced total emissions, and reduced production costs.

The core tasks included

- Assessment of the market opportunity for oxygen enriched air-natural gas burner technology,

- Evaluation of the impact of oxygen enrichment on the performance of selected, commercially available air-natural gas burners,

- Selection of one or two of the above burners to modify for firing at high levels of oxygen enrichment, and

- Conducting field tests of the burner modification technology in heating and/or melting applications within the glass and metals industry.

The project was subsequently amended to include development of an experimentally verified model to predict NOx formation in Air Products' pilot combustion lab. If successful, this model would be used to predict operating methodologies to minimize NOx formation in oxygen-enriched combustion.

2. BACKGROUND

2.1 Benefits and Theory of Oxygen Enrichment

Oxygen enrichment has been used in high temperature heating and melting processes as a low capital means to increase production, conserve energy, and reduce emissions. These advantages to oxygen enrichment are readily understood by considering the basic combustion reaction and what occurs when oxygen is added to combustion air.

Combustion may be regarded as the rapid reaction of oxygen with a fuel (normally hydrocarbon) that leads to the generation of heat. Air is the usual source of oxygen. Air consists of 79% nitrogen (N_2) and slightly less than 20.9% oxygen (O_2) with the balance inert gases such as argon (Ar). Natural gas (CH_4) combustion occurs with air according to the following equation:

$$CH_4 + 2\,O_2 + 8\,N_2 \rightarrow CO_2 + 2\,H_2O + 8\,N_2 + \text{Heat} \qquad \text{(Eq. 1)}$$

Unfortunately, a significant amount of heat is absorbed by the nitrogen, which contributes nothing to the process.

Oxygen enrichment, which increases the oxygen concentration in combustion air to greater than 21%, increases flame temperature and decreases nitrogen content. "Oxy-Fuel" technology is the 100% replacement of combustion air with pure oxygen.

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O + \text{Heat} \qquad \text{(Eq. 2)}$$

Eliminating or reducing the heated nitrogen results in decreased sensible heat escaping in the flue gases and increased heat available to the process, thereby increasing thermal efficiency. Figure 1 shows the improved thermal efficiency due solely to nitrogen elimination at increasing levels of oxygen enrichment. It is apparent that <u>substantial fuel savings can be achieved</u>, particularly at high levels of oxygen enrichment and in processes with high flue gas temperatures. Figure 1 generally understates what can be achieved in practice. The effects of oxygen enrichment are better calculated by taking into account the type and size furnace, gas flow patterns, type of burner, characteristics of the product, excess air levels, composition of the flue gases, etc., in addition to elimination of nitrogen.

As shown in Figure 2, substantial reductions in nitrogen and flue gas volumes can be realized at high levels of oxygen enrichment. This fact can be utilized to reduce total emissions of particulates, corrosive or toxic substances, and of nitrogen oxides formed by the reaction of nitrogen and oxygen.

$$N_2 + O_2 \rightarrow NO \qquad \text{(Eq. 3)}$$

FIGURE 1

FUEL SAVINGS WITH OXYGEN ENRICHMENT

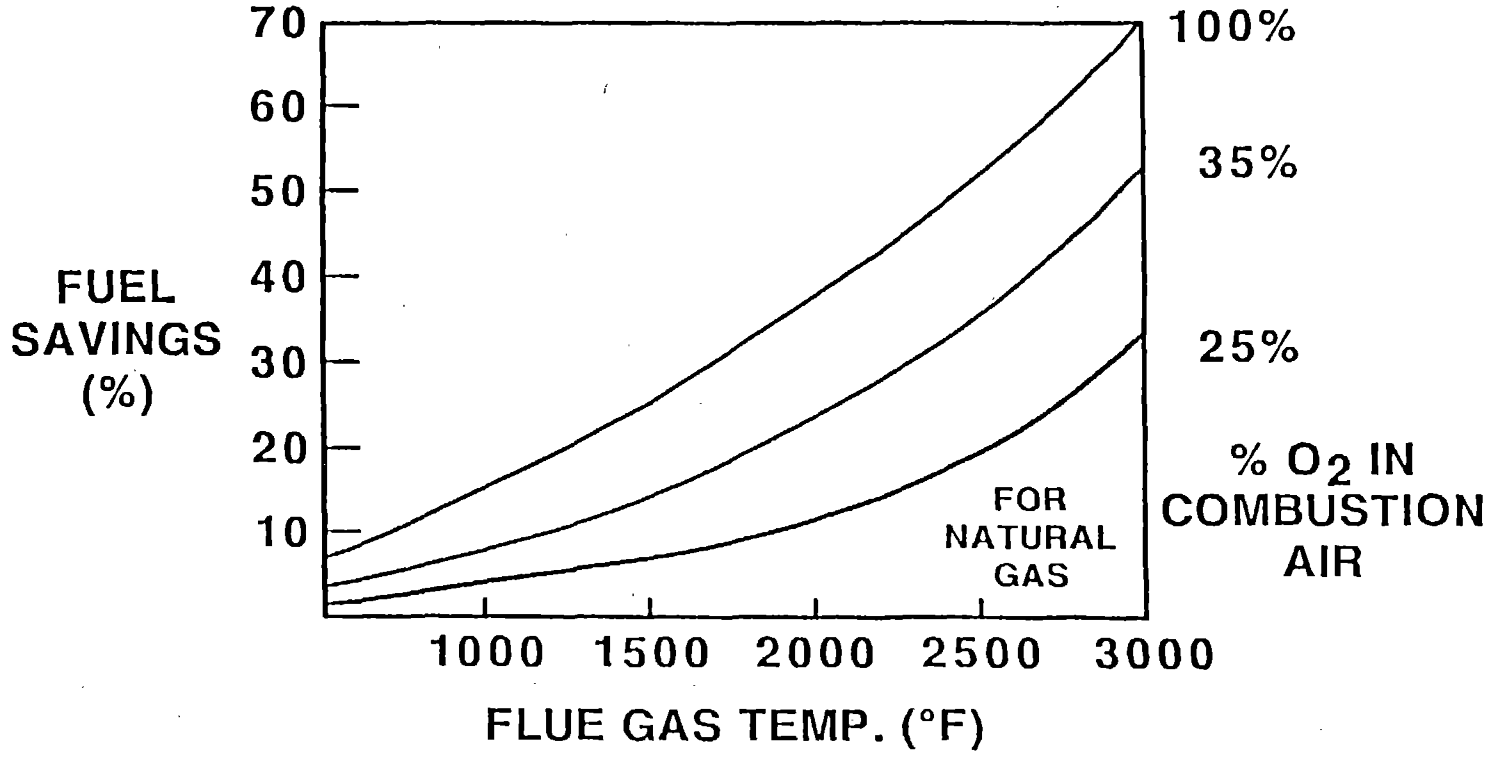
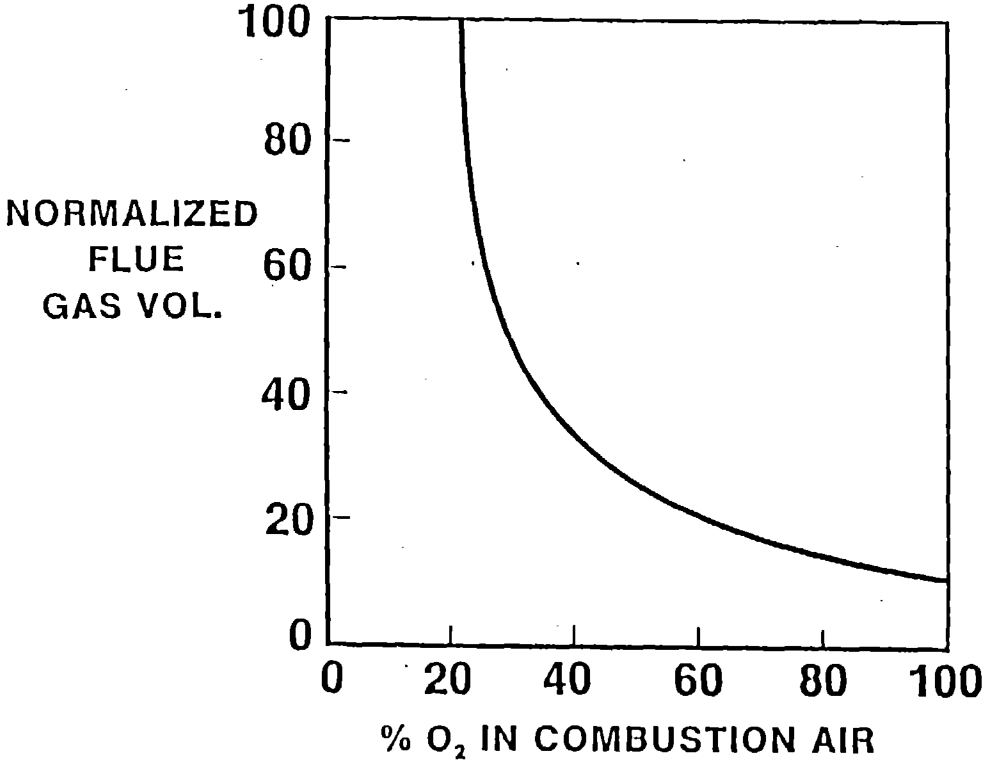


FIGURE 2

REDUCTION IN FLUE GAS VOLUME



Oxygen enrichment can also be employed to increase production. Flue gas volume reduction can be used to debottleneck induced draft fans and flue gas treatment equipment such as baghouses. Primarily, however, enrichment is used to increase capacity of the combustion furnace. By increasing the rate of heat transfer, one can increase the furnace load throughput. Heat is transferred to the furnace load either directly or indirectly by conduction, convection, or radiation:

$$q_{\text{conduction}} \propto k(T_f - T_s)$$

$$q_{\text{convection}} \propto h(T_f - T_s)$$

$$q_{\text{radiation}} \propto \sigma\varepsilon(T_f^4 - T_s^4)$$

Where q is the heat transfer rate, k is the thermal conductivity, h is the convective coefficient, σ is the Stefan-Boltzmann constant, ε is the emissivity, T_f is the flame temperature, and T_s is the temperature of the relatively cool surroundings.

Note that in all of the these modes, the rate of heat transfer depends on the temperature difference between the flame, furnace, and load.

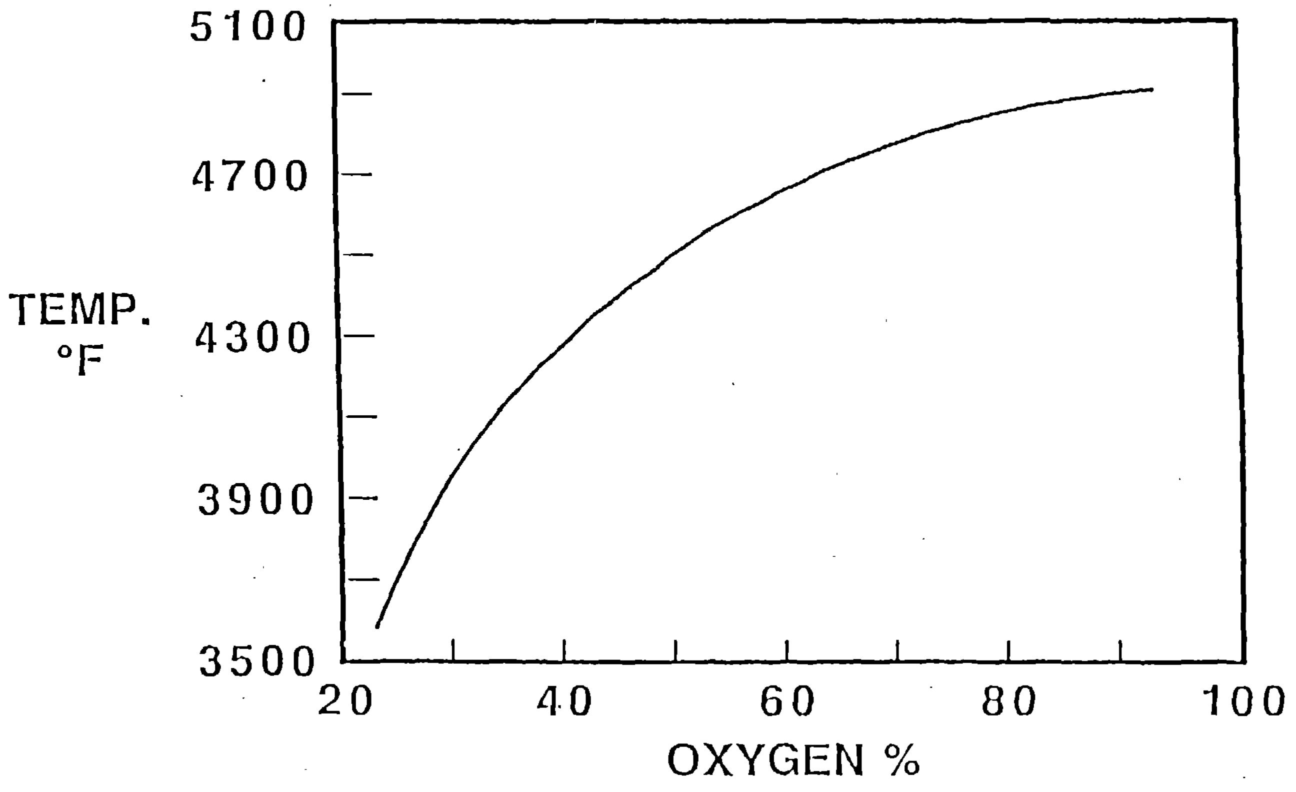
Addition of oxygen to combustion processes increase flame temperature. Figure 3 shows the calculated adiabatic flame temperatures for stoichiometric combustion of natural gas with cold air containing varying concentrations of oxygen. The calculations show that the adiabatic flame temperature increases from 3550°F with air to over 5000°F with pure oxygen. Higher adiabatic flame temperatures are a direct result of eliminating substantial quantities of nitrogen and other inert gases. It should be pointed out that calculated adiabatic flame temperatures are rarely, if ever, achieved in practice. Actual flame temperature in any specific application is governed by many factors such as the degree of mixing between fuel and oxygen, the cooling effect of mixing with recirculating furnace gases, heat loss from the flame, the chemistry of combustion including pyrolysis of the fuel, firing rate, excess air levels, and furnace temperature. Consequently, the actual flame temperature, with or without oxygen enrichment, is extremely difficult to predict. The unpredictable flame temperature and the dramatic decreases in flue gas volume require careful analysis of heat transfer, furnace temperature uniformity, flame geometry, load penetration, etc. when employing oxygen enrichment.

2.2 Oxygen Enrichment Techniques

A schematic of the three basic techniques for oxygen enrichment in heating and melting applications is shown in Figure 4: Premix,

FIGURE 3

EFFECT OF OXYGEN ENRICHMENT ON FLAME TEMPERATURE



Lancing or Undershot, and Oxy-Fuel. The choice of a particular technique, depending upon the type and size furnace, operating benefits, and capital costs, can impact the cost savings.

The premix technique inserts an oxygen diffuser in the primary air main. The increased oxygen concentration uniformly raises the theoretical adiabatic temperature of the entire flame. Specific fuel consumption is thereby decreased while maintaining a sufficient supply of heat to the process. Premix is the simplest and least expensive technique since no furnace modifications are required.

The premix technique is used to increase production or reduce fuel usage by means of a uniform increase in flame and furnace temperature. Cupolas, shaft kilns and glass day tanks, refiners, and forehearths are examples of furnaces where premixing oxygen in the combustion air would generally be the preferred technique.

Undershot enrichment places an oxygen lance under the conventional air burner flame. This produces a higher temperature on the lower portion of the flame without increasing the temperature of the upper zone. The lower portion radiates heat efficiently into the product while the cooler upper portion shields the refractory from any increase in temperature. The specific fuel consumption decreases while sufficient heat is transferred to the process. Although undershot enrichment is slightly more capital intensive

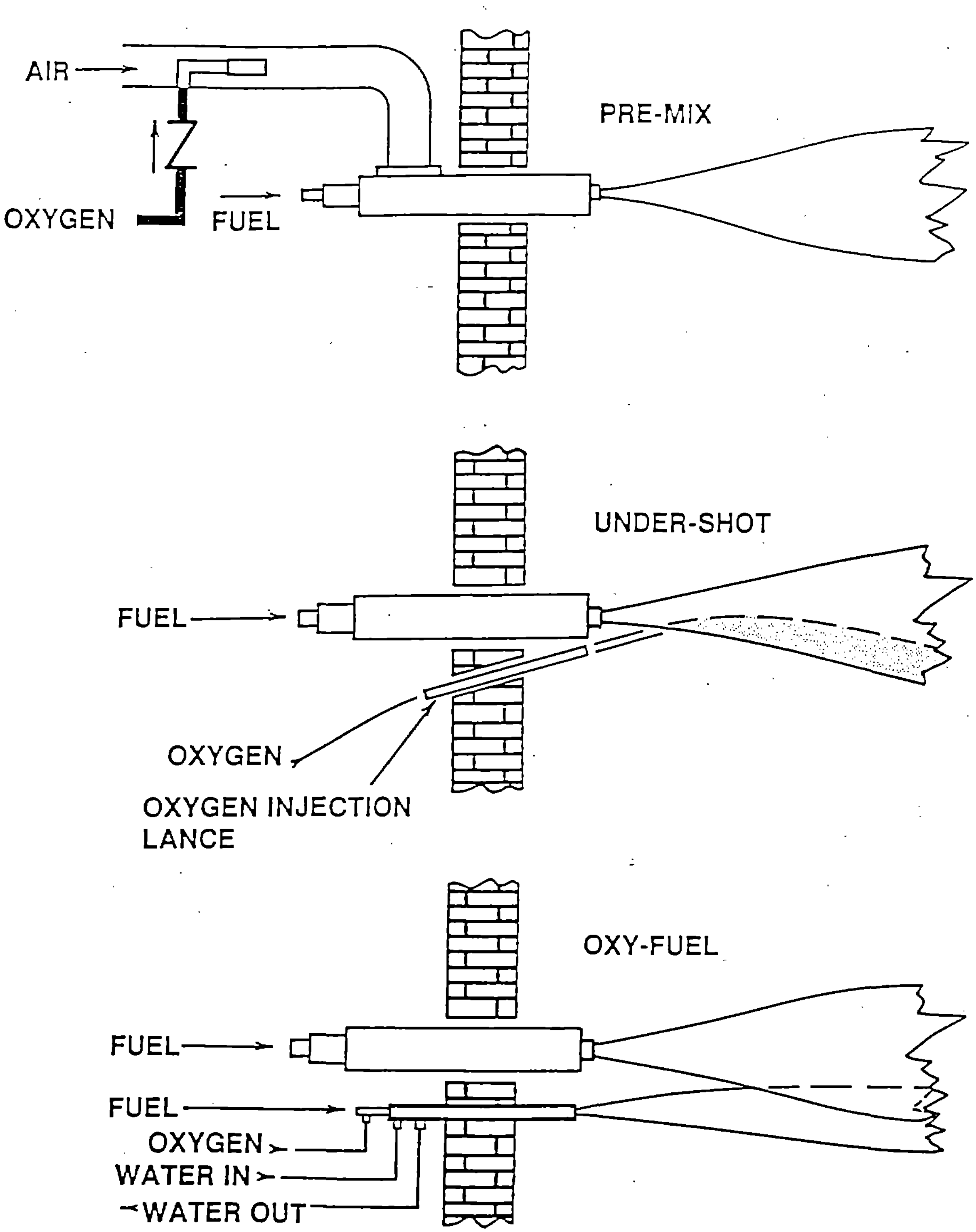


FIGURE 4

OXYGEN ENRICHMENT TECHNIQUES

than the premix technique, it can provide the temperature distributions required for certain applications. Minor, if any, furnace modifications are required to implement this technique.

Undershot enrichment is used when it is desirable to selectively provide modest additional radiant heat transfer from the flame to the product. Adjusting the angle and position of the oxygen lance controls the flame shape, length, and temperature. This technique has been used in steel and copper reverberatory furnaces, rotary kilns, and regenerative glass furnaces (for electric boost replacement and production increase).

The <u>oxy-fuel technique</u> uses an oxy-fuel burner to burn fuel with 100% oxygen. The flame pattern is small and intense, and the burner can be aimed so as not to impinge upon the refractories. Theoretical flame temperatures reach 5000°F, and, since nitrogen is eliminated, oxy-fuel burners combine the greatest benefits of the other techniques. Oxy-fuel burners are frequently water-cooled and may require furnace modifications. Payback on the oxy-fuel system is generally the shortest because savings are maximized and offset the larger capital expenditure required.

An oxy-fuel burner is especially suited for high-temperature melting applications in the metals, glass, and frit industries. The flame temperature of an oxy-fuel burner produces excellent radiant as well as convective heat transfer. Oxy-fuel burners are used either in conjunction with, or as a replacement for, existing burners.

2.3 Oxygen Production Technologies

The following description of oxygen/enriched air production technologies is limited to cryogenic distillation, adsorption, and membrane-based technologies. Other production methods were considered too far from commercialization to be evaluated in the present project.

1. Cryogenic Distillation

This technology involves liquefaction of air by a series of compressions and expansions with intermediate cooling, followed by distillation. Gaseous oxygen is produced on-site for large customers or for oxygen pipelines. Small customers (generally below 20 tons/day) are supplied liquid oxygen, since the costs of transportation and storage are much less than for compressed gaseous oxygen. Oxygen is used by a variety of industries, including medical, welding, and other industrial applications. Therefore, the purity of cryogenically produced oxygen streams is always greater than 99.9%.

The economics of producing and delivering liquid oxygen are sensitive to the cost of electricity, size and efficiency of the air separation plant, the monthly consumption rate of the user, and the distance from the plant to point of use. The schedule price of liquid oxygen is in excess of $120/ton ($0.50/100 cf), although it is not uncommon for large customers to pay $80/ton ($0.33/100 cf).

The cryogenic method of oxygen production is well-established and highly reliable. A major advantage of liquid oxygen is that it provides the user with the most flexible option should oxygen requirements fluctuate, i.e., paying only for amount consumed. The costs are insensitive to variations in instantaneous oxygen demand and average on-stream time.

2. Selective Adsorption

This technology involves alternate pressurization and depressurization of adsorbent beds that can adsorb one component of air (generally nitrogen) more selectively than the other. The adsorbents are either synthetic zeolites or activated carbons. The oxygen streams thus produced are about 90 to 95% pure.

The economics of producing highly enriched air by adsorption are sensitive to the installed capital cost, capacity utilization, and the price of electricity. In a less than 24-hour/day operation, and in operations in which the demand for enriched air may fluctuate, the overall capacity utilization of an on-site adsorption system is likely to be much less than the optimum. Economic evaluations performed by Air Products indicate that a typical, fully loaded 10-ton/day adsorption system may produce oxygen-enriched air at about $75/ton of equivalent liquid oxygen. However, actual costs for smaller units with partial capacity utilizations are likely to be higher.

The adsorption-based, highly enriched air production technology is reliable and well understood. Purity levels are not a problem for most of the anticipated combustion applications. However, the technology is not cost-competitive with partial capacity utilization, and therefore may be suited only to those applications that continuously need highly enriched air streams at a constant rate.

3. Separation of Membranes

This technology involves passing air over a membrane that is selectively permeable to one component of air (generally oxygen) compared to the other (generally nitrogen). The membranes are typically thin (<0.1 μ to 1 μ) polymer films (e.g., cellulose acetate, and polydimethyl siloxane). The membrane modules may be spiral-wound-hollow fibers or arranged as flat plates. The system may be operated under pressure, under vacuum, or a combination of the two. The concentration of oxygen in the enriched air stream under optimum conditions is limited to 30%, although current research efforts on new membranes may lead to improvements in purity.

The economics of producing enriched air by membrane technology are sensitive to the life of the membrane, total installed capital cost, the price of electricity, and capacity utilization. Similar to adsorption-based systems, overall capacity utilization of membrane systems is likely to be lower than the optimum in batch operations and in operations in which demand continuously fluctuates between high and low levels. Economic evaluations performed by Air Products indicate that a typical, fully utilized system producing enriched air equivalent to 10 tons of liquid oxygen per day may do so for about $60/ton of equivalent liquid oxygen. However, the actual cost of smaller units with partial capacity utilization is likely to be higher.

Application of membrane technology to the production of enriched air is relatively new, although membrane systems have been used in desalination and other gas separation processes. Questions regarding operational reliability and membrane life can be answered only after long-term pilot plant tests. The technology may be best suited only to those applications that need enriched air streams continuously at a relatively constant rate, and in which oxygen purity is not a factor.

2.4 Comparative Economic Evaluation of Low and High Purity Oxygen Production Technologies

Basic to the selection of oxygen technology is purity and cost. Figure 5 compares the economics of producing oxygen and enriched air by the three technologies discussed. Note that the economics are compared in terms of 1 ton of equivalent liquid oxygen. One ton of liquid oxygen is equivalent to

$$\frac{0.123\ (x)\ +87.7}{1.266\ (x)\ -26.6}\ \text{tons}$$

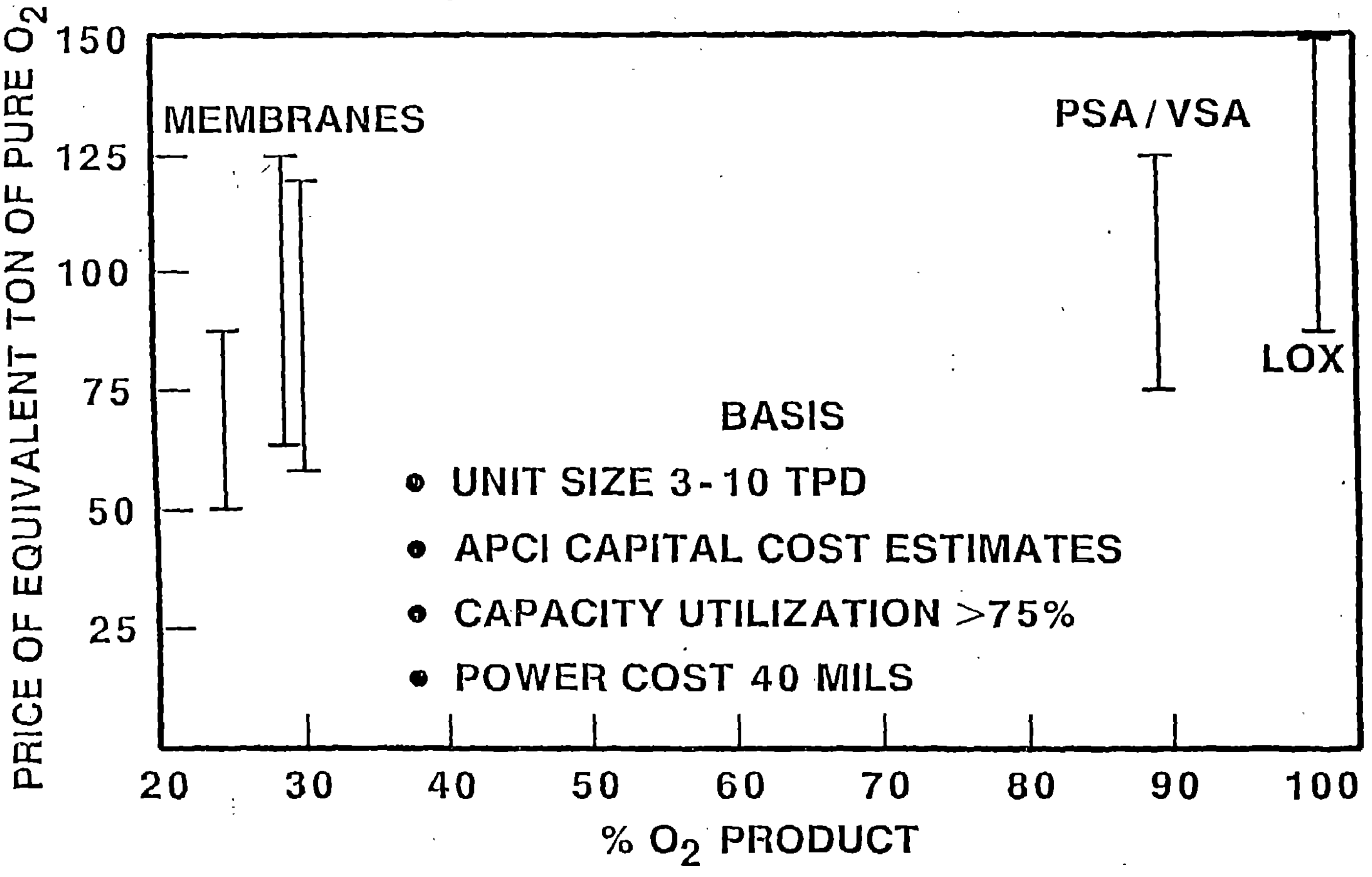
of an oxygen-containing stream that contains x% oxygen by volume.

There is considerable overlap on the cost of the technologies, so each combustion application site must be individually evaluated. The adsorption-based systems are marginally more economical than liquid oxygen, but liquid oxygen is insensitive to capacity utilization considerations. Fortunately, the purity levels of the two oxygen streams are not significantly different. Therefore, the research under the project is geared towards burners that use high-purity oxygen (>90%) for combustion of the fuel.

Enriched air streams from membrane systems were not considered further in this project. They are only semicommercial and offer no overwhelming cost advantage. Further, high-purity oxygen is desired in combustion applications. Not only does the presence of nitrogen promote NO_x emissions, but as pointed out in

FIGURE 5

ECONOMICS OF ENRICHED AIR / OXYGEN PRODUCTION



Section 2.1, the greatest benefits of oxygen are achieved at the high levels of enrichment approaching oxy-fuel conditions.

The benefits of oxy-fuel (high-purity oxygen) can be achieved at no added cost. A proprietary combustion model developed at Air Products indicates the breakeven price of oxygen for a given furnace application is proportional to the price of natural gas and is rather insensitive to the level of enrichment. In other words, if the cost of producing oxygen at a given site is independent of the purity level (Figure 5), the maximum reduction in operating costs is achieved at the maximum usage level of oxygen. Table 1 illustrates operating costs for a slot forge furnace.

Table 1

Effect of Enrichment Level
On Breakeven Oxygen Price

	3% Enrichment	Membrane-based 30% Oxygen Stream	Oxy-Fuel
Fuel Savings, %	26	46	69
Breakeven Oxygen Price, $/CSCF	0.52	0.52	0.55
Oxygen Consumption MMSCF/Month/Furnace	0.38	0.66	0.95
Operating Savings $/Month/Furnace	635	1128	1867

NOTE:
- Assumes furnace capable of heating 1 ton of steel per hour with 6MM BTUH fuel input.
- Natural gas at $5.00/MMBTU and oxygen at $0.35/CSCF (about $85/ton).

3. MARKET ASSESSMENT

3.1 Market and Process Characterization

Table 2 is a summary of the market characterization. Industries using natural gas to melt or heat materials at temperatures higher than 2000°F were characterized according to total natural gas consumption, process efficiency, continuous or batch operation, furnace type, and furnace sizes. Reports published by GRI, DOE, and various industry associations were used as sources of information.[1-13] A computer search was performed to ensure reasonable completeness and accuracy.

In Table 3, the specific processes are further characterized as to operating parameters and predicted benefits to oxygen. The information concerning the nature and cleanliness of the furnace atmosphere and the types of air-fuel burners used today is based primarily on Air Products' industry contacts. The information on the percentage of furnaces using recuperation is based on literature data[1-16] and may underestimate the actual current use of recuperators. Estimated percent fuel savings and percent reduction in flue gas volume when using oxy-fuel are both based on predictions made by the Air Products proprietary furnace model. The numbers shown are for complete conversion of an air-fuel fired furnace without recuperation to the oxy-fuel technology. The variation in percent fuel savings is the result of different types

Table 2: MARKET ASSESSMENT

	Industry	Production (Yr) (Million Tons)	Furnace			Process Temperature (°F)	Energy Used (10^{12}BTU/yr)	Process Efficiency (%)	Batch or Continuous
			Type	No.	Size				
1.	Forging Iron & Steel	5-10	Box slot	Total 8000-18000	0.25-2 tons/hr	2300-2500	100 (1978)	3-20	Batch 1-2 shifts/day
2.	Soaking Pits	~ 50 (1979)	One-way fired, two-	Total ~ 1000	10-200 tons capacity	2300-2500	50 (1979)	20-30	Batch 3 shifts/day
3.	Reheat Fces	~ 100 (1979)	Two, three or five zone	Total ~ 850	2-10 TPH	2500	250 (1979)	30-40	Continuous
4.	Induction Fces Iron & Steel	7-10	Coreless channel	Total 4000-5000	<1-100 tons capacity	up to 3000		70-85	Batch 1-2 shifts/day
5.	Secondary Aluminum	3-6 (1976)	Reverbs Open well	Total 250	5-50 tons capacity	2000-2200	35-70 (1976)	10-25	Batch 3 shifts/day
6.	Aluminum Melting for Castings	1.5-2 (1981)	Reverbs Crucible Induction	1474 5535 1111	0.25-5 tons capacity	2000-2200	8-10	10-20	Batch 1-2 shifts/day
7.	Secondary Brass and Copper	2 (1976)	Reverbs Rotary	200-300	1-50 tons capacity	2200-2500	5-7	10-20	Batch 1-3 shifts/day
8.	Fiber Glass	2.7 (1983)	Unit melters	~ 100	20-150 TPD	2500-2800	20-40	25-35	Continuous
9.	Pressed and Blow Ware	2 (1977)	Regenerative, Unit melters Day tanks	~ 200	5-200 TPD	2500-2900	15-40	15-50	Continuous Batch
10.	Frit Smelters	0.3-0.5	Box smelters Rotary	~ 75	10-30 TPD	2000-2900	3-5	10-20	Continuous Batch

Table 3: TECHNOLOGY ASSESSMENT

	Industry	Temp °F	Flue Gas	Use of Recuperators	Air Fuel Burners	Fuel Sav. %	Prd. Rate Increased %	Flue Gas Reductions %	Quality
1.	Forging	2300-2500	Clean	10%	High excess air Slow mixing 1-6 MMBTU/HR	60-70	10-20	<90	
2.	Soaking Pits	2300-2500	Dirty	70%	Slow Mixing 10-30 MMBTU/HR	60-75	10-20	<90	
3.	Reheat Furnaces	2500	Clean	75%	Slow mixing 5-20 MMBTU/HR	30-40	10-20	<70	
4.	Induction Furnaces	Up to 3000	N/A	N/A	None	5-15	10-20	N/A	
5.	Secondary Aluminum Melting	2000-2200	Dirty Corrosive	5%	Slow mixing being replaced with high-velocity 1-20 MMBTU/HR	50-60	10-20	>80	
6.	Secondary Brass Copper Melting	2200-2500	Dirty Corrosive	5%	Slow mixing 1-10 MMBTU/HR	60-70	10-30	>90	
7.	Fiber Glass Melting	2500-2800	Dirty Corrosive	80%	Standard nozzle-mix 1-2 MMBTU/HR	65-75	10-20	>90	Improved
8.	Pressed and Blow Ware	2500-2900	Dirty Corrosive	75% some with regenerators	Standard nozzle-mix 1-2 MMBTU/HR	65-75	10-30	>90	Improved
9.	Frit Smelting	2000-2900	Dirty Corrosive	0%	Nozzle-mix 1-2 MMBTU/HR	65-75	10-50	>90	Improved

of furnaces operating at different process temperatures rather than any inaccuracy of the computer model. Our model has been shown to agree well with the actual data collected in field tests. The impact of oxygen enrichment on quality and rate of production is based on Air Products' industry experience.

Industry segments which are ideal for the application of oxygen enrichment technology are those having a large number of furnaces, using a large amount of energy, where process temperatures are high, process efficiencies are low, flue gases are dirty and corrosive, and where well-designed oxy-fuel burners may duplicate or exceed the performance of the existing air-fuel burners. A general economic analysis of the benefits of oxygen in any industrial segment is difficult to perform because the costs of both energy and oxygen vary with specific circumstances. Also, in most cases the substantial savings due to quality improvement and reductions in flue gas volume are difficult to quantify.

In furnaces already equipped with recuperators or regenerators, oxygen enrichment may still be economically viable. Oxygen may be used to increase the rate of production, improve product quality, increase the length of a campaign, or address other specific combustion problems. In general, the percent fuel savings achieved as a result of oxygen enrichment in a recuperated furnace is less than that achieved in a nonrecuperated furnace. For example, Air Products' furnace model indicates that for a 2500°F nonrecuperated furnace, installation of oxy-fuel burners would lead to 65% fuel savings. On the other hand, if the furnace were equipped with a recuperator preheating the combustion air to 1000°F, installation of oxy-fuel burners would lead to a 40% reduction in the firing rate.

Some aspects other than fuel savings need to be considered when analyzing oxygen enrichment in furnaces equipped with heat recovery. Since the air rate is reduced as a result of oxygen enrichment, the resulting efficiency leads to higher air preheat temperatures and may or may not cause recuperator, regenerator, and burner materials to fail. As the level of enrichment increases, the volume of flue gases decreases. Less draft is needed as the flue gas flow rate is reduced. The reduced draft requirement may alleviate the problem of high positive furnace pressures or may require proper control of negative furnace pressures.

3.2 Recuperation vs. Oxygen Enrichment

The brief discussion presented here is an attempt to assess the competition between recuperation and oxygen enrichment for the industries studied under the market assessment task. Table 4 is a summary of the discussion.

Table 4: RECUPERATION

Industry	Capital M$/Fce	Payback Years	Annual Maintenance % of Capital	Physical Constraints	Increase in NO_x	Increase in Furnace Pressure	Current Use %
1. Forging Iron & Steel	25-35	2-3	5-15	Moderate	Yes	Yes	<5
2. Soaking Pits	200-300	2-3	10-15	Severe	Yes	Yes	70
3. Reheat Furnaces	1000-1500	2-3	5	Severe	Yes	Yes	80
4. Induction Furnaces	-	-	-	--	---	---	--
5. Secondary Aluminum Melting	200-1000	2-4	10-20	Moderate to Severe	Yes	Yes	5
6. Secondary Brass & Copper	100-750	1-3	5-10	Moderate to Severe	Yes	Yes	5
7. Fiberglass	1000-1500	2-3	5-10	Moderate	Yes	Yes	80
8. Pressed & Blown Glass	500-1000	2-4	10-20	Moderate	Yes	Yes	75

Natural Gas at $5/MM BTU's

- Capital Costs: Capital costs vary depending on the size of the recuperator, the type of recuperator, and the air preheat temperature. The costs shown in Table 4 include the recuperator, related piping, hot air burners, draft control, other related controls, engineering, and installation. The recuperators capable of supplying high air preheat temperatures (>1000°F) are more expensive than those with lower air preheat temperatures (<1000°F). In general, the capital cost of recuperation is 5-10 times that of oxy-fuel burner systems.

- Maintenance: It is difficult to determine average maintenance costs, even for a particular type of recuperator in a specific industry segment.[14] Maintenance costs can be expected to be high if the furnace is operated in a fuel-rich mode, and if there are frequent start-ups and shutdowns. Realistically, maintenance costs should include not only the cost of materials and labor, but also the extra fuel cost when the recuperator is not in service, as well as the cost of furnace downtime. Total maintenance costs can be very high (e.g., 20% of initial capital) compared to those for an oxy-fuel burner system.

- Payback: The payback period for an oxy-fuel burner system rarely exceeds 12 months. The payback periods for recuperators often exceed 2 or 3 years.

- Physical Constraints: Recuperators take up a lot of physical space, and retrofitting a furnace with a recuperator may not always be possible. Oxy-fuel burner systems do not require significant physical space, and therefore are easier to install.

- Emissions: NO_x emissions have been shown to increase up to 10 times when preheated air is used for combustion instead of cold air.[15,16] The reduced temperature of exhaust gases from the recuperator may cause fouling of heat transfer surfaces. NO_x emissions increase with low level oxygen enrichment, however, with oxy-fuel burner systems they are not expected to be a problem. With oxygen enrichment, the temperature of the flue gases is not reduced substantially, and the volume of flue gases has been shown to decrease by more than 90%.

- Furnace Pressure: An oxy-fuel burner system reduces the volume of flue gases and alleviates the problem of high furnace pressure. On the other hand, recuperators cause a flow restriction and tend to increase furnace pressure. Normally, reliable furnace pressure controls are recommended as part of the recuperation package.

- Changes in Process Parameters: With the recuperator as well as with the oxy-fuel system, the process parameters need to be readjusted. The controls can be complex, and lack of familiarity necessitates good operator training.

In summary, recuperators are a good investment in those cases in which the flue gases are clean, maintenance costs can be expected to be low, there are no physical constraints and no limitations on NO_x emissions, furnace pressure problems can be alleviated, and the high capital costs and long paybacks are acceptable. In all other applications, oxy-fuel systems appear to have a competitive advantage.

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4. OXYGEN ENRICHMENT OF COMMERCIAL AIR-NATURAL GAS BURNERS

4.1 Test Facility

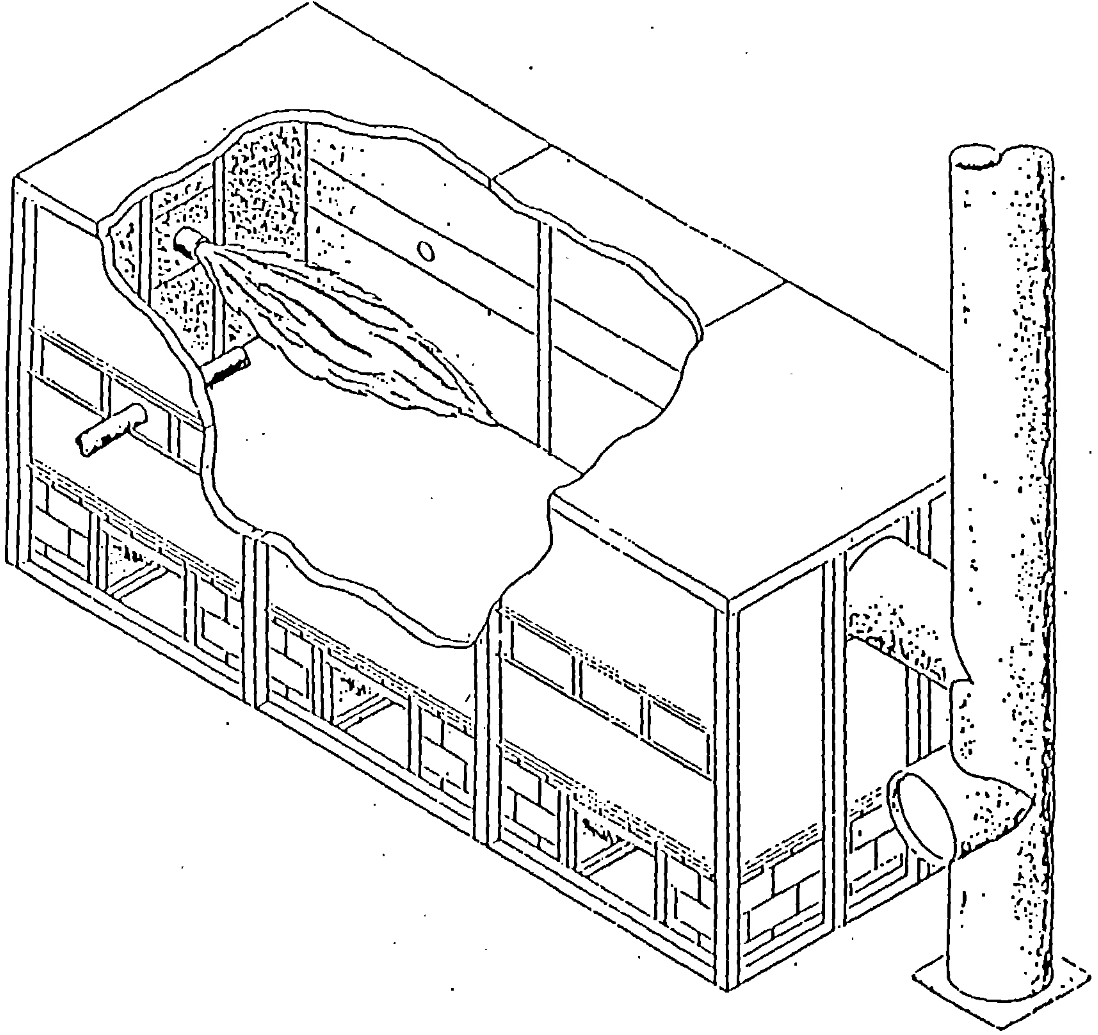
The burner test facility, shown schematically in Figure 6, is a 20'x8'x5', refractory-lined, water cooled furnace. A single test burner fires from one end with the flue located at the opposite side. The furnace is capable of firing burners rated up to 10 MMBTU/Hr at temperatures approaching 2500°F. It is instrumented with thermocouples that are mounted through the furnace wall panels, roof, and flue. Access ports are located along the sidewalls that permit flame observation as well as gas temperature and heat flux determinations.

A separate control room houses a process computer that monitors air, oxygen, and natural gas flow rates, furnace temperatures, gas temperatures, and flue gas composition. A number of safety interlocks prevent potentially unsafe operation.

4.2 Test Procedure

- The desired firing rate, air, oxygen, natural gas, and stoichiometry are the basic inputs to the system. Air, oxygen, natural gas flows, and associated pressure drops are controlled and continuously monitored by the process computer in the control room. Oxygen concentration in the enriched

FIGURE 6
BURNER TEST FACILITY



air stream, furnace temperature profile, and flue gas temperature are also continuously monitored.

- The furnace is allowed to reach thermal equilibrium under the conditions of interest. Equilibrium is defined when a thermocouple, located at the center roof position, varies not more than 15°F over 15 minutes.

- The furnace and burner internals are continuously monitored by the thermocouples for over-temperatures. For the burners, thermocouples are located at the pilot hole with the tip near the face of the burner nozzles.

- Flow gases are sampled regularly on-line, dried, and analyzed for CO, CO_2, NO, and excess oxygen. The CO level is maintained at less than 200 ppm. Standard infrared analyzers are employed which are calibrated using known compositions at two or more points.

- Negative furnace pressure is controlled by a flue damper to keep air infiltration to a minimum.

For the NOx tests described in Section 7.5, extra precautions were taken to seal the furnace, and the furnace pressure was maintained positive (ca + 0.1" water) so as to eliminate air infiltration.

- Suction pyrometer and heat flux probe measurements are taken after the furnace reaches equilibrium. Table 5 shows measurements taken on only one side of the longitudinal axis, at the following positions:

Table 5

Probe Positions

Distance Measured From the Burner Axis, ft	Distance from the Burner Along the Furnace, ft		
	3.9	7.3	13.8
0	x	x	x
1.3	x	x	x
2.5	x	x	x
2.8	x		x

The suction pyrometer is fully water-cooled and houses a thermocouple as the measuring device. The pyrometer aspirates the furnace gas over the thermocouple at very high speed to increase the convective heat transfer. The thermocouple is surrounded by a number of concentric radiation shields. These two features improve the measurement accuracy to be within ±20°F.

The heat flux meter is a cylindrical probe with a black, serrated front surface. The rear of the probe is water cooled. When subjected to heat flux, the front of the detector becomes hot creating a temperature gradient through the length of the probe. The incident heat flux is obtained by measuring the temperature of both ends of the probe with two thermocouples.

The measurement error is ±20°F for the suction pyrometer and ±2 M BTU/hr ft^2 for the total heat flux meter. The data are statistically screened, analyzed, and fitted to a general expression containing exponential and polynomial functionalities. The root mean square error of the fit between the model and the data is 80°F or better for the suction pyrometer and 6 M BTU/hr ft^2 for the total heat flux meter. Symmetry around the longitudinal axis has been assumed in generating the contour plots, . Furnace sidewall temperatures support this assumption.

Although shown in the contour plots, extrapolation is not expected to be reliable less than 4 feet away from the burner along the axis of the flame.

4.3 Burner Selection

The objective of this phase of the project was to evaluate the impact of oxygen enrichment on the performance of existing, commercial air-natural gas burners. Of particular importance was burner survivability at high levels of enrichment since it was shown that the maximum benefits are achieved at greater than 50% oxygen enrichment.

To make use of existing burner expertise and insure commercial relevance, major burner manufacturers serving the heating/melting process industries were contacted. Each manufacturer was provided with the opportunity to nominate a burner model most likely to perform well at high levels of enrichment. The following burners, schematically shown in Figures 7-12, were evaluated in the program:

- Surface Combustion (Figure 7)
- North American 4425-8A (Figure 8)
- North American 6514-8B (Figure 9)
- Maxon Kinemax Series G (Figure 10)
- Bloom 1250-012 (Figure 11)
- Eclipse MVTA-248 (Figure 12)

Each burner is summarily characterized in Table 6. In addition to design parameters, market factors such as application, market position, and cost were considered. Since each burner was a candidate for subsequent retrofit modification during this project, existing patent coverage was also considered.

These burners are a representative cross section of the important heating/melting markets in the glass and metals industries (see Section 3.1). Technically, all burners are of the common

FIGURE 7

SURFACE COMBUSTION ENRICHED AIR BURNER

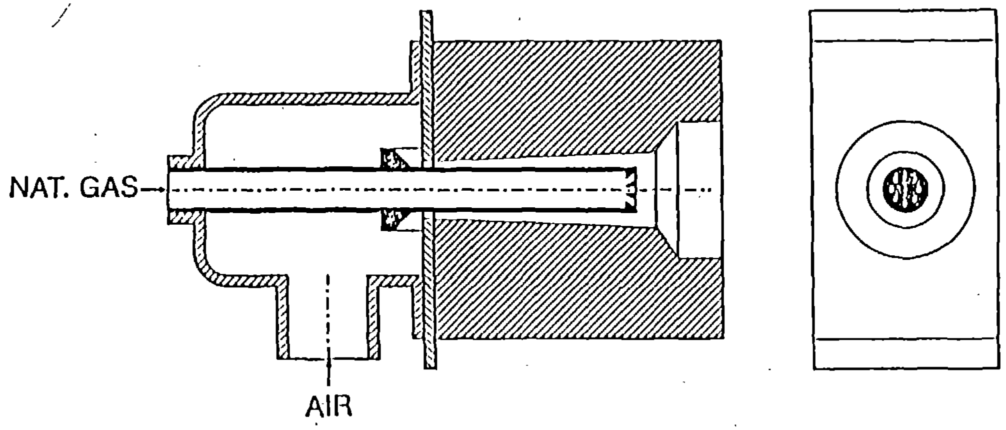


FIGURE 8

NORTH AMERICAN 4425

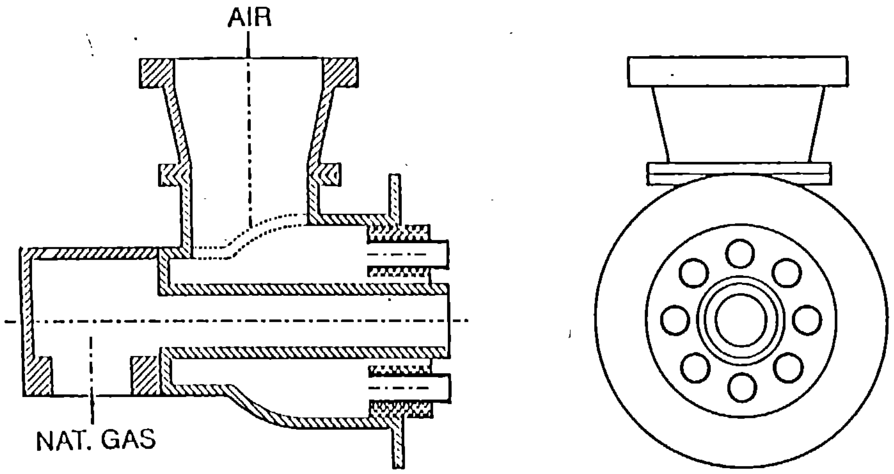


FIGURE 9

NORTH AMERICAN 6514
NAT. GAS

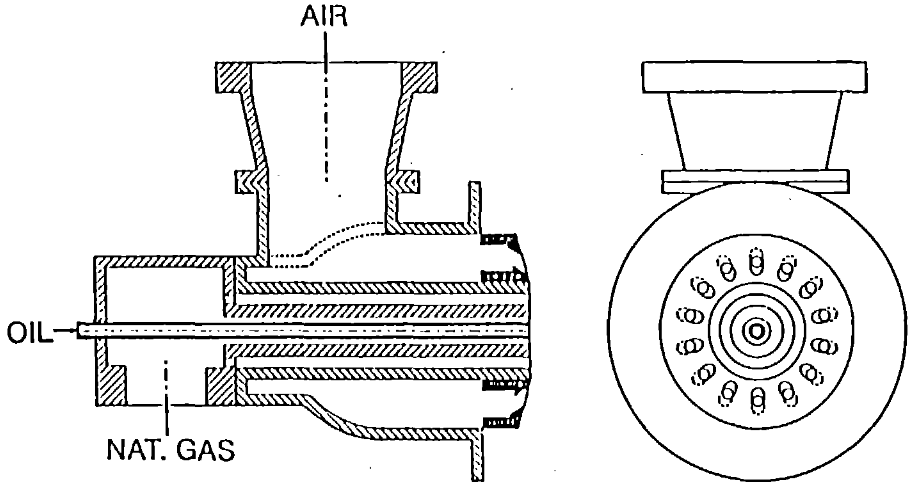


FIGURE 10

MAXON KINEMAX – G

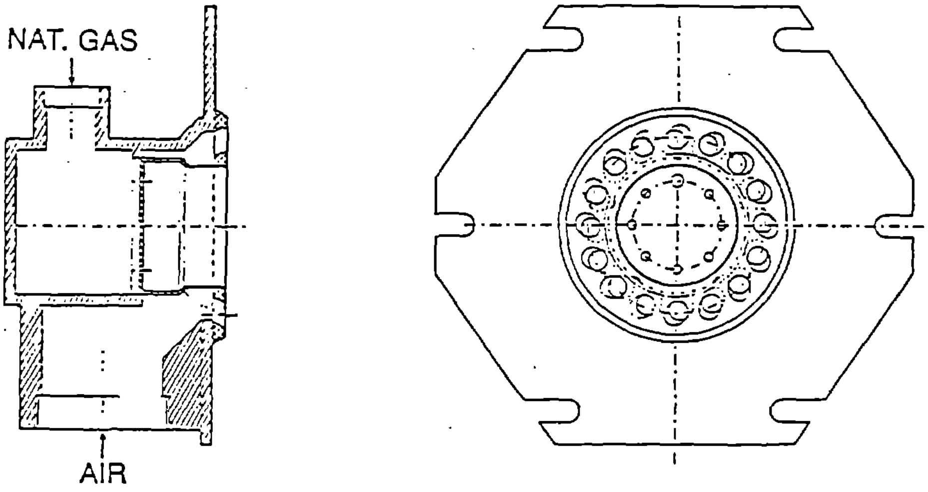


FIGURE 11

BLOOM BURNER 1250 – 012

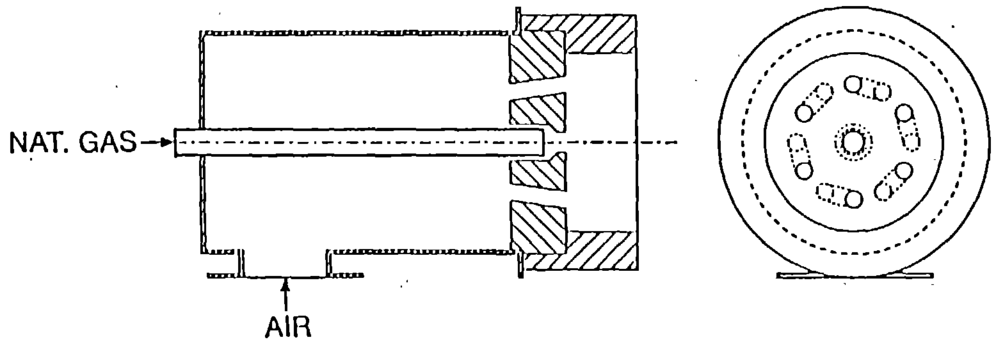


FIGURE 12

ECLIPSE MVTA-248 BURNER

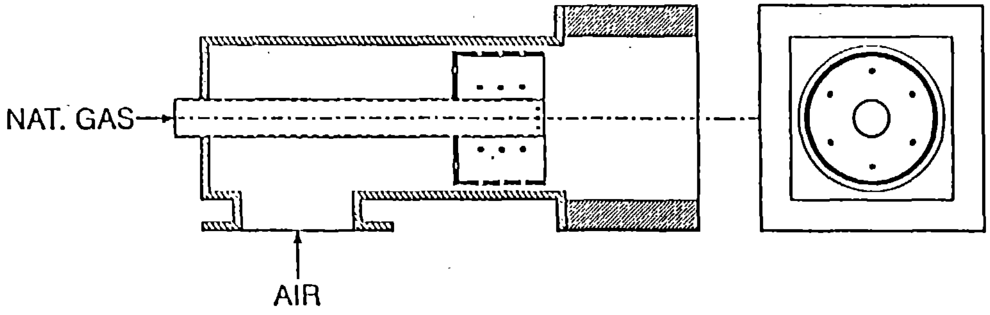


Table 6: BURNER SELECTION

Burner Mfgr	Surface Combustion	North American MFG	North American MFG	Maxon Corp	Bloom Eng	Eclipse Inc
Burner Type	Enriched Air	4425-8A	6514-88	Kinemax Series G	1250-012	MVTA-248
Schematic	Figure 7	Figure 8	Figure 9	Figure 10	Figure 11	Figure 12
MMBTU/Hr @ 1 PSIG Air	4.0	4.0	7.0	4.0	5.5	4.5
Price, $/Burner	3000	1000	2500	1500	6000	1200
Applications						
Industry	Soaking Pits Reheat Furnaces	Glass Melting Forging	Forging Nonferrous Melting	Glass Melting Forging	Soaking Pits Reheat Furnaces	Kilns Heat Treating
Industry Position	None	Excellent	Excellent	Fair	Excellent	Fair to Poor
Patents	Expires 1991	None	None	None	Expired 1982	None
Design Parameters						
Size & Weight	Average	Average	Large & Heavy	Average	Very Heavy & Very Large	Average
Materials	Standard	Inconel			High Temp. Refractory	
Stability		Premix Holes				Premix Holes
Tile Design	Tapered Step	Cylindrical	Cylindrical	Cylindrical	Cylindrical	Cylindrical
Air Flow	Swirl/Tangential Slots 170.2 fps	Straight Tubes 333.3 fps	Diverging Holes 274.5 fps	Swirl Plate 195.1 fps	Diverging Swirl Refr 318.8 fps	Large Tunnel 129.7 fps
Gas Flow	Swirl & Straight 320.0 fps	Open Tube 106.7 fps	Annual Space 51.9 fps	Straight Holes 100.0 fps	Open Tube 122.2 fps	Open Tube 160.0 fps
NG/Air Ratio,						
Area	0.05	0.31	0.53	0.2	0.26	0.08
Velocity	2.0	0.32	0.19	0.50	0.38	1.14

nozzle-mix type and rated at 4 to 7MMBTUH with 1 PSIG air. The natural gas was typically fed at the center of the burner. Some burners incorporated the means of generating swirl in the combustion air. One, the North American 6514, is a dual fuel (natural gas or oil) design. Only the Surface Combustion burner is specifically designed for oxygen enrichment. With exception of the Surface Combustion and perhaps the Bloom burners, which are aerodynamically stabilized, the burner flames are hot block stabilized. Since oxygen increases flame temperature, one might expect moving the flame from a hot block configuration would enhance survivability.

4.4 Burner Evaluation

Table 7 summarizes the results of the six burners tested. The results indicate conventional air-natural gas burners are capable of using oxygen enriched air at concentrations up to 30% oxygen. Above this level, all burners experienced progressive performance deterioration as indicated by shorter flame length, skewed heat release, increased burner temperature, and soot formations.

The specific results obtained for each burner as well as process implications are given in Appendix A. A nonproprietary version of these results was provided to each respective burner manufacturer. The results obtained with the North American 4425 are illustrative.

Table 7: PERFORMANCE SUMMARY
UNMODIFIED COMMERCIAL AIR-FUEL BURNER

BURNER	PERFORMANCE			
	26% O_2	35% O_2	100% O_2	MAXIMUM BURNER TEMP., °C
SURFACE COMBUSTION	EXCELLENT	EXCELLENT	FAIR	400
BLOOM ENGINEERING	EXCELLENT	GOOD	FAIR	400
MAXON KINEMAX	GOOD	FAIR	FAIR	325
NA4425	GOOD	FAIR	POOR	450
ECLIPSE MVTA248	FAIR	POOR	FAILED (NG/O_2 TUBE SCALING)	-
NA6514	GOOD	FAILED	-	1175

Furnace Temperature

The reference furnace temperature was measured at the center of the roof. The variation of furnace temperature with increasing firing rates and increasing oxygen enrichment levels is shown in Figure 13. The temperature increased significantly with increased firing rates and enrichment levels for all the burners tested. The data clearly indicate that reduction of the firing rate combined with oxygen enrichment will maintain a constant furnace temperature. The data also show the potential for increase in furnace temperature with oxygen enrichment at a constant firing rate; the increase in the furnace temperature leads to an increased rate of production.

Furnace Temperature Uniformity

The difference between the temperature at the center of the roof and that at the center of the hearth is shown in Figure 14. This difference is used as a measure of furnace temperature uniformity. The sidewall temperatures were symmetrical about the flame axis. The data show that furnace temperature uniformity was better at higher firing rates and low oxygen enrichment levels. This appears to be a direct result of an increase in the combined volumetric flow rates of the fuel and the air stream. Increased volumetric flow rates led to higher velocities and better temperature uniformity.

FIGURE 13. FURNACE TEMPERATURE
NORTH AMERICAN 4425-8A

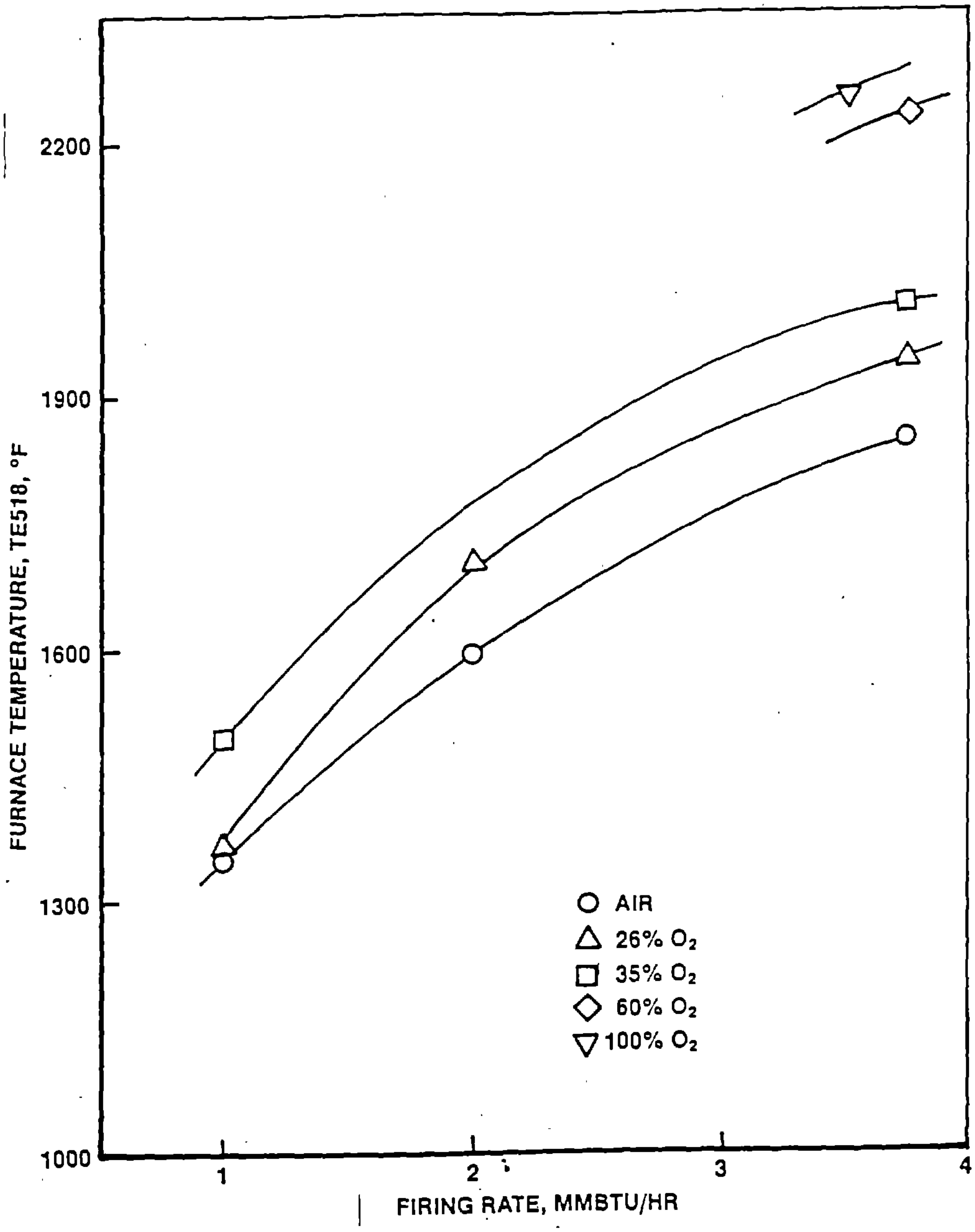
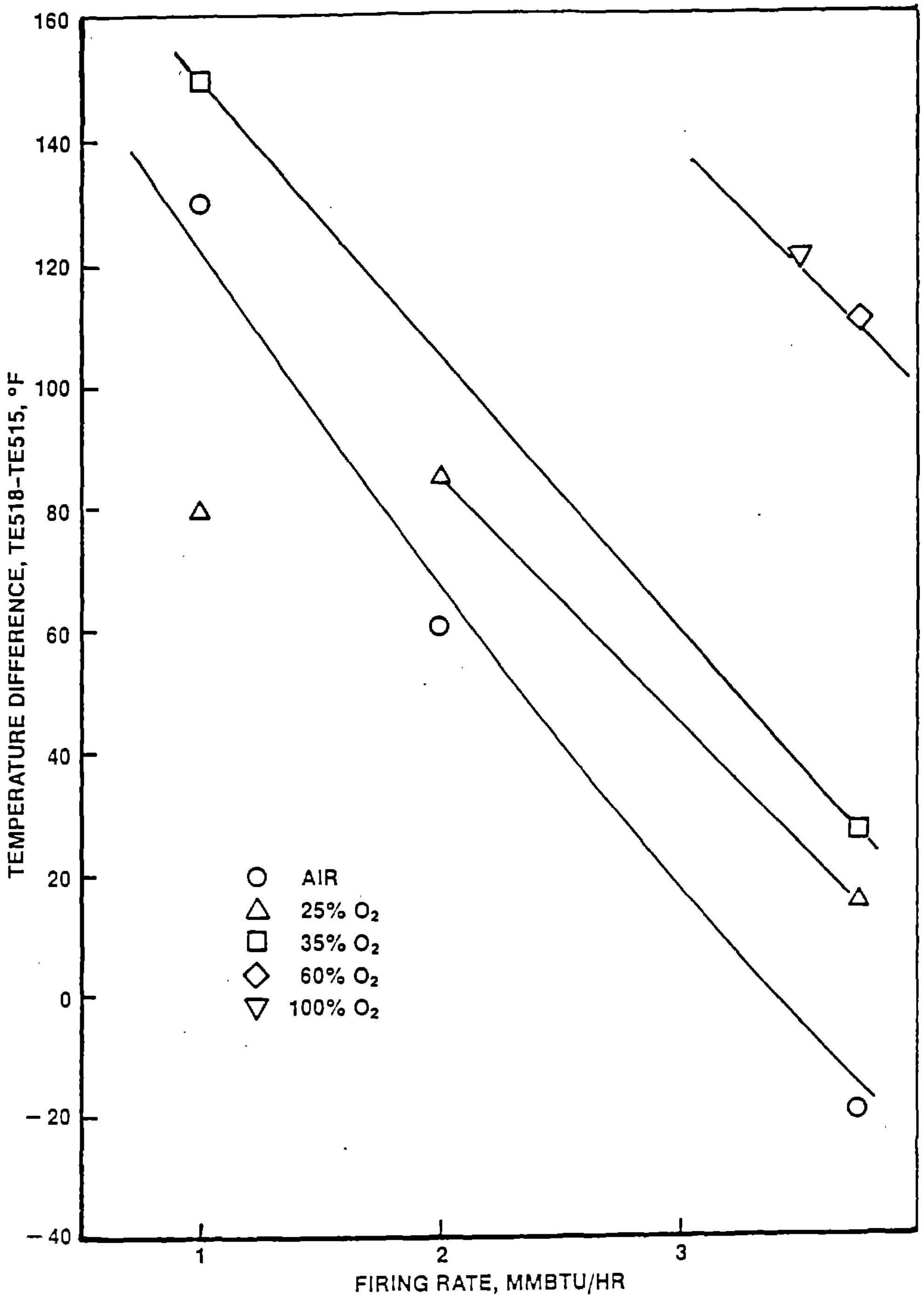


FIGURE 14. TEMPERATURE UNIFORMITY
NORTH AMERICAN 4425-8A



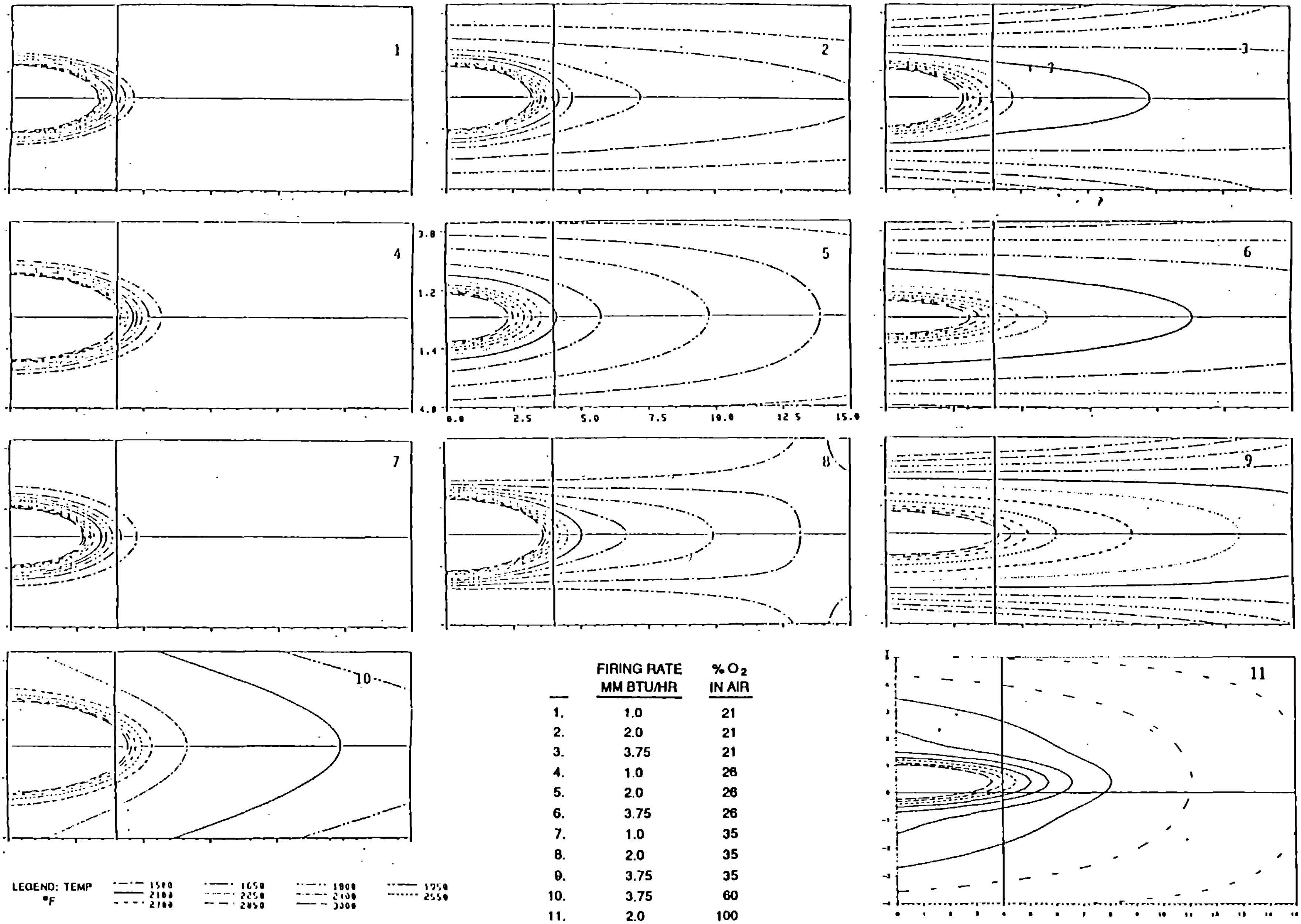
Gas Temperature Profiles

A suction pyrometer was used to measure gas temperatures at various locations inside the furnace. After statistical analysis, the data were reduced to isotherms in the central plane along the length of the flame. For reasons of clarity, only two isotherms (2200° and 2250°F) are presented here.

As shown in Figure 15, the effect of firing rate on the isotherms was much greater than the effect of oxygen enrichment. The variations in the temperature profiles obtained with all the burners were qualitatively similar. At a constant oxygen concentration in the combustion air, increased firing rates lead the contours away from the burner. Increasing the oxygen concentration from 21% to 35% at a constant firing rate has minimal affect except in the core of the flame. Gas temperatures in the core of the flame increase with oxygen and firing rate. At very high concentrations (60-100%), the temperature profiles show some broadening and inconsistent longitudinal movement.

FIGURE 15. NORTH AMERICAN MFG. BURNER MODEL 4425

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F



	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	1.0	21
2.	2.0	21
3.	3.75	21
4.	1.0	26
5.	2.0	26
6.	3.75	26
7.	1.0	35
8.	2.0	35
9.	3.75	35
10.	3.75	60
11.	2.0	100

The data in Figure 15 indicate that low level oxygen enrichment can be used for production increase purposes without significantly affecting flame length or shape. However, if higher enrichment levels are to be achieved, careful attention must be given to changes in the flame length and shape.

Total Heat Flux Profiles

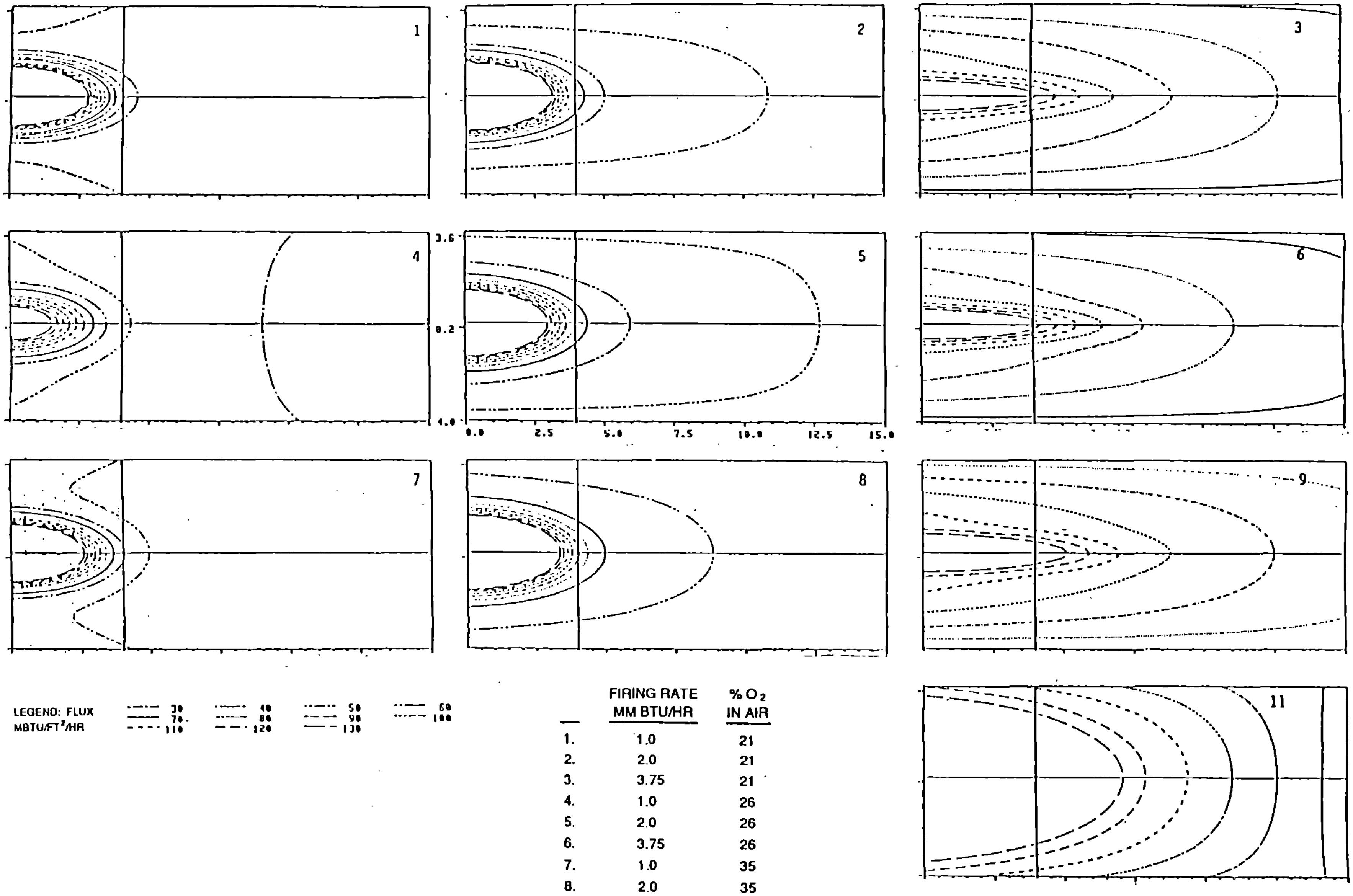
The data obtained by the total heat flux meter are reduced to the iso-heat flux contours presented in Figure 16. At a constant oxygen concentration in the air, increased firing rates lead to substantial longitudinal movement and some narrowing of the contours. At a constant firing rate, increasing the oxygen concentration from air to 26% leads to no substantial changes. The contours appear to move away from the burner with no broadening as the oxygen concentration is increased to 35% at a constant firing rate. The heat flux profile with 100% oxygen is noticeably broad and very steep along the length of the flame.

NOx Emissions

Data collected by an infrared analyzer have been corrected to 0% oxygen in the flue and have been plotted as a function of the firing rate and the oxygen concentration in the combustion air.

FIGURE 16. NORTH AMERICAN MFG. BURNER MODEL 4425

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT²/HR



	FIRING RATE MM BTU/HR	% O₂ IN AIR
1.	1.0	21
2.	2.0	21
3.	3.75	21
4.	1.0	26
5.	2.0	26
6.	3.75	26
7.	1.0	35
8.	2.0	35
9.	3.75	35
10.	3.75	60
11.	3.5	100

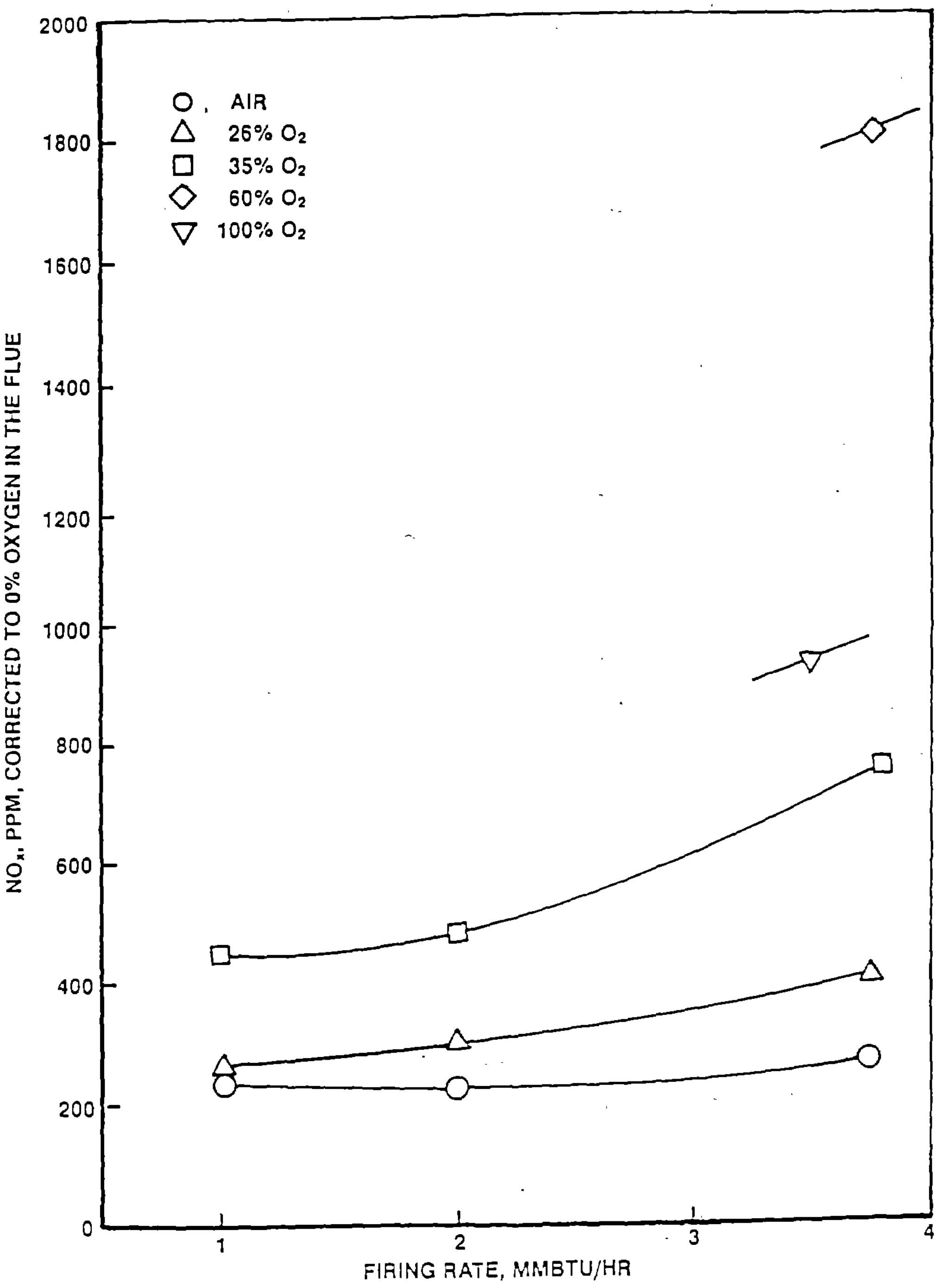
Figure 17 indicates that for up to 60% oxygen in the combustion air, NOx emissions increase strongly with increasing O_2 concentration in air and only weakly with increasing firing rates. NOx emissions with close to 100% oxygen in the combustion air, however, are much lower than for 60% oxygen in the combustion air.

Fuel-Air Mixing

A higher percentage of excess oxygen in the flue (i.e., higher excess air) is needed to achieve complete combustion when the firing rate is low and the enrichment level is high. This appears to be a result of decreasing volumetric flow rates through the burner which reduces the intensity of mixing. CO level could be maintained below 100 ppm with only 1% excess oxygen when firing with up to 35% oxygen in air. For higher enrichment levels, 4 to 6% excess oxygen was needed for complete combustion.

The color of the flame changed from blue to yellow to a bright cream color as the enrichment level was increased from air to 35% O_2 in air to 100% oxygen. Sooting was observed on the probes at high enrichment levels and low firing rates.

FIGURE 17. NO_x EMISSIONS
NORTH AMERICAN 4425-8A



Burner Temperatures

One of the important considerations when employing oxygen enrichment is the physical survival of the burners. Burners were typically instrumented to measure the temperature near the face of the burner nozzle. The temperature levels measured with the various burners were widely different and showed no consistent trend. In some cases the temperature never exceeded 600°F, but in others the temperature levels were much higher and rose sharply with oxygen enrichment. Based on metallurgical considerations, 1100°F is considered to be the upper limit for physical survival of metallic burner components.

4.5 Conclusions

Oxygen enrichment leads to an increase in flame temperature with no change in fuel input. This observation indicates that oxygen is a useful means to reduce flue gas volume, conserve energy, and increase production in heating and melting processes. Care must be exercised particularly at high enrichment levels and firing rates, since there is a reduced furnace temperature uniformity with no change in fuel input, and a concentration of the gas temperature and heat flux profile at the burner. The furnace should be operated with higher excess oxygen to counter reduced fuel-air mixing.

In as much as the burners evaluated are representative of air-natural gas burners on the market, all burners can be enriched to 30% oxygen. All burners evaluated in this project performed well up to 9% enrichment (30% oxygen).

The aerodynamically stabilized Surface Combustion and Bloom burners were acceptable at all levels of enrichment.

The hot block stabilized North American 4425 and Maxon Kinemax burners performed well only up to moderate oxygen levels, suggesting that higher flame temperature resulting from enrichment was limiting. The North American 6514 dual fuel and Eclipse burners failed at $\geq$35% oxygen. This suggests any oxy-fuel conversion technology should consider moving the flame away from the burner tile.

At levels of enrichment above 35% oxygen, performance progressively deteriorated due to loss of flame momentum and poor mixing. These results can be attributed to the reduced volumetric air flow from the air tubes as one progressively replaces the nitrogen in the air with oxygen, and suggests one needs to increase oxidant velocity in any oxy-fuel conversion technology.

5. OXY-FUEL MODIFICATION TECHNOLOGY

5.1 Development Criteria

In contrast to low level enrichment, it has been shown that the maximum economic benefits to oxygen enrichment are achieved at oxy-fuel conditions; i.e., 90-100% oxygen. Furthermore, NOx emissions increase initially with enrichment, but are minimized at 100% oxygen (see Section 7.5). The technical objective of developing new burner systems for high levels of oxygen enrichment is to minimize the undesirable effects of enrichment such as short flame lengths, skewed heat release patterns, potentially excessive temperature levels, material compatibility, and NOx generation, while maximizing the desirable effects such as increased fuel efficiency, increased productivity, reduced total emissions, and reduced production costs.

As was demonstrated, existing air/natural gas burners cannot survive or produce acceptable flame characteristics at oxygen levels >35%. As previously noted, current oxy-fuel technology requires replacement of the existing air-natural gas burners with oxy-fuel burners, usually water-cooled, specially designed to handle the resulting high flame temperature. The new flame characteristics are usually quite different. Although effective and currently used in many applications, burner switchout can be expensive, requiring furnace wall modifications, and caution and experience are necessary when using these higher temperature flames.

The goal was set to develop burner modification technology to convert existing air/natural gas burners to fire at oxy-fuel conditions while maintaining burner life, and similar flame characteristics as with air except at reduced fuel input.

5.2 Burner Selection and Strategy

The two burners selected for modification and further testing were:

- North American 4425-8A
- Maxon Kinemax G

Cross sectional schematics of each appear in Figures 8 and 10, respectively.

The major factors in the selection were:

(1) Intermediate performance during previous enrichment testing. Although flame characteristics were only fair to poor, both survived oxy-fuel conditions.

(2) Good potential retrofit market. Both burners have a fair to excellent market position in the targeted metals and glass industries (see Tables 2 and 6) where fuel/process efficiency is important.

(3) Original designs are nonproprietary.

(4) Not too bulky or heavy.

(5) Reasonably priced.

The experimental approach was to first test any modification technology in Air Products' open-air burner facility to test survivability. If warranted, the burner was further characterized in the combustion lab furnace. The lab furnace was described in Section 4.1. The open-air facility consists simply of an outdoor burner stand to which air, oxygen, and natural gas are metered in a manual fashion.

The underlying technical approach to burner modification was to increase the respective oxygen and natural gas linear velocities. This approach can be appreciated when it is recognized that total replacement of air with 100% oxygen, coupled with attendant fuel savings, reduces total oxidant and natural gas volume by about

85%. As shown with earlier enrichment test results, the reduction of oxidant volume and nozzle linear velocity with increasing oxygen enrichment adversely affects the performance of the unmodified burners:

(1) Loss of flame momentum.

(2) Reduction of gas mixing at the burner surface which can lead to soot and other products of incomplete combustion.

(3) Shorter, lazy flames. The previously reported furnace gas temperature profiles were generally broader and more concentrated towards the burner end.

(4) Burner failure due to flame impingement on the block and/or tendency of the high temperature oxy-fuel combustion to occur deep within the burner block.

5.3 Modified North American 4425

Five modifications (A-E) were tested and compared to the unmodified air/natural gas burner.

Each of the above modified burners survived oxy-fuel operating conditions. No soot was observed. Furnace gas temperature and heat flux profiles for each modification are given in

Figures 19-23 and 24-27, respectively. Further demonstrating the success of this approach to burner modification, Figure 28 shows that burner modification A produces a similar furnace gas temperature profile to the unmodified air/fuel burner with only 2 MMBTUH versus 3.75 MMBTUH for air. To give a visual appreciation, a photograph of this burner firing is shown in Figure 29.

By manipulating the natural gas and oxygen velocities, it is possible to adjust the heat release pattern of the burner and simulate the air-fuel burner case to a certain extent. Without the high velocity inert gases from air in the furnace to distribute the heat, the temperature and heat flux contours are more concentrated at the furnace end where the burner is located. These modified burners are particularly applicable for furnaces with burners firing opposite each other. The slightly lower temperature at the tip will reduce the overall roof temperature. Moreover, there is less temperature gradient at the portion of the furnace close to the burner. Thus, there will be fewer cold spots between the neighboring burners.

FIGURE 19. NORTH AMERICAN 4425 MODIFICATION A

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F
FIRING RATE: 2 MM BTU/HR % O_2 IN AIR: 100

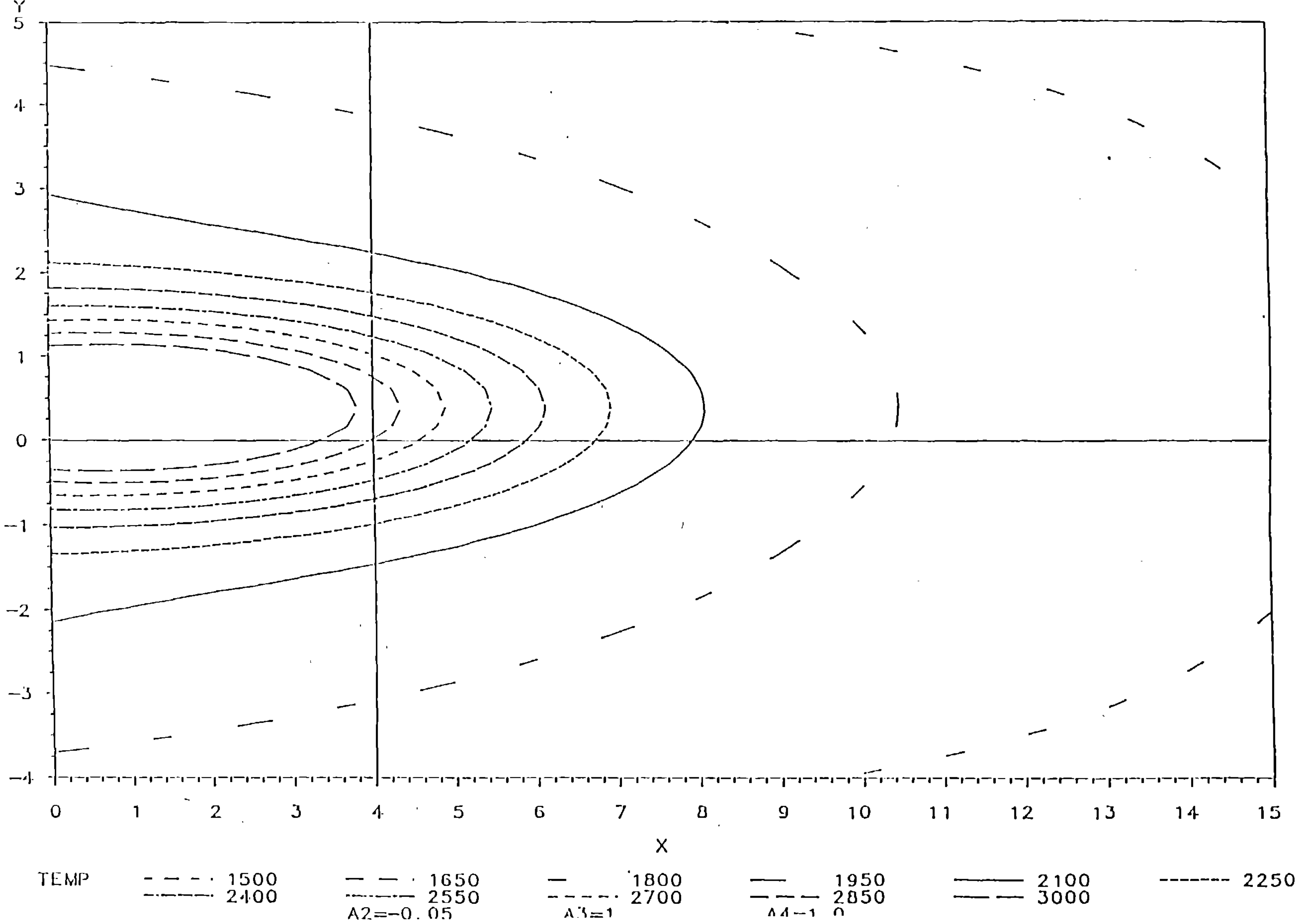


FIGURE 20. NORTH AMERICAN 4425 MODIFICATION B

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F
FIRING RATE: 2 MM BTU/HR   % O_2 IN AIR: 100

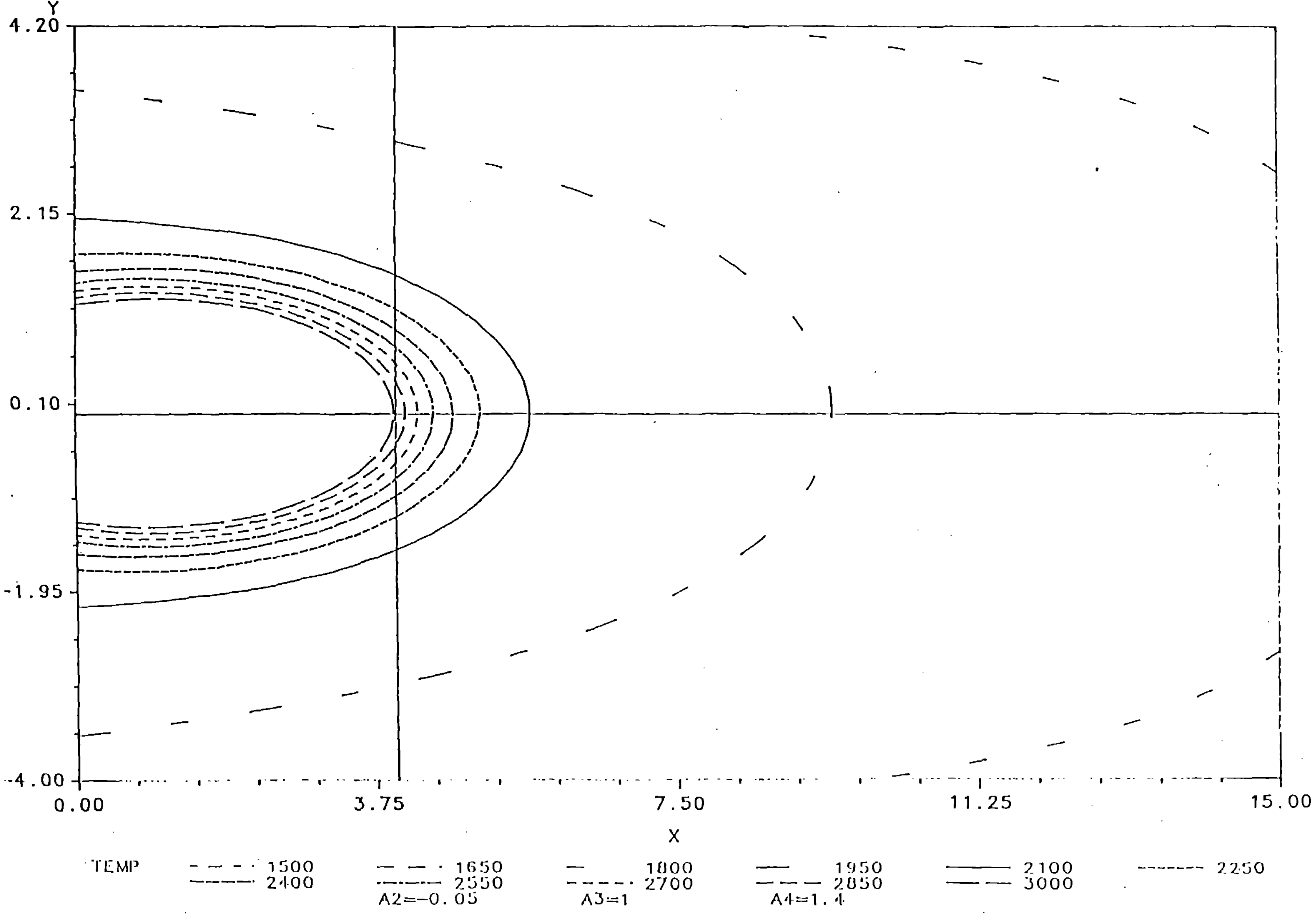


FIGURE 21. NORTH AMERICAN 4425 MODIFICATION C

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F
FIRING RATE: 2 MM BTU/HR % O_2 IN AIR: 100

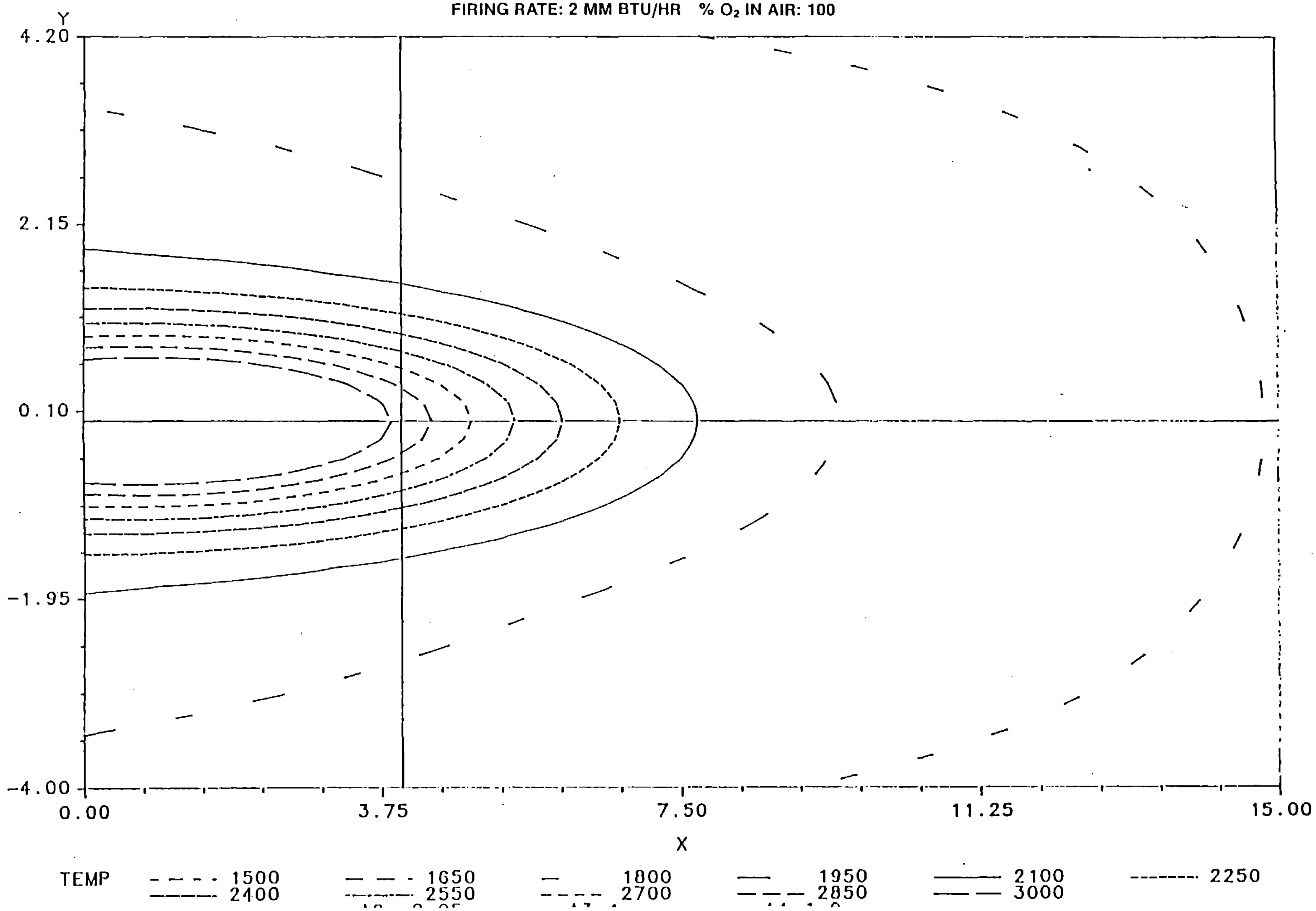


FIGURE 22. NORTH AMERICAN 4425 MODIFICATION D

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F
FIRING RATE: 2 MM BTU/HR   % O_2 IN AIR: 100

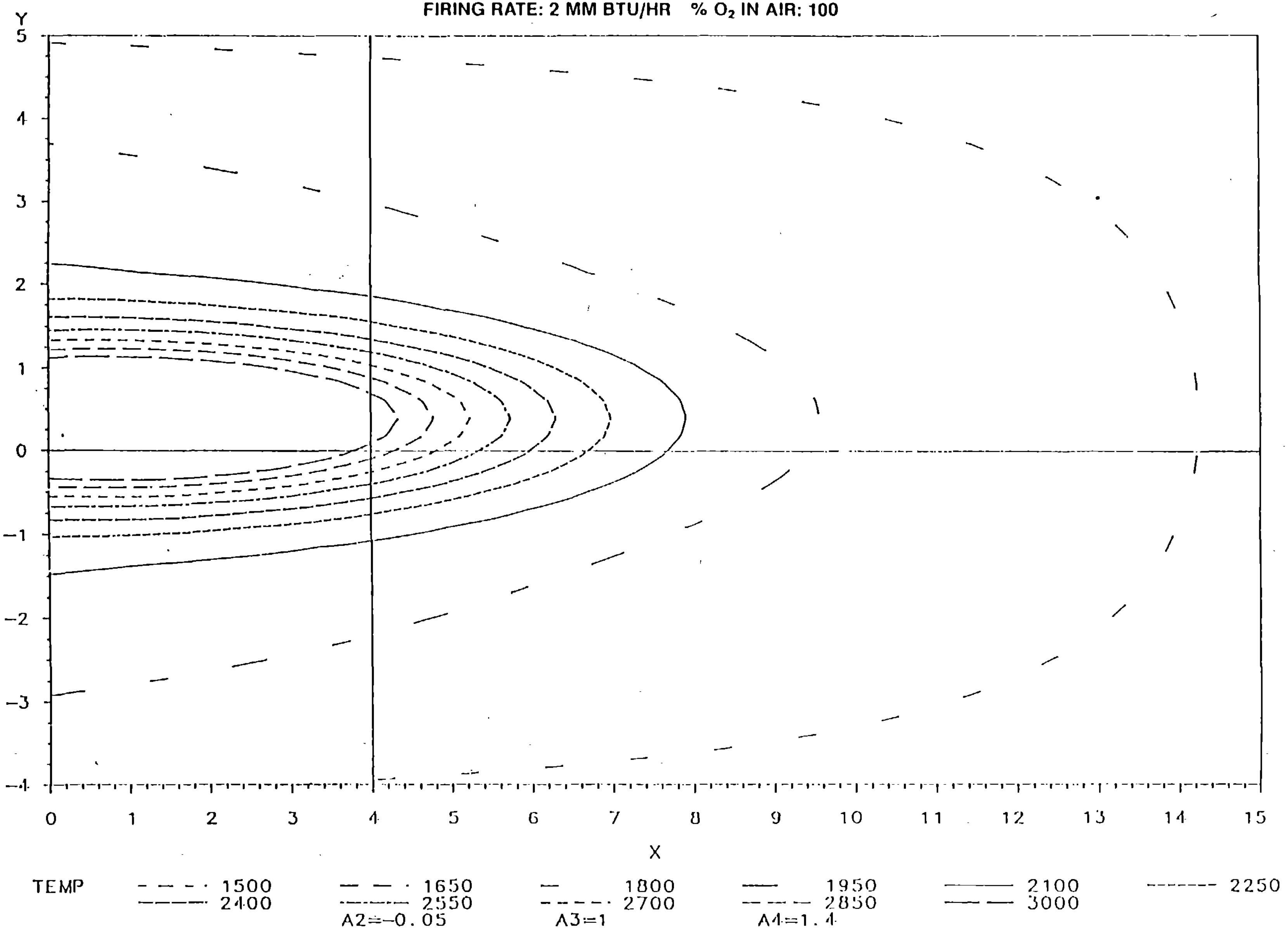


FIGURE 23. NORTH AMERICAN 4425 MODIFICATION E

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F

FIRING RATE: 2 MM BTU/HR   % O_2 IN AIR: 100

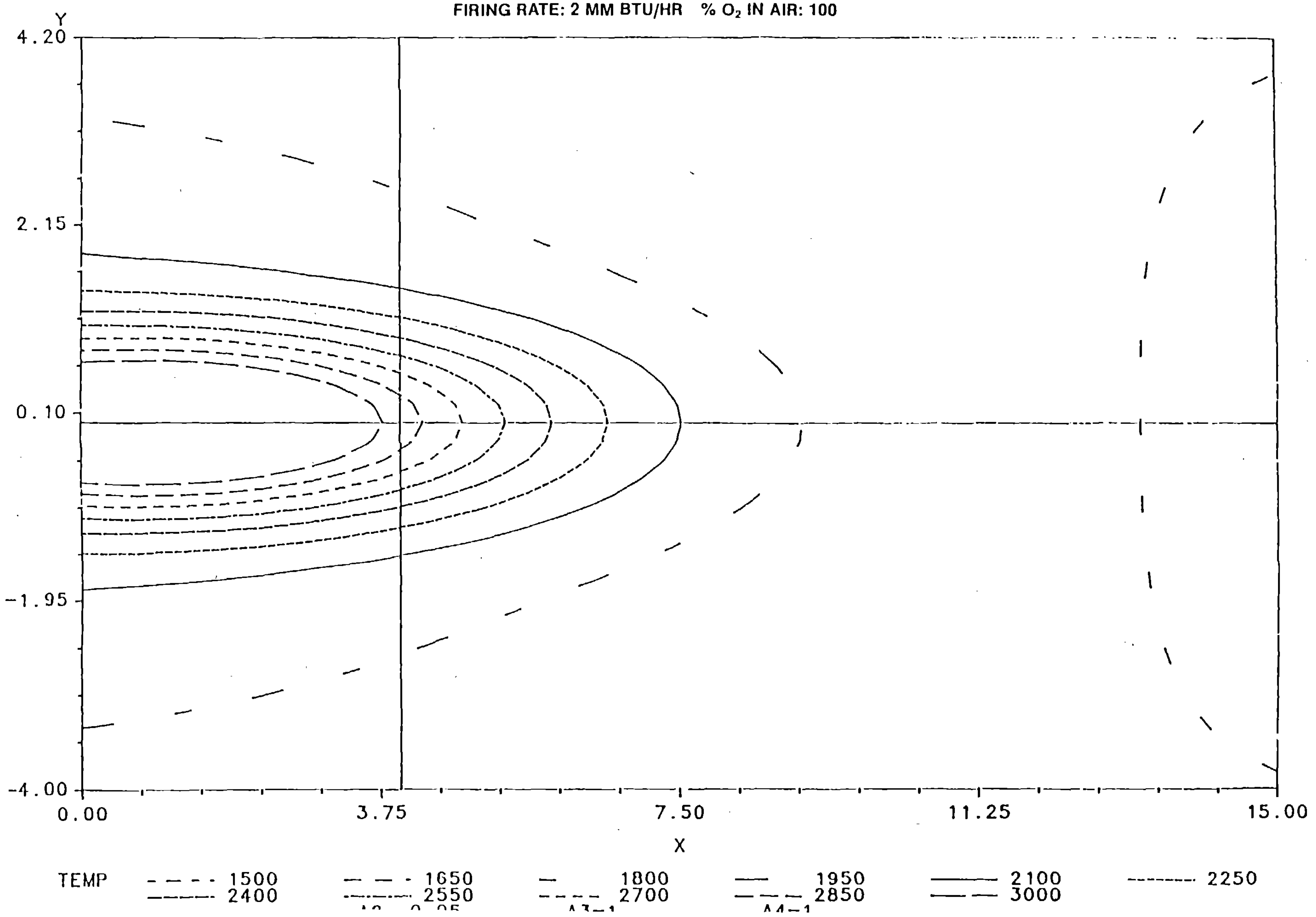


FIGURE 24. NORTH AMERICAN 4425 MODIFICATION A

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT²/HR

FIRING RATE: 2 MM BTU/HR   % O_2 IN AIR: 100

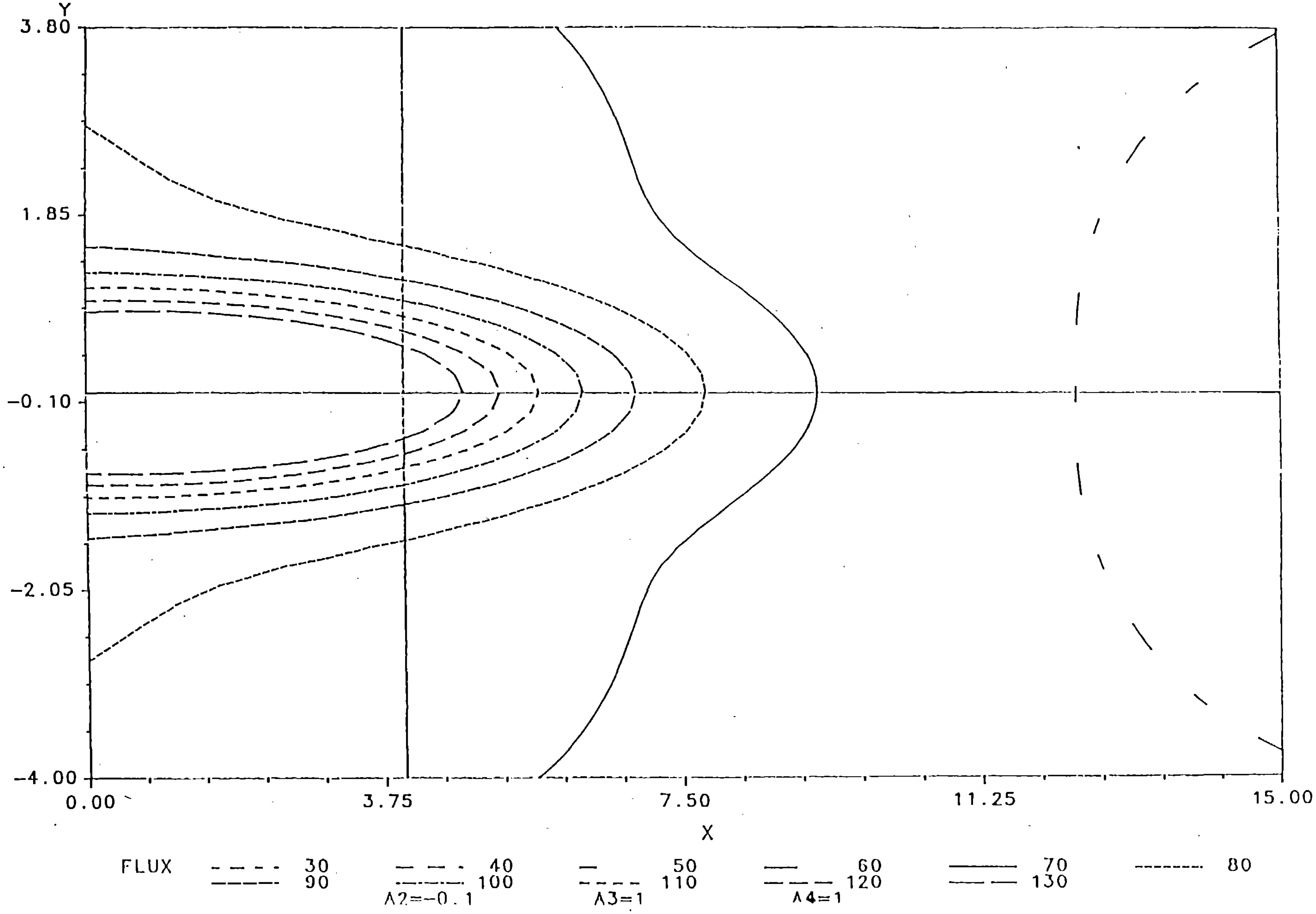


FIGURE 25. NORTH AMERICAN 4425 MODIFICATION B

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT²/HR
FIRING RATE: 2 MM BTU/HR   % O_2 IN AIR: 100

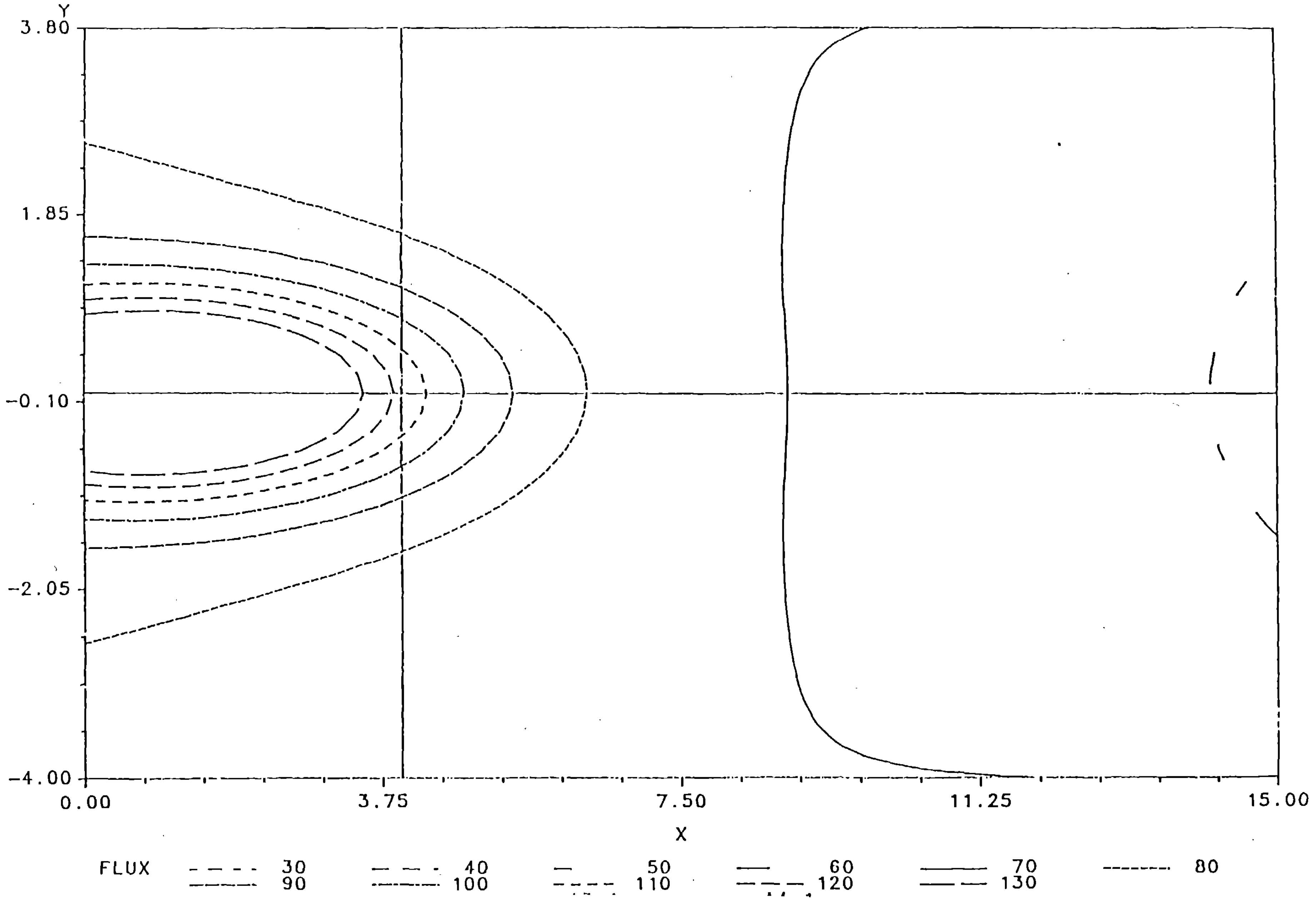
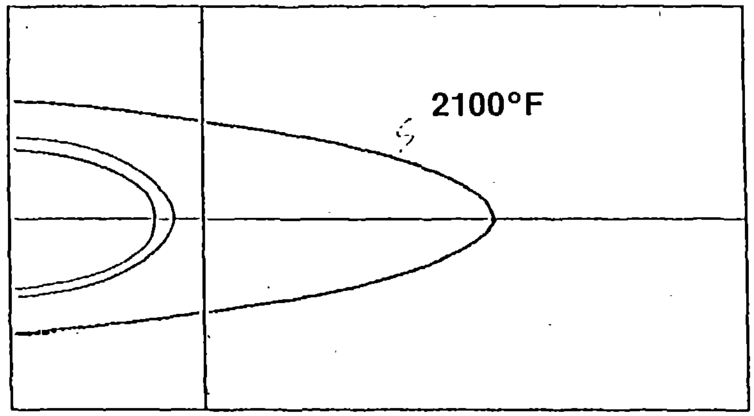


FIGURE 28

NA 4425

STANDARD 3.75 MMBTU/HR AIR



MODIFICATION A 2 MMBTU/HR 100% O_2

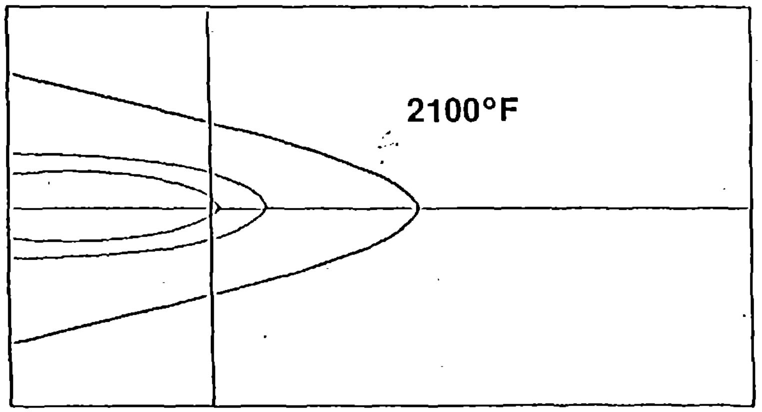
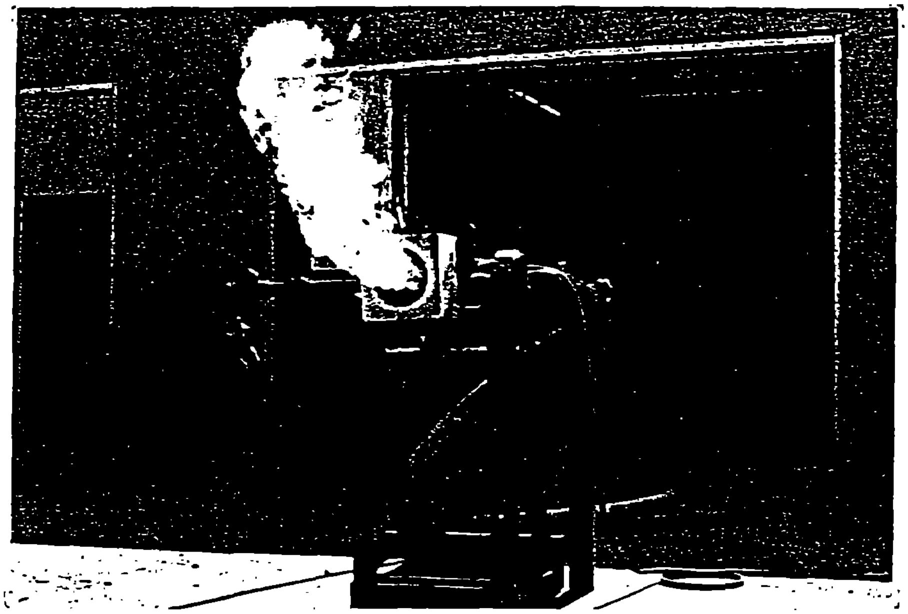


FIGURE 29
NORTH AMERICAN 4425
MODIFICATION A



5.4 Modified Maxon Kinemax

The key differences between the North American (Figure 8) and the Maxon (Figure 10) burner are:

(1) The Maxon burner has 8 natural gas and 16 angular air holes, versus 1 and 8 nozzles, respectively, for the North American burner.

(2) The natural gas holes are recessed in a cup; i.e., not on an even plane with the air tubes as with the North American burner.

(3) There is a removable swirl plate containing the angular holes.

(4) The burner block is tapered (see Figure 33) to increasingly smaller diameters from the burner/nozzle plate, in contrast to the cylindrical geometry of the North American block.

Three basic modifications (A-C) were tested.

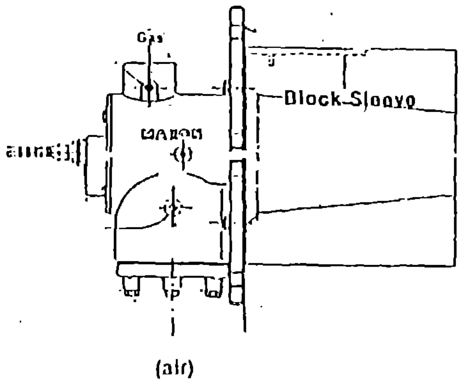
Modification A

The general modification strategy demonstrated successfully with the North American burner was employed on the Maxon burner. For timeliness, the nozzle configurations were made to "look similar" to the North American. Focus was on burner survivability.

FIGURE 33

MAXON

KINEMAX™



After only two days operation in the combustion lab this modified burner failed. A portion of the refractory plate and two nozzles in that area had melted. The furnace gas temperature isotherms and heat flux profiles are given in Figures 34 and 35. No further research was conducted on this modification.

Modifications B and C

Modifications B and C are very similar, but both are different than Modification A, which failed.

Modifications B and C burners survived for two days of operation in the combustion lab at which point testing was stopped. Visually, the flame was very narrow inside the burner block and broadened as it moved away from the block. No flame impingement on the Maxon block was observed at this high ratio.

Modifications B and C gave similar flame patterns, both visually and based on comparison of furnace gas temperatures (Figure 37) isotherms and heat flux (Figures 38 and 39) profiles. However, the flame is somewhat shorter than the air fuel flame (compare air-fuel with modification B oxy-fuel in Figure 40).

Extensive modifications would likely be required to achieve identical flame patterns. This is beyond the "simple retrofit" goal of this project.

No further modifications were tested.

FIGURE 34. MAXON KINEMAX MODIFICATION A

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F
FIRING RATE: 2 MM BTU/HR % O_2 IN AIR: 100

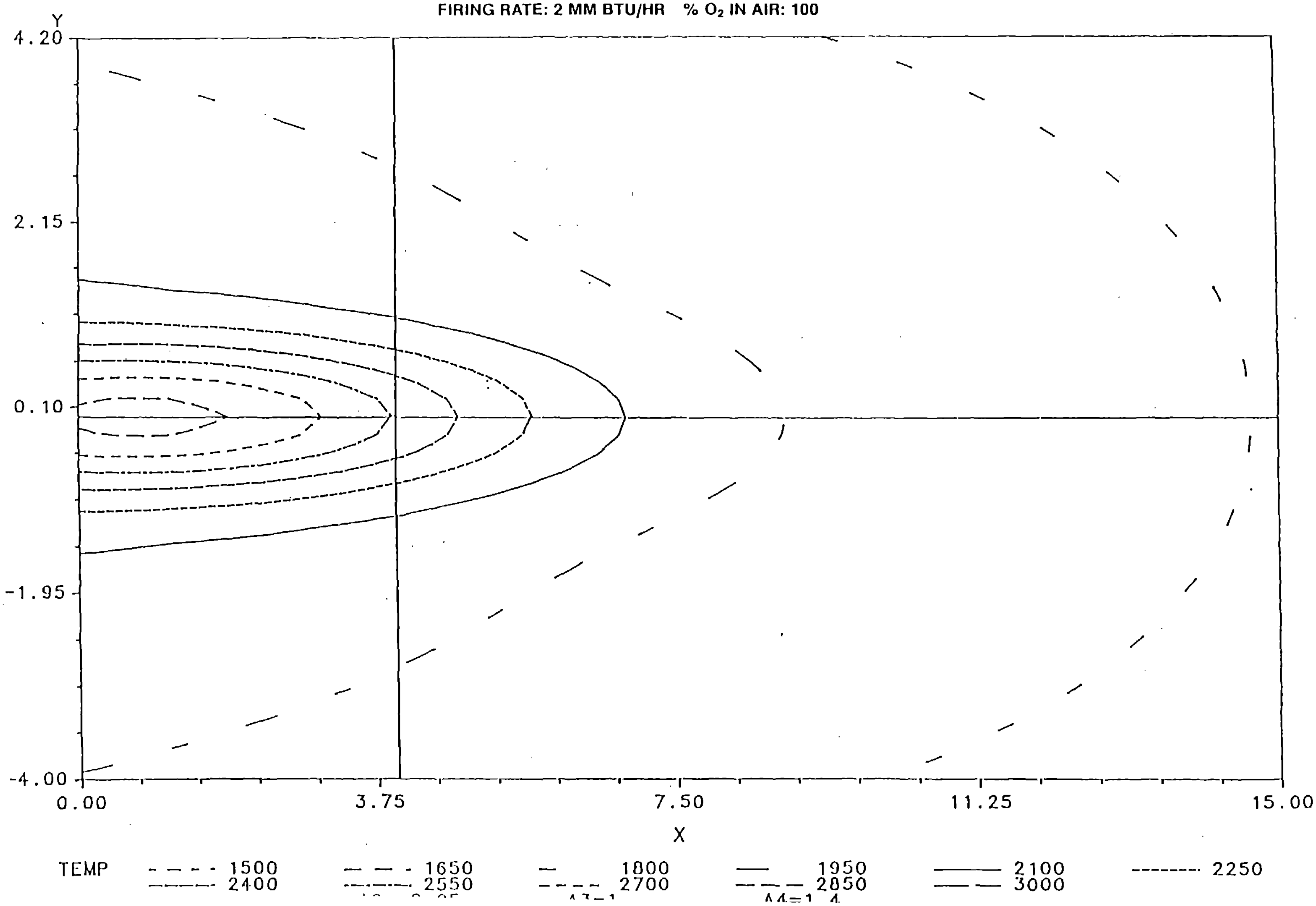


FIGURE 35. MAXON KINEMAX G MODIFICATION A

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT²/HR
FIRING RATE: 2 MM BTU/HR   % O_2 IN AIR: 100

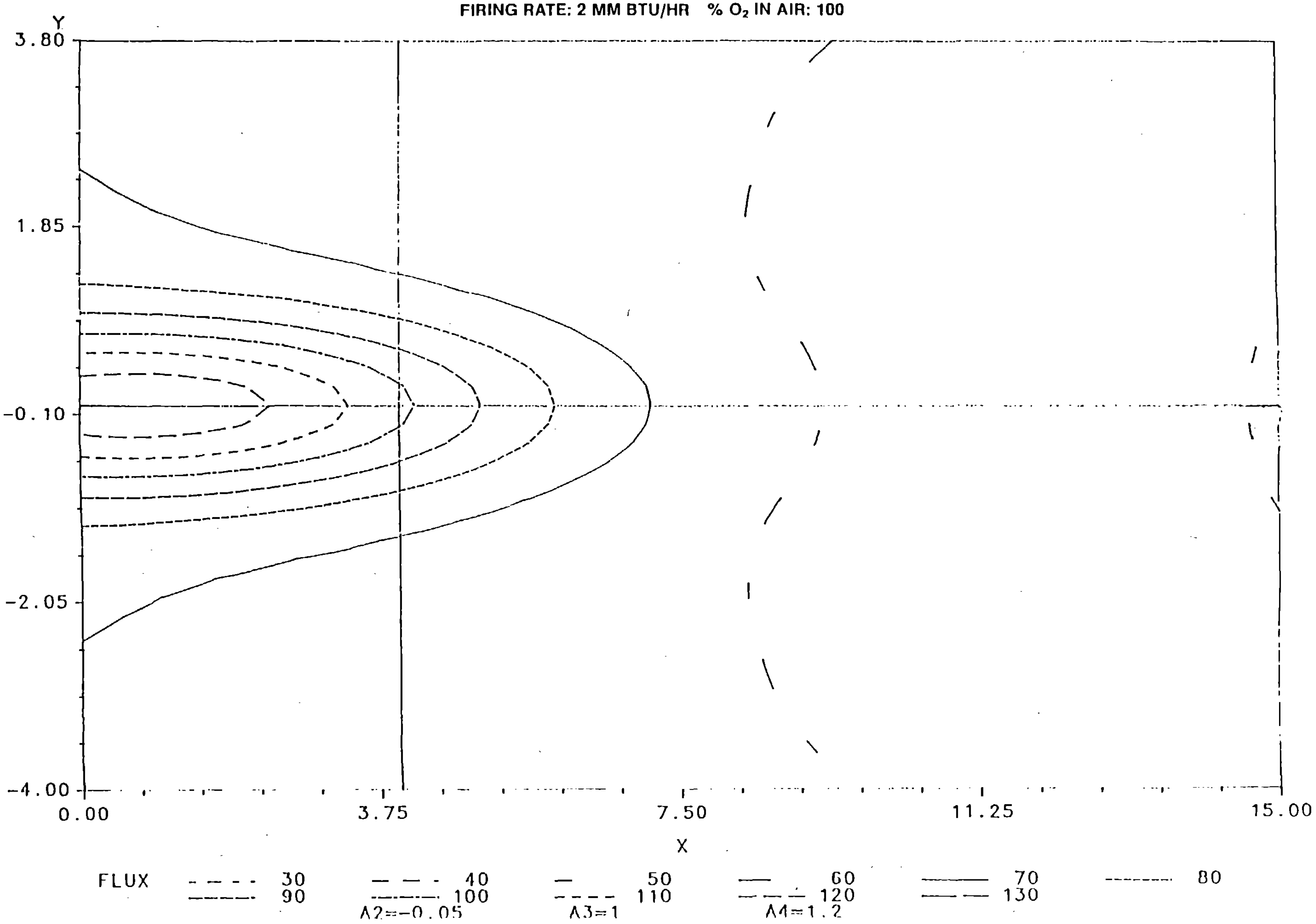


FIGURE 37. MAXON KINEMAX G MODIFICATION B

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F

FIRING RATE: 2 MM BTU/HR   % O_2 IN AIR: 100

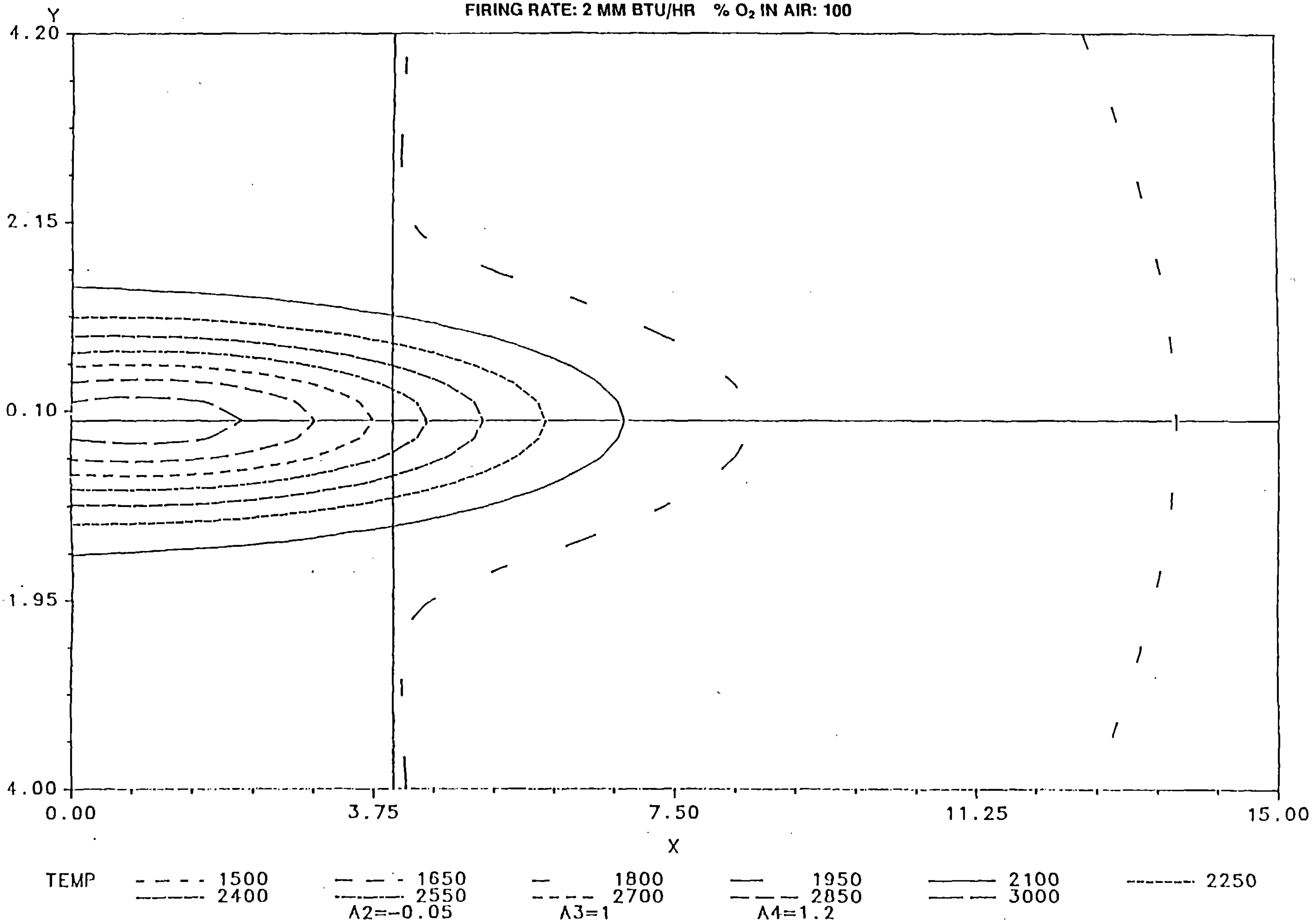


FIGURE 38. MAXON KINEMAX G MODIFICATION B

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT^2/HR

FIRING RATE: 2 MM BTU/HR   % O_2 IN AIR: 100

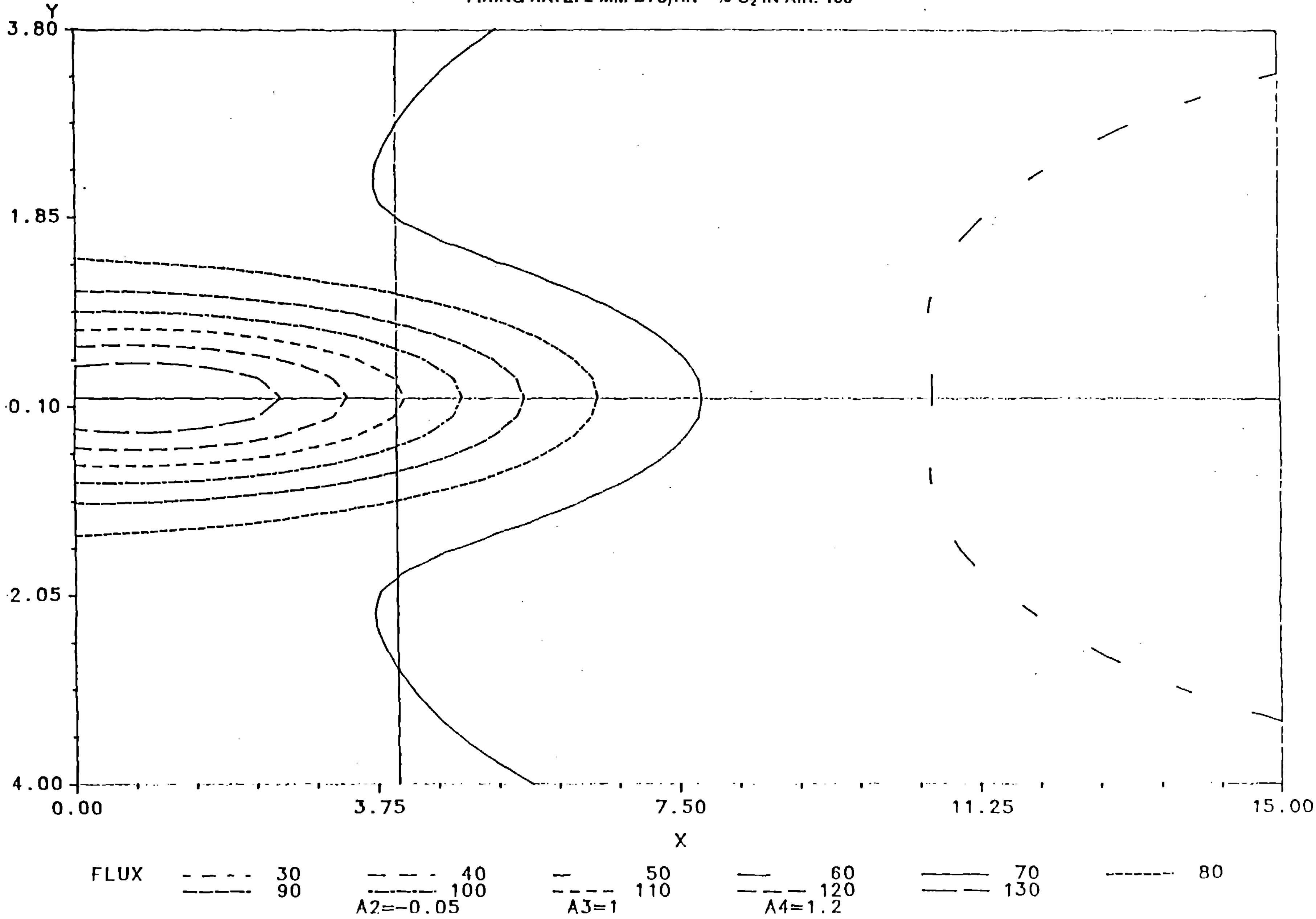


FIGURE 39. MAXON KINEMAX G MODIFICATION C

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT²/HR

FIRING RATE: 2 MM BTU/HR % O_2 IN AIR: 100

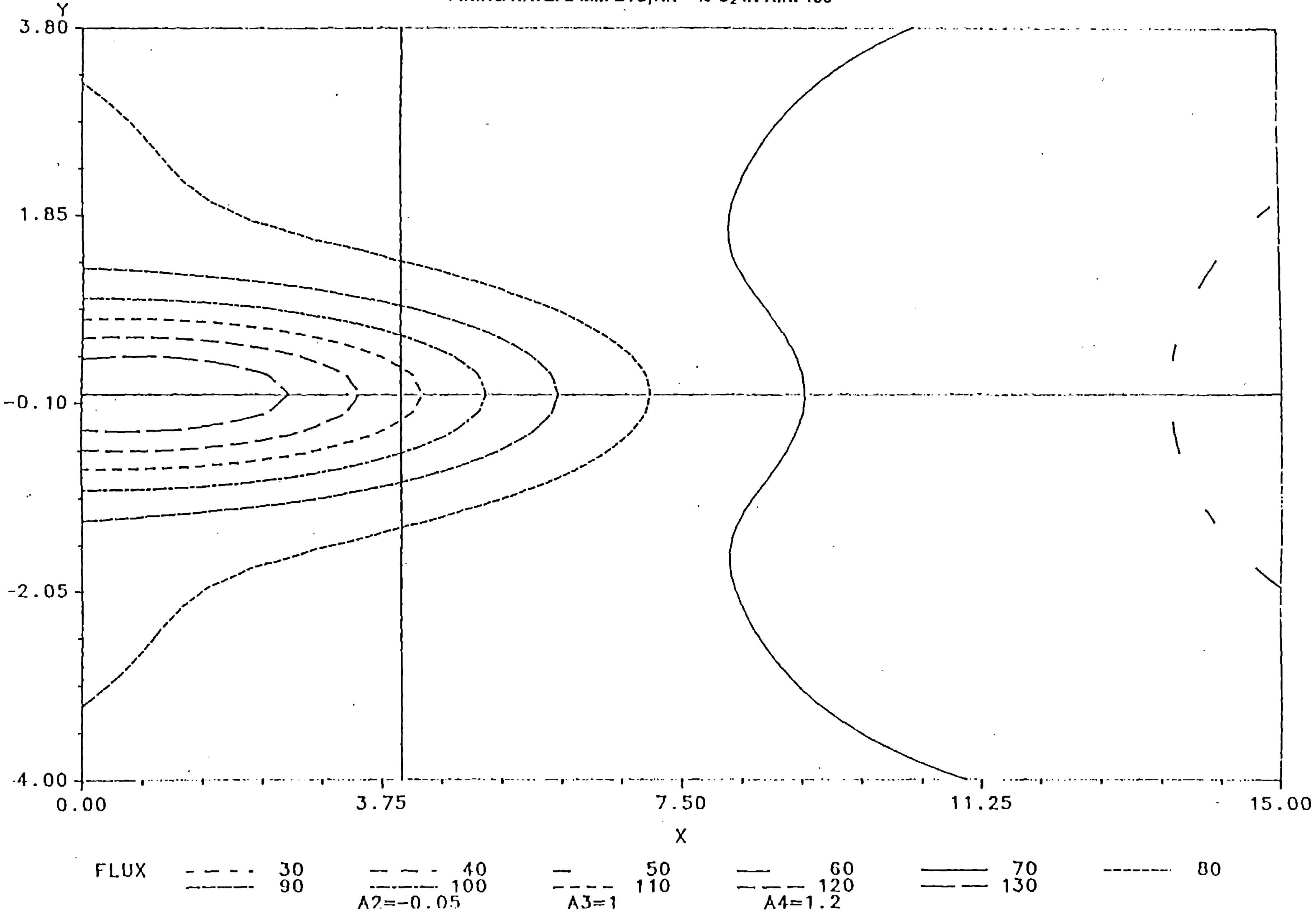
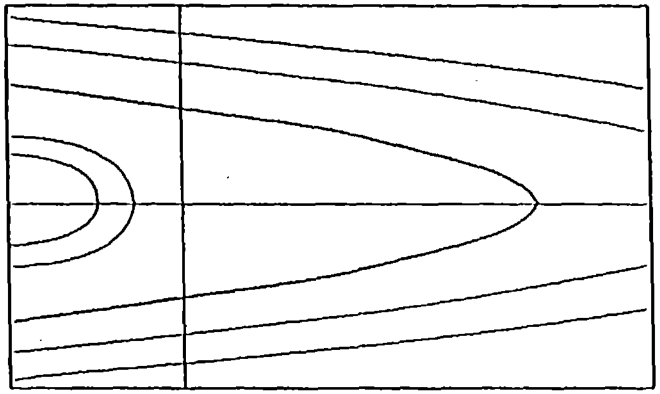


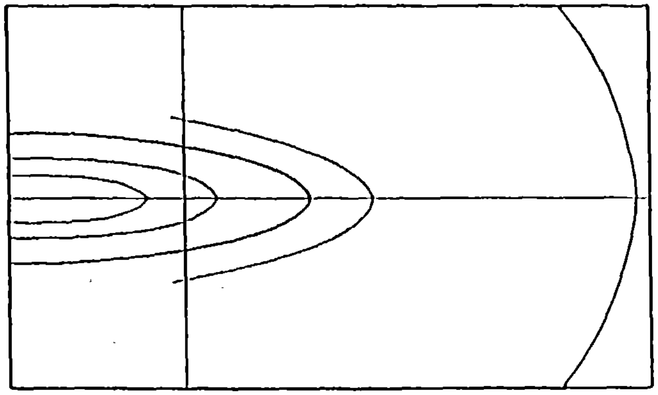
FIGURE 40

MAXON KINEMAX G

STANDARD 3.75 MMBTU/HR AIR



MODIFIED 2 MMBTU/HR 100% O_2



5.5 Conclusions

A retrofit methodology has been demonstrated for conversion of nozzle mix, air/natural gas burners to oxy-fuel firing. In addition to the favorable economic benefits of using 100% oxygen, the primary advantages of the conversion technology are:

- Simplicity of modification.
- No water cooling.
- Retrofit, i.e., purchase of a new burner is not required nor any attendant furnace wall modifications.

Survivability of oxy-fuel conditions was demonstrated for the North American 4425 and Maxon Kinemax G burners. Although demonstrated only for the North American burner, it appears that flame characteristics can be made to approach, at reduced firing rate, those obtained with air/natural gas operations. This is a particularly critical factor where maintenance of a uniform temperature profile is important, such as in forge furnaces. It is also generally a factor in furnaces where excessive roof temperature is of concern.

The key issue now is to demonstrate survivability/performance in commercial heating and melting processes.

6. Field Test Programs

6.1 Selection of Field Test Partners

The objective of this program was to show that the economic competitiveness of natural gas as a fuel option increases with increasing levels of oxygen enrichment. Since the metals and glass industries are large consumers of natural gas and could potentially benefit from this research, these industries were targeted for the two field tests of the new burner technology.

The objectives of the field tests were to determine stability of the new burner technology in a production furnace and quantify any identified process advantages such as energy savings in the selected applications.

Some criteria used in evaluating potential test partners included:

(1) Is the prospect amenable to testing new technology?

(2) Identify additional incentives to increase the economic attractiveness at the existing low energy costs. We continued to focus on those nonrecuperative or regenerative processes, identified in Section 3.1, that exhibit poor energy efficiency.

(3) Ideally, the process would currently use the North American 4425-burner, since we know more about modification of that burner and its lab-demonstrated ability to achieve similar furnace gas temperature distribution.

Before selecting the test partners, the benefits of the technology were discussed with many prospects using different processes. These included nonferrous nonverbatory furnaces, forge furnaces, ladles, container and optical glass melters, and frit smelters. Although there was the expected interest in oxy-fuel generally, and the ease of retrofit advantage, the most popular attribute of this technology was the demonstrated (isotherms) ability to maintain furnace gas temperature.

On the basis of projected economic benefit and technical fit, the following two test partners accepted our proposal to participate in the GRI field test program for foundry ladle preheating and conversion of glass frit smelter to oxy-fuel.

6.2 Foundry Ladle Preheating with Oxy-fuel

Test Period: January-September 1988

SUMMARY -

Ladle preheating is a commonly used practice within the steel industry. The objective of ladle preheating is to uniformly raise the temperature of the ladle lining to a specified level. Productivity is maximized if preheating can be accomplished quickly while preserving the refractory integrity. Current practice generally utilizes air-fuel burners, sometimes equipped with some type of heat recuperation.

Today's refractories and steelmaking processes often require ladle preheat temperatures in excess of 2000°F, which are difficult to obtain with the relatively small temperature gradient afforded by an air-fuel flame. Because of its higher flame temperature oxy-fuel provides the required energy for ladle preheating in a form which is capable of reaching the desired temperature in a shorter period of time while minimizing flue losses and maximizing fuel efficiency.

The major purpose of this test was to determine the survivability of this burner. In this regard, the test was highly successful as burner longevity was excellent.

It was also desirable to determine the technical fit for this type of burner in ladle preheating. Therefore, during August and September of 1988, data was collected at McConway-Torley to compare ladle preheating using the GRI oxygen-fuel burner with that of traditional air-fuel preheating. The data from 34 preheats were collected. At first, the oxygen-fuel burner was placed in the cover of the 21-ton ladle preheater and the data for 25 runs was recorded. Then, the oxygen-fuel burner was replaced by the air-fuel burner and the data for 9 runs was obtained. Comparisons were made in terms of heating rates, final temperatures and energy consumptions.

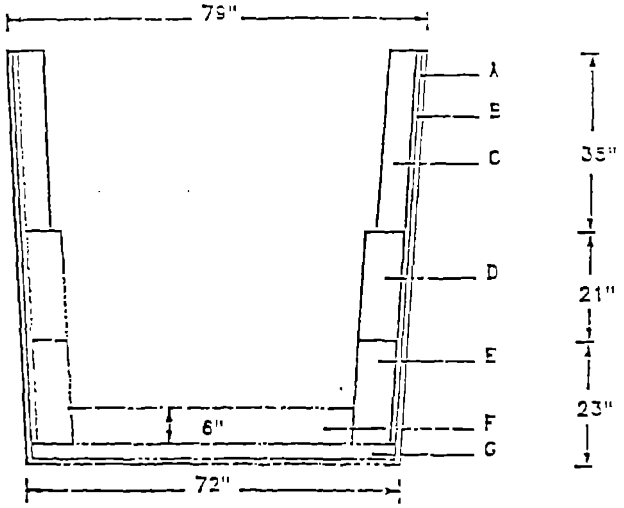
EXPERIMENT

The objective of the test program was to obtain a fair comparison between an air-fuel burner which had been retrofitted to an oxygen-fuel burner producing a similar flame and heat release pattern, and the same unmodified air-fuel burner for ladle preheating. To collect good, comparative data, we installed thermocouples in the lining of a ladle and heated it by an oxygen-fuel practice and then an air-fuel practice.

The modified North American 4425 Burner (Modification A) was used. The design criteria for this burner was to produce a flame and heat release pattern when firing on oxy-fuel as similar to the unmodified air-fuel burner as possible. The base burner is rated for 0.34 TO 4.24 million BTU/hour when firing in the air-fuel mode.

Six thermocouples were installed in the alumina lining of the 21-ton ladle, as shown in Figure 41. Thermocouple locations were specified to cover an array of locations and depths. The thermocouples were inserted into the lining through 5/8-inch diameter holes that were drilled through the steel shell and refractory lining. Each thermocouple is protected by a 3/8-inch diameter ceramic tube.

FIGURE 41
THERMOCOUPLE POSITIONS



A: 0.75" MILD STEEL PLATE SHELL

B: 1" 30% ALUMINA

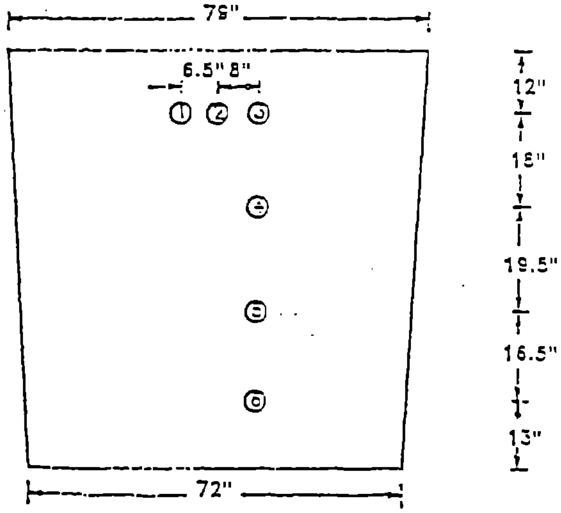
C: 4" 30% ALUMINA

D: 6" 30% ALUMINA

E: 6" 50% ALUMINA

F: 6" 70% ALUMINA

G: 3" 30% ALUMINA + RAM



THERMOCOUPLE MOUNTING DEPTHS (FROM OUTER SHELL SURFACE)

① ④ ⑤ ⑥ : 3" ②: 4" ③: 5"

Table 9

Thermocouple Positions in the Lining of the Ladle

Thermocouple Number	Distance From Top of Ladle (inches)	Approx. Distance From Cold Face (inches)	Approx. Distance From Hot Face (inches)
1	12	3	2.75
2	12	4	1.75
3	12	5	0.75
4	30	3	2.75
5	50.5	3	4.75
6	67.5	3	4.75

As shown in Table 9 and Figure 41, the R-type thermocouples were placed at different distances from the hot face of the lining, as well as different locations in the ladle wall. The test ladle was heated for about 1.6 hours during each preheat from an average starting temperature of approximately 150°F. During each test, natural gas flow rate and temperature data were recorded as a function of time and logged onto an IBM personal computer.

The data acquisition system is pictured in Figure 42.

EFFICIENCY RESULTS AND DISCUSSION

Figures 43 and 44 show the temperature profiles (temperature vs. time) of the thermocouples during oxygen-fuel and air-fuel ladle preheating trials respectively. These are the average results of all runs. Some of the thermocouple data was omitted when there were obvious anomalies due to broken thermocouples or bad connections.

FIGURE 42

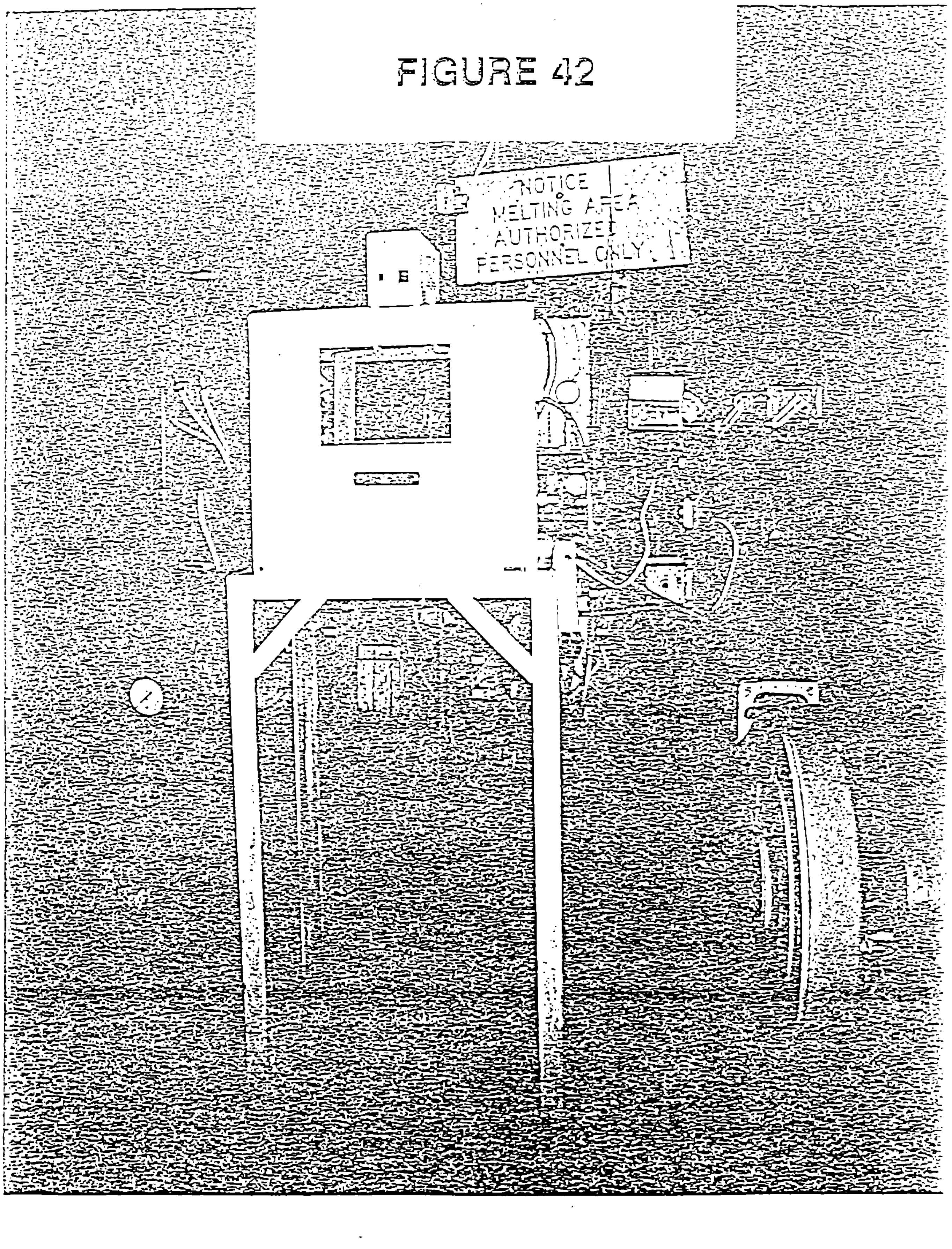
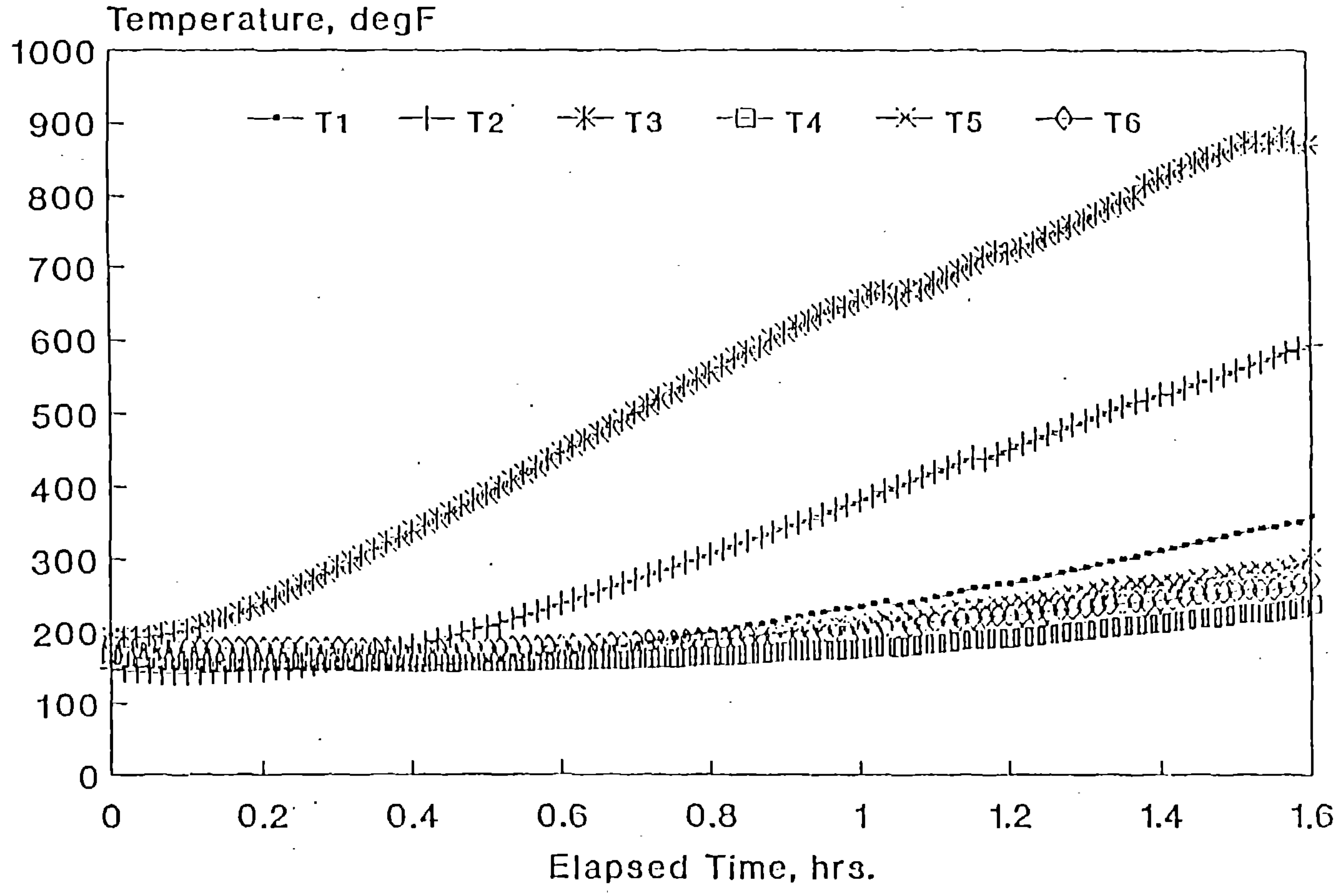


FIGURE 43

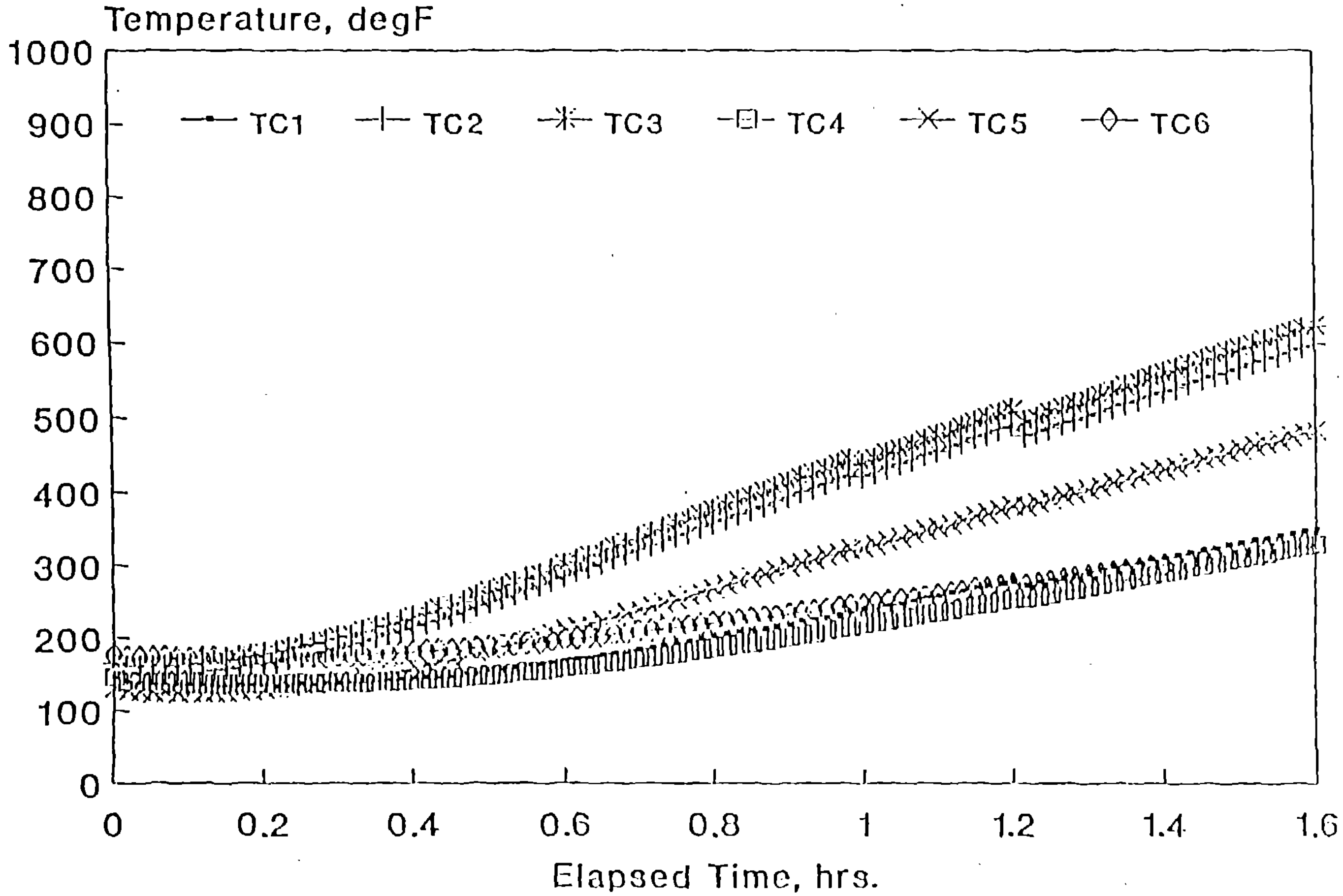
Ladle Temperature Profile
(Oxygen-Fuel Burner)



Ladle Temperature Profile (Oxygen-Fuel)

FIGURE 44

Ladle Temperature Profile
(Air-Fuel Burner)



Ladle Temperature Profile (Air-Fuel)

Of the 25 runs with the oxygen-fuel burner, 17 started from cold ladles and 8 from hot ladles. In the 9 runs of the air-fuel burner, 6 started from cold ladles and 3 from hot ladles. The ratio of the number of cold ladles to the number of hot ladles is nearly the same in both cases (about 2 to 1). The average starting temperatures are also very similar (about 150°F). The average preheating time is 1.6 hrs. The final temperature of thermocouple #3, which best represents the hot face refractory temperature (at 1.6 hrs) for the oxygen-fuel burner, was about 870°F while for the air-fuel burner it was about 623°F. Thus the heating rate of the oxygen-fuel burner is higher than that of the air-fuel burner. The obvious advantage is that less time is needed to reach the same temperature for the oxygen-fuel burner than with the air-fuel burner. For example, it took 0.93 hrs for the oxygen-fuel burner to reach 623°F (thermocouple #3), and 1.6 hrs for the air-fuel burner to reach the same temperature.

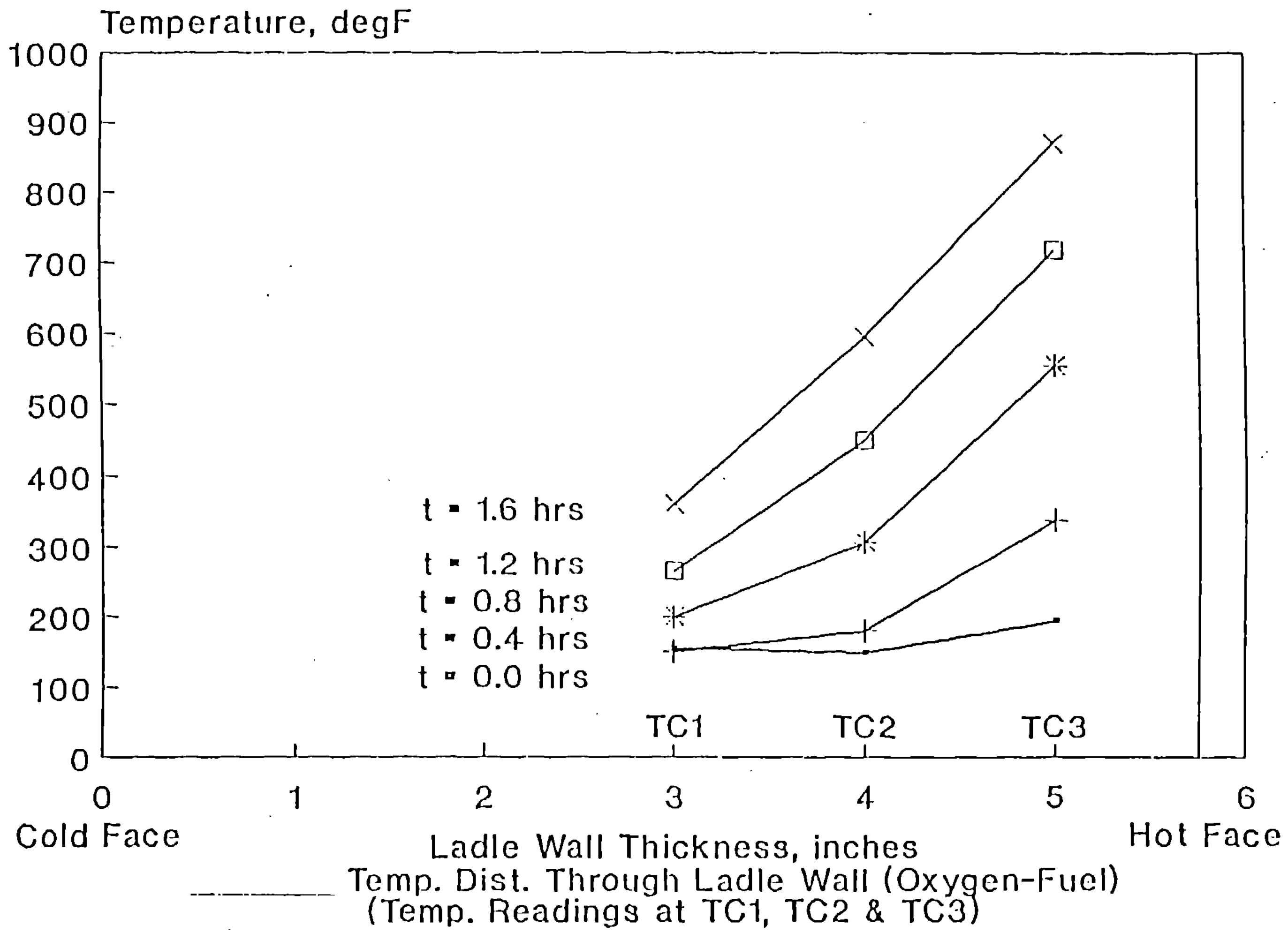
Comparison of Figures 43 and 44 for thermocouple #3 shows that the rate of temperature increase and the final temperature (at 1.6 hrs) are higher for the oxygen-fuel burner. However, temperatures at thermocouple #2 in both cases are very close and temperatures at thermocouple #1 are the same in both cases. Temperatures at thermocouple #4, #5, and #6 for the air-fuel burner are higher than that of the oxygen-fuel burner. This can be explained as follows. When the air-fuel burner test started, the ladle lining was much thinner except near the top of the ladle (which was above wear line) because the ladle had been used for many heats. Thus, thermocouple tips were very close to the hot ladle face. Therefore, it became obvious that this data is not typical.

Figures 45-46 and Figures 47-48 show the temperature profile of the ladle wall during the ladle preheating trials using the oxygen-fuel preheater and the air-fuel burner, respectively. The data of Figures 45 and 47 were taken from thermocouple #1, #2, and #3 separately. The data of Figures 46 and 48 were taken from thermocouple #4, #2, and #3 separately. It was consistently found that the temperature gradient (the temperature change vs the distance change) in the case of the oxygen-fuel burner is higher than that of the air-fuel burner.

Figures 49 and 50 show the temperatures vs ladle axial distance during the ladle preheating trials using the oxygen-fuel burner and the air-fuel burner separately. The data shown in these figures were obtained from thermocouples #1, #4, #5 and #6. In Figure 47, the temperature at thermocouple #1 is the highest because the thermocouple location is closer to the burner. In Figure 50, the temperature at thermocouple #5 is the highest.

The average natural gas consumption of the air-fuel burner is 3800 SCF per run. The average natural gas consumption of the oxygen-fuel burner is reduced 37% to 2400 SCF per run and the average oxygen consumption is 4400 SCF per run. The energy cost of the oxygen-fuel burner is approximately $22.48 per run and the energy cost of the air-fuel burner is approximately $13.30 per run, as shown in Table 10.

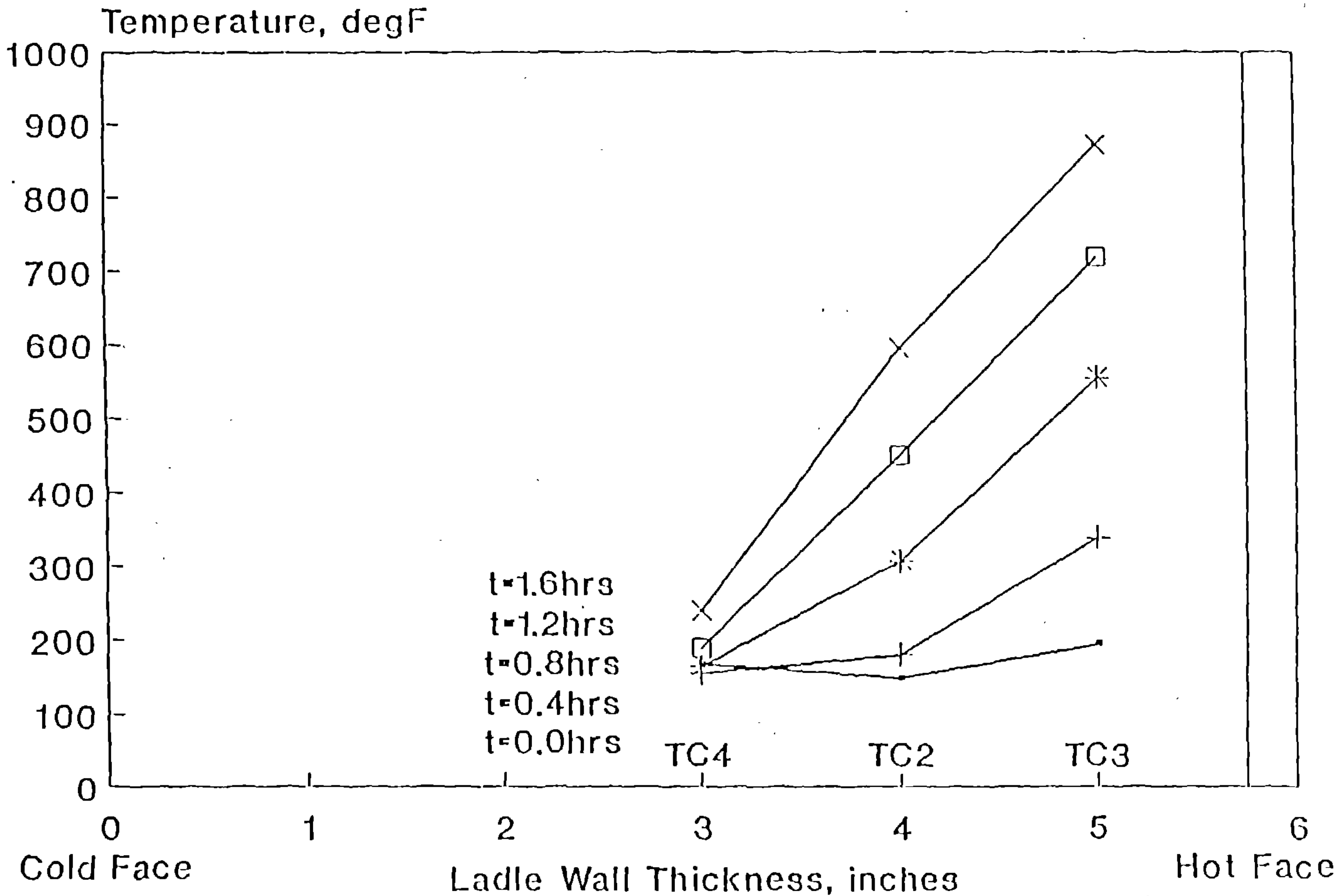
FIGURE 45



Temp. Dist. Through Ladle Wall
(Oxygen-Fuel Burner)

FIGURE 46

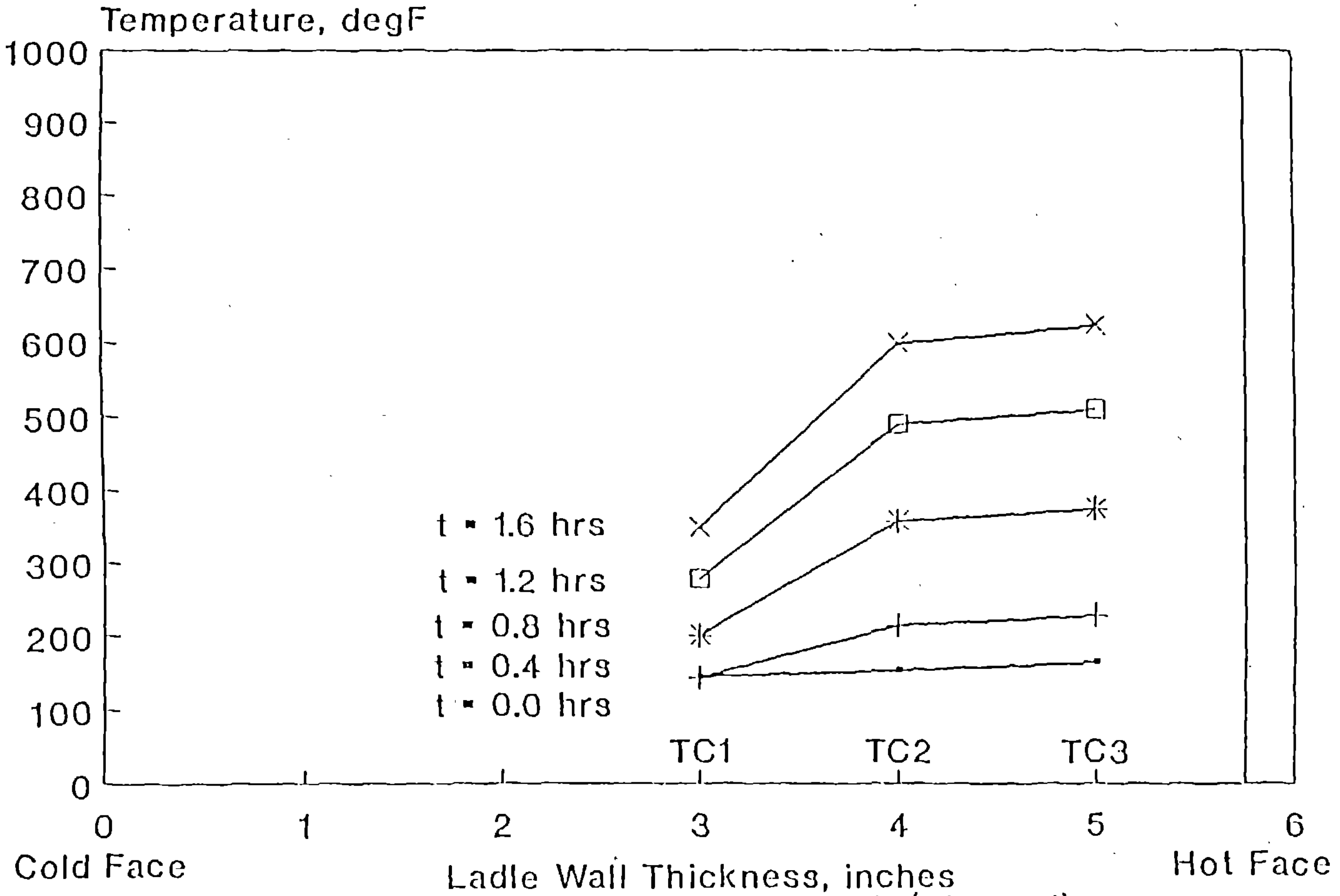
Temp. Dist. Through Ladle Wall
(Oxygen-Fuel Burner)



Temp. Dist. Through Ladle Wall (Oxygen-Fuel)
(Temp. Readings at TC4, TC2 & TC3)

FIGURE 47

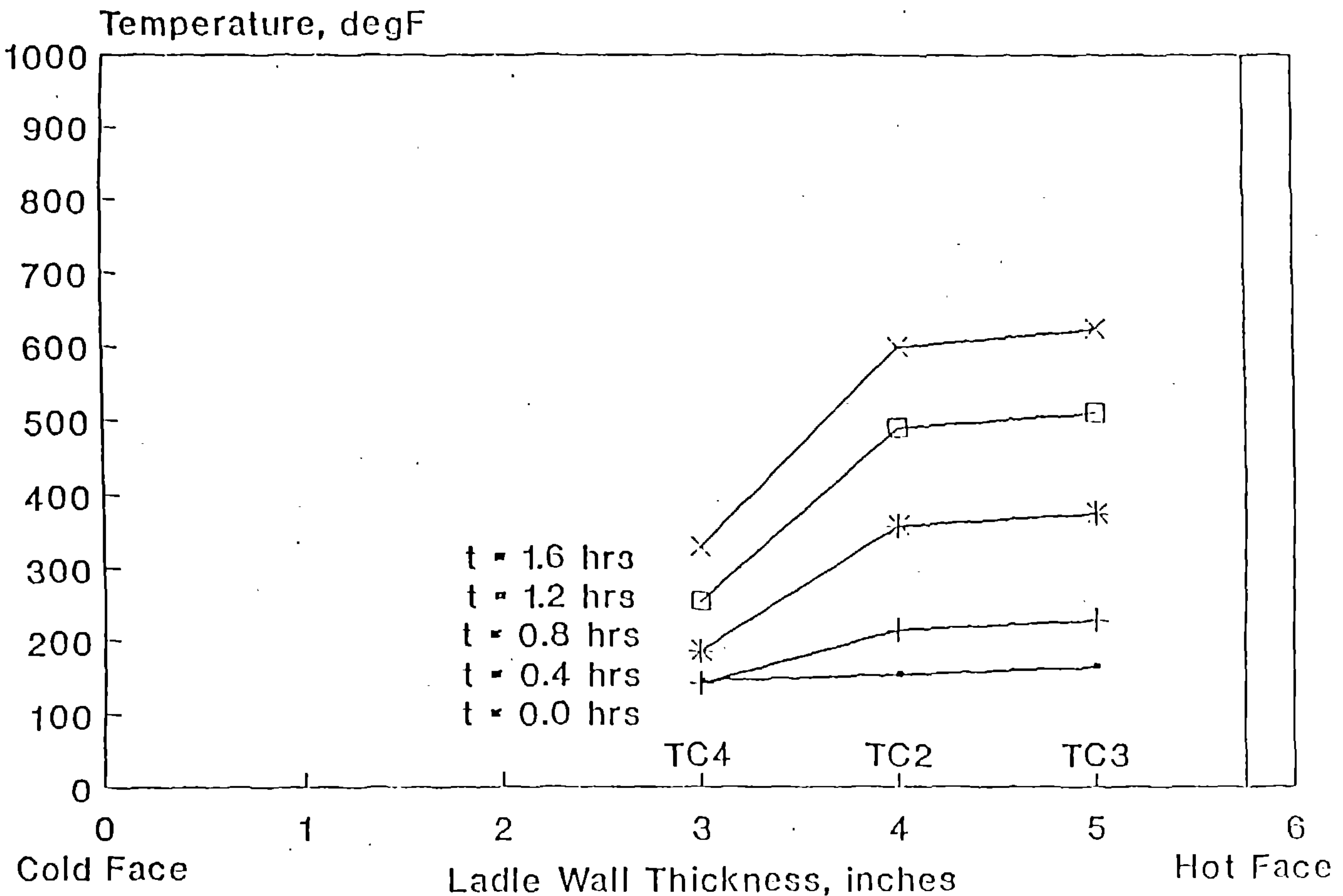
Temp. Dist. Through Wall
(Air-Fuel Burner)



Temp. Dist. Through Ladle Wall (Air-Fuel)
(Temp. Readings at TC1, TC2 & TC3)

FIGURE 48

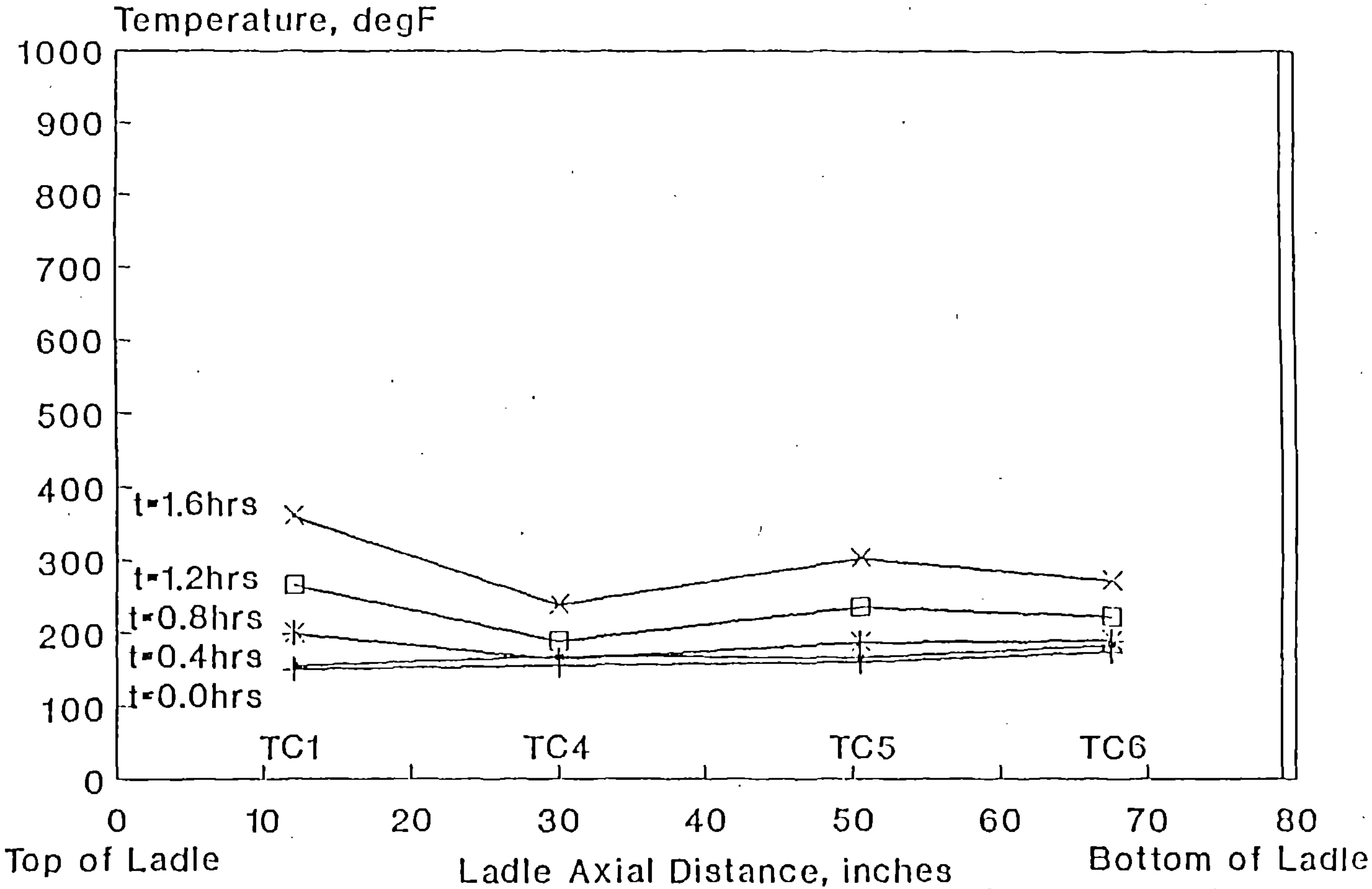
Temp. Dist. Through Wall
(Air-Fuel Burner)



Temp. Dist. Through Ladle Wall (Air-Fuel)
(Temp. Readings at TC4, TC2 & TC3)

FIGURE 49

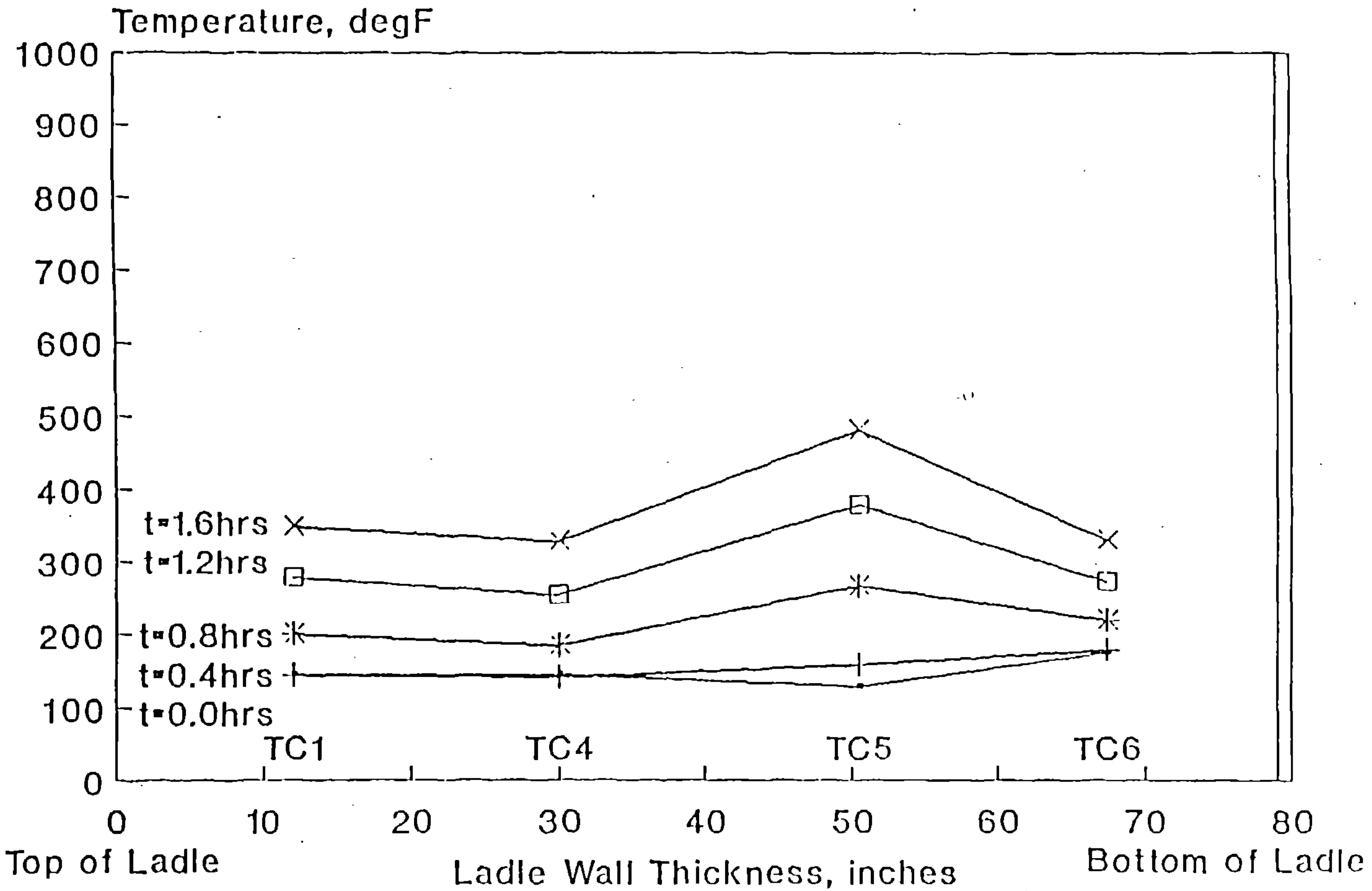
Temp. Dist. Along Axial Distance
(Oxygen-Fuel Burner)



Temp. Dist. Along Ladle Axial Distance (Oxygen-Fuel)
(Temp. Readings at TC1, TC4, TC5 & TC6)

FIGURE 50

Temp. Dist. Along Axial Distance
(Air-Fuel Burner)



Temp. Dist. Along Ladle Axial Distance (Air-Fuel)
(Temp. Readings at TC1, TC4, TC5 & TC6)

Table 10

Average Energy Consumption of Each Preheat

Preheater	Oxygen Consumption (SCF)	Natural Gas Consumption (SCF)	Total Cost (Dollars)
GRI Oxygen-fuel	4400	2400	22.48
Air-fuel		3800	13.30

It should, of course, be noted that the ladle was heated to a significantly higher temperature during the oxy-fuel runs. Actual energy (natural gas) savings are about 62% when adjusted for the more rapid heatup time achieved with the oxy-fuel burner. Comparing Figure 43 (oxy-fuel) with Figure 44 (air-fuel), the oxy-fuel burner required only 0.87 hours and 1.6 MMBTUH (or 1392 SCF natural gas) to reach 600° (T3) in contrast to 1.51 hours and 2.4 MMBTUH (or 3624 SCF natural gas) for air-fuel. Since the computer could not record the natural gas consumption for individual heats during the air-fuel evaluation period, an average natural gas consumption was calculated based on similar tests during the previous year.

BURNER SURVIVABILITY

The modified North American 4425 Air-Fuel Burner survived 100% oxygen-fuel use in an environment of constant thermal cycling for over 9 months of continuous use without any sign of deterioration. The only burner failure during this period was the result of an unsuccessful attempt to simplify the flame safety device. We are convinced that average burner life would exceed 1 year even in such very harsh service.

CONCLUSIONS

From the data collected during the ladle preheating test, the following can be concluded:

1. An air-fuel burner converted to oxygen-fuel can give higher preheating temperatures than prior to conversion.

2. The oxygen-fuel burner can give a higher heating rate (shorter heating time to reach the same temperature) than the air-fuel burner.

3. Life of the refractory wall of the preheater increases when switching from air-fuel to oxy-fuel due to the decreased gas volume and thus lowered erosion rate. Ladle refractory life is increased to the extent that the ladle is more uniformly heated and/or heated more nearly to the desired (optimum)

temperature in the often limited amount of time available for preheating. Metal quality is generally unchanged; however, yield may increase due to less skull formation.

4. The temperature gradient (the temperature change vs the distance change) using the oxygen-fuel burner is steeper than that of the air-fuel burner.

5. The energy cost of the converted oxygen-fuel burner is higher than that of the air-fuel burner.

6. Two factors interfered with more accurate collection of data for the air-fuel case. The first is that the natural gas consumption had to be estimated from the previous year's data. The second is that the ladle refractory needed to be relined during these tests, and therefore the thermocouples were closer to the refractory surface than they were during oxy-fuel data collection.

7. Burner survivability in this application exceeded expectations.

8. It is not recommended that this burner normally be applied for the application of ladle preheating since fuel savings were significantly less than those routinely achieved with conventional (high velocity) oxy-fuel burners (37% vs. 70-76%). This result can be explained by the fact that this

burner was specifically designed to duplicate the heat release pattern of the air-fuel burner (prior to modification) while the ladle preheating application works best with the characteristics of a conventional oxy-fuel burner (i.e., higher flame velocity and more flame penetration). The results summarized in Table 11 are illustrative of conventional oxy-fuel burner performance in ladle preheating.

TABLE 11

LADLE PREHEATING WITH CONVENTIONAL OXY-FUEL BURNERS

	Average Firing Rate (MM BTU)	Time to Preheat (Hrs)	Average Firing Rate (MM BTU)	Time to Preheat (Hrs)	Net Natural Gas Savings	Preheat Time Decrease
Company A	6.0	1.5	1.77	1.5	70.5%	N/A
Company B	5.8	2.5	2.75	1.5	71.6%	40.0%
Company C	6.2	1.3	2.40	0.8	76.1%	38.5%

6.3 Frit Smelter Conversion to Oxy-fuel

Test Period Dates: May 9, 1988 - May 27, 1988
August 2, 1988 - August 12, 1988
February 20, 1989 - September 1989

SUMMARY

The objective this test was to demonstrate burner performance and survivability in a frit-smelting furnace, while quantifying production and quality benefits. The focus was on the burner's flame shape and mixing characteristics for an extended period in a glass furnace.

Proven benefits from the oxy-fuel trial held from May 9 to May 27, 1988 were: 1) a 27% production increase, 2) 60% fuel reduction rendering natural gas a favored energy source, 3) 200°F reduction in flue gas temperature, which decreases process maintenance and increases stack life, 4) improved frit quality, specifically color and hardness, 5) maintained flame shape and characteristics, and 6) ease of installation into frit smelter, requiring minimal

furnace modifications. The principal incentive to the host was to reduce flue gas volume passing through the scrubber so that a third smelter could be run simultaneously with smelters 1 and 2. Current limitations demanded that only two smelters be run simultaneously.

The nonwater-cooled burner life in this environment was inadequate and signs of thermal degradation appeared within 5 days of operation. Hence, two versions of the original design were tested in an effort to improve burner life. These versions improved burner life to 2 months. A water-cooled burner which produces similar flame shape and characteristics was also mated to the existing North American manufactured burner block. This burner showed no sign of deterioration after 5 months. The host plans to adopt use of the oxy-fuel burners in its furnace.

APPLICATION DESCRIPTION

The frit making industry can be divided into three parts: raw material preparation, smelting, and frit handling. This trial dealt specifically with the frit smelting operation. Smelting involves the melting together of raw materials entering the composition until a relatively uniform glass is formed. Successful execution of this product is dependent on thorough mixing of the raw materials, proper heating, and the distribution of the heat through the batch.

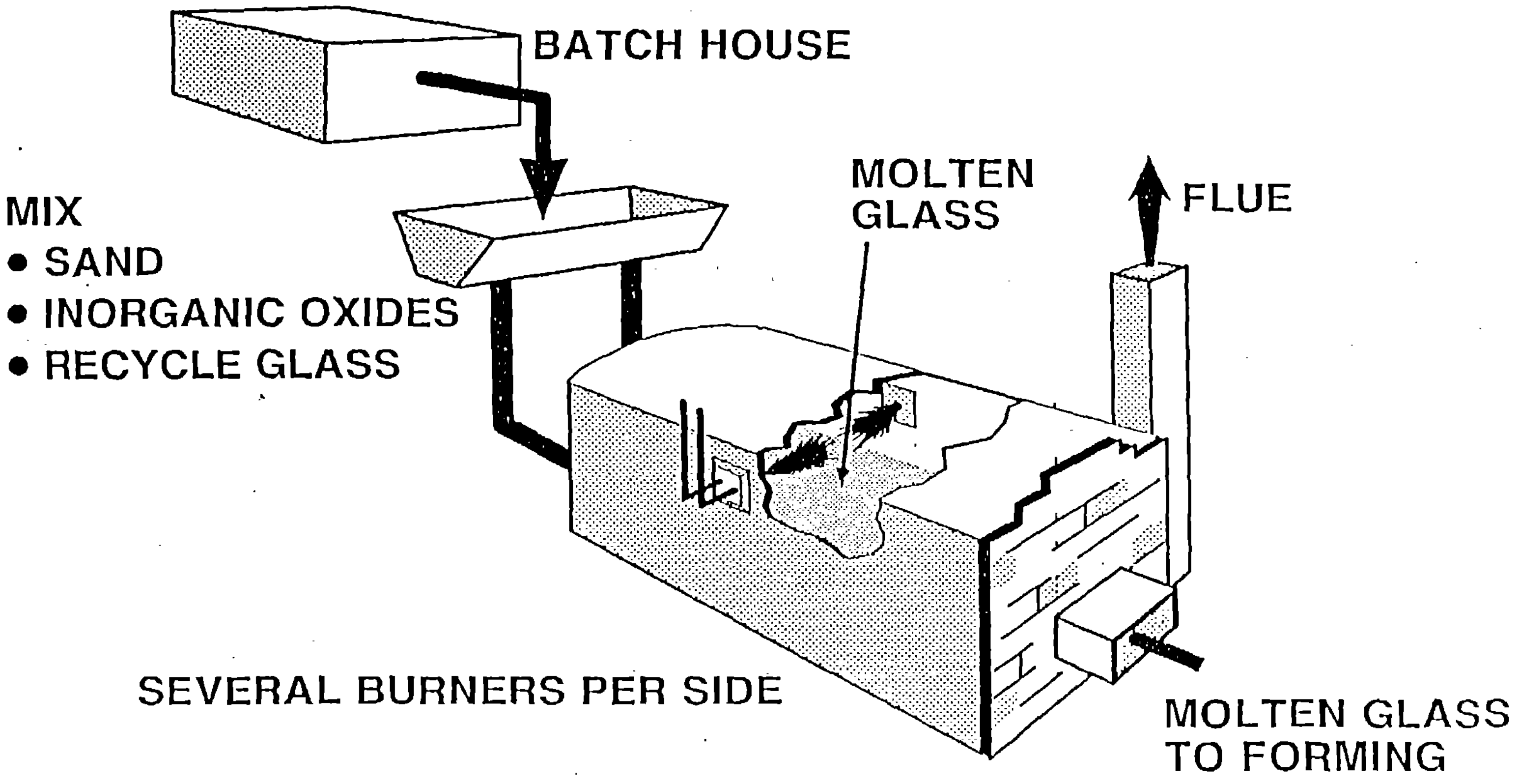
The host uses the hearth type of frit smelter, which is known for its simple construction and fairly long life (see Figure 51). The refractory lining can easily be changed when badly worn. The smelter is essentially a refractory box with the bottom sloping to a point near one side where the spout is located. Most furnaces are fired with oil or gas, whereby the flame passes over the surface of the batch. The burners are placed along both sides of the smelter with the flue at one end and the batch feeder at the opposite end. The batch composition is generally corrosive consisting, in various combinations, of sodium nitrate, borax, feldspar, fluorides, tin or zirconium oxides. The batch melts at a furnace temperature of 2200-2250°F.

The box type smelter is divided into three zones listed in order of decreasing firing rate: smelt, auxiliary, and puddle. Once the unit is brought up to temperature, the batch is fed through a hole in the end of the smelter where it forms a mound. As the batch begins to melt, the borax gives off steam, causing an agitation which helps mix the batch. The melted glass flows down the tank where it exits the spout and continues to the drying and packaging process.

At the host site there are 9 air-gas burners: 4 in the smelting zone, 2 in the auxiliary zone, and 3 in the puddle zone. The burners in the smelting zone were designed to fire between 0.8-1.25 MM BTU/hour, the auxiliary zone 0.3-0.75 MM BTU/hour. The depth of the glass in the smelter is 0.2 feet. Expensive

FIGURE 51

DIRECT FIRED UNIT SMELTER FOR GLASS FRIT PRODUCTION



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stack maintenance was required every month to repair damage due to excessive flue gas temperature.

The smelter operated 5 days a week, 24 hours a day. The unit shut down at 11:00 p.m. Friday night and began heating up at 4:00 p.m. Sunday afternoon.

Furnace monitoring capabilities at this facility were limited. Every hour an optical pyrometer was used to monitor the frit temperature at the spout and also at the back wall between the batch feed pipes. A radiation pyrometer was also used to automatically monitor spout temperature. Hand adjustment of each burner was necessary to maintain a constant temperature, i.e., there was no automatic control of the burner firing rate with relation to the radiomatic temperature. Control of the furnace pressure was limited to opening and closing a 2' x 6' door in the smelter stack. There was no capability to obtain exhaust flue gas temperature or composition.

Due to the very inefficient operation of a frit smelter, use of oxygen in this application offered the following benefits:

- Fuel Savings - By increasing the amount of available heat input, less fuel is required to melt the same amount of material; thus, furnace operates much more efficiently.

- Production Increase - The increased available heat can also be used to melt more material if a production increase is required.
- Reduce Flame Gas Volumes - There is very little flue gas volume produced with oxy-fuel. This also leads to further benefits involving the number of smelters that can be operated simultaneously. If the plant is limited by flue gas volumes due to scrubber capacity, then reducing the flue gas volume gives the flexibility to operate more than one smelter at the same time. This was a prime incentive for our host site.
- Increased Stack Life - Reducing the flue gas volume also reduced the temperature of the flue gas stream. Therefore, less stack maintenance is required to repair damage caused by excessive temperatures.
- Improved Frit Quality - Statistical Process Control was used to quantify benefits.

SYSTEM DESCRIPTION

Both air-cooled and water-cooled burners were retrofitted and tested in the frit smelter.

The first burner tested was the modified North American 4425-7A.

The tubes were insulated with a ceramic cookie whose function was to retard thermal degradation of the tubes while preventing the corrosive batch material from attacking the metal. Minimizing batch build-up on the end of the tubes was also critical because any distortion of the flame due to plugged tubes promoted rapid degradation of the burner face. A thermocouple was placed inside each burner body with a digital read-out at the control panel in order to monitor burner temperature conditions.

The water-cooled burner was a nozzle-mix, oxygen-fuel burner designed for installation into the burner mounting and tile assembly for North American 4425-7A burners. The burner's face pattern and nozzle dimensions were similar to the modified North American 4425-7A burner. Thermocouples were positioned at the burner face and at the inlet and outlet water connections.

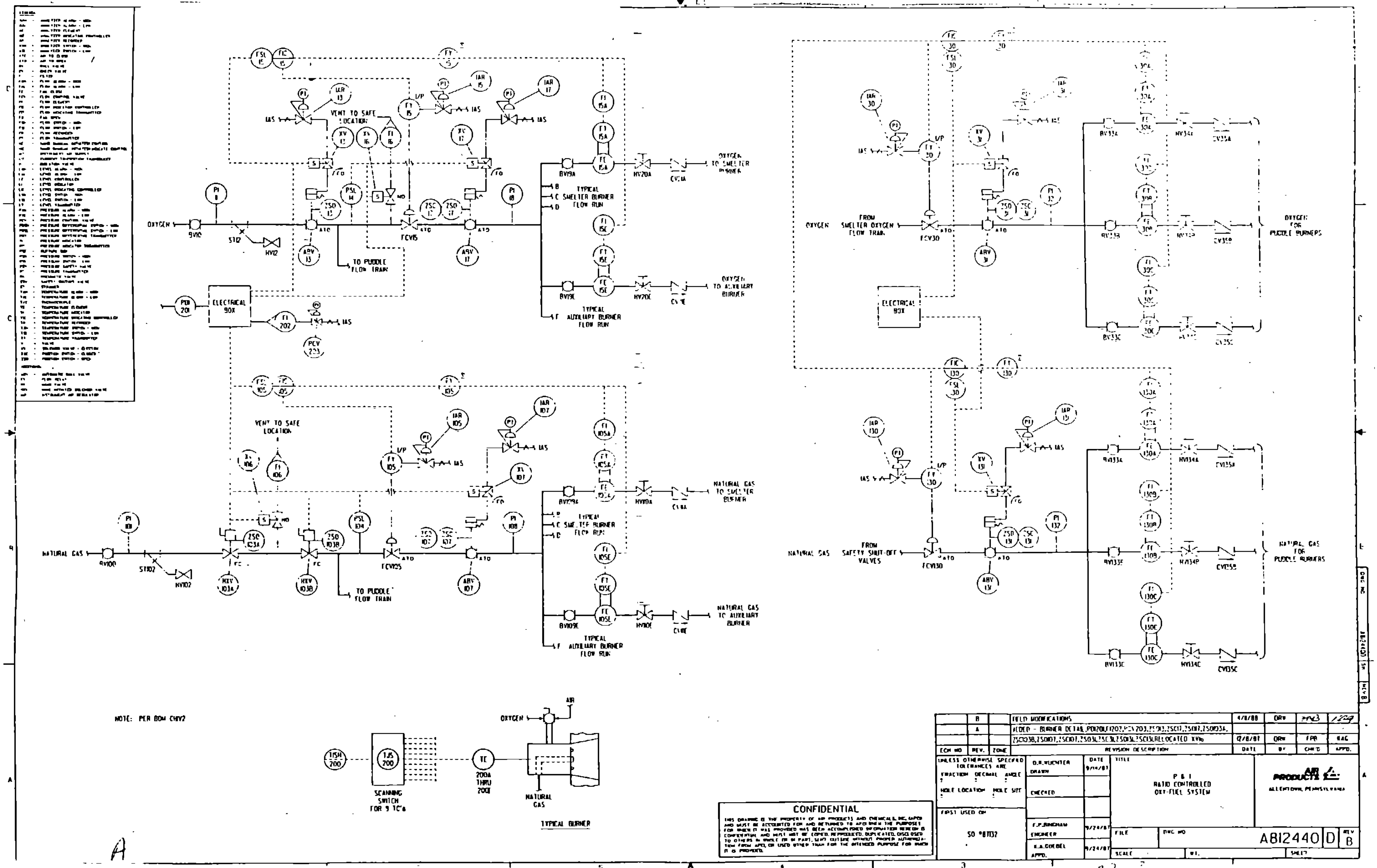
Oxygen exits through tubes that extend from the base of the oxygen nozzles through the water filled chamber terminating at the oxygen plenum. The oxygen plenum narrows to an inlet pipe with a perpendicular inlet connection.

Fuel exits through 1 flow tube that extends from the base of the fuel nozzle through the water filled chamber, oxygen plenum, and inlet pipe terminating parallel to, and through the end of, the oxygen inlet pipe where the fuel connection is made.

The smelter used in this trial already had 9 North American burners installed, so there were no furnace modifications required. The air/natural gas burners were removed and replaced with oxy-fuel burners. Each burner was supplied with a new burner block. Additional oxygen piping was required from the oxygen tank to the oxygen flow control skid and from the skid to each burner. Installation of the water-cooled burner also required additional piping to supply water to each burner.

Figure 53 depicts the piping and instrumentation diagram for the ratio controlled oxy-fuel system. The 2 automatic oxygen-natural gas burner flow control systems were designed to monitor and control the flow of gaseous oxygen and natural gas to 9 oxy-fuel burners. They controlled the total oxygen flow rates and ratio of the flow of oxygen to the flow of natural gas. The total flows were controlled by microprocessor-based process controllers. Each burner had a manual flow run for oxygen and natural gas. The relative flows to individual burners and the ratio of oxygen to natural gas on each burner were manually controlled. Each of the 2 control systems may be considered as a collection of subsystems:

FIGURE 53. RATIO CONTROLLED OXY-FUEL SYSTEM



- Main oxygen flow train
- Main natural gas flow train
- Burner manual oxygen flow train (for 6 burners in smelter-auxiliary flow system and 3 burners in the puddle flow system)
- Burner manual natural gas flow train (for 6 burners in the smelter-auxiliary zone and 3 burners in the puddle zone system)
- Main control panel

The flow skid with the flow trains mounted on it was located near the frit furnace. The main control panel was located in an area next to the other furnace controls.

System specifications were as follows:

- The oxygen flow rate was 630 to 12,600 SCFH in the smelter-auxiliary zone and 225 to 4500 SCFH in the puddle zone.
- The natural gas flow rate was 315 to 6300 SCFH in the puddle zone.
- Oxygen supply requirements were 20,000 SCFH at 100 PSIG, 40-100°F.
- Natural gas supply requirements were 10,000 SCFH at 6 PSIG, 40-100°F.
- Material of construction for piping and components was brass for oxygen and natural gas.

- Maximum operating pressure was 250 PSIG.
- Designed operating pressure was 20-50 PSIG.

A 9000-gallon tank to contain the liquid oxygen was anchored on a cement pad approximately 250 feet from the smelter. Ambient vaporizers were also installed to convert the liquid oxygen to gaseous oxygen. Figure 54 depicts the customer station set-up.

The oxygen flow system's prime function was to regulate and meter the total flow of oxygen to the oxy-fuel burners. The oxygen flow systems are located in the oxygen houseline between the oxygen storage facility and the smelter. The natural gas flow system is almost identical to the oxygen flow system except for two manual reset shutoff valves. The natural gas flow system's prime function was to regulate, meter, and ratio the oxygen flow to the total flow of natural gas to the oxy-fuel burner. The natural gas flow systems were located in the natural gas houseline between the natural gas supply line and the smelter.

The control panel instrumentation enabled remote monitoring and control of the oxy-fuel burner's total BTU output. The control panel contained 4 microprocessor-based process controllers mounted in a shelf on the front of the panel. Also on the front of the panel were electrical switches and lights used to turn the system off and on and monitor its operation. Some of the features included were:

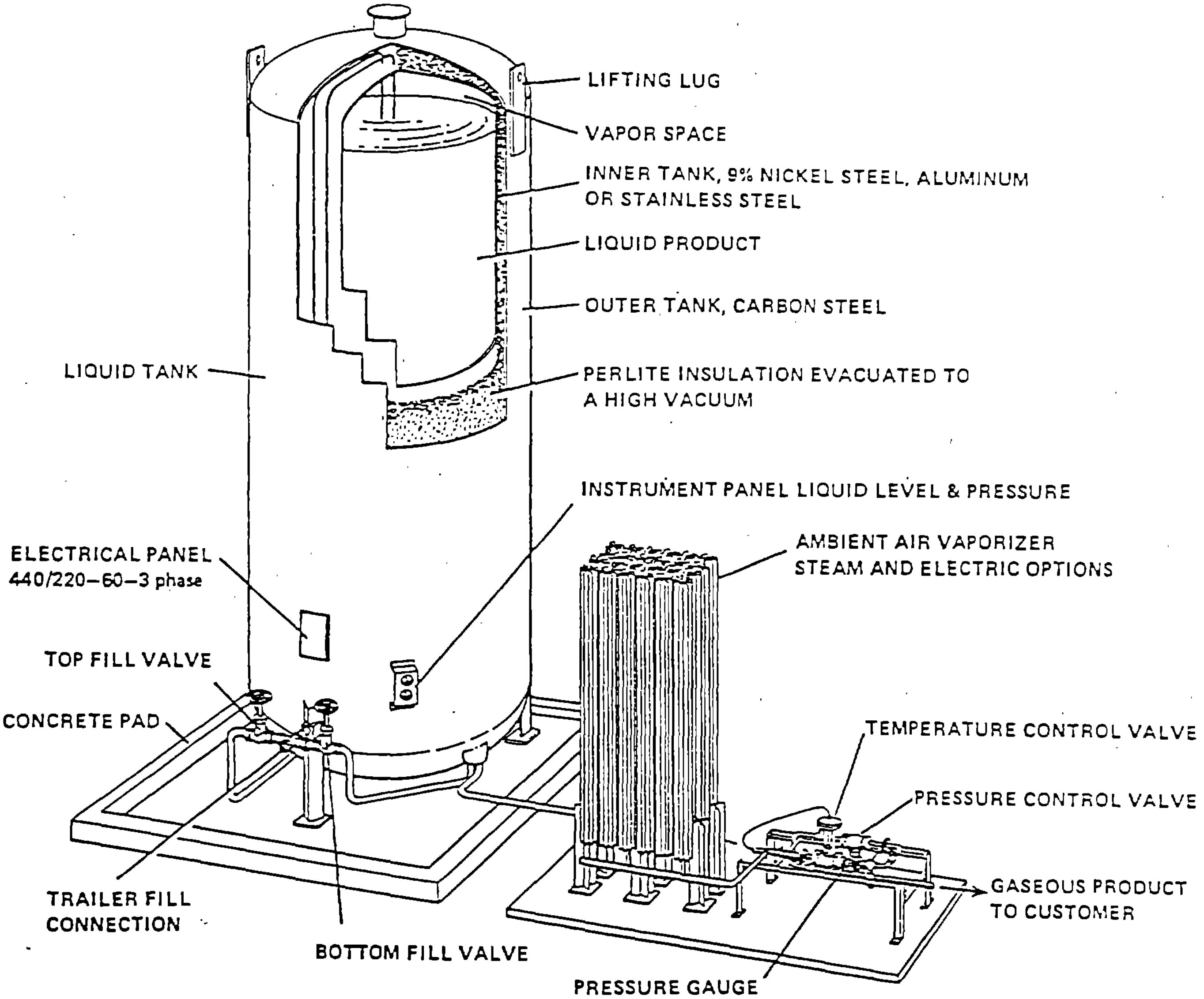


FIGURE 54

TYPICAL LIQUID TANK INSTALLATION

AIR PRODUCTS

- Emergency stop button
- Natural gas and oxygen safety valve reset
- Smelter-auxiliary burner stop
- Smelter-auxiliary burner start
- Puddle burner stop
- Puddle burner start
- Low oxygen pressure
- Low natural gas pressure

RESULTS AND DISCUSSION

Refer to Table 12 for a summary of the operating results achieved from the original nonwater-cooled oxy-fuel burner.

Table 12*

Nonwater-cooled Oxy-Fuel Trial

May 10 - May 27, 1988

	Before O2	After O2	% Change
Spout Wall (°F)	2,150	2,200	+2.3
Back Wall (°F)	2,430	2,470	+1.6
Outside Wall Stack Temp. (°F)	350	150	-57.0
Total Average Natural Gas Flow (SCFH)	11,500	4,650	-59.6
Total Oxygen Flow (SCFH)	--	9,900	--
Production Rate (Bags)	14	19	+35.7

*Note that these results were based on a particular type of frit product manufactured during the test period. Different operating parameters are required for other products which will vary the results.

Production and process benefits were encouraging, however, burner survivability in this environment was poor. Burner body temperatures ranged in excess of 450°F. Within 27 hours of start-up, 2 of the puddle burners had to be shut off due to excessive heat ranges indicated by thermocouples. Production was maintained by allowing 1 burner to cool while the other was fired and vice versa until the furnace could be shut down. Production and fuel benefits were calculated during this time frame.

The flame shape and characteristics produced from these oxy-fuel burners were excellent. Flame length was approximately 4 feet, covering more than half of the smelter width. The flame emerging from the burner block was tight and conical. The host was extremely pleased with the flame characteristics and production benefits. However, the burners failed due to a thermal deterioration related to frit accumulation adversely affecting nozzle mix symmetry and therefore the pattern of natural gas and oxygen mixing. To minimize process upsets to the host, the original air/gas burners were reinstalled until new modified burners could be tested in Air Products' combustion lab.

Another variation of this burner was designed and tested. The design modification was specifically chosen to lengthen the oxygen and natural gas tubes (while maintaining the same inner and outer diameters) in an effort to extend the flame into the furnace and minimize the flame mixing inside the burner block. The insulation cookie was also extended in order to protect the metal surface from heat exposure and pitting. It was determined that these burners operated at a significantly lower temperature than the original version. See Table 13 for results.

Table 13

Average Oxy-Fuel Burner Temperatures(1) After 150 Hours Firing Time

Thermocouple Location	Original Nonwater-Cooled Oxy-Fuel (°F)			Extended Tube Nonwater-Cooled Oxy-Fuel (°F)	Water-Cooled(2) Oxy-Fuel (°F)		
	Smelt	Auxiliary	Puddle	Puddle	Smelt	Auxiliary	Puddle
Burner Body	170	202	373	143	---	---	---
Burner Face	---	---	---	1900	---	---	107
Water Inlet(2)	---	---	---	---	---	---	97
Water Outlet(2)	---	---	---	---	98	95	96

(1) Thermocouples were not installed in the same location on each burner design, therefore some data points are missing.

(2) Four gpm cooling water.

Unfortunately, the burner displayed poor durability in the frit smelter environment. It was concluded that the cause for the burner failure was thermal degradation due to exposure of the burner tubes to excessive temperatures.

Introduction of a water-cooled burner was the final design modification. A single water-cooled, oxy-fuel burner was installed in February 1989, the remainder being the original air-fuel burners. AFter five months in the smelter, there was no indication of burner failure. Therefore, in August 1989, the remainder of the smelter was retrofitted with water-cooled, oxy-fuel burners, and process parameters measured.

Fuel consumption was one process parameter that was considerably reduced by oxy-fuel. Table 14 breaks down oxygen and natural gas flow rates for each zone by burner type. Table 15 summarizes the total specific fuel consumption.

The water-cooled burner displayed essentially the same 63% reduction in specific natural gas consumption as the nonwater-cooled burner (65%). Table 15 lists the change in specific fuel consumption in standard cubic feet per pound of frit produced.

Table 15

Specific Fuel Consumption

Burner Type	Specific Fuel Consumption SCF/lb	% Change
Air/Natural Gas	9.2	---
Nonwater-Cooled	3.2	-65
Water-Cooled	3.4	-63

Table 16 summarizes the production increase obtained which was in excess of 30% compared to production capabilities attained with air/natural gas firing.

Table 16

Production Rate
Product 38098

	Production (Bag/hr)*	% Change
Air/Natural Gas	14.1	---
Nonwater-Cooled	19.0	+34.8
Nonwater-Cooled Extended Tube (2 burners)	15.3	+8.5
Water-Cooled	18.5	+31.2

*One bag of product weighs 100 pounds.

TABLE 14

AVERAGE FUEL CONSUMPTION BY ZONE FOR PRODUCT 38098

Burner Type	Natural Gas Flow Rate (SCFH) Smelt	Natural Gas Flow Rate (SCFH) Auxiliary	Natural Gas Flow Rate (SCFH) Puddle	Total Natural Gas (SCFH)	% Change From Air/ Natural Gas	Oxygen Flow Rate (SCFH) Smelt	Oxygen Flow Rate (SCFH) Auxiliary	Oxygen Flow Rate (SCFH) Puddle	Total Oxygen Flow (SCFH)
Air/Natural Gas	8,000	2,000	1,500	11,500	-0-	---	---	---	---
Nonwater-Cooled (9 Burners)	3,250	700	700	4,650	-60	6,800	1,500	1,500	9,800
Extended Tube Nonwater-Cooled (2 Burners)	---	---	1,160	10,350	-10	---	---	2,500	2,500
Water-Cooled (9 Burners)	3,100	800	1,500	5,400	-53	6,850	1,700	3,400	11,950

Exceeding this range turned the frit blue and underheating turned the frit brown. Introduction of oxy-fuel increased the chances of exceeding the temperature range and therefore turning the frit blue; however, it was much easier to control the smelter temperatures with the oxy-fuel and refrain from overstepping the temperature range. The frit hardness was also monitored. Introduction of oxy-fuel improved the hourly moving range of hardness values obtained, producing a frit with a more consistent hardness level. This parameter was important since the host's customers requested a specific and consistent hardness level.

CONCLUSIONS AND RECOMMENDATIONS

From the data collected during the test periods, the following conclusions can be drawn:

1. The nonwater-cooled oxy-fuel North America 4425-7A burner produced a marketable flame with the shape and characteristics necessary for the frit or glass industry.

2. The nonwater-cooled burner showed poor signs of survivability in a frit environment where temperatures inside the furnace exceeded 2400°F.

3. A production increase can be obtained in a frit smelter when applying oxy-fuel technology.

Another benefit proven during the trial was a significant reduction in flue gas volume, which lead to less particulate carryover and an increase in the conversion of raw material to product. The reduced flue volume also reduces the load on the scrubbers so that all 3 smelters can be operated simultaneously. Since there was no way to accurately measure the amount of product being carried out of the stack, the plant measured the amount of raw material converted to frit product. This number was termed percent conversion and did not include batch material lost to ignition or dusting. Increasing the percent conversion meant that more product was produced from the equivalent amount of batch input. Table 17 summarizes the flue volume and percent batch conversion for each burner.

Table 17

Percent Batch Conversion
Flue Volume

Burner Type	Flue Volume (SCFH)	% Change	Percent Batch Conversion (%)	% Change
Air/Natural Gas	98,000	---	60.0	---
Nonwater-Cooled	9,500	-90.3	77.0	+28.3
Nonwater-Cooled Extended Tubes (2 burners)	---	---	67.0	+11.7
Water-Cooled	9,500	-90.3	75.0	+25.0

Statistical process control was used by the host to monitor quality benefits. Two specific parameters, color and hardness, were checked throughout the trial. Color was most readily affected by the oxy-fuel. A tight range was developed where the smelter should operate to produce the best quality frit color.

It is also recommended that further investigation of the water-cooled oxy-fuel option be continued. Although initial performance of this burner is outstanding, production and process benefits should be quantified. Due to the flame shape and characteristics produced by this burner, the glass industry is a recommended application of oxy-natural gas burners.

4. Fuel savings of 50% or more are possible by using oxy-fuel in a frit smelter.

5. Product quality stays the same or is improved by employing oxy-fuel technology.

6. Flue gas volume reduction greater than 70% can be expected by converting a smelter to oxy-fuel.

7. Flue exhaust temperatures decrease by more than 50% which increases the stack life and capital induced from stack maintenance and repair.

8. A water-cooled oxy-fuel burner can survive for more than 5 months in a frit smelter while maintaining excellent flame shape and characteristics.

9. Particulate losses are reduced by the reduction in flue gas volume, thereby increasing batch conversion to product by 25%.

It is recommended that use of the nonwater-cooled oxy-fuel burner in a frit smelter (or environment where the temperatures exceed 2400°F) be discontinued due to the inadequate burner survivability in this environment. The nonwater-cooled burners may be appropriate for lower temperatures or low furnace pressure applications.

With high-quality fuels like natural gas, which contains only trace amounts (if any) of organically bound nitrogen, fuel NOx is not a concern.

Oxygen enrichment of air/natural gas combustion processes increases the flame temperature because of the reduction in inert nitrogen concentration. Resulting increased flame radiation and reduced flue gas volumes reduce the amount of energy lost with the exhaust gases. As previously discussed, this leads to significant commercially-demonstrated advantages such as increased production in heating/melting applications, increased energy efficiency, reduced particulates, and reduced total gaseous emissions by substantial reduction of flue gas volume. However, at low to intermediate enrichment levels when the concentrations of nitrogen are still significant, the higher flame temperatures may also lead to higher NOx formation.

It is important to understand how NOx is formed in natural gas combustion processes and the impact of oxygen enrichment on the NOx levels. With this understanding, combustion control techniques to minimize NOx formation can be identified rather than relying solely on expensive treatment systems.

The core tasks of this project are

1. to develop a computer model to predict the NOx concentrations in the exhaust products of an oxygen-enriched air-natural gas flame; specifically a computer coded model to predict flue

7: NOx Modeling

7.1 Background

In this environmentally conscious age, increasingly more stringent regulations are being placed on discharges to the atmosphere from industrial processes. Nitrogen oxides (NOx), which consist primarily of nitric oxide (NO) in the furnace, have captured considerable attention in recent years because of their adverse affect on the general population, smog, acid rain, and ozone formation. Approximately 30% of acid rain is due to NOx. Other than automobiles, the largest sources of NOx are power plants and industrial processes.

There are three methods of NOx formation. Thermal NOx is formed by the reaction of nitrogen with oxygen at high temperatures. Prompt NOx is formed by the relatively fast reaction between nitrogen, oxygen, and hydrocarbon radicals. Fuel NOx is formed by the direct oxidation of organo-nitrogen compounds contained in the fuel. The overall reactions are as follows:

$$N_2 + O_2 \rightarrow NO, NO_2 \qquad \text{Thermal NOx}$$

$$CH_4 + O_2 + N_2 \rightarrow NO, NO_2, CO_2, H_2O \qquad \text{Prompt NOx}$$

$$R_3N + O_2 \rightarrow NO, NO_2, CO_2, H_2O \qquad \text{Fuel NOx}$$

In nonattainment areas, permits are required if a new plant resulting in more than 100 tons/yr NOx emissions or a modification to an existing plant resulting in more than 40 tons/yr NOx emissions is planned. To receive a permit the plant must employ technologies which result in the Lowest Attainable Emission Rate (LAER), not Best Available Control Technology (BACT). LAER does not consider if the technology is economically viable. If a permit is required a plant must also create or purchase NOx off-sets and take other actions regarding excessive NOx such that a net improvement in the ambient air quality results.

In PSD areas, permits are required if a new plant resulting in more than 100 or 250 tons/yr NOx emissions (depending on industry) or a modification to an existing plant resulting in more than 40 tons/yr NOx emissions is planned. To receive a permit BACT must be employed.

If the PSD area has almost reached ambient 0.053 ppm NOx or has increased nearly 0.013 ppm from its base line value (first time measured in August, 1977), then the area will fall under nonattainment regulations.

Various state and local agencies have additional regulations. The South Coast Air Quality Management District's (SCAQMD) regulations are the most interesting and appear to be most likely to be emulated in other areas. SCAQMD sets NOx emission/unit of production regulations for various industries. Current operating

NOx at various O_2 enrichment levels in a furnace with a natural gas-fired burner at one end and the flue at the other end,

2. conduct an experimental program to verify the performance of the model, and

3. identify the most important parameters in the production of NOx and formulate strategies for reducing NOx in combustion processes using oxy-natural gas burners.

7.2 NOx Emissions Regulations

The purpose of this section is to provide a concise regulatory perspective to the NOx emissions issues facing the heating and melting process industries. It should be appreciated that the actual regulations are voluminous and specifics vary by state and process.[1,2]

The U.S. is divided into 10 EPA Air Quality Districts. The EPA has set 0.053 ppm as the NOx ambient air standard. Districts exceeding this level (only Southern California today) fall under nonattainment regulations. Areas with less than 0.053 ppm NOx ambient concentrations fall under Prevention of Significant Deterioration (PSD) regulations. Enforcement and permitting is sometimes delegated to the respective state regulatory agencies.

glass plants must emit less than 5.5 lb. NOx per ton of glass. This limit drops to 4.0 lb/NOx per ton of glass after December 31, 1992. Even when operating within permitted guidelines, NOx emission fees can also be charged.[3]

References

1. Federal Register, 40CFR51

2. Rules and Regulations, SCAQMD, Regulation XI, Rule 1117 (1989).

3. A.J. Teller, et al. "Control of Emissions from A Container Glass Furnace," 49th Conference Glass Problems, 15 Nov 1988, p. 196.

7.3 Current NOx Control Technologies

Reduction of NOx emissions can be accomplished by both combustion modification and flue gas treatment. Combustion modification, which includes changing the operating conditions, modifying burner design, and modifying combustion system design, is an effective means to reduce NOx by preventing its formation. Flue gas treatment represents a group of postcombustion techniques that lower NOx emissions by converting NOx into less harmful compounds such as N_2 and HNO_3.

The following summaries describe both combustion modification and flue gas treatment technologies. Other reviews of NOx control techniques can be found in references 1-5. Supplemental references 17-22 have also been provided for details beyond the scope of this report.

Combustion Modification Techniques

Combustion modification encompasses a group of NOx reduction techniques that includes (1) change of operating conditions, (2) modification of burner design, and (3) modification of combustion system design.

1. Change of Operating Conditions

Changing the operating conditions of a furnace is the most easily implemented of all of the combustion modification techniques. A change of operating conditions involves no capital cost since most of the necessary equipment is already in place (e.g., natural gas or air flow controllers). This category of combustion modification includes the following techniques: Low Excess Air, Reduced Air Preheat, Heat Input and Reduction and Furnace Load Size Change, and Ambient Air Infiltration Reduction.

A. Low Excess Air

Low excess air is a combustion modification technique that can effectively reduce NOx emissions by decreasing the amount of oxygen available for reaction with nitrogen. An added benefit of low excess air is that it also enhances energy conservation through increased fuel savings. Below 5% excess air is becoming standard practice on most gas-fired furnaces.[2]

While low excess air has been used to reduce NOx emissions up to 69% in steel soaking pits,[3] success is not always guaranteed. In the case of one aluminum melter, low excess air resulted in an increase in NOx emissions.[3]

Low excess air results in lower NOx emissions because fewer oxygen atoms are available to react with nitrogen molecules via the thermal NOx mechanism (Zeldovich Mechanism):

$$\begin{array}{ll} O + N_2 = NO + N & \\ \underline{N + O_2 = NO + O} & \\ N_2 + O_2 = 2\ NO & \text{(NET)} \end{array}$$

Thermal NOx formation, as the name suggests, occurs at high temperatures, and is initiated by reaction of an oxygen atom with a nitrogen molecule. It has been observed that thermal NOx formation passes through a maximum with an increase in excess air.[1] Occurrence of the maximum can be attributed to the lower flame temperatures at high excess air (in which the excess air acts as a diluent and cools the flame).

If excess air is cut back too far, soot and CO may be formed,[2] which are not only pollutants but may also have an impact on product quality.

Low excess air technology is summarized as follows:

Advantages

- Fuel savings result from not heating large quantities of excess air.

- Short payback periods for addition of the minor control equipment and modifications to existing furnaces because of increased fuel savings.

Disadvantages

- Possibility of soot and CO formation at low excess air levels which simply results in substitution of one pollutant (CO) for another (NOx).

- Possible adverse effects of soot and CO on product quality.

B. Reduced Air Preheat

Reduced air preheat lowers NOx emissions, because lower combustion air temperatures result in lower flame temperatures which inhibit the formation of thermal NOx. Although NOx emissions can be reduced using lower combustion air temperatures, lower thermal efficiencies also result.[1] Typically, combustion air is preheated using recuperators and regenerators, which recover heat from the flue gas. Davies found that for waste heat recovery, fuel savings were 32% with recuperators and 49% with regenerators over the no preheat case.[6] In cases where reduced air preheat is the only alternative for reducing NOx emissions, possible integration of flue gas heat recovery with other processes in the facility should be considered. Even though furnace efficiency would be lowered, overall facility efficiency would be maintained.

C. Heat Input Reduction and Furnace Load and Size Change

Heat input reduction and furnace load size change have also been cited as techniques for lowering thermal NOx formation.[1,3] Lower firing rates and furnace load reduction is generally not an attractive means to lower NOx emissions because of reduced furnace production and the associated capital cost of underutilized equipment.[1] It should be considered a NOx emission reduction technique of last resort.

D. Ambient Air Infiltration Reduction

Complete elimination of NOx is best achieved by preventing its formation through the removal of all potential nitrogen inputs to the furnace. Simply removing the contained nitrogen in the fuel and combustion air (using 100% oxygen for instance) may not be sufficient since some infiltration of ambient air into the furnace may occur. The amount of ambient air infiltration depends on the furnace pressure and where the pressure measurement is taken in the furnace.

To reduce air infiltration, operating the furnace at positive pressure would be most desirable because less cold air would be introduced leading to the added benefit of higher thermal efficiencies.[7] However, positive pressure could be a potential hazard to personnel since combustion gases may leak out into the surrounding work area. Neutral furnace pressure may also lower air infiltration, but would be difficult to maintain and dependent on the pressure tap location since the furnace pressure is not uniform.

Although the relative importance of air infiltration in NOx formation is not clear, as more stringent NOx emission standards are issued, the need to identify all potential sources of nitrogen should be addressed.

2. Modification of Burner Design

Modified burners, particularly low NOx burners, represent the most cost-effective approach to lowering NOx emissions because the burner is an integral piece of equipment in furnaces. Combustion modification techniques such as reduced air preheat, while cost-effective in capital investment terms, may result in higher operating costs because of lower furnace efficiencies. Therefore, replacement or modification of burners in existing furnaces makes sense from both capital cost and operating expense perspectives.

The design of low NOx burners requires careful consideration of natural gas and oxidant mixing, and combustion patterns in the furnace, both of which affect flame temperature and NOx levels. The combustion pattern plays an important role in NOx formation because higher flame temperatures can result if the flame cannot radiate effectively to the furnace walls or the furnace load. Mixing may occur entirely outside the burner within the furnace (nozzle mix burners) or before exiting the burner (premix burner). The degree of mixing in a nozzle mix burner is determined by the momentum (or velocity) of the natural gas and oxidant streams, the degree of swirl, and the relative positions of the fuel and oxidant nozzles. Intense mixing and premixing can result in higher flame temperatures.

Low NOx burners have been classified as good mixing, divided-flame, self-recirculation, stage combustion, and combination.[8]

Good Mixing Type low NOx burners have air jets that impinge the fuel jets at or close to right angles. The result is a conical flame shape which has rapid heat removal because it produces a maximum radiation surface, that is, the flame can radiate more effectively to the walls of the furnace. Good mixing low NOx burners produce low levels of NOx and soot because the residence time in the high temperature regions is shortened.

Divided Flame Type low NOx burners have grooved fuel nozzle tips that create several independent small flames. Low NOx emissions are possible because the flame temperature is decreased and residence time in the high temperature regions is short.

Self-Recirculation Type low NOx burners produce low levels of NOx and soot by recirculating some partially combusted hot gas into the air or fuel jets. The recirculated gas essentially acts as a diluent for the air or fuel streams, which lowers the flame temperature.

Staged Combustion Type burners are classified as either fuel-rich or air-rich, depending on the equivalence ratio in the first stage. The fuel-rich type adds the remaining air in the second stage. The air-rich type injects the remaining fuel in the second stage. Both fuel-rich and air-rich two-stage combustion results in low NOx levels because of reduced flame temperature, since combustion is delayed and the flame is spread over a wider area. Staged combustion type burners apply only to a single burner effecting fuel/air mixing patterns, while staged combustion refers to a combustion system strategy that often involves using multiple burners or fuel/air injection ports. See also Staged Combustion under Modification of Combustion System design.

An example of a staged fuel burner is the John Zink Staged Fuel LoNOx Burner, a nozzle mix burner that uses fuel staging to create a primary and secondary combustion zone. The primary zone, which contains all the combustion air, is fuel lean. The remaining fuel is injected into the secondary combustion zone and is combusted with the unreacted oxygen left from the primary zone. The excess air results in complete combustion of the fuel in the primary zone, but at a low flame temperature. The degree of fuel/O_2 mixing in the primary zone can be controlled by adjustment of guide vanes which induce swirling of the air stream. High swirling gives a shorter and hotter flame which is caused by intense mixing near the burner face. NOx emissions were found to increase with higher swirling.[9]

Combination Type low NOx burners use any combination of good mixing, divided flame, self-recirculating, and staged combustion.

3. Modification of Combustion System Design

Modification of combustion system design, unlike the other combustion modification techniques, can often involve major capital expenditures. Combustion system design modification techniques include Flue Gas Recirculation, Staged Combustion, Reburning, Steam and Water Injection, and Pulse Combustion.

A. Flue Gas Recirculation

Flue gas recirculation lowers NOx emissions by reducing flame temperature through dilution of the combustion air with combustion gases. A 60% reduction in NOx emissions using 10% (by weight) flue gas recycle and a 75% reduction with 20% recycle has been reported.[1] Retrofitting existing furnaces requires extensive burner modifications to maintain flame stability; in addition, significant operating costs are associated with the recirculating fan.[3] Flue gas recirculation is a low-cost method for reducing NOx emissions in furnaces already equipped with a flue gas circulator system for temperature control.

B. Staged Combustion (Air/Fuel and Fuel/Air Staging)

Staged combustion has been found to lower NOx emissions by 30 to 68%.[10] This technique is a combustion system modification that uses multiple injection ports or burners (see also Staged Combustion type burners). Air/fuel staged combustion has a fuel-rich primary combustion zone to reduce oxygen availability and peak temperatures, followed by secondary air injection to complete burning. The lower oxygen level and lower flame temperature results in lower NOx formation rates. Heat removal before the secondary zone further reduces the flame temperature. A disadvantage is that CO and soot may be formed in the fuel-rich primary combustion zone which may adversely affect product quality.

Alternatively, fuel/air staged combustion, known also as reburning, provides in-furnace reduction of NOx by creating a second combustion zone that is typically fuel-rich.[11] Any NOx that is formed in the primary combustion zone is reduced in the reburn zone. The reburn fuel (≤20% of total fuel) is injected downstream of the main burners at a 10-20% air deficiency. Reburn fuel must be low in fuel nitrogen content to prevent the formation of fuel NOx. Natural gas is a good choice for reburn fuel since it contains only trace amounts of nitrogen, even if the fuel used in the primary zone is burning coal or oil. Excess air for burnout enters farther downstream at lower temperatures. Residence time and temperature are key operating parameters, both of which are optimized when reburn fuel is introduced as close to the primary zone as possible. NOx reduction of up to 85% is possible, but 50% NOx reductions can be expected on a continuous basis. While reburning has received much attention in research, the process has not been applied at full-scale facilities in the U.S.[11]

C. Steam and Water Injection

Steam and water injection has been found to lower NOx emissions by lowering the flame temperature through quenching.[1] A 90% reduction in NOx emissions has been reported using water injection; however, furnace thermal efficiencies can decrease by as much as 10%.[1] Steam injection can also lower soot formation, thereby reducing the amount of excess air, which helps offset the reduction in thermal efficiencies (see Low Excess Air). However, steam and water injection can increase CO emissions.

This technique has been tested on a full-scale utility boiler[1] and a subscale steel furnace using both natural gas and distillate oil. It has shown to be effective in reducing NOx, but drops in thermal efficiencies were high.

Steam and water injection can be summarized as follows:

Advantages

- Lower NOx emissions
- Lower cost of operation (water/steam)

Disadvantages

- Reduced thermal efficiencies
- Increased CO emissions - one pollutant (NOx) is replaced with another (CO)

D. Pulse Combustion

Pulse combustion is a periodic, yet self-sustaining combustion process that requires the combustion reaction heat release rate and local pressure oscillation to be in phase such that the fundamental acoustic mode of the combustion is excited.[12,13] Pulse combustion has found uses in domestic space and water heaters and in industrial dryers. Industrial use of pulse combustion has been limited by small unit size (100 to 250,000 BTU/hr) and possibly by the lack of understanding of the principles behind its operation. However, pulsed combustion has been shown to produce low levels of soot, CO, and NOx.[12]

Pulse combustion is summarized below:

Advantages

- Increased convective heat transfer
- High intensity of heat removal
- Cleaning of heater surfaces
- Low NOx emissions (~30-60 PPM)
- Reduced cost of air draft and blowers

Disadvantages

- Noise

- Vibration

- Excessive heat fluxes

- Equipment maintenance

Flue Gas NOx Reduction Techniques

Postcombustion flue gas treatment techniques are classified as wet or dry processes in which NOx is converted into less harmful or more easily handled compounds like N_2 and HNO_3. Wet flue gas techniques can be distinguished from dry techniques by the use of liquid phase absorption as one of the steps in NOx removal, while the dry techniques may remove NOx entirely by gas phase reaction or by adsorption. Dry flue gas techniques may range from the simple injection of ammonia into the flue, in which the NH_3 reacts with NOx to form N_2 (Selective Noncatalytic Reduction - SNR); or ammonia injection in the presence of a catalyst (Selective Catalytic Reduction - SCR); or to more exotic approaches such as using electron beam radiation coupled with ammonia injection. Wet flue gas techniques are typically more complex and expensive than dry techniques because wet techniques use flue gas/liquid absorbent contactors and require regeneration of the scrubber solution. Both wet and dry techniques produce by-products to varying degrees, including nitrates and ammonium salts, which create additional disposal problems.

Most development work employed dry processes because of simplicity of operation and lower costs. Wet processes have historically not been as economically viable as dry processes.[2] Because of higher capital costs, wet/dry techniques are used after simpler combustion modification techniques have failed to adequately reduce NOx.

1. Dry Flue Gas Techniques

Dry flue gas NOx reduction techniques are generally less complicated, lower in capital cost, and produce fewer by-products than wet flue gas techniques. Dry processes are generally integrated into air preheaters, boilers, and process heaters because of high temperature operation (600-2200°F). The dry flue gas techniques considered here are: (1) Selective Noncatalytic Reduction; (2) Selective Catalytic Reduction; (3) Activated Carbon Molecular Sieves; (4) Electron Beam Radiation; Simultaneous Hydrocarbon and Ammonia Injection; and (6) Rapid Reduction of Nitrogen Oxides (RAPRENOx).

The overall advantages and disadvantages of dry flue gas techniques can be summarized as follows:

A. Selective Noncatalytic Reduction (SNR)

SNR is a postcombustion process that uses ammonia (NH_3) to reduce NOx to nitrogen. This is a gas phase reaction that involves the injection of NH_3 into flue gas at a specific temperature window (2200 to 1600°F). The temperature range can be extended downward to 1200°F by the simultaneous injection of hydrogen. At temperatures below 1200°F, the NH_3 will go unreacted, and at temperatures above 2200°F, there will be a tendency to convert NH_3 to NOx. SNR is more effective in steady state operating units because of its sensitivity to operating temperature. SNR techniques are patented processes (Exxon and PPG), and some royalties can be involved.

The governing overall equations for these reactions are as follows:

$$NO + NH_3 + O_2 + H_2O \xrightarrow{(H_2)} N_2 + H_2O$$

$$NH_3 + O_2 + H_2O \xrightarrow{(H_2)} NO + H_2O$$

These equations are very simplified; the reaction involves 14 steps, including chain branching and free radicals. The efficiency of the reaction(s) is heavily dependent on injection at an optimal temperature and gas/gas mixing characteristics within the unit.

Dispersion of NH_3 into the flue gas is usually made through a series of injectors, which can be placed in the flue ducting, sprayed cross or counter to the flue gas flow, or flush-mounted crossflow wall injectors. The appropriate injection location is determined by temperature/residence time in order to achieve adequate flue gas coverage. The quantities of NH_3 are typically very small: ratios are $NH_3/NO = 1.0:2.0$ and $H_2/NH_3 = 0:3.0$ on a mass basis. A carrier gas, steam or air, is used to convey the reducing agent(s) into the flue stream as well as to promote gas/gas mixing. Residence times on the order of a few tenths of a second are required for the reaction to proceed to completion at high temperatures. Longer residence times (1 sec.) may be required at the lower injection temperatures. With optimal injection location and sufficient residence time, NOx reductions of up to 75% are achievable. This technology is currently used in refinery furnaces, industrial and utility boilers, and glass furnaces in the U.S., Japan, and Germany.

SNR may be characterized as follows:

Advantages

- Proven, operating technology.
- Requirement of minor furnace/boiler modifications, favoring retrofit units.
- Less cost compared with dry flue treating systems (capital and operating costs).
- Low system maintenance.

Disadvantages

- Possible presence of unreacted NH_3 (a pollutant) in flue emissions.
- Formation of ammonia bisulfate/sulfites, possibly causing increased heat recovery system fouling.
- Lower efficiency in units with wide production swings or wide temperature variations across the flue duct.

B. Selective Catalytic Reduction (SCR)

SCR is a dry flue gas treatment that uses NH_3 injection and a catalyst to reduce NOx into N_2 and H_2O at optimum operating temperatures between 570 and 750°F. SCR can operate over a lower temperature range than SNR because the catalyst effectively lowers the activation energy for the NOx reduction reactions. The process has been used successfully with utility boilers and refinery heaters in Japan, the United States, West Germany, and Austria, where it has been shown to reduce NOx emissions by over 90%.[3,8]

The overall governing reactions at the lower temperatures are:

$$NH_3 + NO \rightarrow N_2 + H_2O \tag{1}$$

$$NH_3 + NO + O_2 \rightarrow N_2 + H_2O \tag{2}$$

Note that the presence of oxygen enhances NOx reduction, as shown by reaction (2). However, NOx formation can occur in the presence of O_2 at higher temperatures (above 750°F), in which the following (overall) reactions begin to contribute:

$$NH_3 + O_2 \rightarrow NO + H_2O \qquad (3)$$

$$NH_3 + O_2 \rightarrow N_2O + H_2O \qquad (4)$$

The optimum NH_3/NO ratio is 0.95, but in commercial units the ratio may range from 1.05 to 1.2.

The catalysts used in SCR are typically tubular- and honeycomb-shaped since granular- and pellet-shaped catalysts are subject to plugging. SCR catalysts are usually based on TiO_2 and V_2O_5 because of their resistance to poisoning by SOx. TiO_2- and V_2O_5-based catalysts resist SOx levels up to 2,000 PPM, 100 PPM of which is SO_3. However, in industrial environments the catalysts can become deactivated and will typically last 2-3 years at up to 80% NOx removal with less than 5 PPM NH_3 slippage. Unreacted NH_3 must be kept to a minimum since it is also classified as a pollutant. NH_3 slippage can be caused by catalyst deactivation or by difficulty in matching the NH_3 injection pattern to nonuniform NOx flows in the duct ahead of the SCR unit.

SCR is characterized as follows:

Advantages

- More effective NOx removal than SNR (90% versus 70%).
- Proven operating technology.
- Lower and wider operating temperature range than SNR.
- Can handle transient operating conditions better than SNR.

Disadvantages

- NH_3 slippage - unreacted NH_3 can show up in flue emissions. (NH_3 is considered a pollutant).
- Fouling and deactivation of catalyst by dust and reactive species such as SO_3.
- Major modifications required to flue stack and heat recovery system - resulting in a higher capital cost than SNR.

- Presence of dust particles, which can "blind" catalyst sites.

- Presence of SOx, which can damage catalyst.

- Reaction of SOx with NH_3 to form ammonium sulfate and ammonium bisulfate, which can cause corrosion if deposits occur.

C. Activated Carbon Molecular Sieves

Activated carbon molecular sieves have been shown to reduce NOx emissions by (1) enhancing oxidation of NO into NO_2 followed by adsorption of the NO_2 onto the sieve, and (2) by catalytically reducing NOx into N_2 using NH_3.[14] For oxidation/adsorption, both NOx and SO_2 can be removed simultaneously since activated carbon can also be used as an adsorbent for SO_2. The catalytic reduction of NO using NH_3 over activated carbon has been shown to lower NOx emissions up to 90%.

Since NO is weakly adsorbed and NO_2 is more strongly adsorbed at temperatures below 212°F, the first step is oxidation of NO into NO_2 followed by adsorption of the NO_2 onto the sieve. The NO_2 is desorbed from the sieve using thermal regeneration at temperatures above 212°F; NO_2 is a by-product which can be sent to a nitric acid plant. A multiple-bed system allows continuous operation. The major disadvantage of this process is that it requires large molecular sieve beds and gas reheat.

Activated carbon molecular sieve technology is summarized below:

Advantages

- Simultaneous removal of NO and SO_2.
- Possible NOx removal by oxidation or reduction.

Disadvantages

- Large amounts of sieve required.
- Regeneration heat to desorb NO_2 (oxidation/adsorption) required.
- Additional waste disposal problems (oxidation/adsorption) created by by-product NO_2.

D. Electron Beam Radiation

This flue gas treatment technique combines Electron Beam Radiation with NH_3 injection to simultaneously remove up to 90% of the NOx and SO_2 contained in flue gas. The process operates at temperatures at or below 212°F and produces a powdery product consisting of ammonium nitrate and sulfate that can be collected by an electrostatic precipitator for use as fertilizer. However, the process has a high projected capital cost associated with the electron beam generator, is still in the experimental stage, and has not been offered commercially.[5]

E. Rapid Reduction of Nitrogen Oxides (RAPRENOx)

RAPRENOx is a flue gas technique that uses cyanuric acid [$C_3N_3(OH)_3$], which is commonly employed as a swimming pool water chlorine stabilizer, to reduce NOx into N_2 and H_2O. Cyanuric acid sublimes and decomposes into isocyanic acid (HNCO) when heated above 626°F:

$$C_3N_3(OH)_3 \rightarrow 3\ HNCO$$

The isocyanic acid then reacts with NOx to form N_2 and H_2O. RAPRENOx can effectively reduce NOx over a temperature range of 842-1,652°F. However, at lower temperatures (212-840°F) it actually produces NOx. The process is still at the experimental stage and initial experiments have shown NOx reductions by over 99%.[15]

Dry flue gas techniques can be summarized as follows:

Advantages

- Lower capital and operating costs.
- No significant new equipment required.
- High NOx removal efficiencies.
- Tested in large units.
- Little waste generation.

Disadvantages

- Inlet particulate matter sensitive.
- Usually requires NH_3.

- Possible corrosion problems due to $(NH_4)_2SO_4$ and NH_4HSO_4 formation.

- High temperature requirement means that units must be placed in power generator and heat recovery sections of furnaces-- may require some modification of flue ducts.

2. Wet Flue Gas Techniques

Wet flue gas NOx treatment processes are typically installed downstream of heat recovery equipment but before the flue stack because of lower operating temperatures.

Since NO has poor reactivity and is not readily absorbed by aqueous solutions, one approach is to oxidize NO into NO_2 and N_2O_5, both of which are more strongly absorbed than NO. Absorption of NO_2 and N_2O_5 follows the oxidation step. Two techniques using this approach are (1) Oxidation/Adsorption and (2) Oxidation/Absorption/Reduction. Another approach is to simultaneously absorb and react NO either by oxidation or catalytic reduction in the liquid phase, as used in (3) Absorption/Oxidation and (4) Absorption/Reduction. The following briefly describes the four key wet NOx removal techniques.

A. Oxidation/Absorption

NO is first oxidized into NO_2 and N_2O_5 using ozone, as shown by the overall reactions:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO + O_3 \rightarrow N_2O_5 + O_2$$

Alternatively, chlorine dioxide can be used in place of ozone:

$$NO + ClO_2 + H_2O \rightarrow NO_2 + HNO_3 + HCl$$

Activated carbon can also be used as a catalyst to enhance the oxidation of NO in air.

The NO_2 and N_2O_5 are then absorbed into a solution of sodium hydroxide. The result is a liquid containing nitrates and nitrites that is sent to either a treatment or disposal system, or the nitric acid can be removed for industrial use. Clearly, disposal of the nitrate and nitrite by-products creates problems.

B. Oxidation/Absorption/Reduction

The oxidation step for this process is the same as in the previous Oxidation/Absorption process. This technique has the advantage of simultaneously removing NOx and SOx; these are absorbed together into a lime/limestone scrubbing solution, which also reduces NOx into NH_3 and SOx into $CaSO_4$ by the following overall reaction:

$$NO_2 + SO_2 + CaCO_3 + H_2O \rightarrow CaSO_4 + NH_3 + CO_2$$

By-products of $CaSO_4$ and NH_3 present disposal problems.

C. Absorption/Reduction

NO and SO_2 are simultaneously removed by absorption into a solution containing ferrous ion, which forms an adduct with NO. NO and SO_2 are then reduced into $(NH_4)_2SO_4$ and NH_3 by the following overall reaction:

$$NO + SO_2 + HN_3 + H_2O \rightarrow (NH_4)_2SO_4$$

Unless $(NH_4)_2SO_4$ can be used on-site or sold as product, this process creates additional waste disposal problems.

D. Absorption/Oxidation

NO is absorbed into an oxidizing solution that may contain sodium or potassium permanganate, hydrogen peroxide, or sodium or calcium hypochlorites. By-products typically include $NaNO_2$ and KNO_3.

The wet flue gas treatment process[16] can be summarized as follows:

Advantages

- Simultaneous removal of NOx and SOx.
- Not sensitive to flue gas particulate matter.
- High SOx reduction.

Disadvantages

- Low solubility of NO in aqueous solutions.

- Generator of nitrates and potential water pollutants.

- More equipment intensive.

- Low demand for by-products/waste disposal problems.

- Flue gas reheat required.

- Moderate NOx removal efficiencies (less than 90%).

- May be limited to high SOx/NOx ratios.

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7.4 Model Description

The computer model to predict NOx levels in flue gas is called GRREK, an acronym for Gas flow and Radiation with Reaction Equilibrium and Kinetics. GRREK incorporates submodels for calculating fluid flow, radiation heat transfer, and chemical kinetics.

GRREK is constructed of interconnected modules. This approach has several advantages. Parallel development of modules decreases program development and debugging time. The program can be easily modified by substituting more efficient routines or improved kinetics when they become available. Unneeded modules can be inactived while solving a particular problem in order to reduce the computation time.

The detailed solution procedure is described in reference 1. The gas phase conservation equations consist of mass, momentum, turbulence, species concentration, and energy. The solution is initiated by interactively solving these equations. Then the radiative equation is solved which provides a source term for the energy equation. The gas phase equations are then resolved using the radiative source term. This iterative procedure is continued until a converged solution is achieved. The chemistry module, which calculates species concentration, and the radiation module can be activated and deactivated for a set of iterations when divergence difficulties are encountered. Relaxation parameters control how much variation is allowed per iteration for each variable to help avoid solution divergence.

The fluid flow module has its source in the combustion model (COMO) developed by Babcock and Wilcox for the U.S. Department of Energy.[1] COMO is a numerical model for predicting furnace performance in axisymmetric geometries. The model was originally written to study pulverized coal combustion in utility boilers. COMO also consists of relatively independent modules that represent the major processes in pulverized coal combustion: flow, heterogeneous and homogeneous chemical reaction, and heat transfer. This modularity makes COMO readily adaptable to other types of chemical processes.

The fluid flow module is designed to solve the full Navier-Stokes equation for steady state, turbulent, two-dimensional axisymmetric (cylindrical) flows. The furnace is divided into control volumes. The governing equations are integrated over each control volume, assuming some distribution for the dependent variables. The assumed distribution is iteratively corrected until a converged solution is obtained. The partial differential equations are discretized using finite difference techniques.[2] The module solves the resulting algebraic equations to predict the pressure and velocity fields. The k-e approximation is used to model turbulence and the overall macromixing in the furnace.

The chemistry module quantifies the effect of homogeneous gas phase chemical reactions within the furnace. A common assumption in combustion modeling is that the chemical reaction rates are controlled by the rate of turbulent mixing. This "fast kinetics" assumption, valid when the reaction time scales are much less than the mixing time scales, greatly simplifies the model equations and provides reasonably accurate predictions for the major chemical components. The reasonable chemical predictions lead to reasonable temperature and velocity field calculations since they are all interrelated. For the NOx chemistry, where reaction time scales are similar in magnitude to those for mixing, the "fast kinetics" hypothesis is not valid. A full kinetic description is used in GRREK.

To meet the objectives of this work, the reaction set employed must contain detailed descriptions of the hydrocarbon combustion, thermal NOx, and prompt NOx kinetic mechanisms. Westbrook and Dryer have reported a large number of potential reactions in a typical combustion process.[3] A rough kinetic sensitivity analysis was performed to determine a realistic but manageable reaction set to describe the combustion/NOx chemistry by seeing if an equation had any detectable impact on a methane flame.[4] The analysis was performed by simulating a premixed gas/oxidant flame under adiabatic conditions. Table 18 displays the resulting set of 115 reactions chosen to represent the complex chemistry. Thermodynamic properties for the reacting species are evaluated based on the JANAF databank.[5] A second reduced set of 33 reactions shown in [9] was also tested. The program is designed so that any number of reactions including the appropriate kinetic data can be entered into the input data set. As well be shown later the predictions using either set were very similar.

The control volume is treated as a perfectly stirred reactor (PSR) in the solution procedure. For initialization purposes only, each control volume is assumed to be at chemical equilibrium. During subsequent interactions, the steady state solutions to the fully kinetic component material balance equations are determined via a Newton-Raphson convergence. If the Newton-Raphson method fails, which is possible for near-equilibrium control volumes, the transient PSR equations are integrated to their steady state solution via a stiff ODE solver.[7]

Table 18: Full Set of NOx Reactions

1	CH_4	+	M	=	CH_3	+	H+M
2	CH_4	+	H	=	CH_3	+	H_2
3	CH_4	+	O	=	CH_3	+	HO
4	CH_4	+	HO	=	CH_3	+	H_2O
5	CH_4	+	HO_2	=	CH_3	+	H_2O_2
6	CH_4	+	CH_2	=	$2CH_3$		
7	CH_3	+	M	=	CH_2	+	H+M
8	CH_3	+	H	=	CH_2	+	H_2
9	CH_3	+	O	=	CH_2O	+	H
10	CH_3	+	O	=	CH_2	+	HO
11	CH_3	+	HO	=	CH_2	+	H_2O
12	CH_3	+	HO	=	CH_2O	+	H_2
13	CH_3	+	O_2	=	CH_2O	+	HO
14	CH_3	+	O_2	=	CH_3O	+	O
15	CH_3	+	HO_2	=	CH_3O	+	HO
16	CH_3O	+	M	=	CH_2O	+	H+M
17	CH_3O	+	O	=	CH_2O	+	HO
18	CH_3O	+	HO	=	CH_2O	+	H_2O
19	CH_3O	+	O_2	=	CH_2O	+	HO_2
20	CH_2O	+	M	=	CHO	+	H+M
21	CH_2O	+	O	=	CHO	+	HO
22	CH_2O	+	H	=	CHO	+	H_2
23	CH_2O	+	HO	=	CHO	+	H_2O
24	CH_2O	+	HO_2	=	CHO	+	H_2O_2
25	CHO	+	M	=	CO	+	H+M
26	CHO	+	H	=	CO	+	H_2
27	CHO	+	O	=	CO	+	HO
28	CHO	+	O	=	CO_2	+	H
29	CHO	+	HO	=	CO	+	H_2O
30	CHO	+	O_2	=	CO	+	HO_2
31	CH_2	+	H	=	CH	+	H_2
32	CH_2	+	O	=	CO	+	H_2
33	CH_2	+	O	=	CH	+	HO
34	CH_2	+	HO	=	CH_2O	+	H
35	CH_2	+	HO	=	CH	+	H_2O
36	CH_2	+	O_2	=	CO_2	+	H_2
37	CH_2	+	O_2	=	CO	+	H_2O
38	CH_2	+	O_2	=	CHO	+	HO
39	CH_2	+	O_2	=	CH_2O	+	O
40	CH	+	H	=	C	+	H_2
41	CH	+	O	=	CO	+	H
42	CH	+	HO	=	CHO	+	H
43	CH	+	O_2	=	CHO	+	O
44	C	+	O_2	=	CO	+	O
45	C	+	HO	=	CO	+	H
46	CO	+	HO	=	CO_2	+	H
47	CO	+	HO_2	=	CO_2	+	HO
48	CO	+	O_2	=	CO_2	+	O
49	CO_2	+	M	=	CO	+	O+M
50	H_2O_2	+	M	=	2HO	+	M
51	H_2O_2	+	H	=	HO_2	+	H_2
52	H_2O_2	+	HO	=	HO_2	+	H_2O
53	H_2O_2	+	O_2	=	$1HO_2$		
54	HO_2	+	O	=	O_2	+	HO
55	HO_2	+	HO	=	O_2	+	H_2O
56	HO_2	+	H	=	1HO		
57	HO_2	+	H	=	O_2	+	H_2
58	HO_2	+	M	=	O_2	+	H+M
59	O_2	+	H_2	=	2HO		
60	H	+	O_2	=	HO	+	O
61	O	+	H_2	=	HO	+	H
62	HO	+	H_2	=	H_2O	+	H
63	H_2O	+	O	=	2HO		
64	H_2O	+	M	=	HO	+	H+M
65	O_2	+	M	=	2O	+	M
66	HO	+	M	=	H	+	O+M
67	H_2	+	M	=	2H	+	M
68	N	+	HO	=	NO	+	H
69	N	+	O_2	=	NO	+	O
70	N	+	NO	=	N_2	+	O
71	C	+	NO	=	CN	+	O
72	CH	+	N	=	CN	+	H
73	CH	+	N_2	=	CHN	+	N
74	CH	+	NO	=	CHN	+	O
75	CH	+	NH	=	CHN	+	H
76	CH_2	+	N_2	=	CHN	+	NH
77	CH_2	+	NO	=	CHN	+	HO
78	CH_2	+	N	=	CHN	+	H
79	CHN	+	HO	=	CN	+	H_2O
80	CHN	+	O	=	NCO	+	H
81	CHN	+	O	=	NH	+	CO
82	CHN	+	O	=	CN	+	HO
83	CN	+	H_2	=	CHN	+	H
84	CN	+	O	=	CO	+	N
85	CN	+	O_2	=	NCO	+	O
86	CN	+	HO	=	NCO	+	H
87	NCO	+	H	=	NH	+	CO
88	NCO	+	O	=	NO	+	CO
89	NCO	+	N	=	N_2	+	CO
90	NCO	+	NO	=	N_2O	+	CO
91	NCO	+	M	=	HNO	+	O
92	NH	+	O_2	=	HNO	+	O
93	NH	+	O_2	=	NO	+	OH
94	NH	+	O	=	NO	+	H
95	NH	+	HO	=	HNO	+	H
96	NH	+	HO	=	H_2O	+	N
97	NH	+	N	=	N_2	+	H
98	NH	+	H	=	H_2	+	N
99	NH	+	NO	=	N_2O	+	H
100	HNO	+	M	=	NO	+	H+M
101	HNO	+	HO	=	NO	+	H_2O
102	HNO	+	H	=	NO	+	H_2
103	NH_2	+	O	=	NH	+	HO
104	NH_2	+	O	=	NH	+	HO
105	NH_2	+	HO	=	NH	+	H_2O
106	NH_2	+	H	=	NH	+	H_2
107	NH_2	+	NO	=	N_2	+	H_2O
108	NH_3	+	HO	=	NH_2	+	H_2O
109	NH_3	+	H	=	NH_2	+	H_2
110	NH_3	+	O	=	NH_2	+	HO
111	NH_3	+	M	=	NH_2	+	H+M
112	N_2O	+	M	=	N_2	+	O+M
113	N_2O	+	H	=	N_2	+	HO
114	N_2O	+	O	=	1NO		
115	N_2O	+	O	=	N_2	+	O_2

The heat transfer module calculates the radiative transport in the furnace using the method of discrete ordinates.[8] The resulting equations with the appropriate radiative boundary conditions are integrated over each control volume and solved by a point-by-point iterative scheme.

The model geometry represents a cylindrical furnace with a burner at one end and an exit flue at the other end. The grid can be adjusted to provide more nodes at a given location to increase accuracy without severely penalizing computational time. Typically, there should be more node points in the vicinity of the flame and fewer node points near the flue end of the furnace.

GRREK operates on a VAX 11-780 minicomputer. Solution time varies greatly depending on the nature of the problem, anywhere from several minutes to several hours. The input to the program consists of geometry data, gas transport, thermodynamic and chemical properties, reaction chemistry information, radiation parameters, and program control variables (iterations, relaxation, etc.).

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7.5 Comparison of Experimental Results With Model

Two different types of burners were modeled with GRREK. The Air Products KT-3 burner was modeled to represent oxygen-fuel combustion systems. The North American 4425-8A was modeled to represent air-fuel combustion systems. Both burners were tested in the Air Products Combustion Lab Furnace so that model results could be directly compared to experimental data.

Both the KT-3 and 4425-8A burners were modeled with the following common parameters:

furnace length = 17'-8"
furnace diameter = 8.44'
flue diameter = 2'
furnace pressure = 1 atm.
furnace wall emissivity = 0.3
incoming gas temps = 64°F
flue gas composition = 99.5% CH_4 by volume
= 0.5% N_2 by volume

The furnace wall emissivity is a rough average of the refractory and a heat load. Higher emissivities produced virtually the same results for the cases modeled. The thermodynamic properties for the gas species were taken from the JANAF tables. The gas radiative properties were taken from the Hottel Charts.

Oxygen-Fuel Burners

The KT-3 is ideally suited for modeling with GRREK because of its concentric cylinder design. The following parameters were used:

firing rate = 2.37 MMBtu/hr
stoichiometry = 2.0
O_2 in oxidant = 100%
furnace wall temperature = 2000°F
number of reactions = 115
number of species = 30
number of axial nodes = 36
number of radial nodes = 32

The model predicted 0.007 lbs NO/MMBtu in the flue of the furnace. In the lab furnace, 0.012 lbs NO/MMBtu was measured in the flue.

Air-Fuel Burners

The North American 4425-8A air-fuel burner could not be modeled exactly due to the cylindrical coordinate limitation of GRREK. The eight concentrically located oxidizer nozzles surrounding the core fuel gas nozzle were modeled as a thin annulus with the equivalent cross sectional area. The radius of the annulus centerline is the same as the radius to the actual nozzle centers. Eight different cases were modeled as shown in Table 19. Each case used 36 axial nodes and 31 radial nodes.

Table 19

TEST CASES MODELED FOR NA 4425-8A BURNER

Parameter	Units	1	2	3	4	5	6	7	8
Firing Rate	MMBtu/hr	2.0	2.0	2.0	2.0	2.0	2.0	1.5	2.0
Stoichiometry	---	2.0	2.0	2.0	2.5	2.0	2.0	2.0	1.8
O_2 in Oxidant	%	21	21	21	21	24	28	21	21
Furnace Wall Temp.	°F	2,000	1,000	2,000	2,000	2,000	2,000	2,000	2,000
No. of Reactions	---	115	115	33	115	115	115	115	115
No. of Species	---	30	30	19	30	30	30	30	30
Predicted Flue No.	lb/MMBtu	1.74	1.66	1.72	3.26	0.166	0.425	0.143	0.092
No. of Iterations	---	11,957	10,420	9,200	9,226	10,950	12,650	11,150	13,000

Case 1 is considered the base case. Cases 2-8 look at variations of individual parameters in Case 1 to assess their effects on the predicted NO_x. Case 2 uses a lower wall temperature. Case 3 uses a reduced set of reactions. Cases 4 and 8 look at other stoichiometries. Cases 5 and 6 investigate other oxygen levels in the oxidizer. Case 7 looks at another firing rate.

Figure 55 shows a comparison of the experimental data with GRREK's predictions for flue NO as a function of firing rate. The experimental data shows no dependence of flue NO on firing rate for the range of firing rates tested. The model predictions are significantly different from the data.

Figure 56 shows a comparison of the experimental and model predictions for flue NO as a function of stoichiometry. The experimental data show a linear dependence where flue NO increases as stoichiometry increases. GRREK predicted the same flue NO as the data at a stoichiometry of 1.8. At higher stoichiometries, the model predictions were much higher than the data.

Figure 57 compares the experimental data with GRREK's predictions for flue NO as a function of percent oxygen in the oxidizer. The data shows that flue NO increases as the percent O_2 in the oxidizer increases at these low levels of enrichment. The model accurately predicts flue NO at 24% O_2 but, predicts too high at 21% and 28%.

FIGURE 55: FLUE NITRIC OXIDE
FIRING RATE EFFECTS

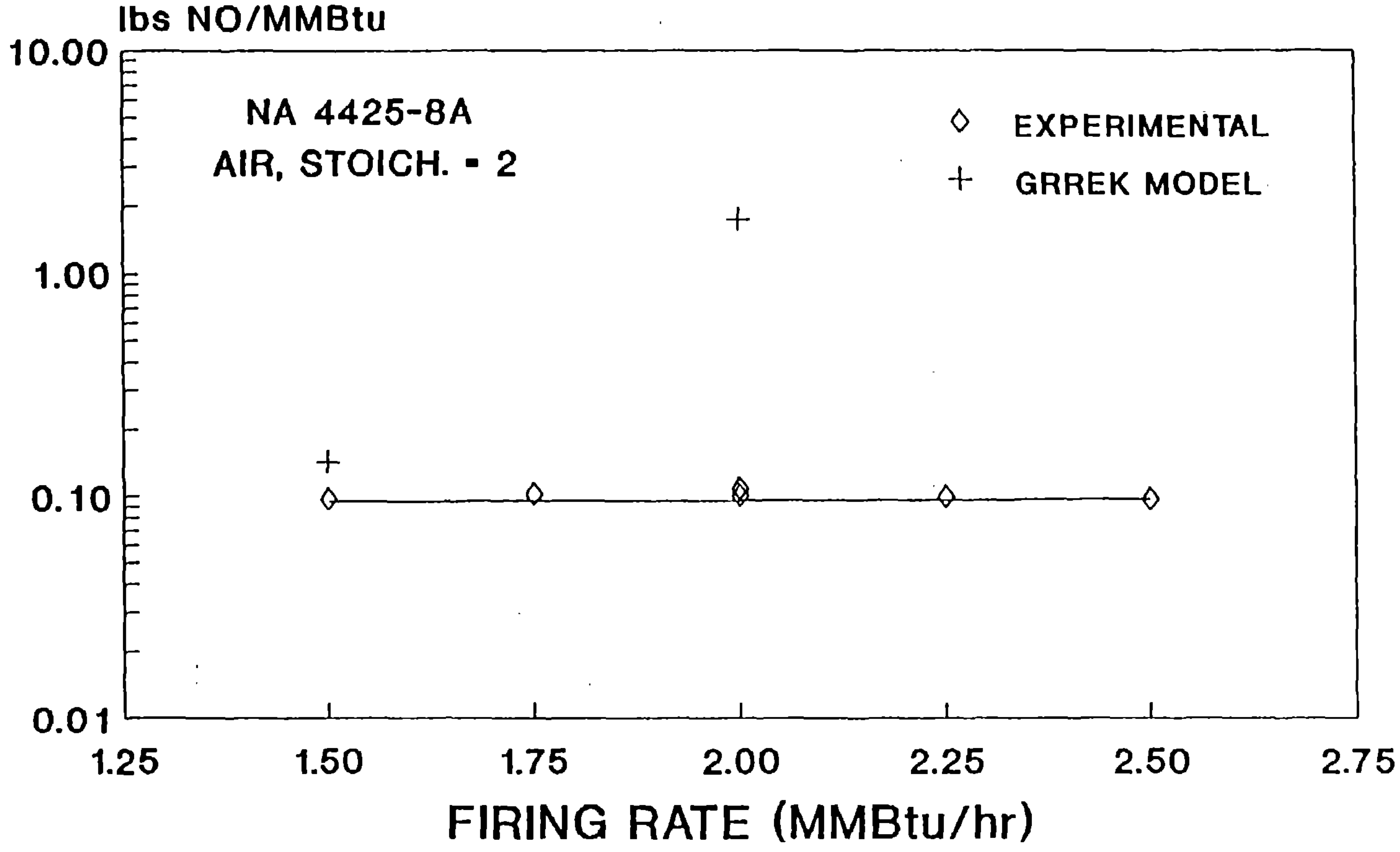


FIGURE 56: FLUE NITRIC OXIDE
STOICHIOMETRY EFFECTS

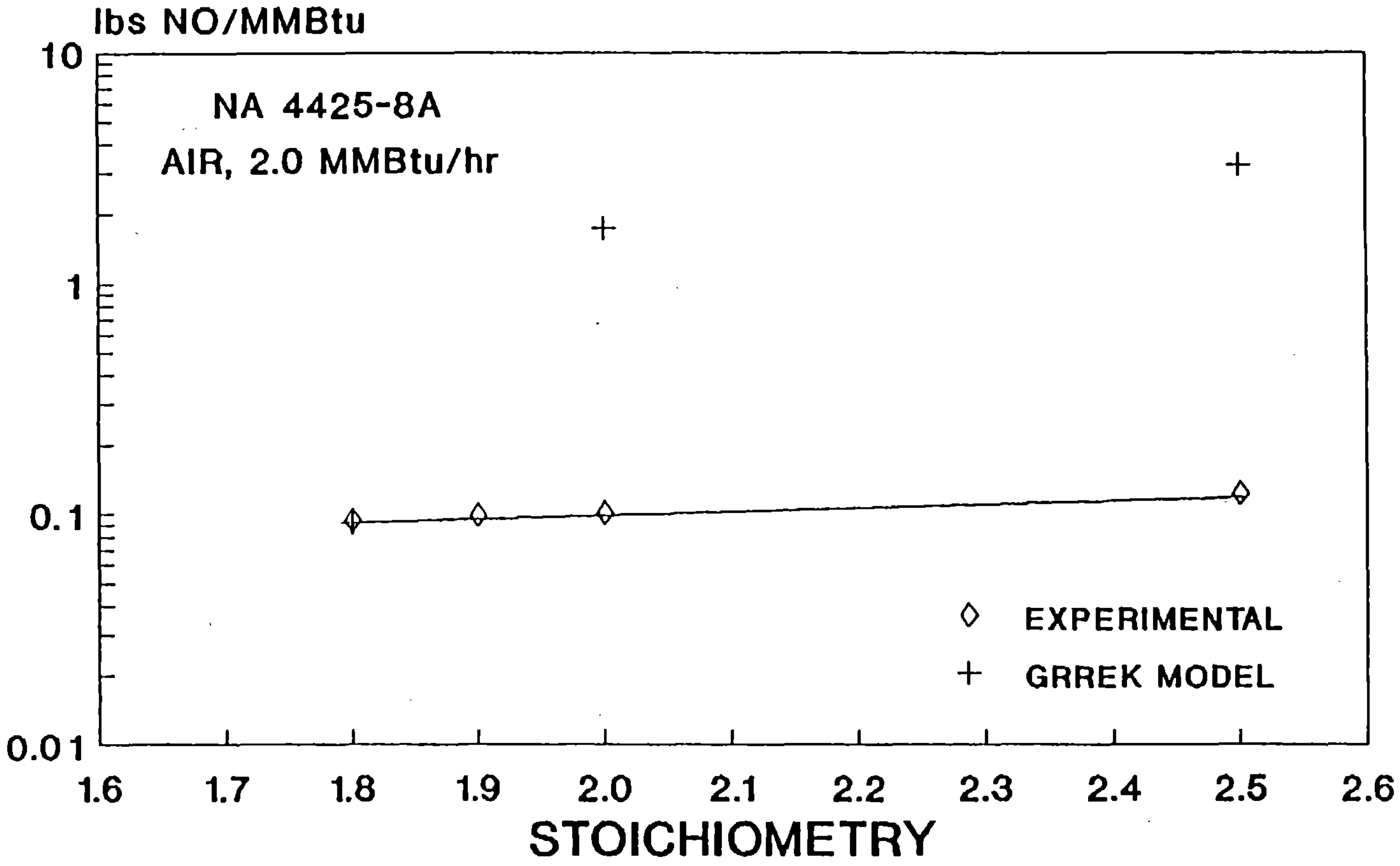
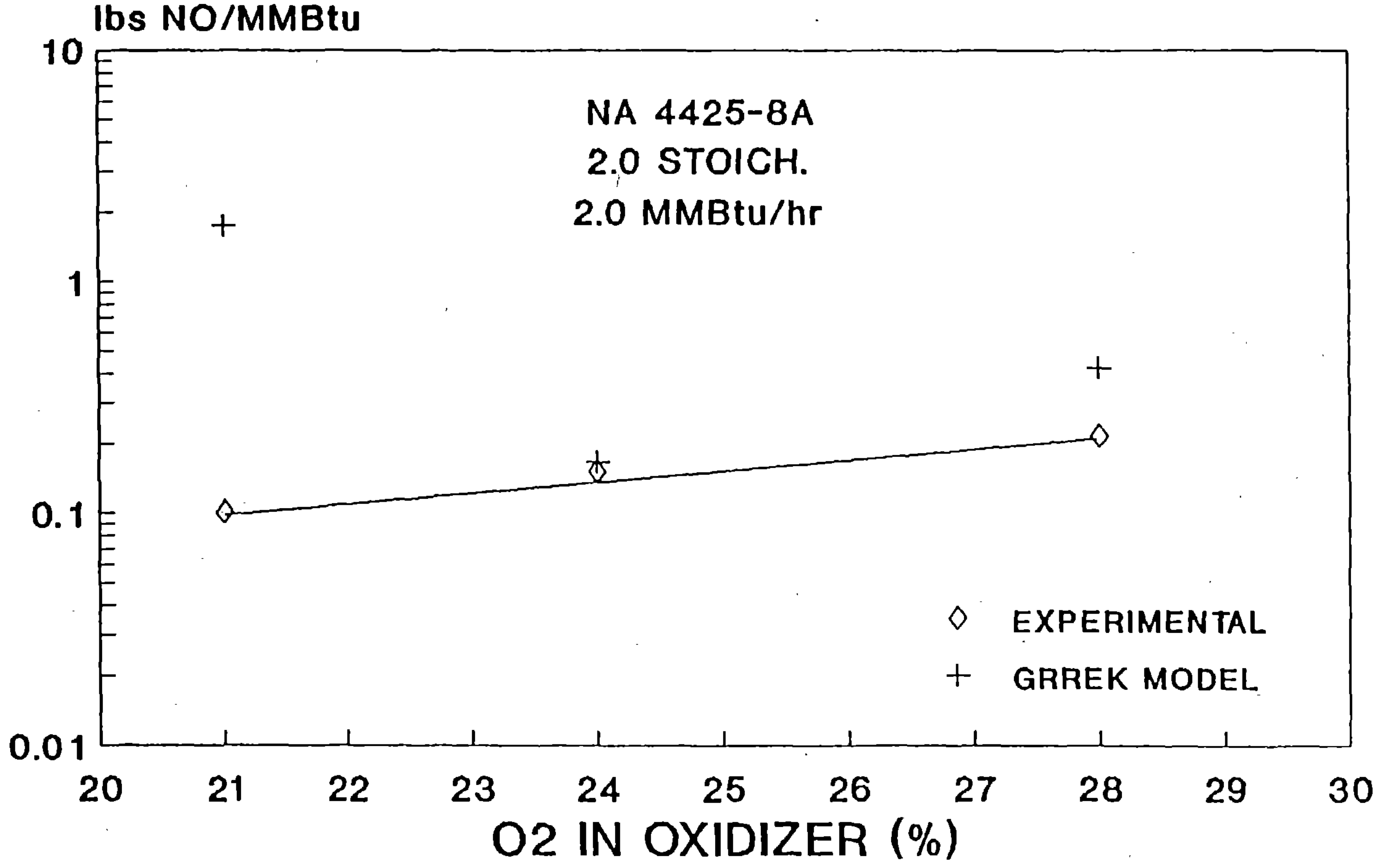


FIGURE 57: FLUE NITRIC OXIDE

OXYGEN EFFECTS



7.6 Model-based Conclusions and Recommendations

GRREK is difficult to use and is not user friendly. Each test case took 30-40 runs to approach convergence. Each run consisted of a set of iterations at one set of conditions. Due to the complexity of the problem, various conditions had to be run in different sets of iterations until convergence was approached. Some of the constants used to get convergence had to be obtained by trial and error. A great deal of familiarity with the model is required to get converged solutions.

GRREK's prediction for flue NO in the oxygen-fuel test case was fairly reasonable. As previously stated, this geometry is ideally suited to the cylindrical coordinates of the model.

The predictions for the air-fuel test cases were either fairly accurate or an order of magnitude too high. GRREK did not predict the same trends measured in the lab furnace. The predicted gas temperatures are significantly higher than the actual measured temperatures in the furnace.

There are a number of potential explanations for the disparity between the predicted and experimental values. They include:

1. The higher predicted gas temperatures would lead to more predicted thermal NO_X than actually measured.
2. The rectangular furnace was modeled as a cylinder of equivalent area which could affect furnace gas mixing.

3. A grid sensitivity study was not completed due to project time constraints. Such a study could show that more nodes may be needed to create a grid independent solution.
4. The air-fuel burner geometry had to be substantially modified due to GRREK's polar coordinate constraint which could have affected the gas mixing.
5. The actual furnace has water cooled upper wall panels to simulate a load whereas the model can only simulate an angularly constant wall condition.
6. Recent research suggests that the K-E turbulence model may not be very accurate for combustion modeling.
7. GRREK assumes constant properties, no body forces, and no compressibility effects, which was not strictly true in the lab furnace.
8. The burner outlet fuel and oxidizer gas velocities were assumed constant in the modeling. In actuality, there is some velocity profile which may cause a significant difference in the shear mixing between the gases.
9. The results presented for GRREK are not fully converged. Although there appeared to be no more changes in the flue NO for each case, project time constraints prevented further iterations.
10. Each control volume in the model was assumed to be well mixed. This is not strictly true and could produce significant error in the predicted flue NO.

11. Although the best available kinetic data were used, some of the constants may not be that accurate since much of the current combustion research is aimed at improving previous kinetic data.
12. The fuel gas was modeled as 99.5% CH_4 and 0.5% N_2. The actual gas contained some other hydrocarbons in small amounts. The kinetics could be significantly different when all gases are included.

The following are suggestions for future research:

1. Determine the sources of the disparities between the experimental and predicted values.
2. Test different grid sizes to find the grid independent solutions.
3. Run more iterations to fully converge test cases.
4. Run a series of test cases for the oxygen-fuel burner.
5. Test various wall conditions (isothermal and constant heat flux).
6. Try using inlet gas velocity profiles instead of constant velocities.
7. Add a micromixing model so that the species in each control volume are not assumed to be well mixed.
8. Look into the reaction kinetics for fuels containing small amounts of other hydrocarbons besides methane.

7.7 Empirical Conclusions

Although primarily generated for comparison with the numerical model, the empirical data provides several useful observations. This data is summarized in Figures 58-64 for the unmodified North American 4425 and the Air Products KT-3 burners.

Figure 58 demonstrates that specific NOx formation is independent of firing rate for both nozzle mix (North American 4425) and diffusion mix (Air Products KT-3) burners.

Figure 59 demonstrates that specific NOx formation is slightly dependent on stoichiometry. As expected, NOx increases with excess O_2 and decreases with decreasing stoichiometry into a fuel-rich environment. Somewhat surprising is that the dependence is linear and of the same magnitude for both the nozzle mix (North American 4425) and diffusion mix (Air Products KT-3) burners.

As shown in Figure 60, NOx emissions from an air-fuel burner are independent of added nitrogen.

On the other hand, Figure 61, which also incorporates published data,[1] demonstrates that specific NOx formation dramatically (2-3x) increases with increasing levels of oxygen-enrichment (21 -> 28% O_2) in nozzle mix air-fuel burners and that the magnitude of the effect is dependent on the type burner (probably related to mixing intensity).

FIGURE 58: NOX FORMATION
EFFECT OF FIRING RATE

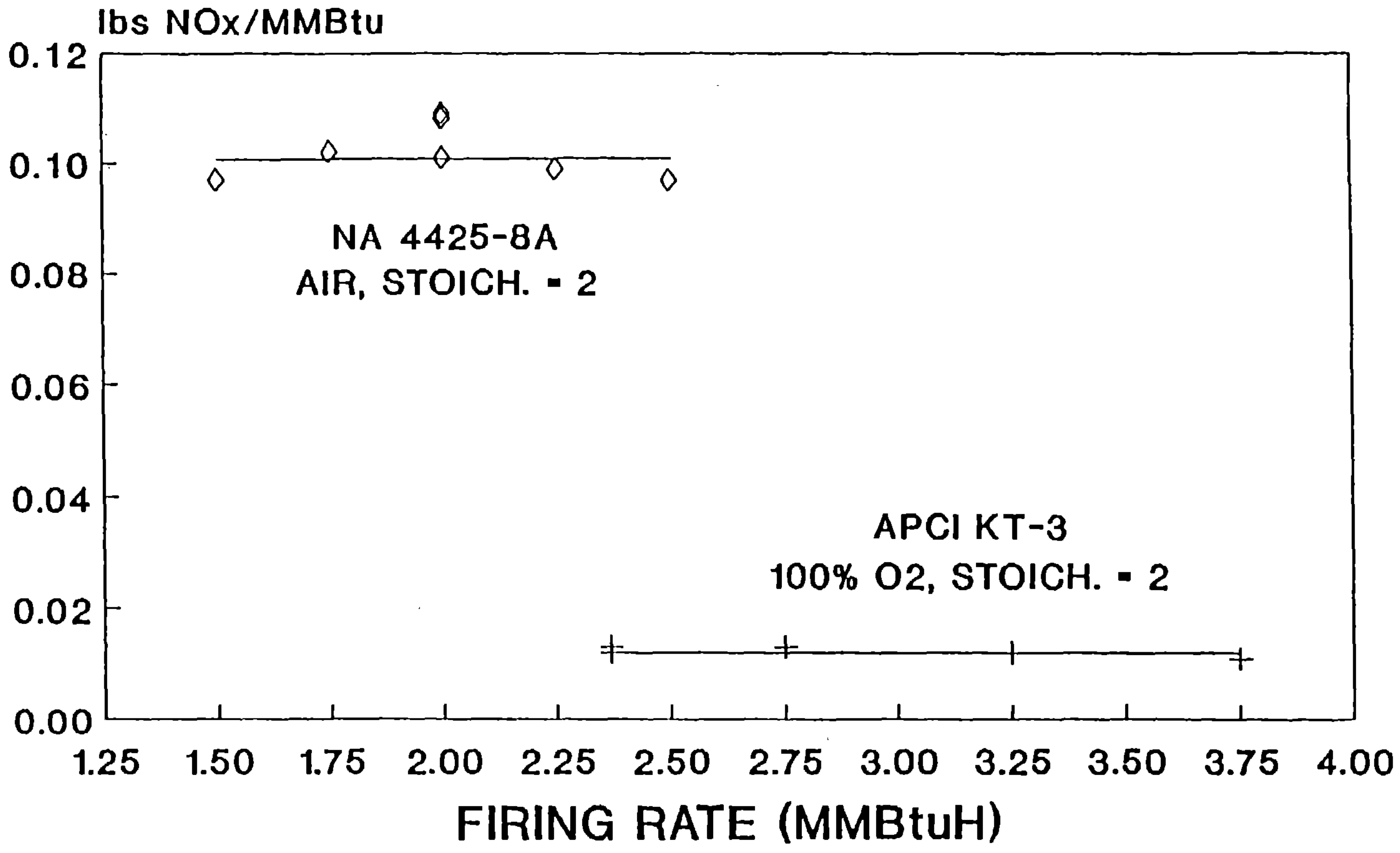


FIGURE 59: FLUE NITRIC OXIDE
EFFECT OF STOICHIOMETRY

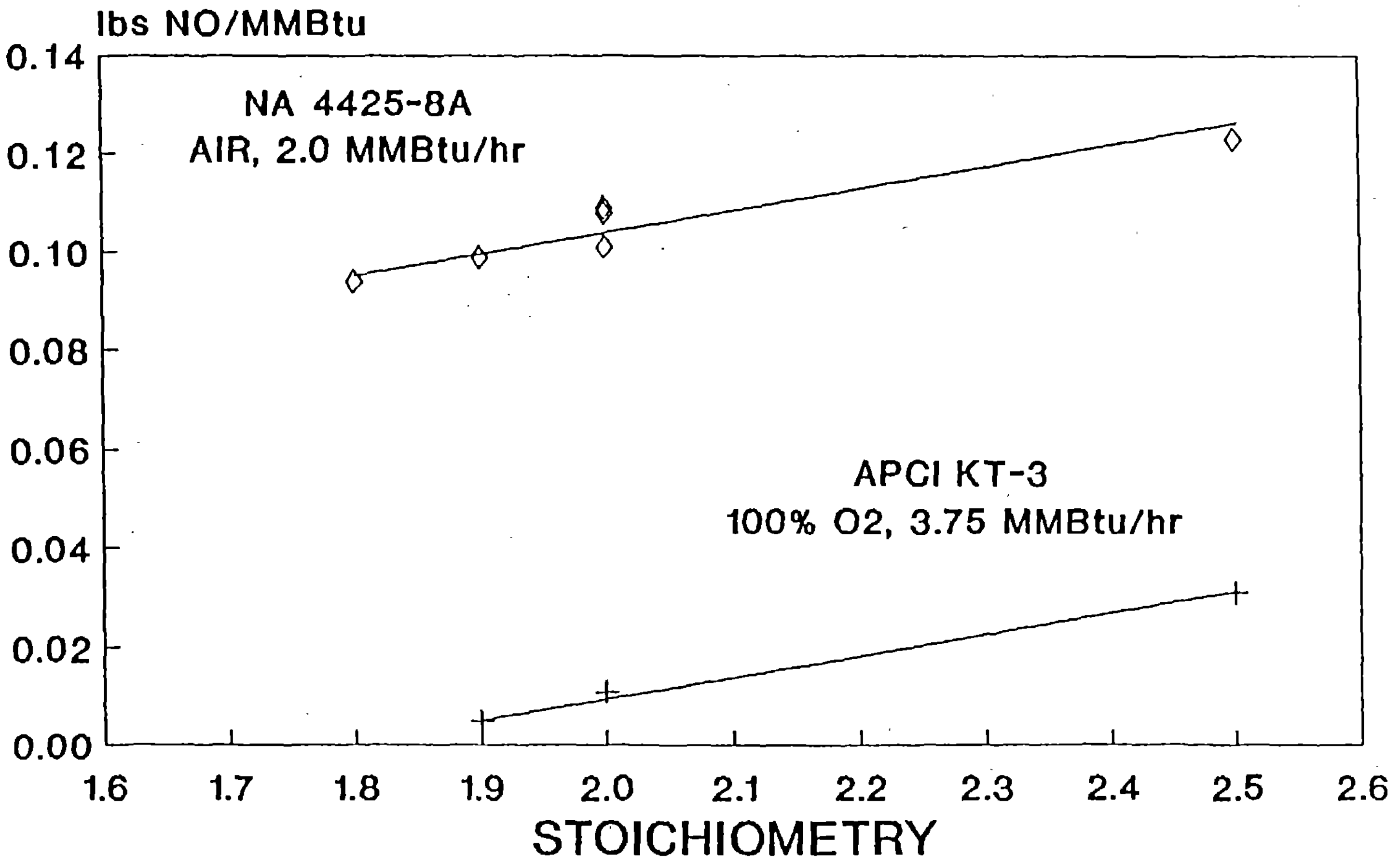


FIGURE 60: FLUE NITRIC OXIDE
EFFECT OF NITROGEN LANCING

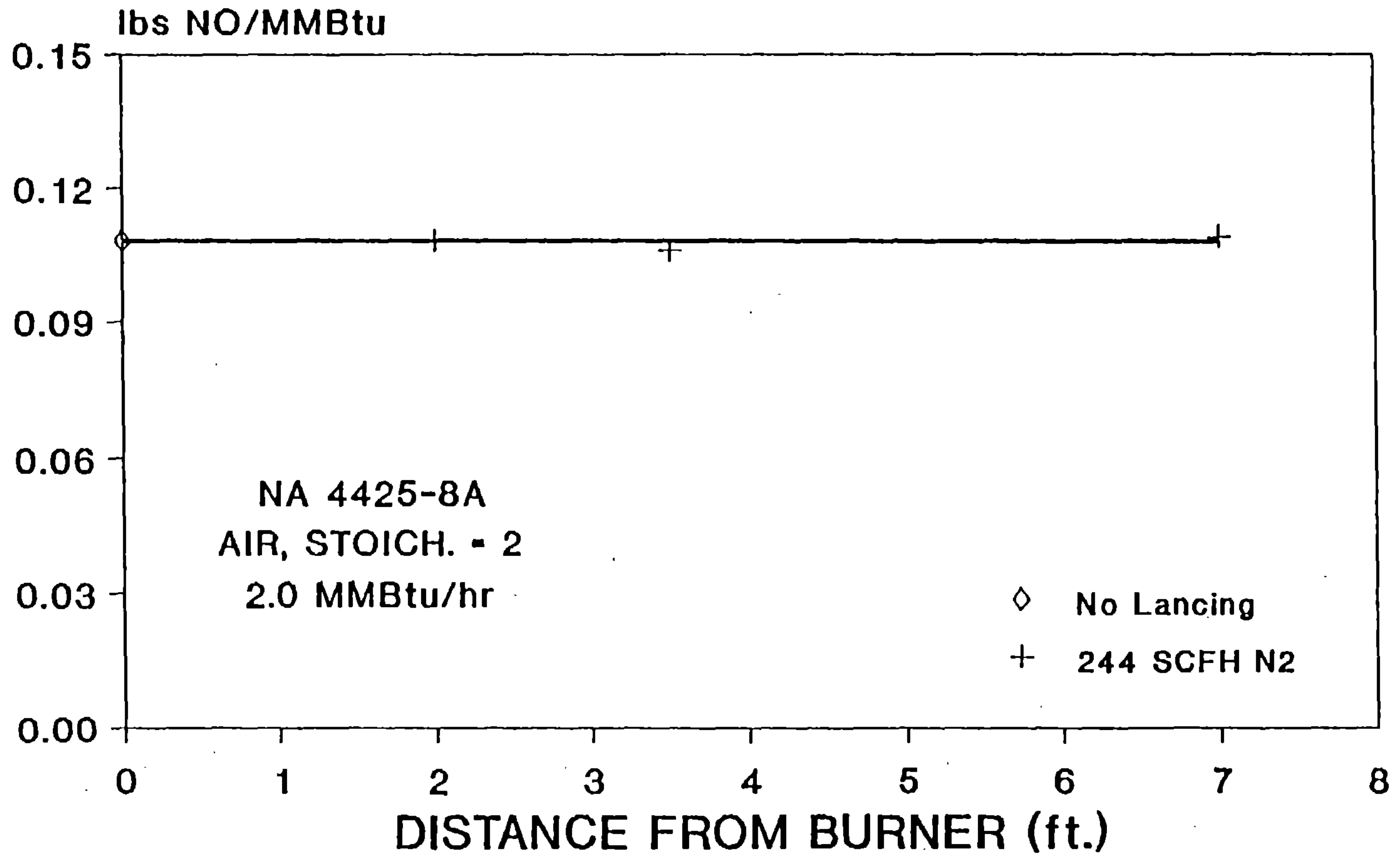


FIGURE 61: NOx FORMATION EFFECT OF OXYGEN ENRICHMENT

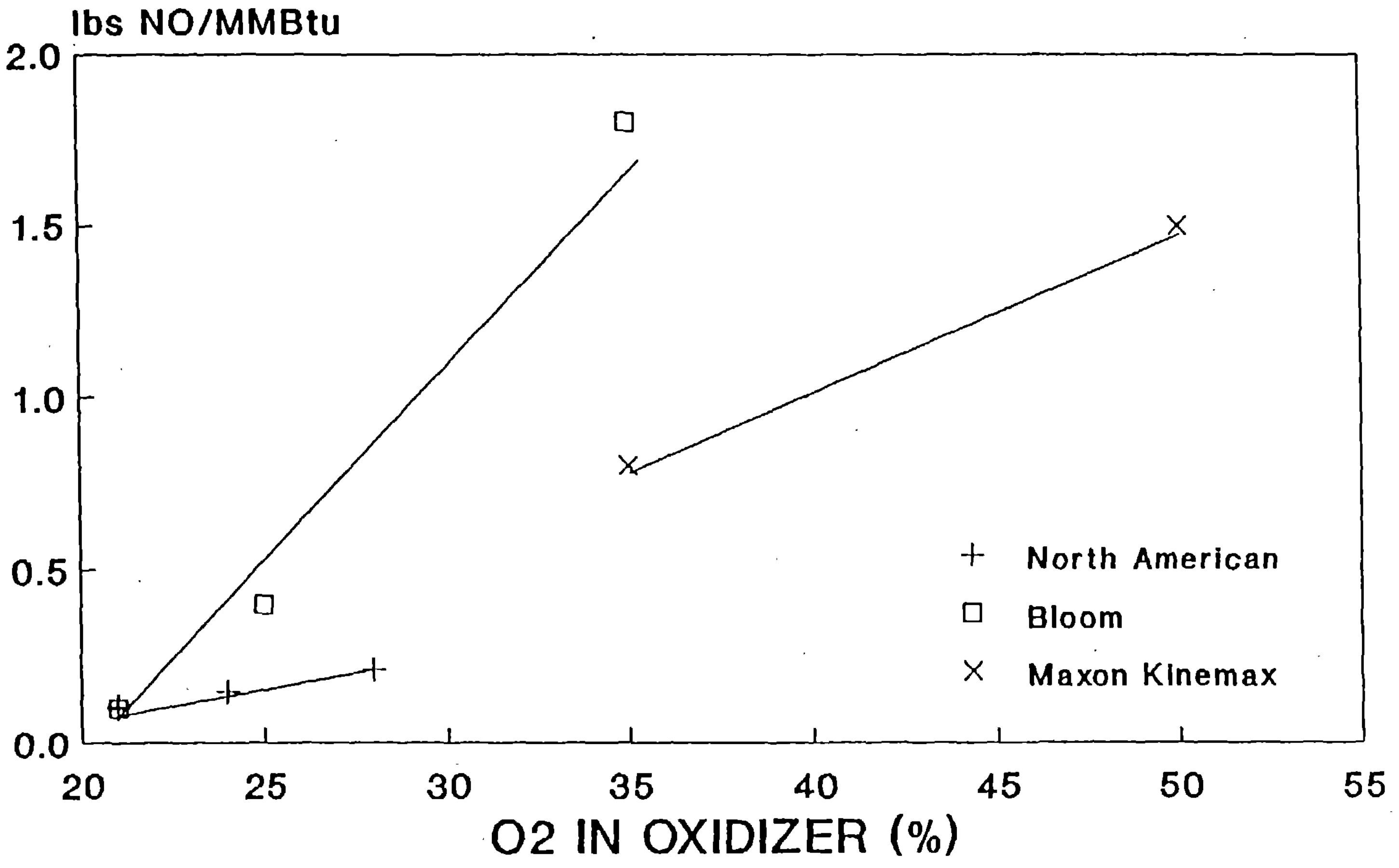


FIGURE 62: NOx FORMATION
EFFECT OF OXYGEN ENRICHMENT

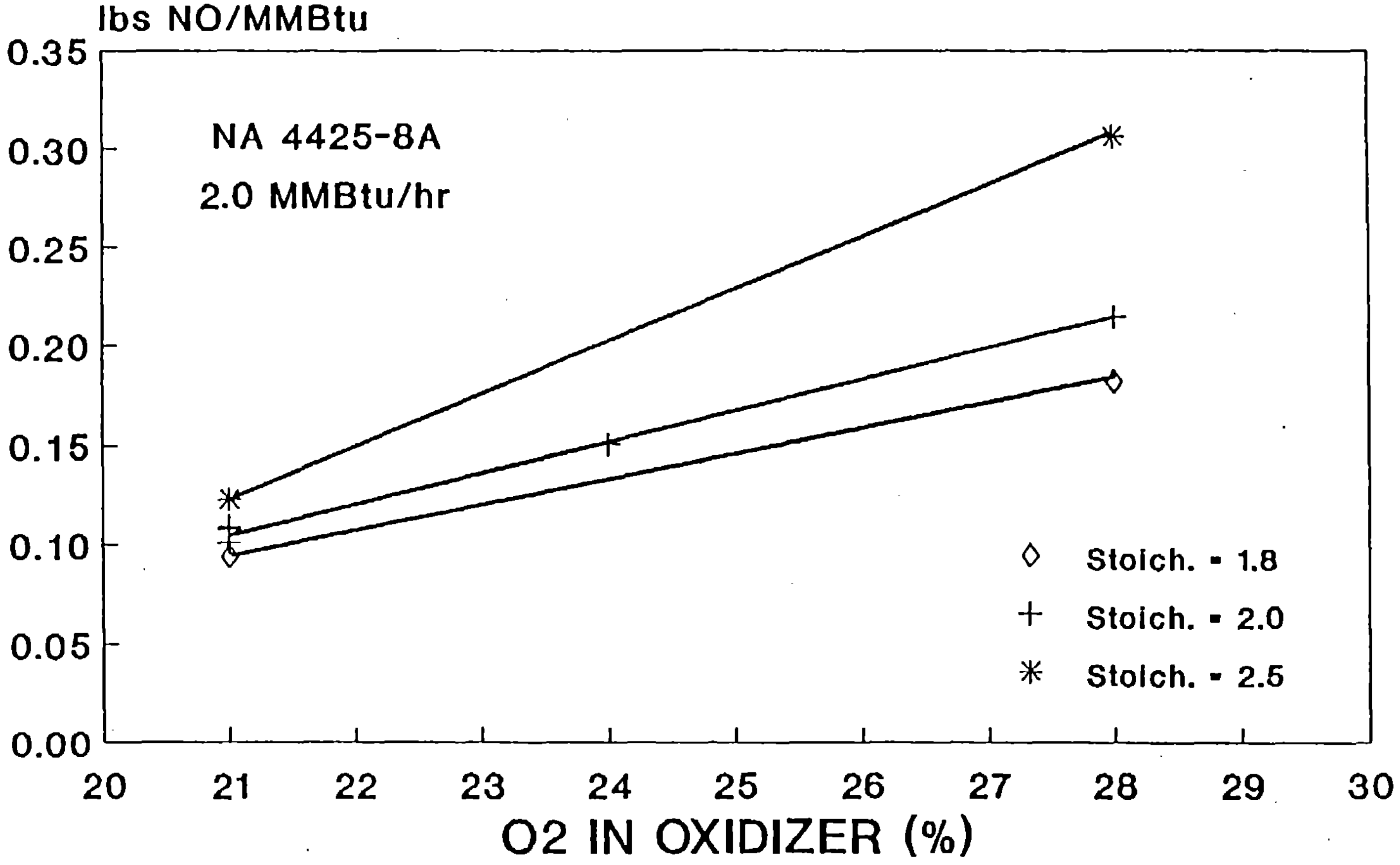


FIGURE 63: NOx FORMATION
EFFECT OF OXYGEN ENRICHMENT

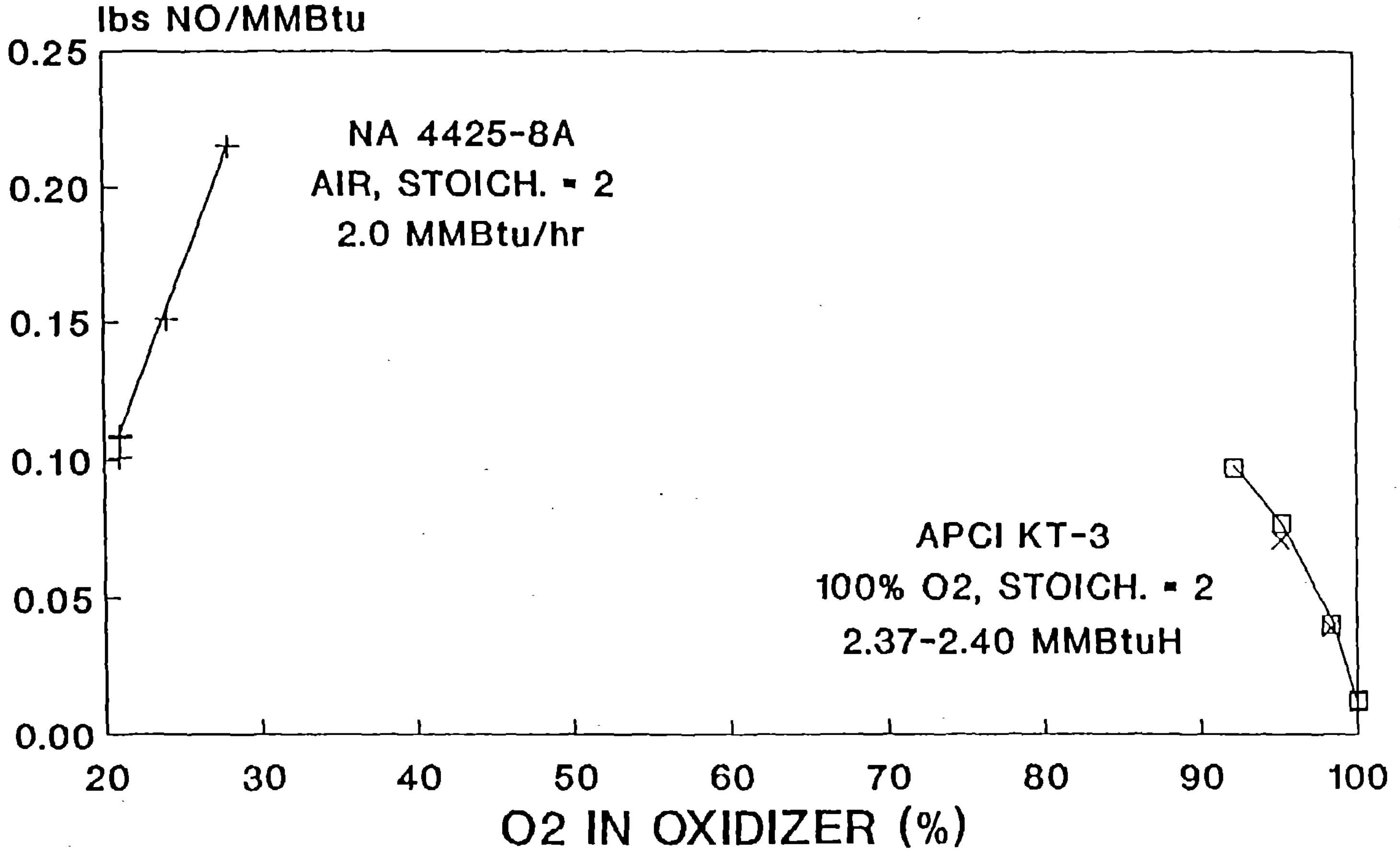
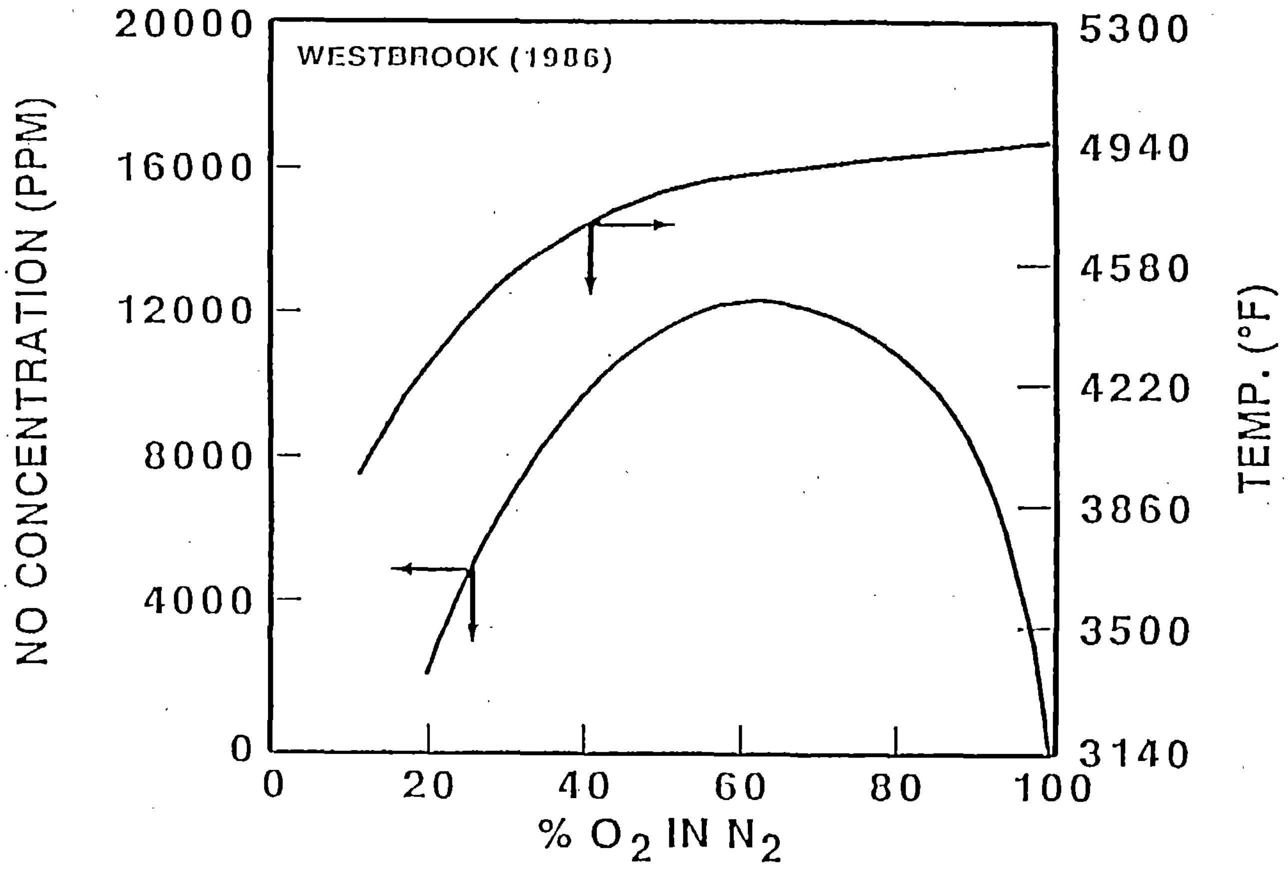


FIGURE 64
ADIABATIC EQUILIBRIUM NO FORMATION

$$1CH_4 + xN_2 + 2O_2 \rightleftarrows NO$$



As shown in Figure 62, any increase in NOx with enrichment is most pronounced when operating above the stoichiometric required amount (O_2: natural gas > 2).

Figure 63 summarizes specific NOx formation as a function of percent oxygen. It is apparent that NOx initially increases with oxygen, peaks, then decreases to a minimum at oxy-fuel conditions, the minimum being established by the N_2 content of the pipeline natural gas (0.5% N_2, this study). The curve shape is expected from thermodynamic considerations; however, the quantitative aspects of the curve will be dependent on burner design as seen in Figure 61.

As shown in Figure 63, use of the KT-3 oxy-fuel burner reduces NOx by at least 9x over air-fuel burners. The oxy-fuel burners are very sensitive to the nitrogen content of the natural gas and oxygen supply. A NOx penalty will be paid on switching from high purity oxygen (cryogenic 100% oxygen or VSA 93% oxygen with only ~3% nitrogen) to the lower purity supply options such as PSA or membrane systems.

Figure 64 shows a plot of adiabatic flame temperature and NOx concentration as a function of enrichment level for natural gas combustion. This NOx data, published by Westbrook in 1986[2], shows the NOx increases with enrichment level up to about 60% oxygen enrichment, plateaus, and then decreases to zero NOx at 100% oxygen. The adiabatic flame temperature also rapidly increases with oxygen enrichment up to the same point where NOx is maximum and then plateaus with only minor increases thereafter. Clearly, when questioning the impact of oxygen enrichment on NOx emissions, or examining how to control NOx emissions, one has to ask "are you practicing low level enrichment or high level enrichment?"

At low levels of oxygen enrichment, flame temperature is the controlling parameter, not nitrogen content. At high levels of enrichment such as greater than 80% oxygen, flame temperature is not the controlling parameter, but rather nitrogen concentration. To minimize NOx at high levels of enrichment, nitrogen content must be minimized. At low levels of enrichment, one must minimize flame temperature, using techniques such as staged combustion. Also, the type of burner can have considerable impact on NOx. Burners with high swirl or tangential mixing lead to higher NOx than diffusion or plug flow, nozzle mix burners.

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APPENDIX A

EVALUATION OF OXYGEN-ENRICHED COMMERCIAL AIR-NATURAL GAS BURNERS

A-1: Surface Combustion

A-2: Bloom 1250

A-3: North American 4425-8A

A-4: Maxon Series G Kinemax

A-5: Eclipse MVTA 248

A-6: North American 6514

BURNER EVALUATION WITH OXYGEN ENRICHMENT

SURFACE COMBUSTION ENRICHED AIR BURNER

15 OCTOBER 1985

Rated Capacity:	4 MM BTU/hour @ 1 psig Pressure and 35% O_2 in Air
Range of Firing Rates Tested:	1 to 3.25 MM BTU/hour
Range of O_2 Concentration in Air Tested:	25 to 100%
Test Period:	1 August 1985 - 15 August 1985

ANALYSIS OF TEST DATA

For a summary of the experimental procedure, see Appendix A.

1. Furnace Temperature (Figure 1)

Equilibrium furnace temperature as measured by a thermocouple in the center of the roof is shown in Figure 1 as a function of the firing rate and the oxygen concentration in air. As expected, the furnace temperature increases sharply with increasing firing rates. Also, the higher the enrichment level, the higher is the furnace temperature.

2. Temperature Uniformity (Figure 2)

The difference between the temperature at the center of the roof and the temperature at the center of the hearth is taken as an indication of temperature uniformity. As expected, the furnace temperature uniformity is improved at high firing rate and at lower oxygen concentrations in the air stream.

3. Gas Temperature Profiles (Figure 3)

The data obtained by suction pyrometer are reduced to isothermal contours presented in Figure 3. Appendix B briefly describes the data reduction procedures.

At a constant oxygen concentration in the air, increased firing rates lead the contours to move away from the burner. At a constant firing rate, increasing the oxygen concentration in air leads to noticeable broadening but no substantial longitudinal movement.

The gas temperature in the neighborhood of the core of the flame can be seen to increase with an increase in both the firing rate as well as the percent oxygen in air.

4. Total Heat Flux Profiles (Figure 4)

The data obtained by the total heat flux meter are reduced to iso-heat flux contours presented in Figure 4. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the air, increased firing rates lead to substantial longitudinal movement and broadening of the contours. At a constant firing rate, increasing the oxygen concentration leads to further longitudinal movement but no further broadening. The heat fluxes in the neighborhood of the core of the flame can be seen to increase with increasing firing rates and increasing enrichment levels.

5. NOx Emissions (Figure 5)

Data collected by infrared analyzer have been corrected to 0% oxygen in the flue and have been plotted as a function of the firing rate and the oxygen concentration in air.

Figure 5 indicates that NOx emissions increase strongly with increasing O_2 concentration in air and only weakly with increasing firing rates.

6. Fuel-Air Mixing (Figure 6)

Figure 6 shows that higher % excess oxygen in the flue (in other words, higher excess air) is needed to achieve complete combustion when the firing rate is low and the enrichment level is high. This appears to be a result of decreasing volumetric flow rates through the burner which reduces the intensity of mixing.

The color of the flame changed from blue to yellow to bright creamy as the enrichment level was increased from air to 35% O_2 in air to 100% oxygen. Sooting was observed on the probes at high enrichment levels and low firing rates.

7. Burner Survival at High Enrichment Levels

For tests in which the oxygen concentration in air exceeded 60%, the burner was instrumented with a thermocouple close to the tip of the gas nozzle.

The temperature, as measured by the thermocouple, increased rapidly with decreasing firing rates and increasing enrichment levels. Based on the measurements, the burner is expected to perform satisfactorily with 60% oxygen in air at all the firing rates and with 100% oxygen at firing rates greater than 2 MM BTU/hour.

PROCESS IMPLICATIONS

1. Fuel Savings

Oxygen enrichment is used in a number of high-temperature furnaces to reduce the firing rate while maintaining the rate of production. Based on the data in this report, the following may be predicted if high enrichment levels are used with the Surface Combustion burner without any modifications.

A. The burner will not be physically damaged.

B. The flame will be more yellow. The gas temperature profile would be more concentrated toward the burner end and be broader.

C. The heat flux profile would be relatively unchanged.

D. The temperature uniformity will suffer. This may necessitate changing the furnace control parameters and the burner orientation.

E. The ability of the burner to uniformly heat the load may deteriorate, particularly if the load is some distance away from the burner.

F. NOx emissions will increase.

G. The furnace will have to be operated at a higher excess oxygen level to counter reduced intensity of fuel-air mixing.

2. Increase in the Rate of Production

Oxygen enrichment may also be used to increase the rate of production. Based on the data in this report, the following may be predicted if high enrichment levels are used with the Surface Combustion burner without any modifications and without changing the firing rate.

A. The burner will not be physically damaged.

B. The gas temperature in the core of the flame will go up, but the overall temperature profile would be relatively unchanged.

C. The heat fluxes will increase substantially leading to increased rate of production.

D. The temperature uniformity will deteriorate somewhat.

E. NOx emissions will increase.

F. The furnace may be operated at an excess oxygen level in the flue that is relatively unchanged.

SUGGESTED BURNER MODIFICATION

Based on the data collected, the following modifications are suggested to improve the performance of the Surface Combustion burner at high enrichment levels:

1. Substantially reduce the air passages in size.
2. Modify the air swirl plate so as to enhance the swirling action.
3. Reduce the inside diameter of the burner block.

APPENDIX A: EXPERIMENTAL PROCEDURE

1. The desired firing rate, the oxygen concentration in the combustion air, and the stoichiometry serve as basic outputs to the system. Air, oxygen, and natural gas flows are controlled and continuously monitored by a computer.

2. The furnace is allowed to reach equilibrium under conditions of interest.

3. The furnace and the burner internals are continuously monitored for over-temperatures.

4. Oxygen-enriched air is analyzed to check the oxygen concentration in the enriched combustion air stream.

5. Flue gases are sampled regularly, dried, and analyzed for CO, CO_2, NO, and excess O_2. CO level is always kept at less than 150 ppm.

6. Furnace pressure is controlled to keep air infiltration to a minimum.

7. Suction pyrometer and heat flux probe measurements are taken after the furnace reaches equilibrium. The measurements are taken on only side of the longitudinal axis. The measurements are taken at the following positions:

Distance Measured from the Burner Axis, ft	Distance from the Burner Along the Furnace, ft		
	3.9	7.3	13.8
0	x	x	x
1.3	x	x	x
2.5	x	x	x
3.8	x		x

APPENDIX B: ANALYSIS OF HEAT FLUX PROBE AND SUCTION PYROMETER DATA

1. The measurement error is ±20°F for the suction pyrometer and ±2 M BTU/hour ft^2 for the total heat flux meter.

2. The data are statistically screened, analyzed, and fitted to a general expression containing exponential and polynomial functionalities.

3. The root mean square error of the fit between the model and the data is 80°F or better for the suction pyrometer and 6 M BTU/hour ft^2 for the total heat flux meter.

4. In generating the contour plots symmetry around the longitudinal axis has been assumed. Furnace sidewall temperatures support this assumption.

5. Extrapolation of the model (although shown in the contour plots) is not expected to be reliable in a region that is less than 4 feet away from the burner along the axis of the flame.

FIGURE 1: FURNACE TEMPERATURE

SURFACE COMBUSTION

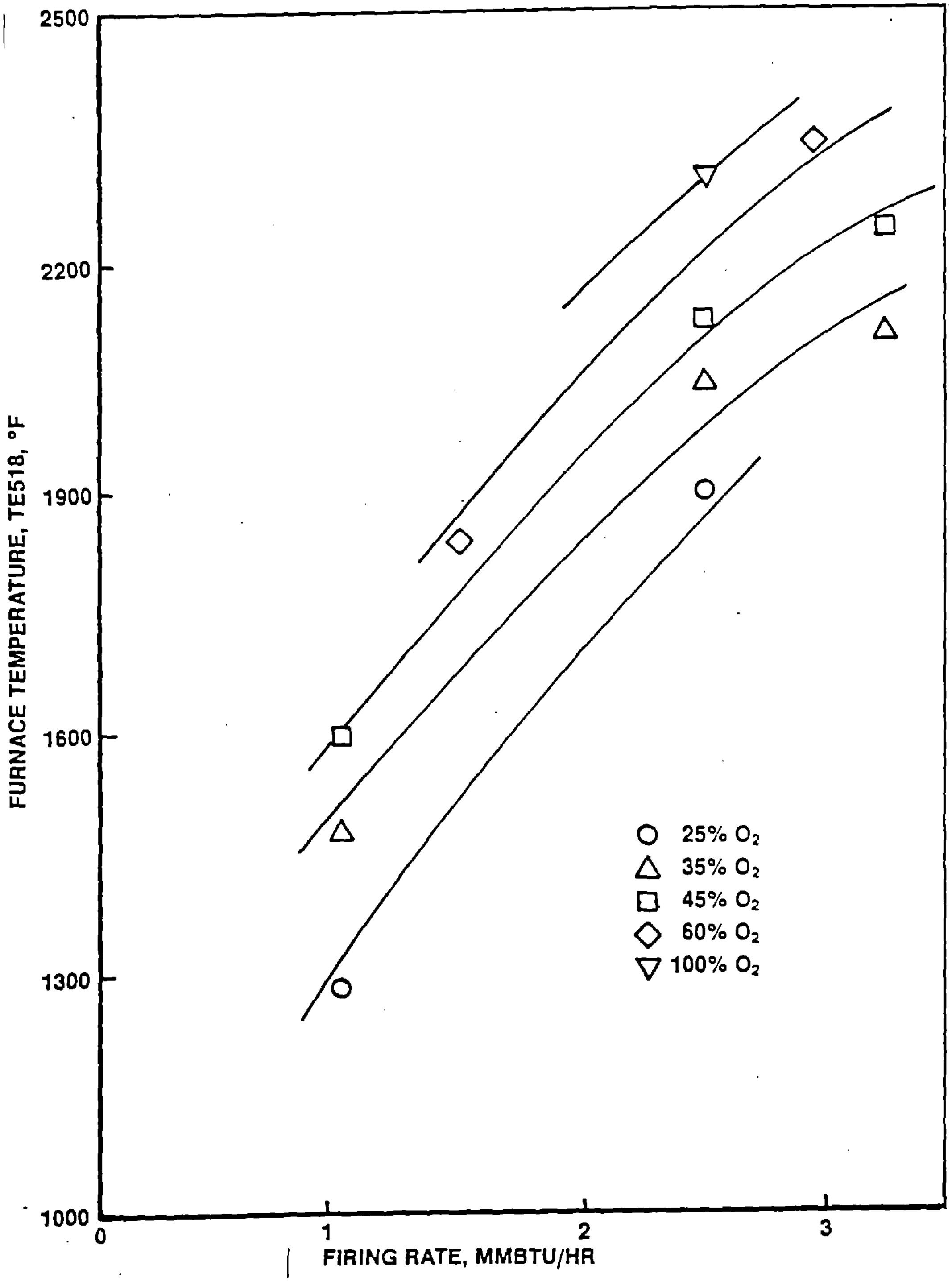


FIGURE 2: TEMPERATURE UNIFORMITY
SURFACE COMBUSTION

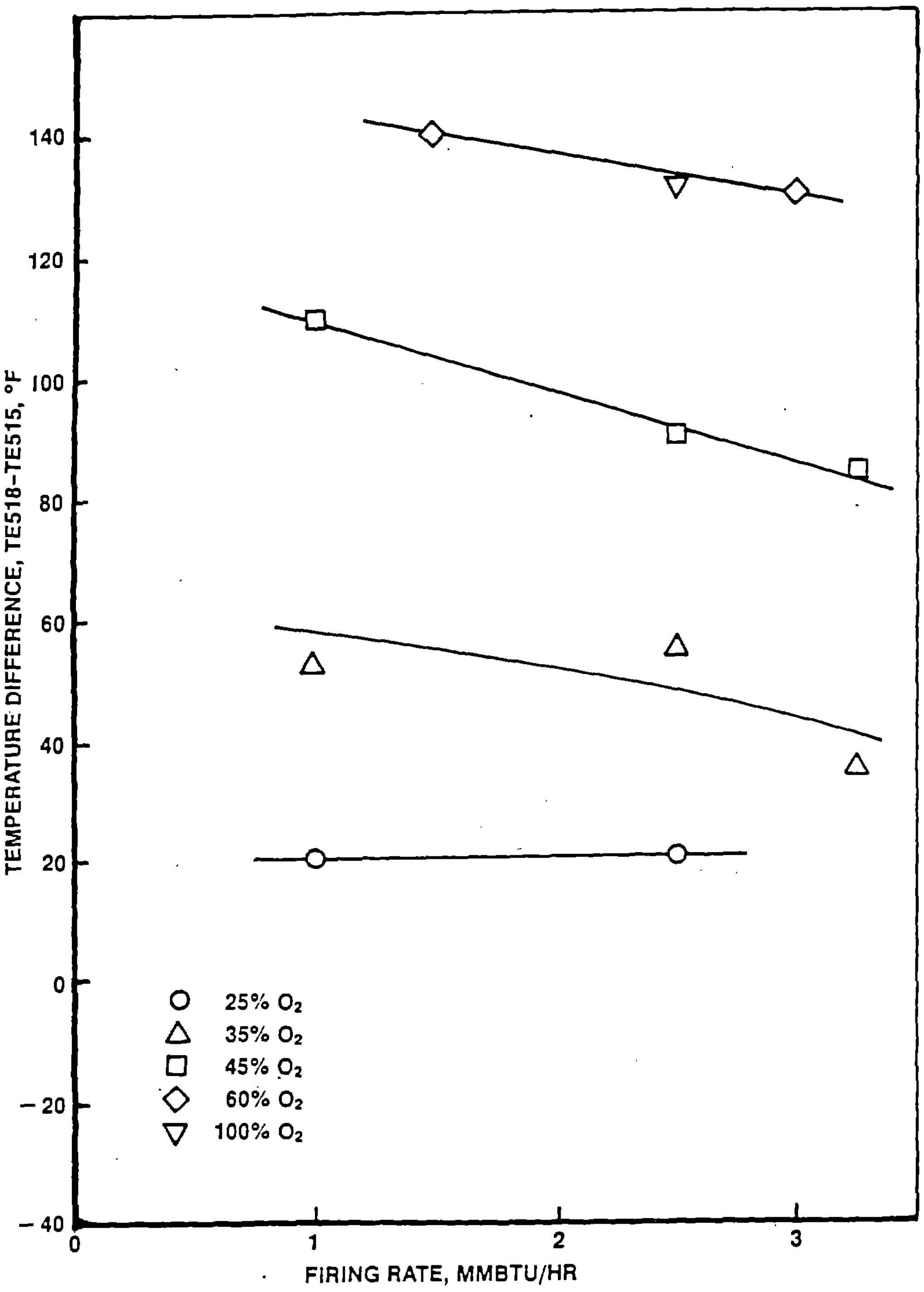
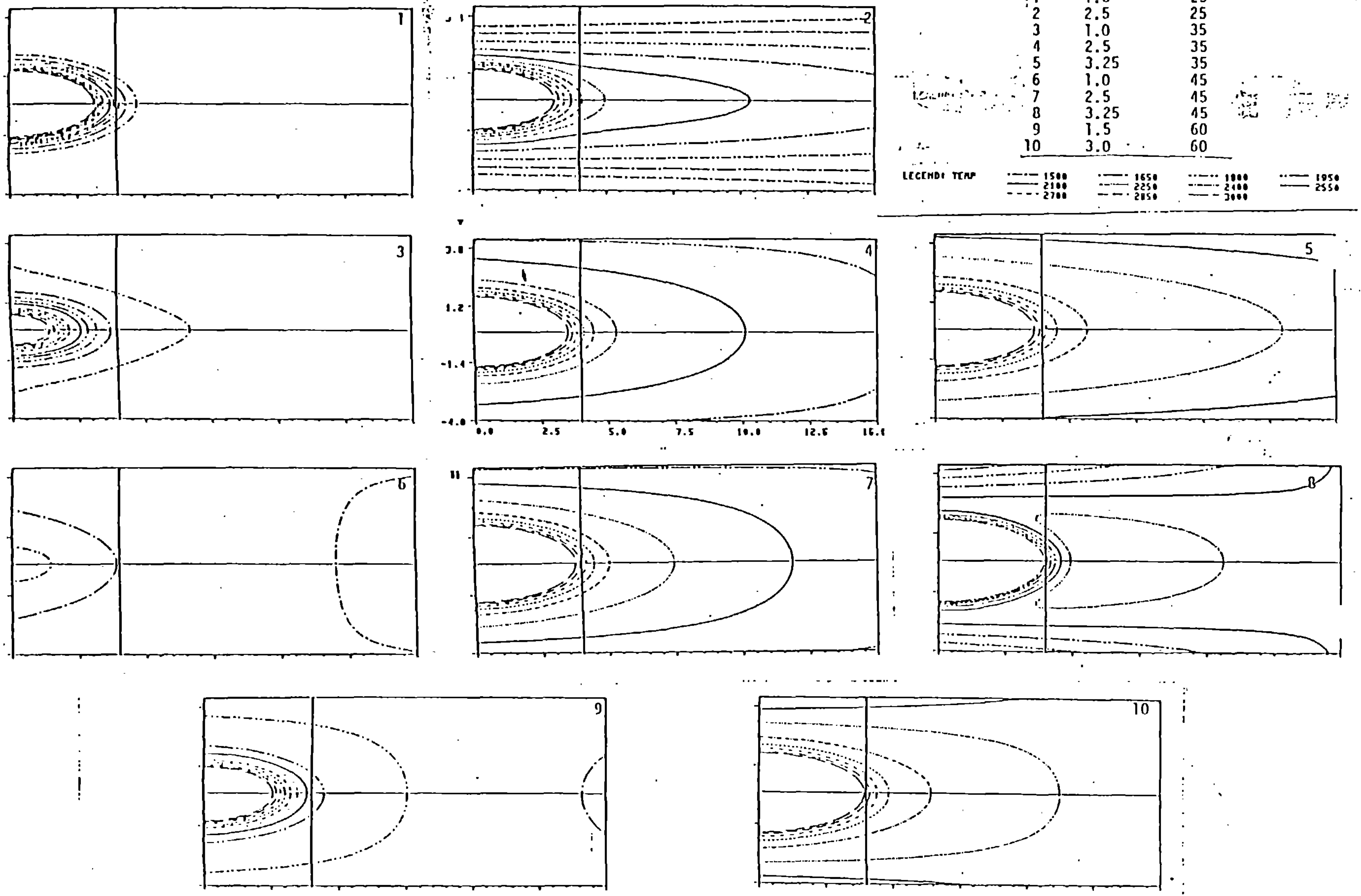


FIGURE 3

SURFACE COMBUSTION ENRICHED AIR BURNER

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F

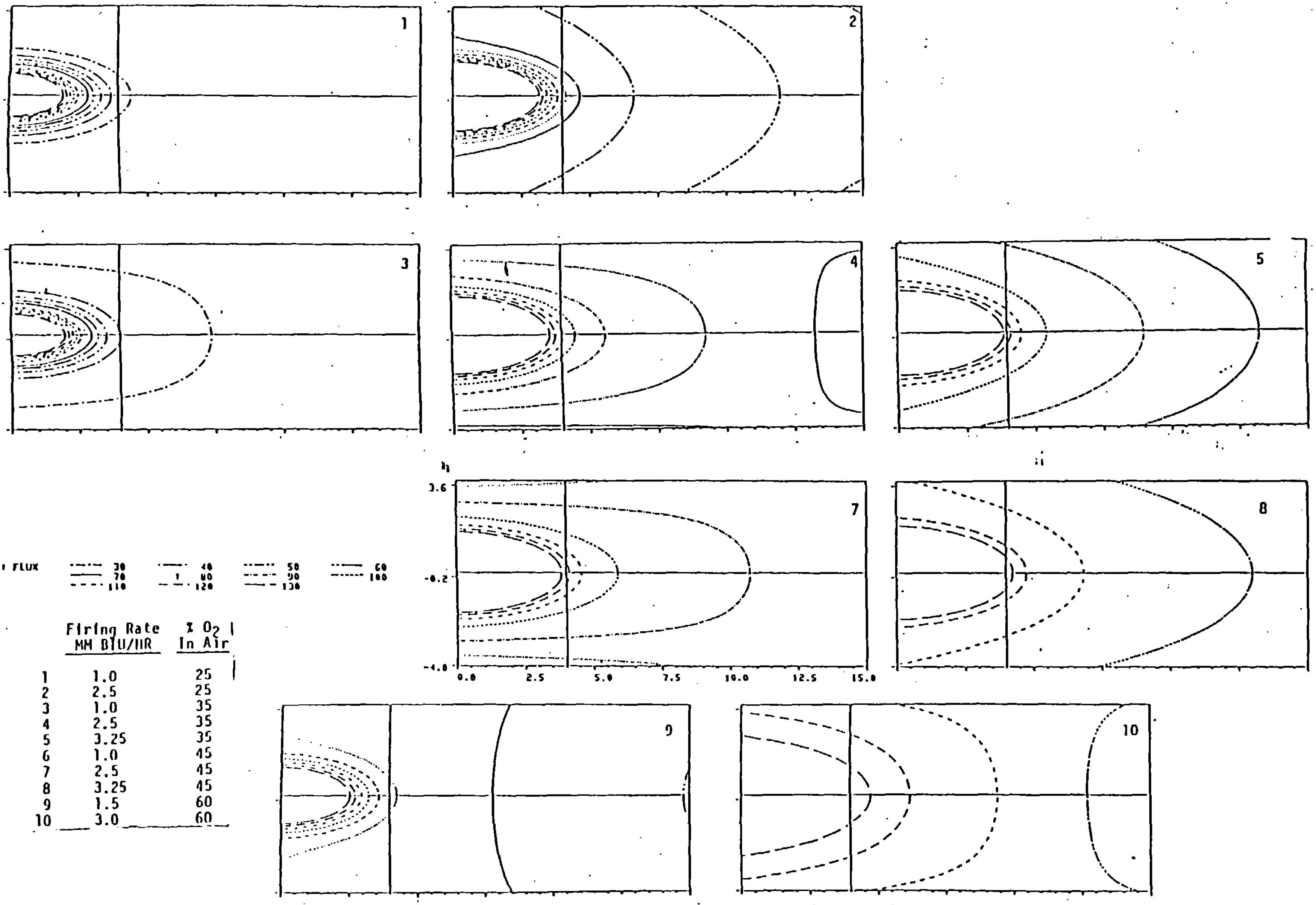


	Firing Rate MM BTU/HR	% O_2 In Air
1	1.0	25
2	2.5	25
3	1.0	35
4	2.5	35
5	3.25	35
6	1.0	45
7	2.5	45
8	3.25	45
9	1.5	60
10	3.0	60

FIGURE 4

SURFACE COMBUSTION ENRICHED AIR BURNER

TOTAL HEAT FLUX BY HEAT FLUX METER. MBTU/FT2/HR



	Firing Rate MM BTU/HR	% O2 In Air
1	1.0	25
2	2.5	25
3	1.0	35
4	2.5	35
5	3.25	35
6	1.0	45
7	2.5	45
8	3.25	45
9	1.5	60
10	3.0	60

FIGURE 5: NO_x EMISSIONS
SURFACE COMBUSTION

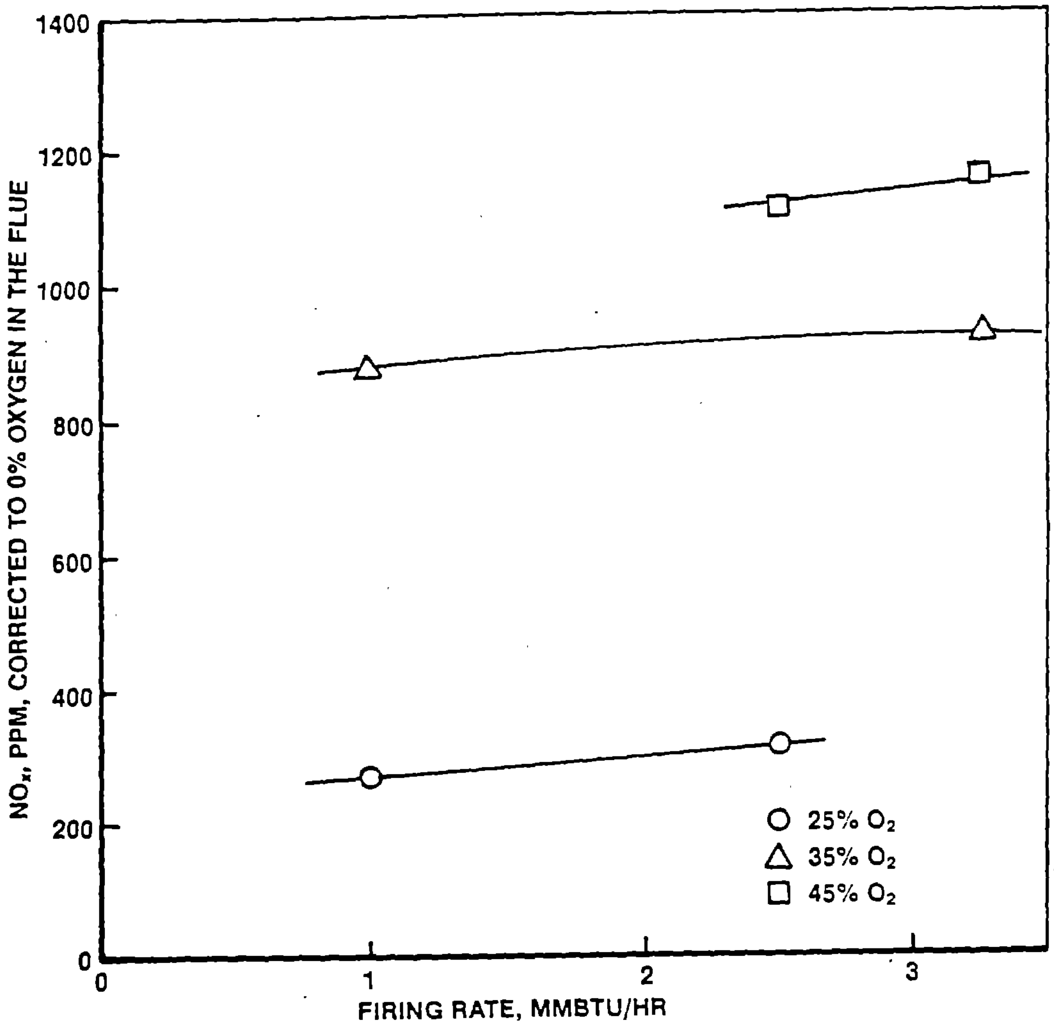
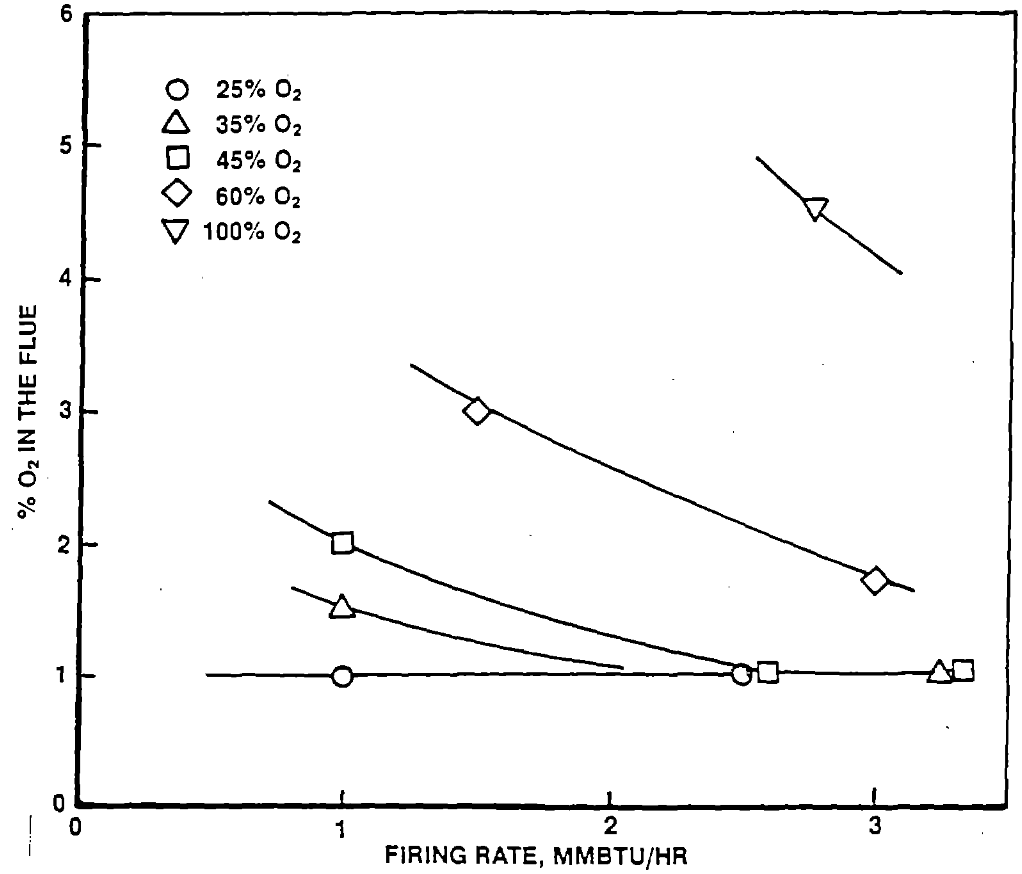


FIGURE 6: CO EMISSIONS, PERCENT O_2 TO KEEP CO BELOW 100 PPM

SURFACE COMBUSTION



BURNER EVALUATION WITH OXYGEN ENRICHMENT

BLOOM 1250

24 DECEMBER 1985

Rated Capacity:	5.5 MM BTU/hour @ 1 psig Air Pressure
Range of Firing Rates Tested:	2 to 3.75 MM BTU/hour
Range of O_2 Concentration in Air Tested:	21 to 100%
Test Period:	9 December - 12 December 1985

ANALYSIS OF TEST DATA

For a summary of the experimental procedure, see Appendix A.

1. Furnace Temperature (Figure 1)

Equilibrium furnace temperature as measured by a thermocouple in the center of the roof is shown in Figure 1 as a function of the firing rate and the oxygen concentration in air. As expected, the furnace temperature increased sharply with increasing firing rates. Also, the higher the enrichment level, the higher was the furnace temperature.

2. Temperature Uniformity (Figure 2)

The difference between the temperature at the center of the roof and the temperature at the center of the hearth is taken as an indication of temperature uniformity. At high firing rate the temperature difference did not increase monotonically as the oxygen concentration was increased from 21 up to 100%. In general however, the furnace temperature uniformity improved with increasing firing rates and decreasing oxygen concentrations in the air stream.

3. Gas Temperature Profiles (Figure 3)

The data obtained by suction pyrometer were reduced to isothermal contours presented in Figure 3. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the combustion air, increased firing rates led the contours to move away from the burner.

The temperature profiles showed some movement away from the burner but no broadening as the oxygen concentration was raised from 21% to 35%. Increasing the oxygen concentration beyond 35% while maintaining a constant firing rate led to some more movement along the length of the furnace and some broadening.

The gas temperatures in the neighborhood of the core of the flame increased with an increase in both the firing rate as well as the percent oxygen in air.

4. Total Heat Flux Profiles (Figure 4)

The data obtained by the total heat flux meter were reduced to iso-heat flux contours presented in Figure 4. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the air, increased firing rates led to substantial longitudinal movement.

At a constant firing rate, increasing the oxygen concentration from 21% to 35% led to some longitudinal movement of the contours. Increase of the oxygen concentration further led to some more longitudinal movement and substantial broadening.

5. NO_x Emissions (Figure 5)

Data collected by infrared analyzer were corrected to 0% oxygen in the flue and were plotted as a function of the firing rate and the oxygen concentration in the combustion air.

Figure 5 indicates that for up to 35% oxygen in the combustion air, NO_x emissions increased strongly with increasing O_2 concentration in air and only weakly with increasing firing rates. NO_x emissions with 60% oxygen in air were lower than those for 35% oxygen in air whereas NO_x emissions with close to 100% oxygen in the combustion air were higher than those for 60% oxygen in the combustion air. This result cannot be easily explained. The NO_x measured with close to 100% oxygen in air are encouraging particularly in light of the fact that the combustion air stream during the testing contained 95% O_2 rather than 100% as desired, due to minor leakage through the air valves.

6. Fuel-Air Mixing

Higher % excess oxygen in the flue (in other words higher excess air) was needed to achieve complete combustion when the firing rate was low and the enrichment level was high. This appeared to be a result of decreasing volumetric flow rates through the burner which reduced the intensity of mixing. CO level could be maintained below 100 ppm with only 1% excess oxygen when firing with up to 35% oxygen in air. For higher enrichment levels, 3 to 5% excess oxygen was needed for complete combustion.

The color of the flame changed from yellow to bright creamy as the enrichment level was increased from air to 35% O_2 in air to 100% oxygen. Sooting was observed on the probes at high enrichment levels.

7. Burner Survival at High Enrichment Levels

The burner could not be instrumented with a thermocouple to measure the temperature of burner internals.

The burner internals were examined for visible damage and minor surface cracking in the refractory air baffle was observed.

PROCESS IMPLICATIONS

Oxygen enrichment is used in a number of high temperature furnaces to reduce the firing rate while maintaining the rate of production. Based on the data in this report, the following may be predicted if oxygen enrichment is used with Bloom 1250 burner without any modifications.

1. The burner will not be physically damaged.

2. The flame will be more luminous. The gas temperature profile would be more concentrated toward the burner end.

3. The heat flux profile would be more concentrated at the burner end.

4. The temperature uniformity will suffer particularly at high enrichment levels. This may necessitate changing the furnace control parameters and the burner orientation.

5. The ability of the burner to uniformly heat the load may deteriorate, particularly if the load is some distance away from the burner.

6. NO_x emissions will increase with low levels of enrichment. With 100% oxygen, NO_x emissions on a per ton product basis will actually decrease.

7. The furnace will have to be operated at a slightly higher excess oxygen level to counter reduced intensity of fuel-air mixing if very high enrichment levels are to be practiced.

SUGGESTED BURNER MODIFICATIONS

Based on the data collected, the following modifications are suggested to improve the performance of the Bloom 1250 burner at high enrichment levels:

1. Reduce the size of the air holes.
2. Reduce the size of the natural gas tube.
3. Reduce intensity of the air swirl.

FIGURE 1: FURNACE TEMPERATURE
BLOOM 1250

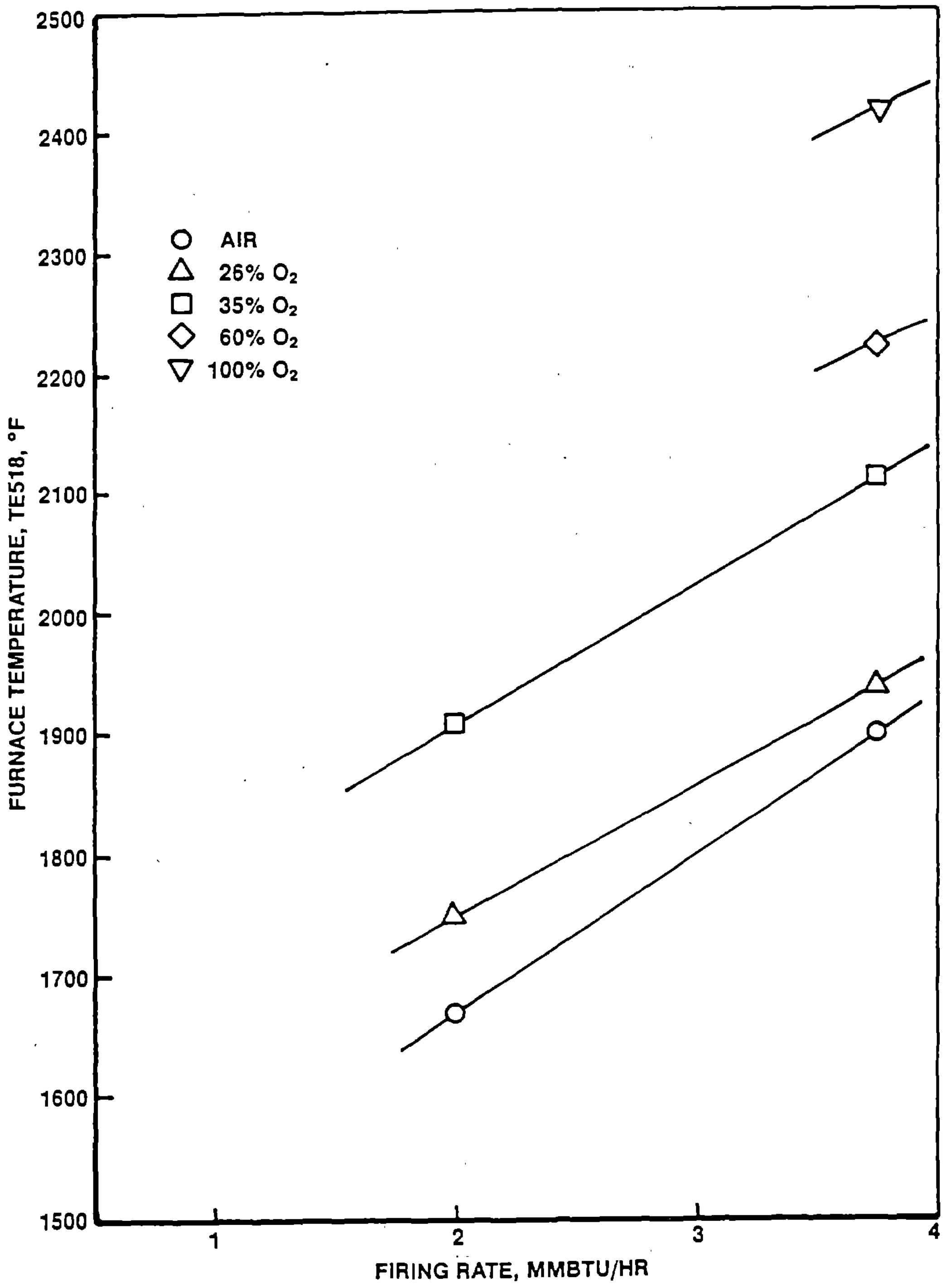
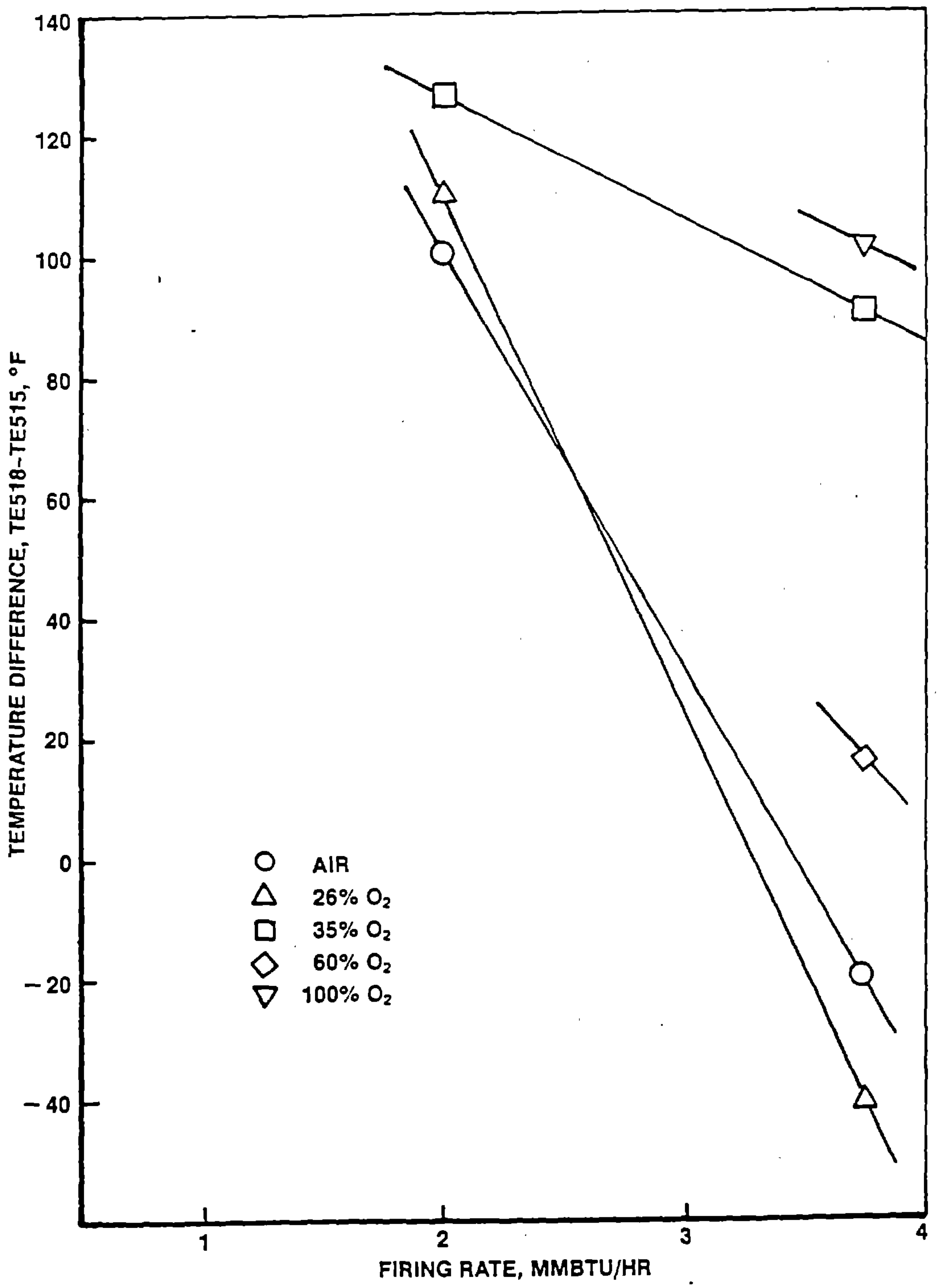
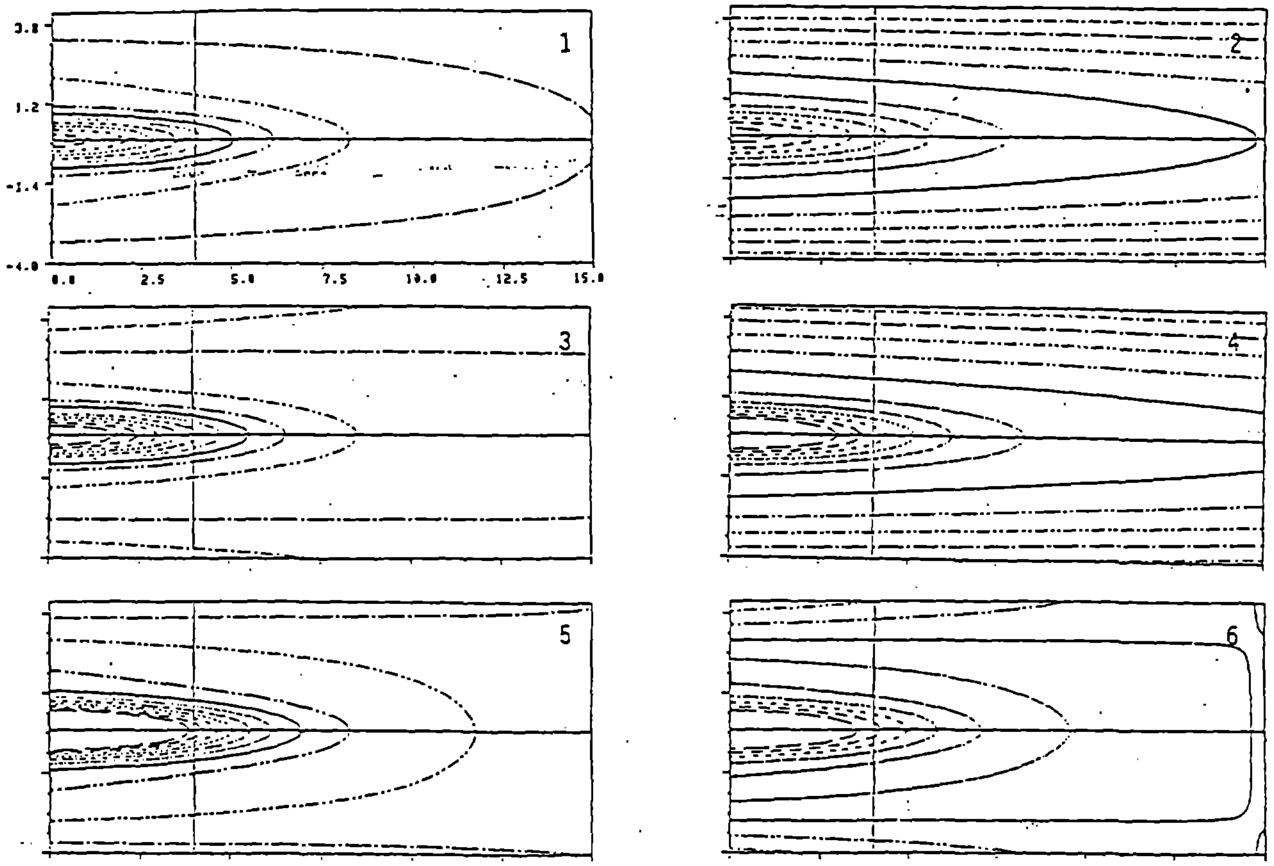


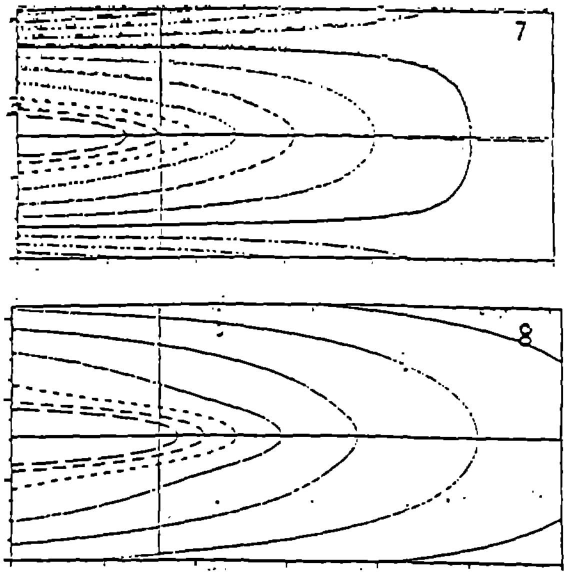
FIGURE 2: TEMPERATURE UNIFORMITY
BLOOM 1250



BLOOM BURNER 1250

GAS TEMPERATURES BY SUCTION PYROMETER, DEG F



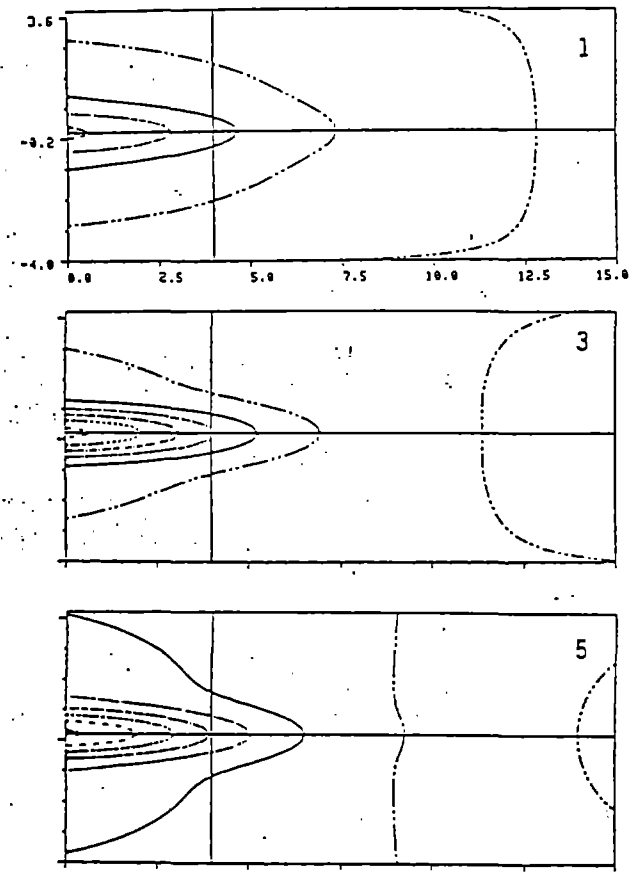


	FIRING RATE MM BTU/HR	% O$_2$ IN AIR
1.	2	21
2.	3.75	21
3.	2	26
4.	3.75	26
5.	2	35
6.	3.75	35
7.	3.75	60
8.	3.75	100

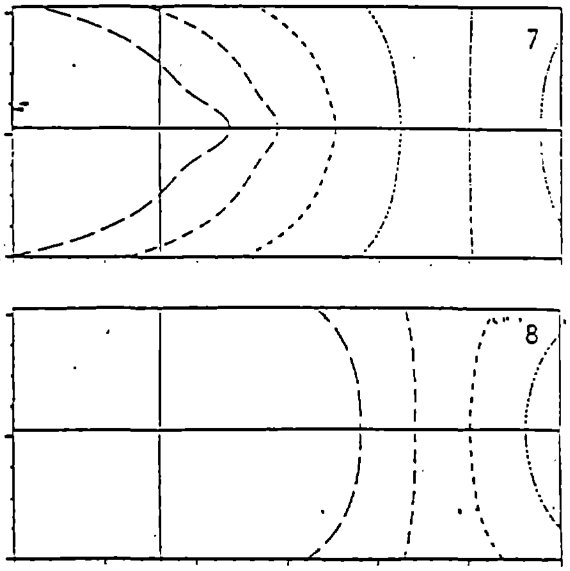
LEGEND: TEMP
1500 1650 1800 1950
2100 2250 2400 2550
2700 2850 3000

BLOOM BURNER 1250

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT2/HR

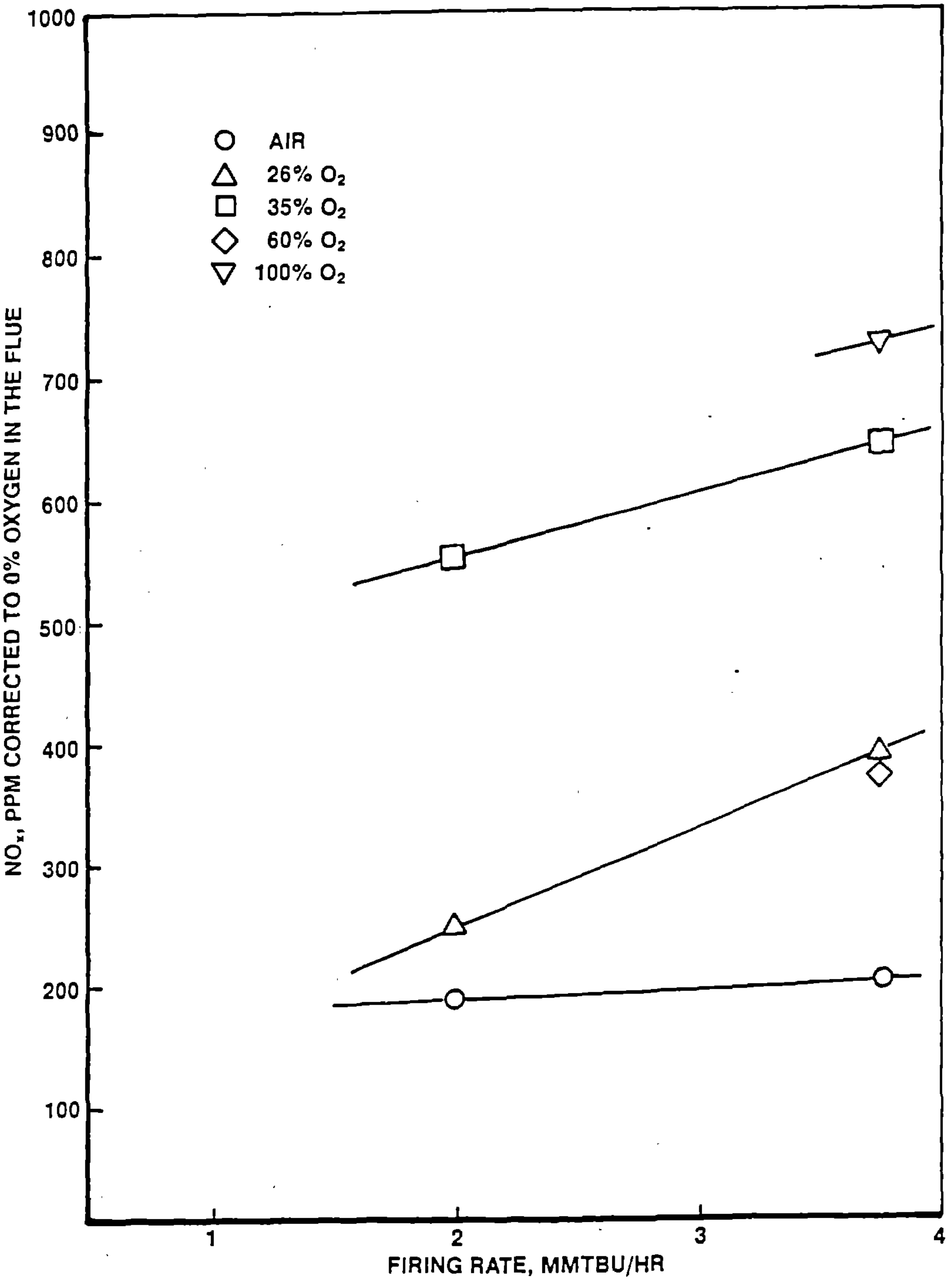


	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	2	21
2.	3.75	21
3.	2	26
4.	3.75	26
5.	2	35
6.	3.75	35
7.	3.75	60
8.	3.75	100



LEGEND: FLUX 30 40 50 60 70 80 90 100 110 120 130

FIGURE 5: NO$_x$ EMISSIONS
BLOOM 1250



APPENDIX A: EXPERIMENTAL PROCEDURE

1. The desired firing rate, the oxygen concentration in the combustion air, and the stoichiometry serve as basic inputs to the system. Air, oxygen, and natural gas flows are controlled and continuously monitored by a computer.

2. The furnace is allowed to reach thermal equilibrium under conditions of interest.

3. The furnace and the burner internals are continuously monitored for over-temperatures.

4. Oxygen enriched air is analyzed to check the oxygen concentration in the enriched combustion air stream.

5. Flue gases are sampled regularly, dried, and analyzed for CO, CO_2, NO, and excess O_2. CO level is always kept at less than 150 ppm.

6. Furnace pressure is controlled to keep air infiltration to a minimum.

7. Suction pyrometer and heat flux probe measurements are taken after the furnace reaches equilibrium. The measurement are taken on only one side of the longitudinal axis. The measurements are taken at the following positions:

Distance Measured From the Burner Axis, ft	Distance from the Burner Along the Furnace, ft		
	3.9	7.3	13.8
0	x	x	x
1.3	x	x	x
2.5	x	x	x
3.8	x		x

APPENDIX B: ANALYSIS OF HEAT FLUX PROBE AND SUCTION PYROMETER DATA

1. The measurement error is ±20°F for the suction pyrometer and ±2 M BTU/hr ft^2 for the total heat flux meter.

2. The data are statistically screened, analyzed, and fitted to a general expression containing exponential and polynomial functionalities.

3. The root mean square error of the fit between the model and the data is 80°F or better for the suction pyrometer and 6 M BTU/hr ft^2 for the total heat flux meter.

4. In generating the contour plots symmetry around the longitudinal axis has been assumed. Furnace sidewall temperatures support this assumption.

5. Extrapolation of the model (although shown in the contour plots) is not expected to be reliable in a region that is less than 4 feet away from the burner along the axis of the flame.

BURNER EVALUATION WITH OXYGEN ENRICHMENT

NORTH AMERICAN SERIES 4425-8A

15 DECEMBER 1985

Rated Capacity:	4 MM BTU/hour @ 1 psig Air Pressure
Range of Firing Rates Tested:	1 to 3.75 MM BTU/hour
Range of O_2 Concentration in Air Tested:	21 to 100%
Test Period:	26 August 1985 - 5 September 1985

ANALYSIS OF TEST DATA

For a summary of the experimental procedure, see Appendix A.

1. Furnace Temperature (Figure 1)

Equilibrium furnace temperature as measured by a thermocouple in the center of the roof is shown in Figure 1 as a function of the firing rate and the oxygen concentration in air. As expected, the furnace temperature increases sharply with increasing firing rates. Also, the higher the enrichment level, the higher is the furnace temperature.

2. Temperature Uniformity (Figure 2)

The difference between the temperature at the center of the roof and the temperature at the center of the hearth is taken as an indication of temperature uniformity. As expected, the furnace temperature uniformity is improved at high firing rate and at lower oxygen concentrations in the air stream.

3. Gas Temperature Profiles (Figure 3)

The data obtained by suction pyrometer are reduced to isothermal contours presented in Figure 3. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the combustion air, increased firing rates lead the contours to move away from the burner and be narrower. Increasing the oxygen concentration in the combustion air from 21% to 35%, while keeping the firing rate constant, has minimal effect except in the core of the flame. The gas temperature profiles at very high oxygen concentrations in the air (e.g. 60 and 100%) show some broadening and inconsistent logitudinal movement.

The gas temperatures in the neighborhood of the core of the flame can be seen to increase with an increase in both the firing rate as well as the percent oxygen in air.

4. Total Heat Flux Profiles (Figure 4)

The data obtained by the total heat flux meter are reduced to iso-heat flux contours presented in Figure 4. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the air, increased firing rates lead to substantial longitudinal movement and some narrowing of the contours. At a constant firing rate, increasing the oxygen concentration from air to 26%, leads to no substantial changes. The contours appear to move away from the burner with no broadening as the oxygen concentration is increased to 35% at a constant firing rate. The heat flux profile with 100% oxygen in the combustion air is noticeably broad and very steep along the length of the flame.

5. NO_x Emissions (Figure 5)

Data collected by infrared analyzer have been corrected to 0% oxygen in the flue and have been plotted as a function of the firing rate and the oxygen concentration in the combustion air.

Figure 5 indicates that for up to 60% oxygen in the combustion air, NO_x emissions increase strongly with increasing O_2 concentration in air and only weakly with increasing firing rates.

The NO_x emissions with close to 100% oxygen in the combustion air however are much lower that for 60% oxygen in the combustion air. This result is encouraging particularly in light of the fact that the combustion air stream during the testing contained 95% O_2 rather than 100% as desired, due to minor leakage thru the air valves.

6. Fuel-Air Mixing

Higher % excess oxygen in the flue (in other words higher excess air) is needed to achieve complete combustion when the firing rate is low and the enrichment level is high. This appears to be a result of decreasing volumetric flow rates through the burner which reduces the intensity of mixing. CO level could be maintained below 100 ppm with only 1% excess oxygen when firing with up to 35% oxygen in air. For higher enrichment levels, 4 to 6% excess oxygen was needed for complete combustion.

The color of the flame changed from blue to yellow to bright creamy as the enrichment level was increased from air to 35% O_2 in air to 100% oxygen. Sooting was observed on the probes at high enrichment levels and low firing rates.

7. Burner Survival at High Enrichment Levels

The burner was instrumented with a thermocouple through the pilot hole - close to the tip of the gas nozzle.

The temperature (Figure 6), increased rapidly with increasing firing rates on air. With oxygen enrichment, the temperatures were much lower than those with air and also failed to show any consistent trends. Based on the measurements, the burner is expected to survive when firing with 100% oxygen. The burner internals were examined for visible damage and none was found.

PROCESS IMPLICATIONS

Oxygen enrichment is used in a number of high temperature furnaces to reduce the firing rate while maintaining the rate of production. Based on the data in this report, the following may be predicted if oxygen enrichment is used with North American burner 4425 without any modifications.

1. The burner will not be physically damaged.

2. The flame will be more yellow. The gas temperature profile would be more concentrated toward the burner end and be somewhat broader depending on the level of oxygen enrichment.

3. The heat flux profile would be more concentrated at the burner end.

4. The temperature uniformity will suffer. This may necessitate changing the furnace control parameters and the burner orientation.

5. The ability of the burner to uniformly heat the load may deteriorate, particularly if the load is some distance away from the burner.

6. NO_x emissions will increase with low levels of enrichment. With 100% oxygen, NO_x emissions on a per ton product basis will actually decrease.

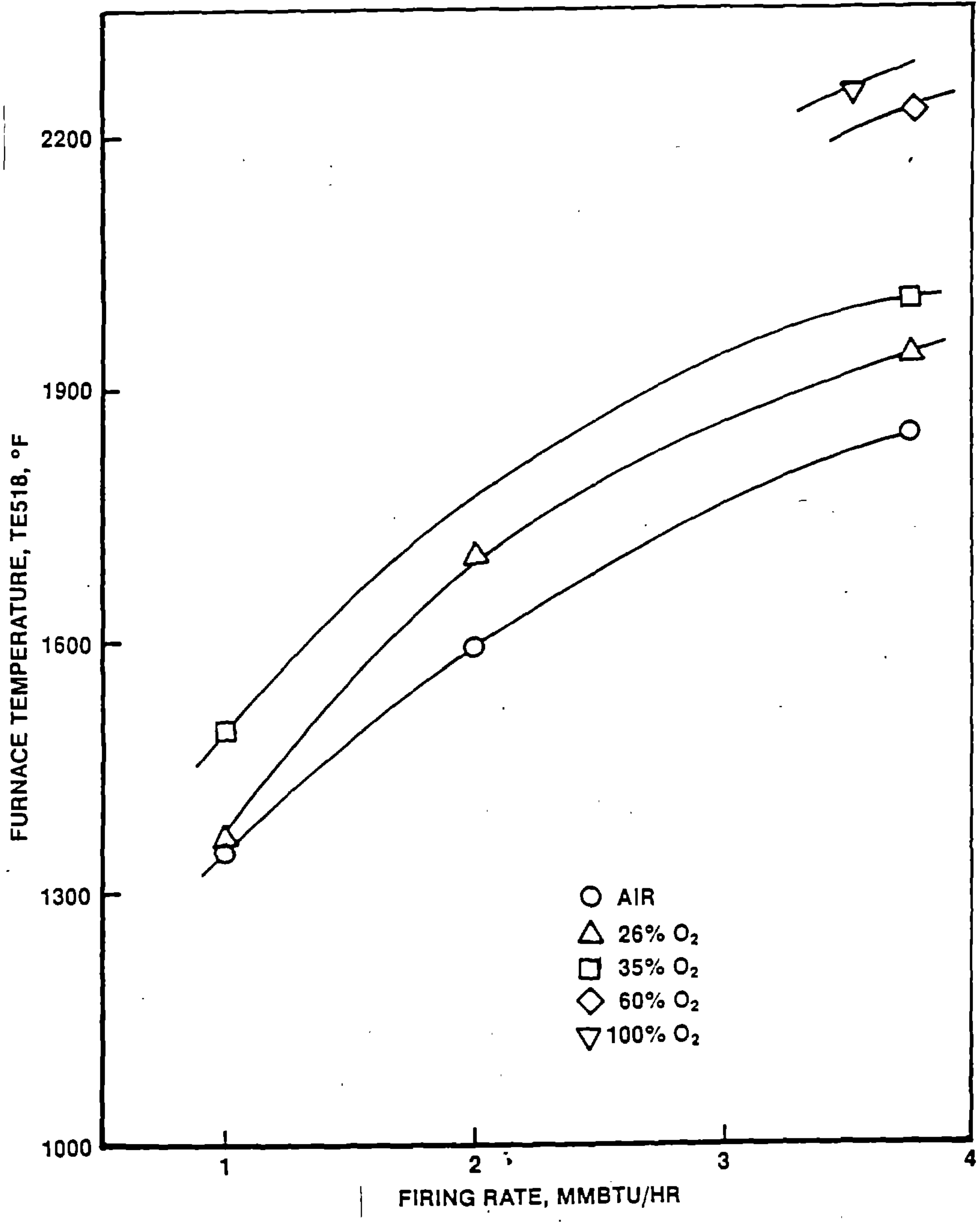
7. The furnace will have to be operated at a higher excess oxygen level to counter reduced intensity of fuel-air mixing at very high enrichment levels.

SUGGESTED BURNER MODIFICATIONS

Based on the data collected, the following modifications are suggested to improve the performance of the North American series 4425 burner at high enrichment levels:

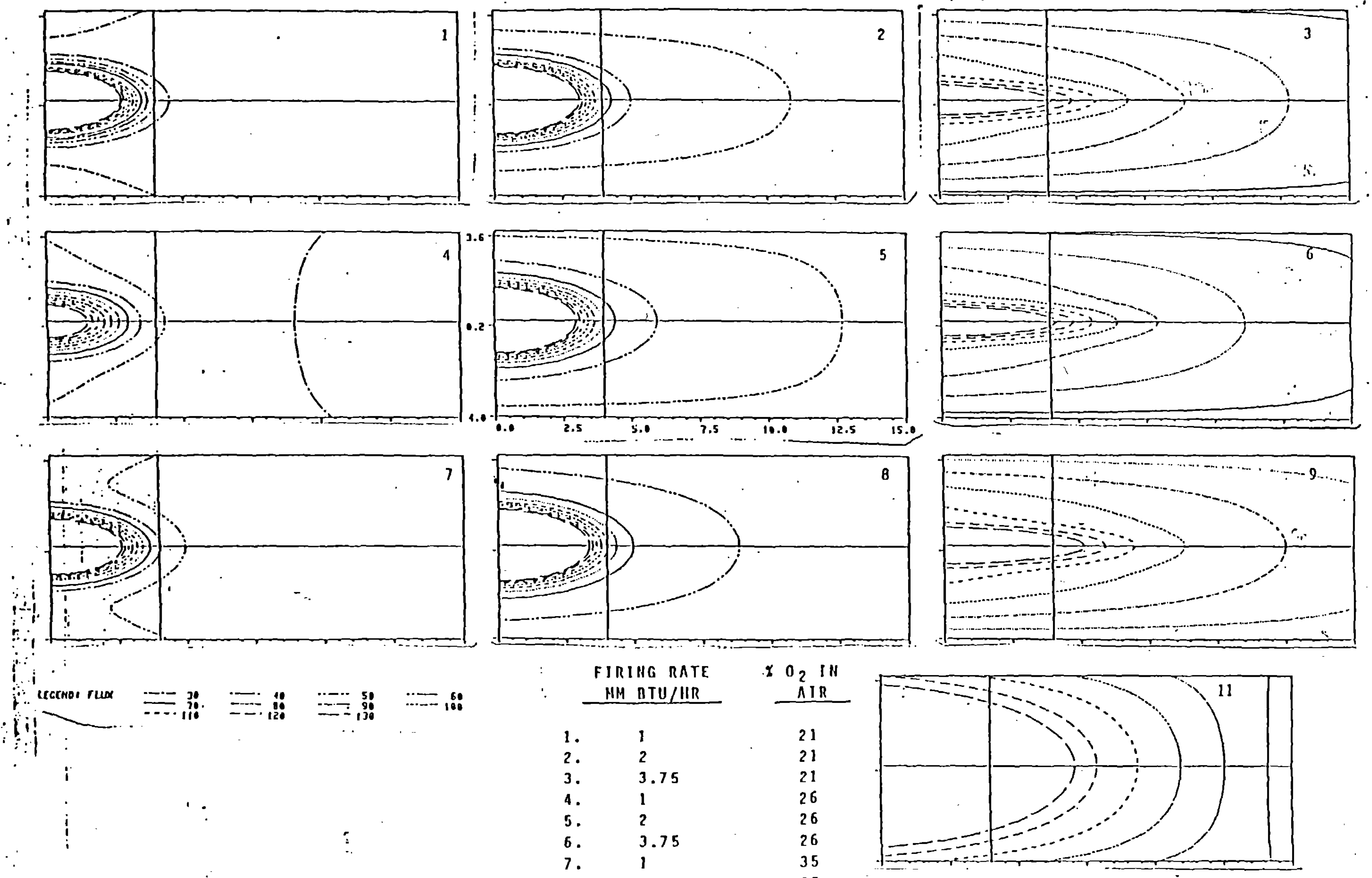
1. Substantially reduce the size of the air tubes.
2. Reduce the size of the natural gas tube.
3. Arrange the tubes in a non-symmetric fashion around the gas tube to simulate undershooting.

FIGURE 1: FURNACE TEMPERATURE
NORTH AMERICAN 4425-8A



NORTH AMERICAN MFG BURNER MODEL 4425

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT2/HR



	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	1	21
2.	2	21
3.	3.75	21
4.	1	26
5.	2	26
6.	3.75	26
7.	1	35
8.	2	35
9.	3.75	35
10.	3.75	60
11.	3.5	100

FIGURE 5: NO_x EMISSIONS
NORTH AMERICAN 4425-8A

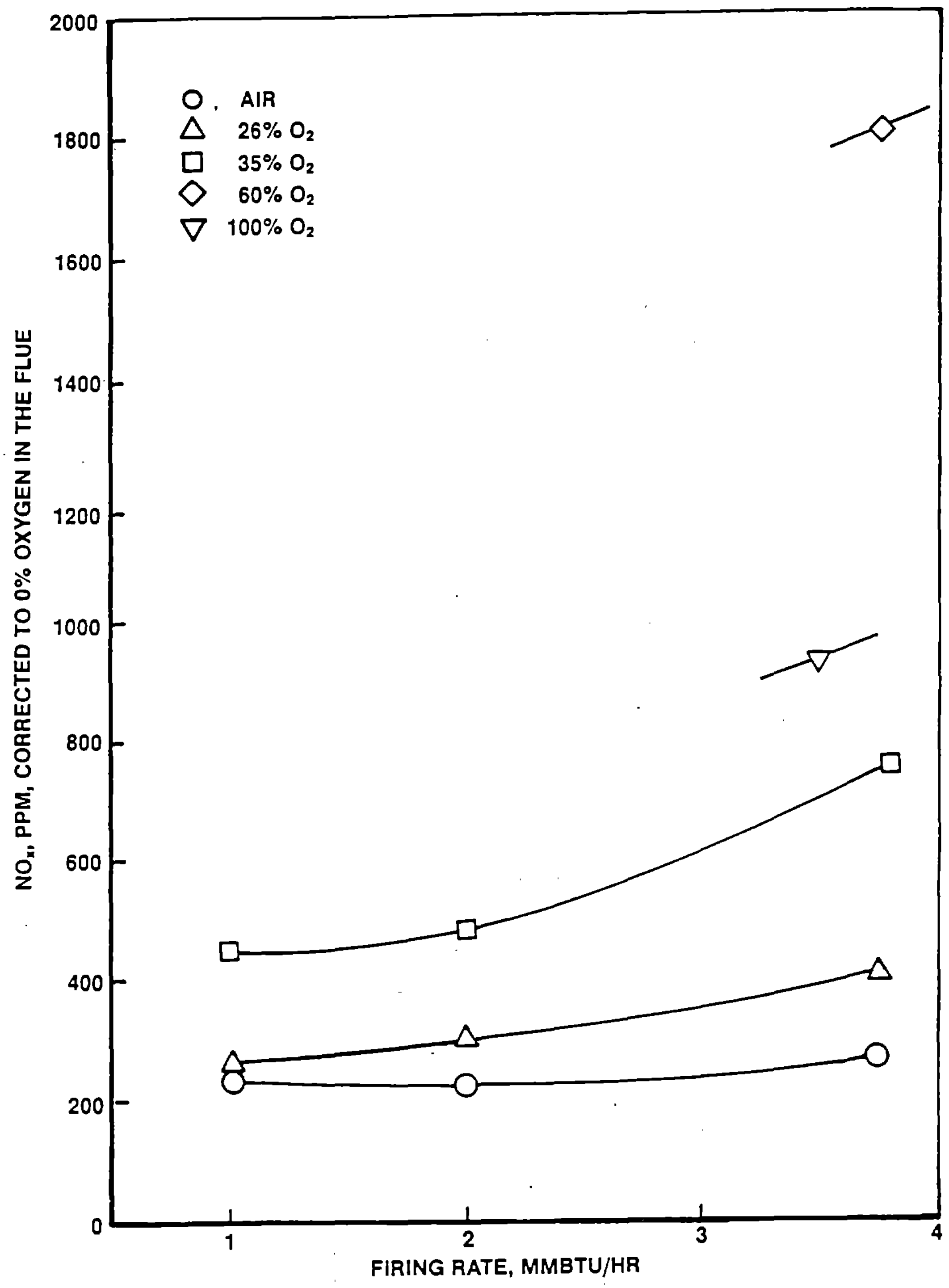
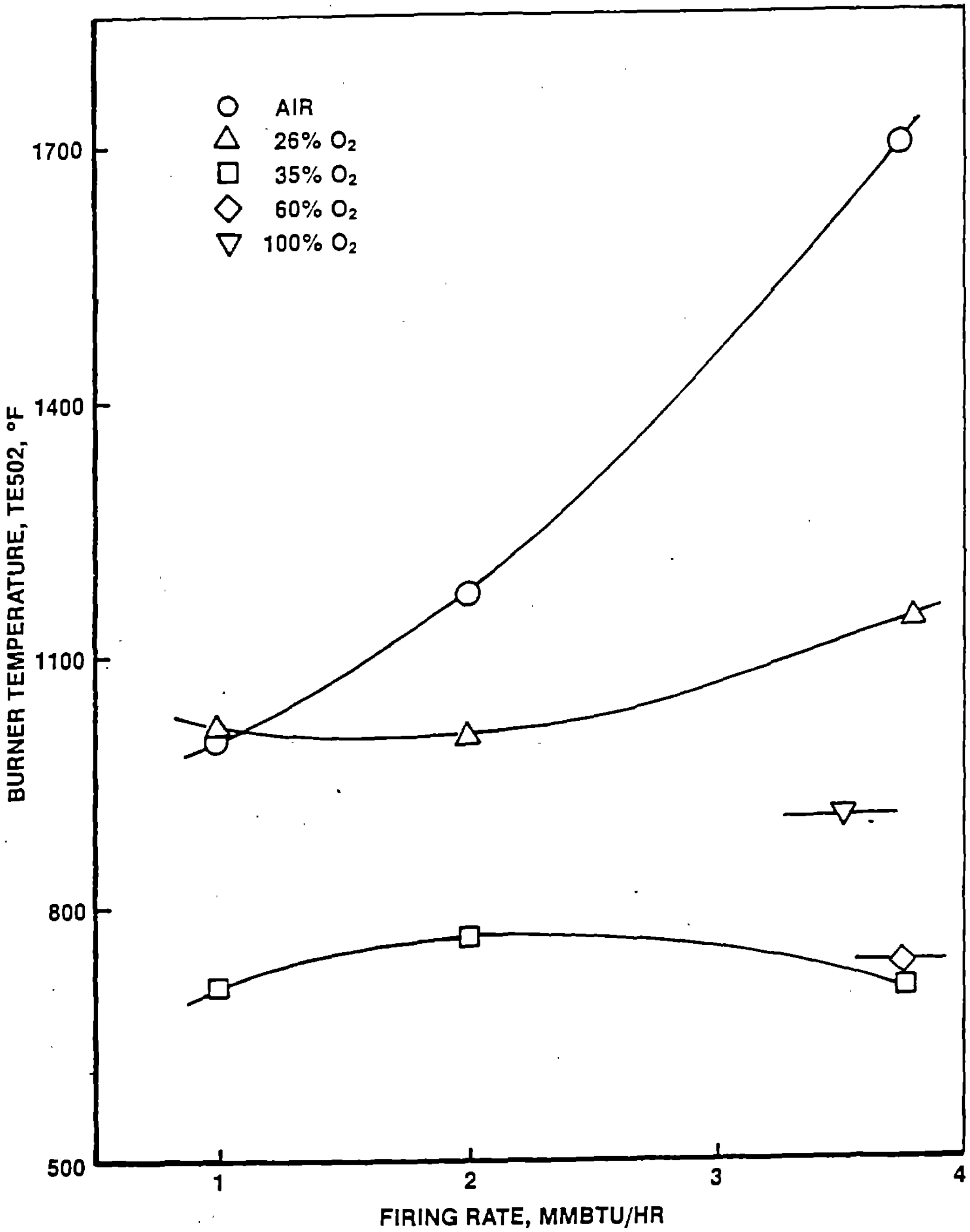


FIGURE 6: BURNER TEMPERATURE
NORTH AMERICAN 4425-8A

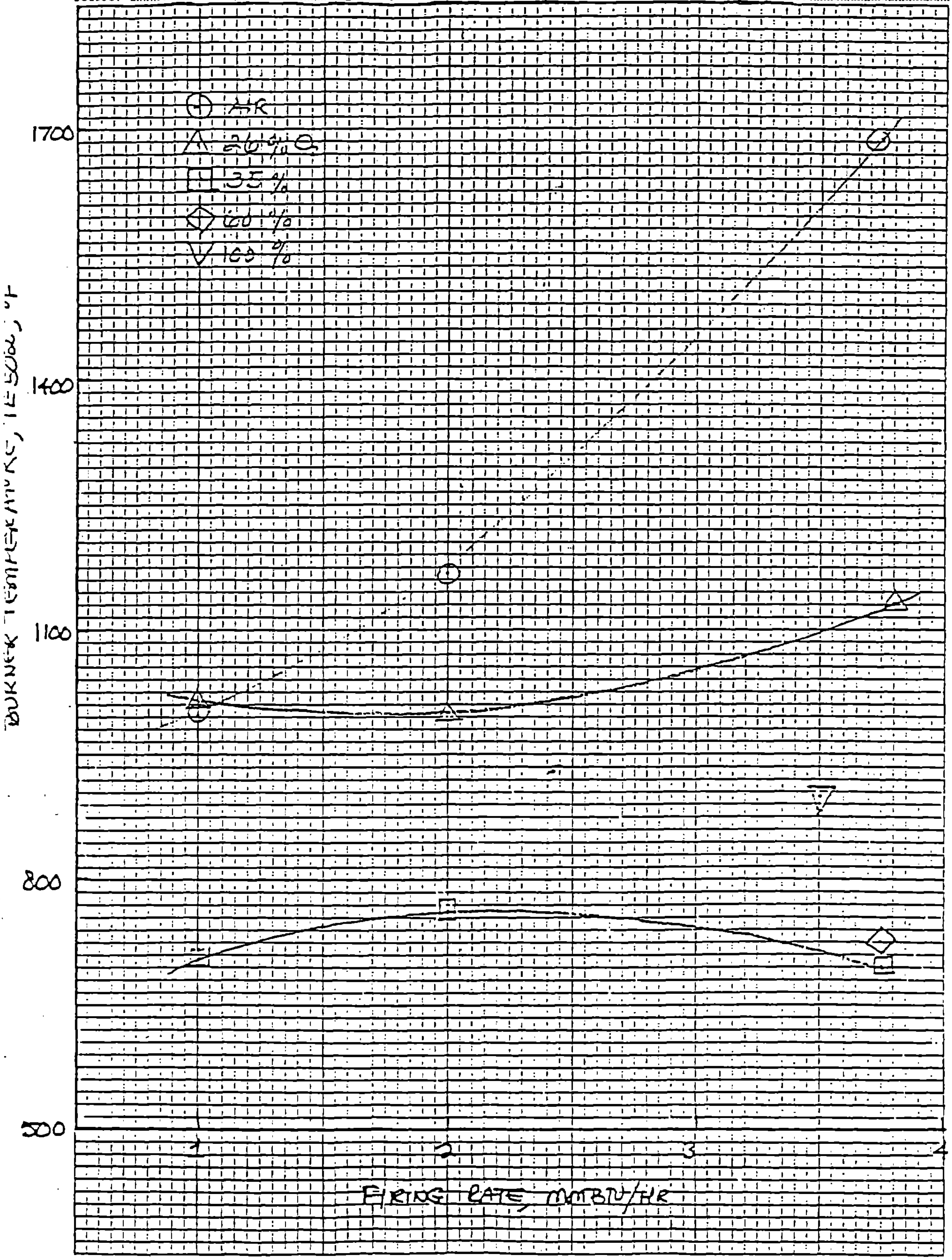


Form 8115

Air Products and Chemicals Inc.

BY .... DATE .... SHEET NO. .... OF ....

SUBJECT FIGURE 6 : BURNER INTERNAL TEMPERATURE NO. ....



APPENDIX A: EXPERIMENTAL PROCEDURE

1. The desired firing rate, the oxygen concentration in the combustion air, and the stoichiometry serve as basic inputs to the system. Air, oxygen, and natural gas flows are controlled and continuously monitored by a computer.

2. The furnace is allowed to reach thermal equilibrium under conditions of interest.

3. The furnace and the burner internals are continuously monitored for over-temperatures.

4. Oxygen enriched air is analyzed to check the oxygen concentration in the enriched combustion air stream.

5. Flue gases are sampled regularly, dried, and analyzed for CO, CO_2, NO, and excess O_2. CO level is always kept at less than 150 ppm.

6. Furnace pressure is controlled to keep air infiltration to a minimum.

7. Suction pyrometer and heat flux probe measurements are taken after the furnace reaches equilibrium. The measurement are taken on only one side of the longitudinal axis. The measurements are taken at the following positions:

Distance Measured From the Burner Axis, ft	Distance from the Burner Along the Furnace, ft		
	3.9	7.3	13.8
0	x	x	x
1.3	x	x	x
2.5	x	x	x
3.8	x		x

APPENDIX B: ANALYSIS OF HEAT FLUX PROBE AND SUCTION PYROMETER DATA

1. The measurement error is ±20°F for the suction pyrometer and ±2 M BTU/hr ft^2 for the total heat flux meter.

2. The data are statistically screened, analyzed, and fitted to a general expression containing exponential and polynomial functionalities.

3. The root mean square error of the fit between the model and the data is 80°F or better for the suction pyrometer and 6 M BTU/hr ft^2 for the total heat flux meter.

4. In generating the contour plots symmetry around the longitudinal axis has been assumed. Furnace sidewall temperatures support this assumption.

5. Extrapolation of the model (although shown in the contour plots) is not expected to be reliable in a region that is less than 4 feet away from the burner along the axis of the flame.

BURNER EVALUATION WITH OXYGEN ENRICHMENT

MAXON SERIES G KINEMAX™

15 DECEMBER 1985

Rated Capacity: 3.7 MM BTU/hour @ 15 osi Air Pressure

Range of Firing Rates Tested: 1 to 3.75 MM BTU/hour

Range of O_2 Concentration in Air Tested: 21 to 100%

Test Period: 16 September - 26 September 1985

ANALYSIS OF TEST DATA

For a summary of the experimental procedure, see Appendix A.

1. Furnace Temperature (Figure 1)

Equilibrium furnace temperature as measured by a thermocouple in the center of the roof is shown in Figure 1 as a function of the firing rate and the oxygen concentration in air. As expected, the furnace temperature increases sharply with increasing firing rates. Also, the higher the enrichment level, the higher is the furnace temperature.

2. Temperature Uniformity (Figure 2)

The difference between the temperature at the center of the roof and the temperature at the center of the hearth is taken as an indication of temperature uniformity. At high firing rate the temperature uniformity is not affected when the oxygen concentration is increased from 21 up to 35%. In general however, the furnace temperature uniformity is improved with increasing firing rates and decreasing oxygen concentrations in the air stream.

3. Gas Temperature Profiles (Figure 3)

The data obtained by suction pyrometer are reduced to isothermal contours presented in Figure 3. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the combustion air, increased firing rates lead the contours to move away from the burner. When firing with combustion air containing 35 or more percent oxygen, the gas temperature contours become narrower as the firing rate is increased.

At the lowest firing rate tested (1 MM BTU/hr), oxygen enrichment has little effect on the gas temperature profiles. At the other firing rates, the temperature profiles show some movement away from the burner but no broadening as the oxygen concentration is raised from 21% to 35%. Increasing the oxygen concentration beyond 35% while maintaining a constant firing rate only broadens the contours. The gas temperature profiles at very high oxygen concentrations in the air (e.g. 60 and 100%) show some broadening and little longitudinal movement when compared to the profiles with 35% oxygen in the combustion air.

The gas temperatures in the neighborhood of the core of the flame can be seen to increase with an increase in both the firing rate as well as the percent oxygen in air.

4. Total Heat Flux Profiles (Figure 4)

The data obtained by the total heat flux meter are reduced to iso-heat flux contours presented in Figure 4. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the air, increased firing rates lead to substantial longitudinal movement and some narrowing of the contours. However, when firing with 100% oxygen, the heat flux contours become broader with increased firing rate.

At a constant firing rate, increasing the oxygen concentration from 21% to 35% leads to significant longitudinal movement of the contours. Increase of the oxygen concentration further to 100%, leads to some more longitudinal movement and substantial broadening.

5. <u>NO_x Emissions</u> (Figure 5)

Data collected by infrared analyzer have been corrected to 0% oxygen in the flue and have been plotted as a function of the firing rate and the oxygen concentration in the combustion air.

Figure 5 indicates that for up to 60% oxygen in the combustion air, NO_x emissions increase strongly with increasing O_2 concentration in air and only weakly with increasing firing rates.

The NO_x emissions with close to 100% oxygen in the combustion air however are much lower that for 60% oxygen in the combustion air. This result is encouraging particularly in light of the fact that the combustion air stream during the testing contained 95% O_2 rather than 100% as desired, due to minor leakage through the air valves.

6. Fuel-Air Mixing

Higher % excess oxygen in the flue (in other words higher excess air) is needed to achieve complete combustion when the firing rate is low and the enrichment level is high. This appears to be a result of decreasing volumetric flow rates through the burner which reduces the intensity of mixing. CO level could be maintained below 100 ppm with only 1% excess oxygen when firing with up to 35% oxygen in air. For higher enrichment levels, 4 to 6% excess oxygen was needed for complete combustion.

The color of the flame changed from blue to yellow to bright creamy as the enrichment level was increased from air to 35% O_2 in air to 100% oxygen. Sooting was observed on the probes at high enrichment levels and low firing rates.

7. Burner Survival at High Enrichment Levels

The burner was instrumented with a thermocouple through the pilot hole close to the tip of the gas nozzle.

The highest temperature (600°F), was observed when firing with 100% oxygen. With air only operation, the temperatures were even lower. Based on the measurements, the burner is expected to survive when firing with 100% oxygen. The burner internals were examined for visible damage and none was found.

PROCESS IMPLICATIONS

Oxygen enrichment is used in a number of high temperature furnaces to reduce the firing rate while maintaining the rate of production. Based on the data in this report, the following may be predicted if oxygen enrichment is used with Maxon series G Kinemax™ burner without any modifications.

1. The burner will not be physically damaged.
2. The flame will be more yellow. The gas temperature profile would be more concentrated toward the burner end and be somewhat broader depending on the level of oxygen enrichment.
3. The heat flux profile would be more concentrated at the burner end.
4. The temperature uniformity will suffer. This may necessitate changing the furnace control parameters and the burner orientation.
5. The ability of the burner to uniformly heat the load may deteriorate, particularly if the load is some distance away from the burner.
6. NO_x emissions will increase with low levels of enrichment. With 100% oxygen, NO_x emissions on a per ton product basis will actually decrease.
7. The furnace will have to be operated at a higher excess oxygen level to counter reduced intensity of fuel-air mixing if very high enrichment levels are to be practiced.

SUGGESTED BURNER MODIFICATIONS

Based on the data collected, the following modifications are suggested to improve the performance of the Maxon series G Kinemax™ burner at high enrichment levels:

1. Substantially reduce the size of the air holes.
2. Reduce the size of the natural gas holes.
3. Reduce intensity of the air swirl.

FIGURE 1: FURNACE TEMPERATURE
MAXON KINEMAX G

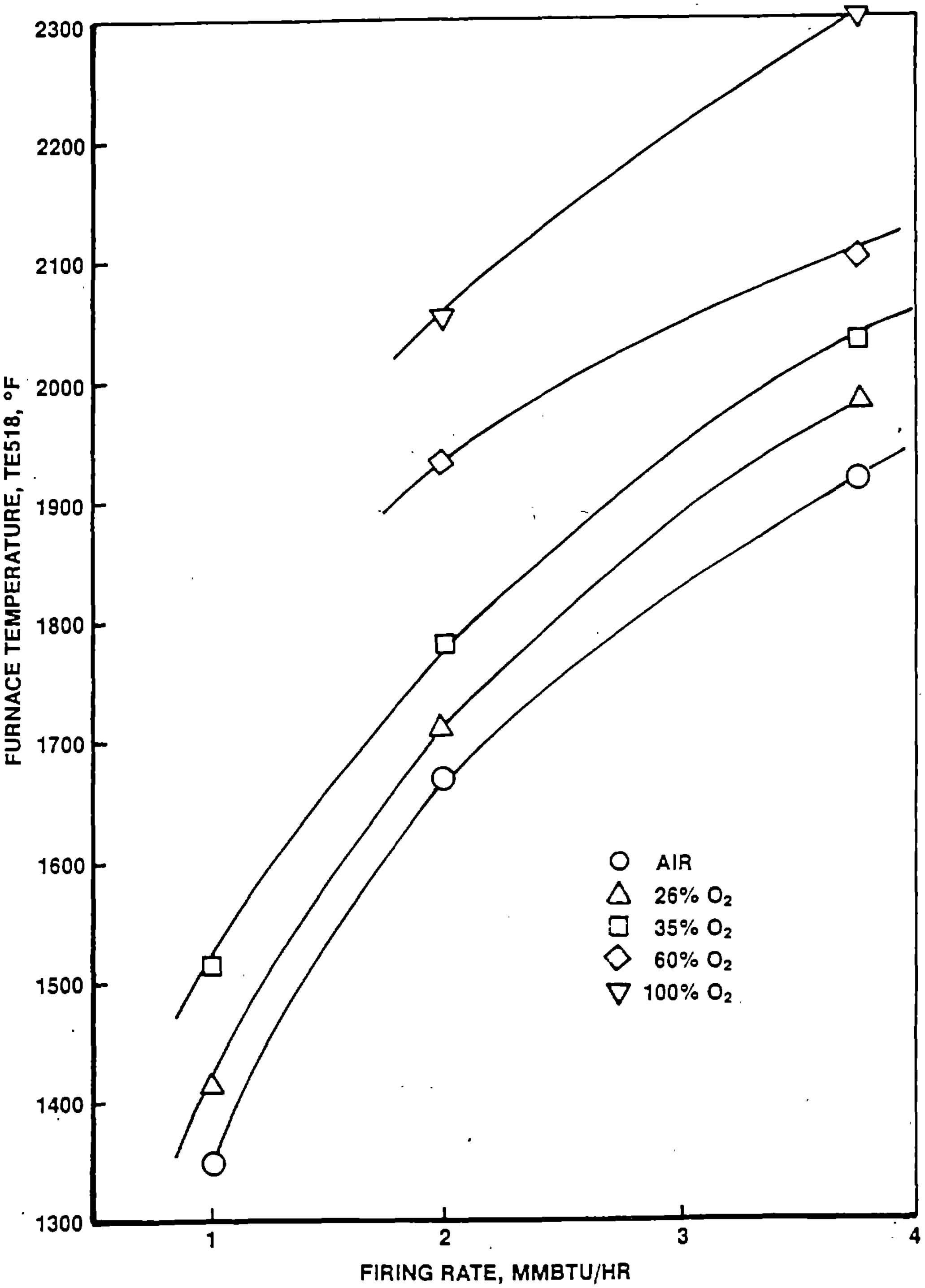
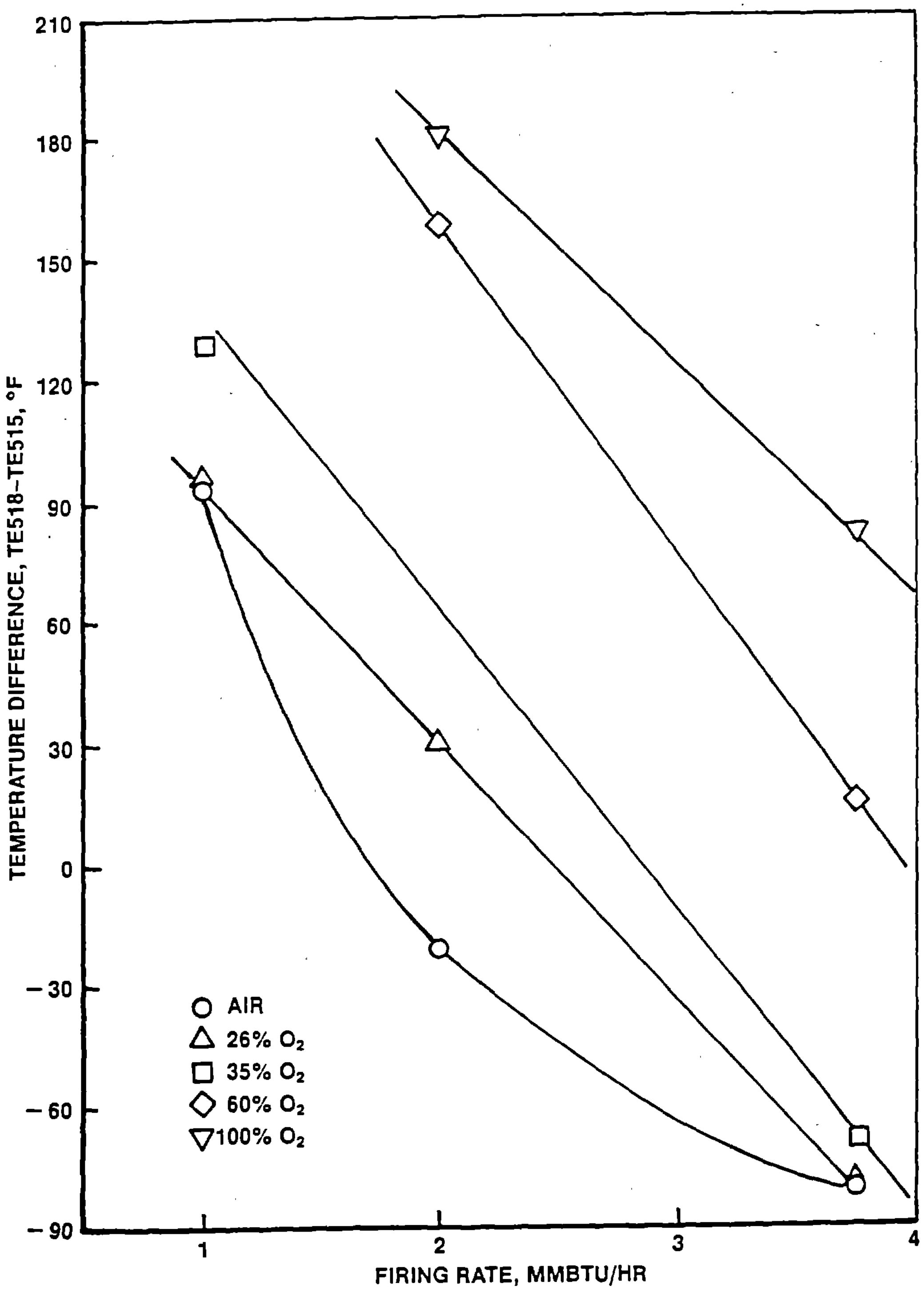
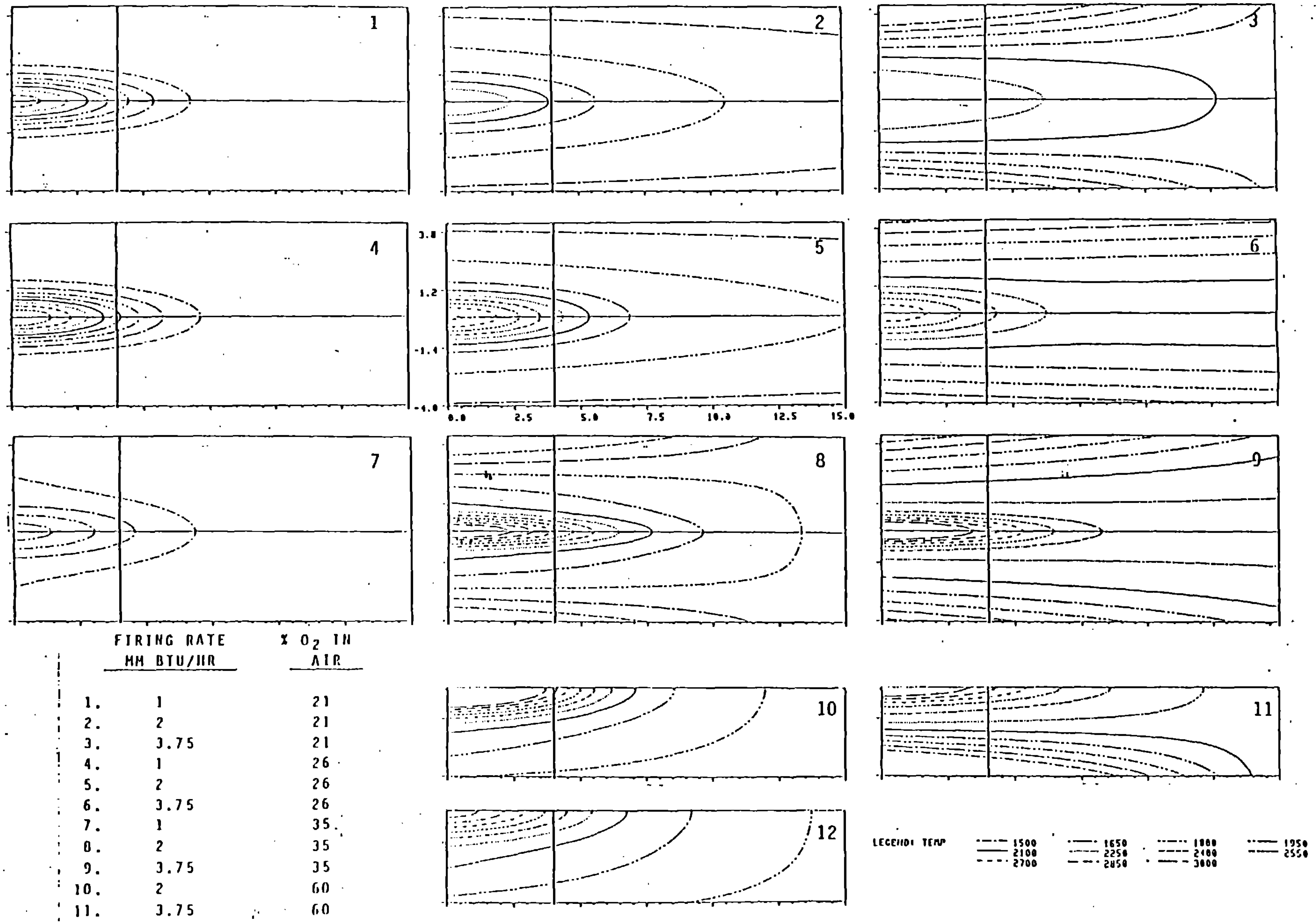


FIGURE 2: TEMPERATURE UNIFORMITY
MAXON KINEMAX G



MAXON KINEMAX BURNER

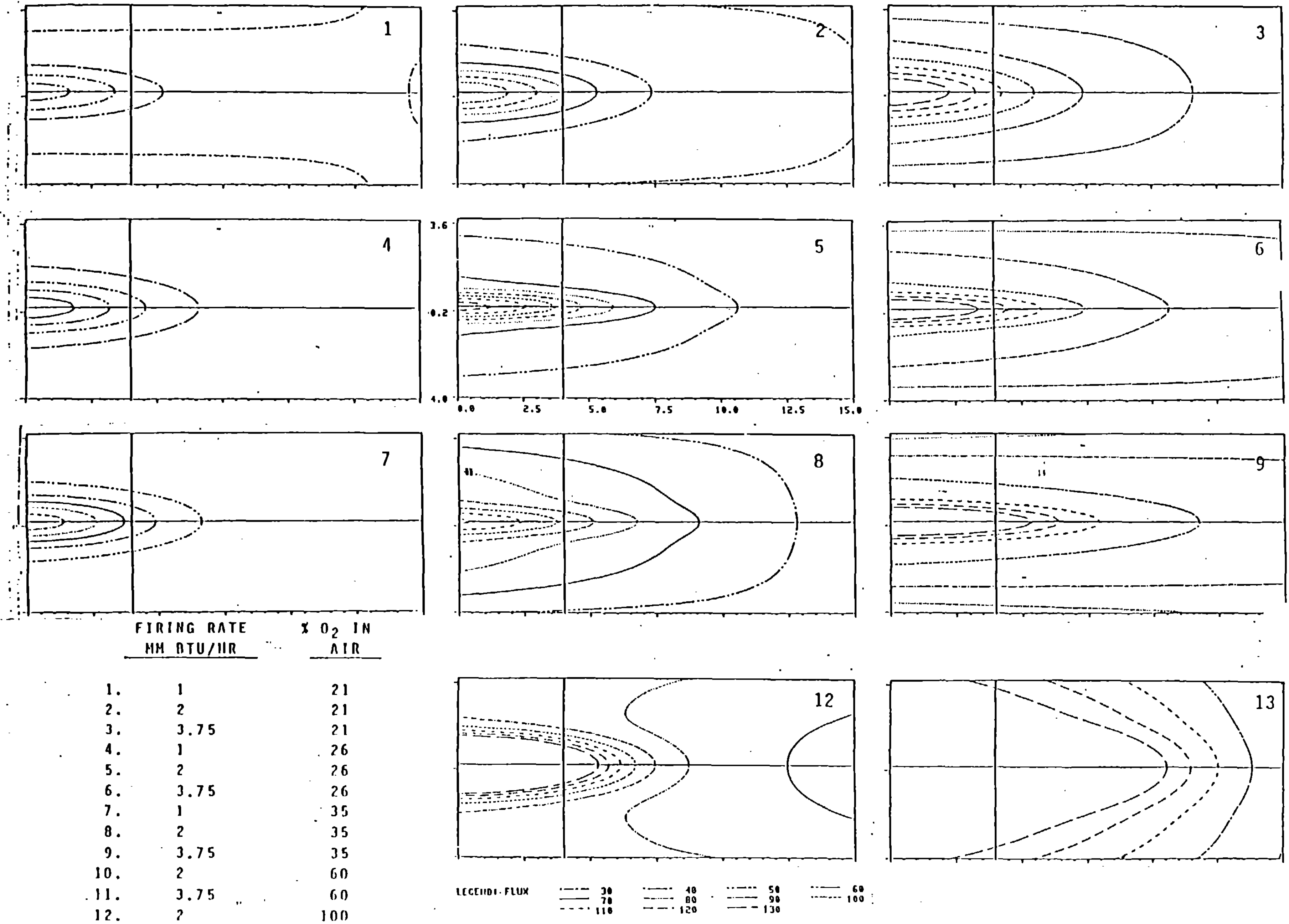
GAS TEMPERATURES BY SUCTION PYROMETER, DEG F



	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	1	21
2.	2	21
3.	3.75	21
4.	1	26
5.	2	26
6.	3.75	26
7.	1	35
8.	2	35
9.	3.75	35
10.	2	60
11.	3.75	60
12.	2	100

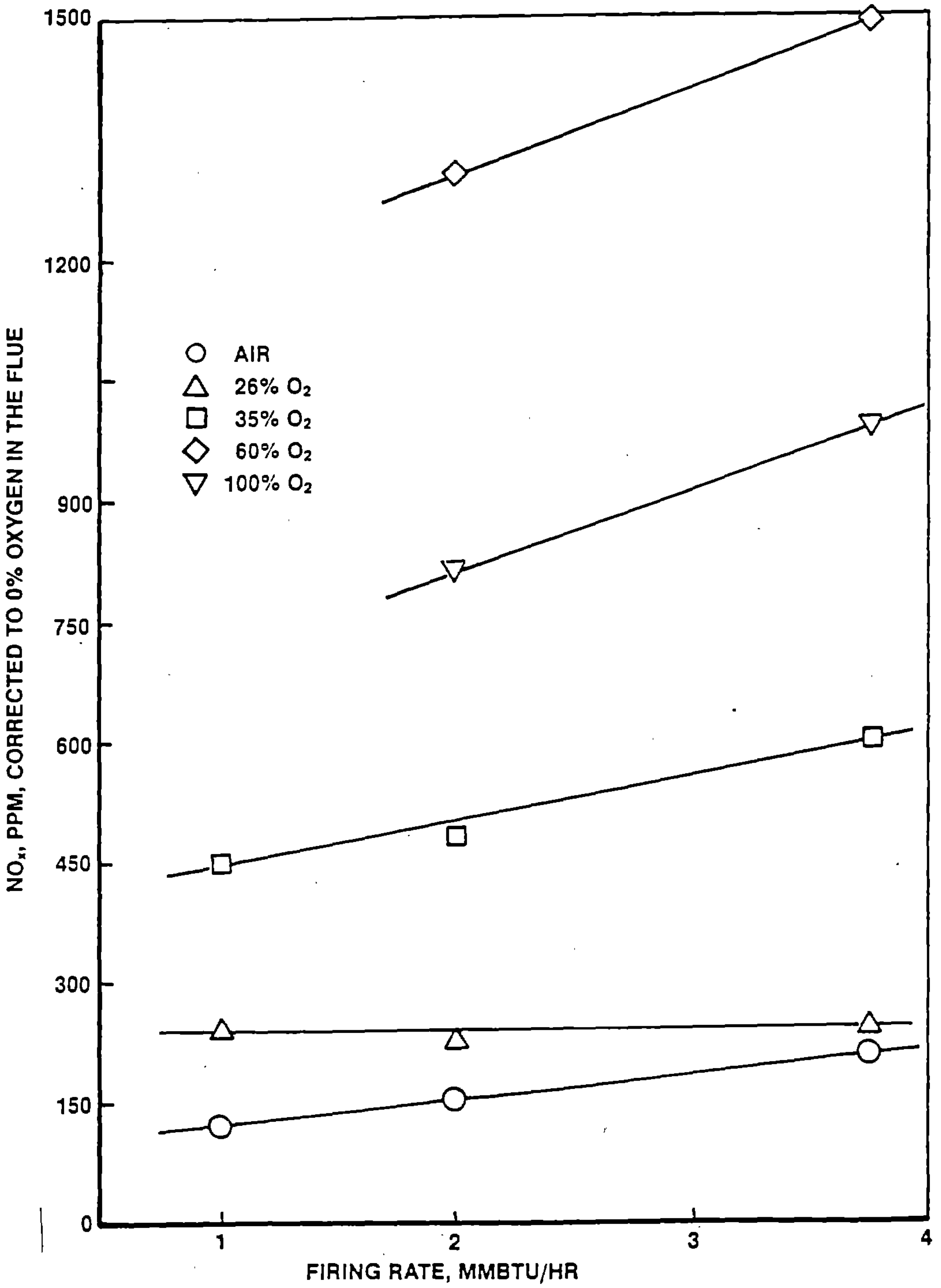
MAXON KINEMAX BURNER

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT2/HR



	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	1	21
2.	2	21
3.	3.75	21
4.	1	26
5.	2	26
6.	3.75	26
7.	1	35
8.	2	35
9.	3.75	35
10.	2	60
11.	3.75	60
12.	2	100
13.	3.75	100

FIGURE 5: NO$_x$ EMISSIONS
MAXON KINEMAX G



BURNER EVALUATION WITH OXYGEN ENRICHMENT

ECLIPSE MVTA 248

18 DECEMBER 1985

Rated Capacity:	4.5 MM BTU/hour @ 1 psig Air Pressure
Range of Firing Rates Tested:	1 to 3.75 MM BTU/hour
Range of O_2 Concentration in Air Tested:	21 to 100%
Test Period:	7 October - 23 October 1985

ANALYSIS OF TEST DATA

For a summary of the experimental procedure, see Appendix A.

1. Furnace Temperature (Figure 1)

Equilibrium furnace temperature as measured by a thermocouple in the center of the roof is shown in Figure 1 as a function of the firing rate and the oxygen concentration in air. As expected, the furnace temperature increases sharply with increasing firing rates. Also, the higher the enrichment level, the higher is the furnace temperature.

2. Temperature Uniformity (Figure 2)

The difference between the temperature at the center of the roof and the temperature at the center of the hearth is taken as an indication of temperature uniformity. At high firing rate the temperature uniformity is not affected when the oxygen concentration is increased from 21 up to 26%. In general however, the furnace temperature uniformity is improved with increasing firing rates and decreasing oxygen concentrations in the air stream.

3. Gas Temperature Profiles (Figure 3)

The data obtained by suction pyrometer are reduced to isothermal contours presented in Figure 3. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the combustion air, increased firing rates lead the contours to move away from the burner. Also, the core of the flame appears to move away from the face of the burner.

At the lowest firing rate tested (1 MM BTU/hr), oxygen enrichment has little effect on the gas temperature profiles. At medium firing rates (2 MM BTU/hour), oxygen enrichment makes the temperature contours broader, particularly at high concentrations of oxygen in the combustion air. There is no evidence of any substantial longitudinal movement with oxygen enrichment. Note that the core of the flame tends to move away at first with oxygen enrichment and then move back towards the face of the burner with even higher enrichment levels.

At high firing rates (3 to 3.75 MM BTU/hour), low enrichment levels make the temperature contours as well as the flame core move away from the burner. At high enrichment levels, the profiles are broader with no further movement along the length of the furnace. The core of the flame appears to move back towards the burner as high enrichment levels are achieved.

4. Total Heat Flux Profiles (Figure 4)

The data obtained by the total heat flux meter are reduced to iso-heat flux contours presented in Figure 4. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the air, increased firing rates lead to substantial longitudinal movement and some narrowing of the contours. Also, the core of the flame appears to move away from the burner, consistent with the gas temperature profiles.

At low firing rate (1 MM BTU/hour), there is no significant effect of increasing the oxygen concentration from 21% to 35%.

At medium and high firing rates (>2 MM BTU/hour), low enrichment levels cause the contours to move away from the burner. Also, there are indications of core movement away from the burner. Increasing the oxygen concentration further causes broadening but no substantial movement along the length of the furnace. Note that a pronounced peak develops at the centerline and that the core moves back towards the burner at high enrichment levels.

5. <u>NO_x Emissions</u> (Figure 5)

Data collected by infrared analyzer have been corrected to 0% oxygen in the flue and have been plotted as a function of the firing rate and the oxygen concentration in the combustion air.

Figure 5 indicates that for up to 60% oxygen in the combustion air, NO_x emissions increase strongly with increasing O_2 concentration in air and only weakly with increasing firing rates.

The NO_x emissions with 100% oxygen were not measured due to instrumentation problems.

6. Fuel-Air Mixing

Higher % excess oxygen in the flue (in other words higher excess air) is needed to achieve complete combustion when the firing rate is low and the enrichment level is high. This appears to be a result of decreasing volumetric flow rates through the burner which reduces the intensity of mixing. CO level could be maintained below 100 ppm with only 2% excess oxygen when firing with up to 35% oxygen in air. For higher enrichment levels, 5 to 8% excess oxygen was needed for complete combustion.

The color of the flame changed from yellow to bright creamy as the enrichment level was increased from air to 35% O_2 in air to 100% oxygen. The flames at high enrichment levels and low firing rates lacked direction and a lot of sooting was observed.

7. Burner Survival at High Enrichment Levels

The burner was instrumented with a thermocouple through the pilot hole close to the tip of the gas nozzle.

The temperature was observed to be almost independent of the firing rate but increased steadily with the enrichment level (Figure 6). Although the highest temperature observed (1300°F with 100% oxygen) is well below the accepted limits for the materials of construction, some scaling was evident on the natural gas tube and the air shroud. There are some concerns about the long-term survival of this burner under high enrichment level conditions.

PROCESS IMPLICATIONS

Oxygen enrichment is used in a number of high temperature furnaces to reduce the firing rate while maintaining the rate of production. Based on the data in this report, the following may be predicted if oxygen enrichment is used with Eclipse MVTA burner without any modifications.

1. The burner may be physically damaged.

2. The flame will be more luminous. The gas temperature profile would be more concentrated toward the burner end and be somewhat broader depending on the level of oxygen enrichment. The core of the flame will move towards the burner. The flame will lack direction.

3. The heat flux profile would be more concentrated at the burner end. The profile at high levels of enrichment will be broader and may exhibit a peak at the centerline.

4. The temperature uniformity will suffer. This may necessitate changing the furnace control parameters and the burner orientation.

5. The ability of the burner to uniformly heat the load will deteriorate.

6. NO_x emissions will increase with enrichment up to 60% oxygen in air.

7. The furnace will have to be operated at a higher excess oxygen level to counter reduced intensity of fuel-air mixing if very high enrichment levels are to be practiced.

BURNER MODIFICATIONS

Major modifications will be needed to the original design of Eclipse MVTA burner to improve the performance at high enrichment levels.

Therefore, no specific burner modifications were identified.

FIGURE 1: FURNACE TEMPERATURE
ECLIPSE MVTA 248

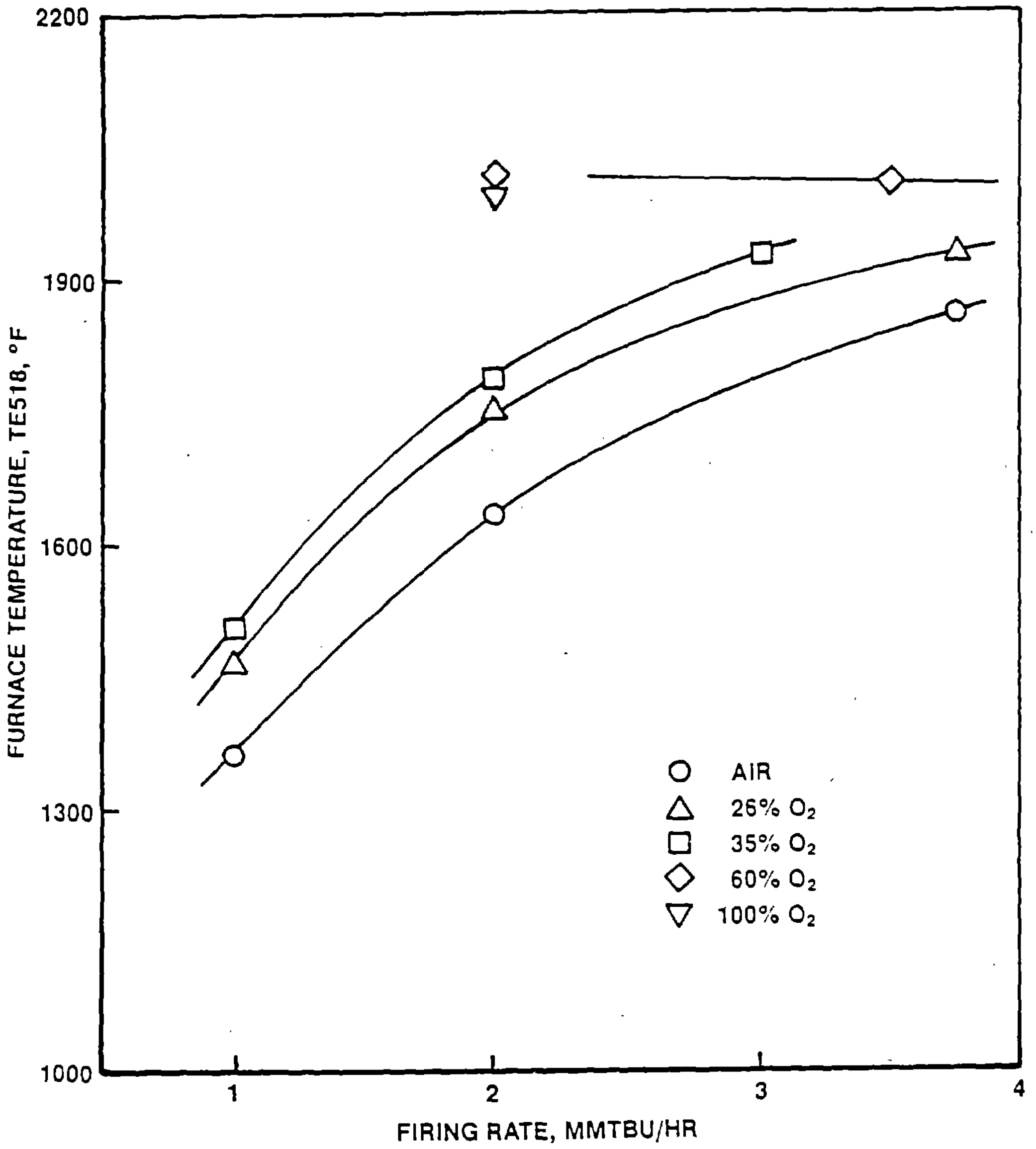
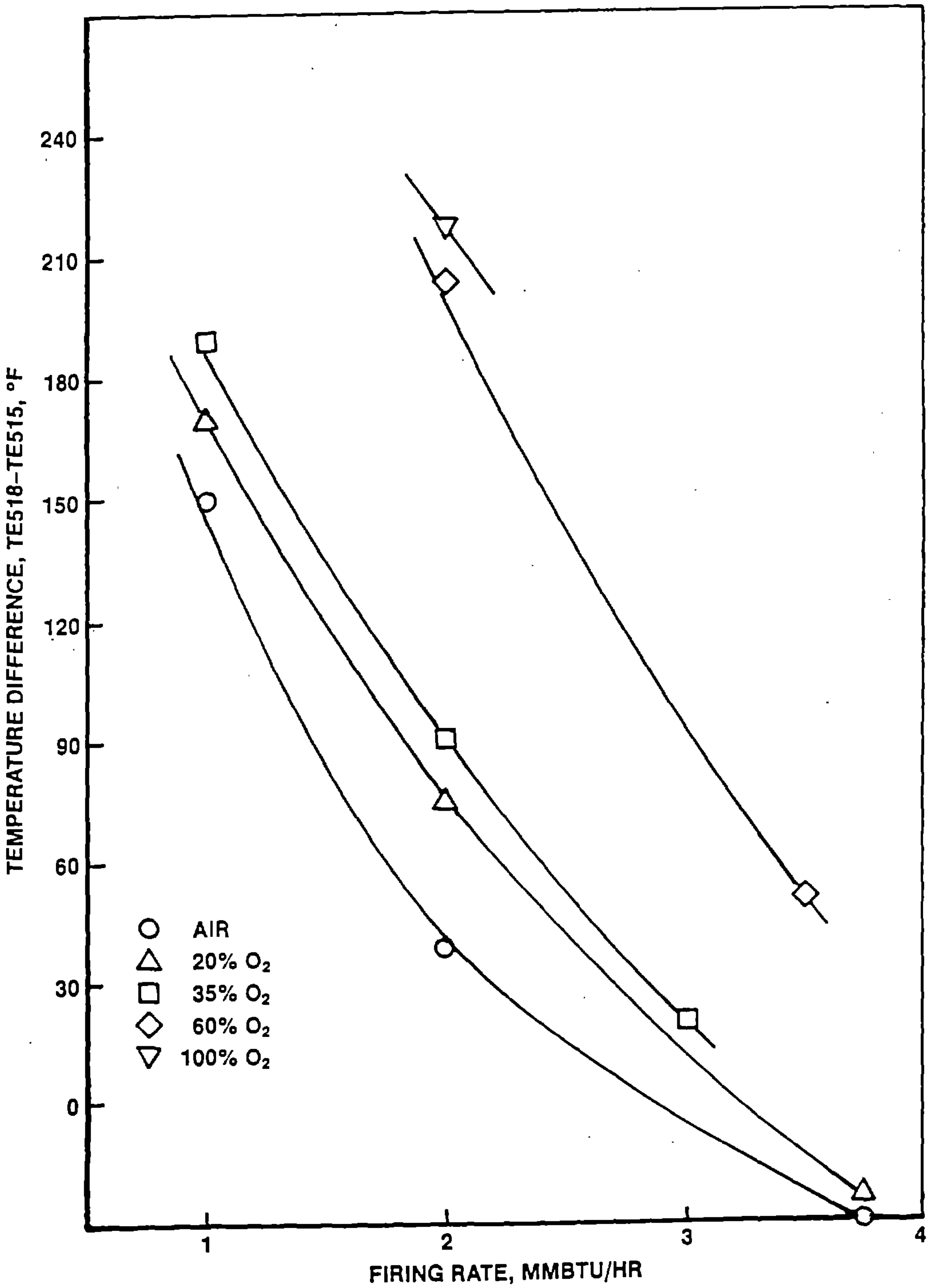


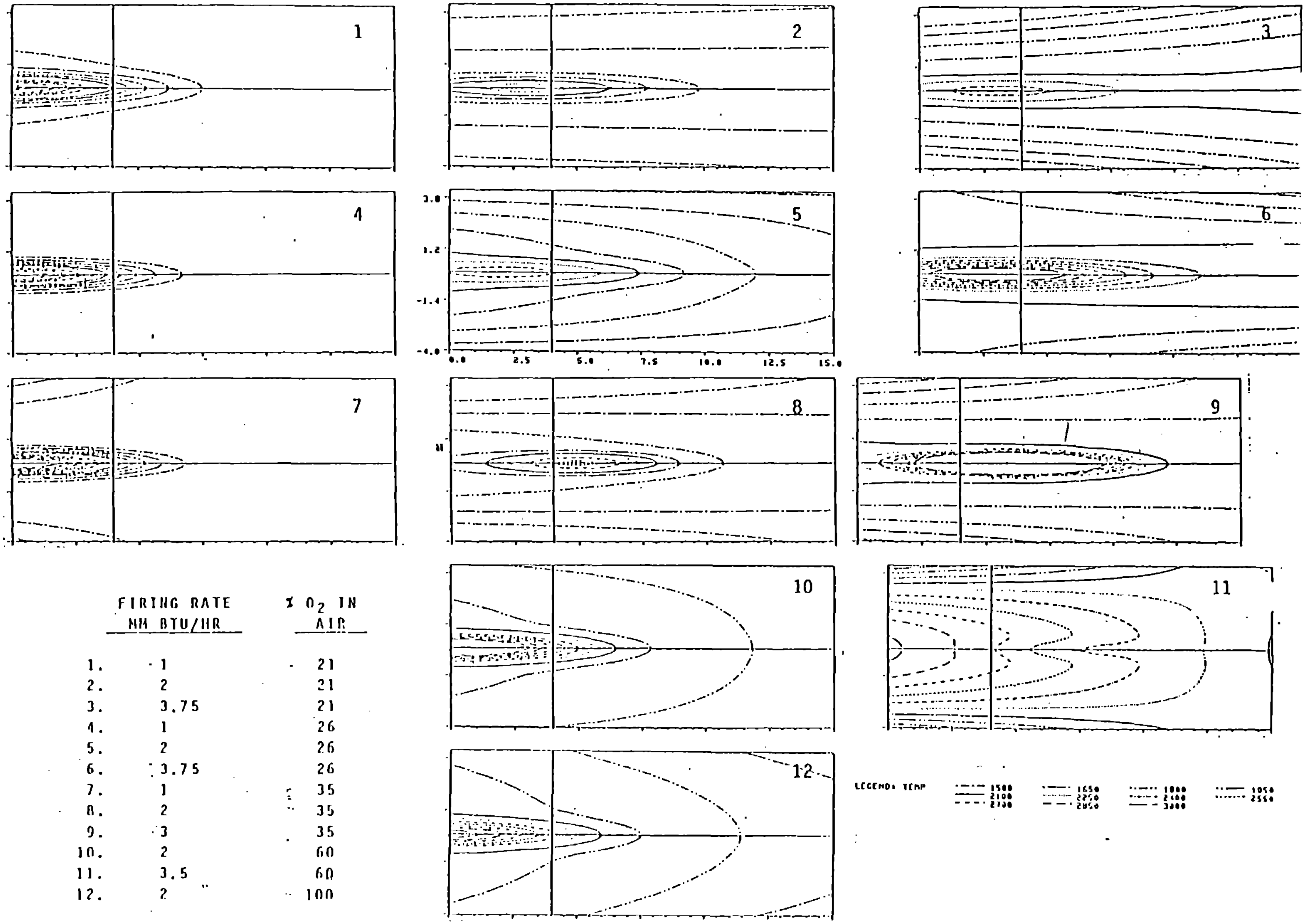
FIGURE 2: TEMPERATURE UNIFORMITY

ECLIPSE MVTA 248



ECLIPSE BURNER 248 MVTA

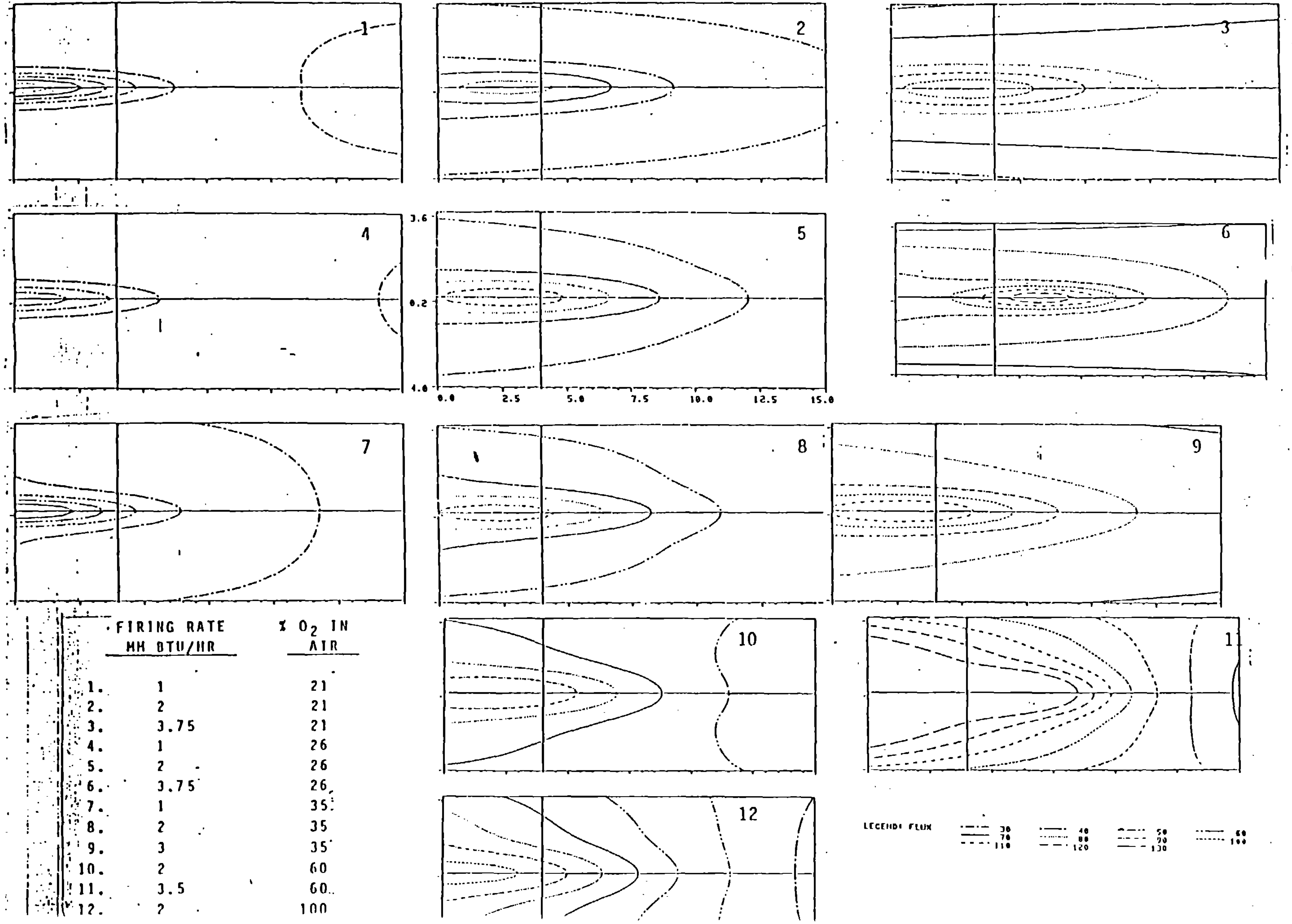
GAS TEMPERATURES BY SUCTION PYROMETER, DEG F



	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	1	21
2.	2	21
3.	3.75	21
4.	1	26
5.	2	26
6.	3.75	26
7.	1	35
8.	2	35
9.	3	35
10.	2	60
11.	3.5	60
12.	2	100

ECLIPSE BURNER 248 MVTA

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT2/HR



	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	1	21
2.	2	21
3.	3.75	21
4.	1	26
5.	2	26
6.	3.75	26
7.	1	35
8.	2	35
9.	3	35
10.	2	60
11.	3.5	60
12.	2	100

FIGURE 5: NO_x EMISSIONS
ECLIPSE MVTA 248

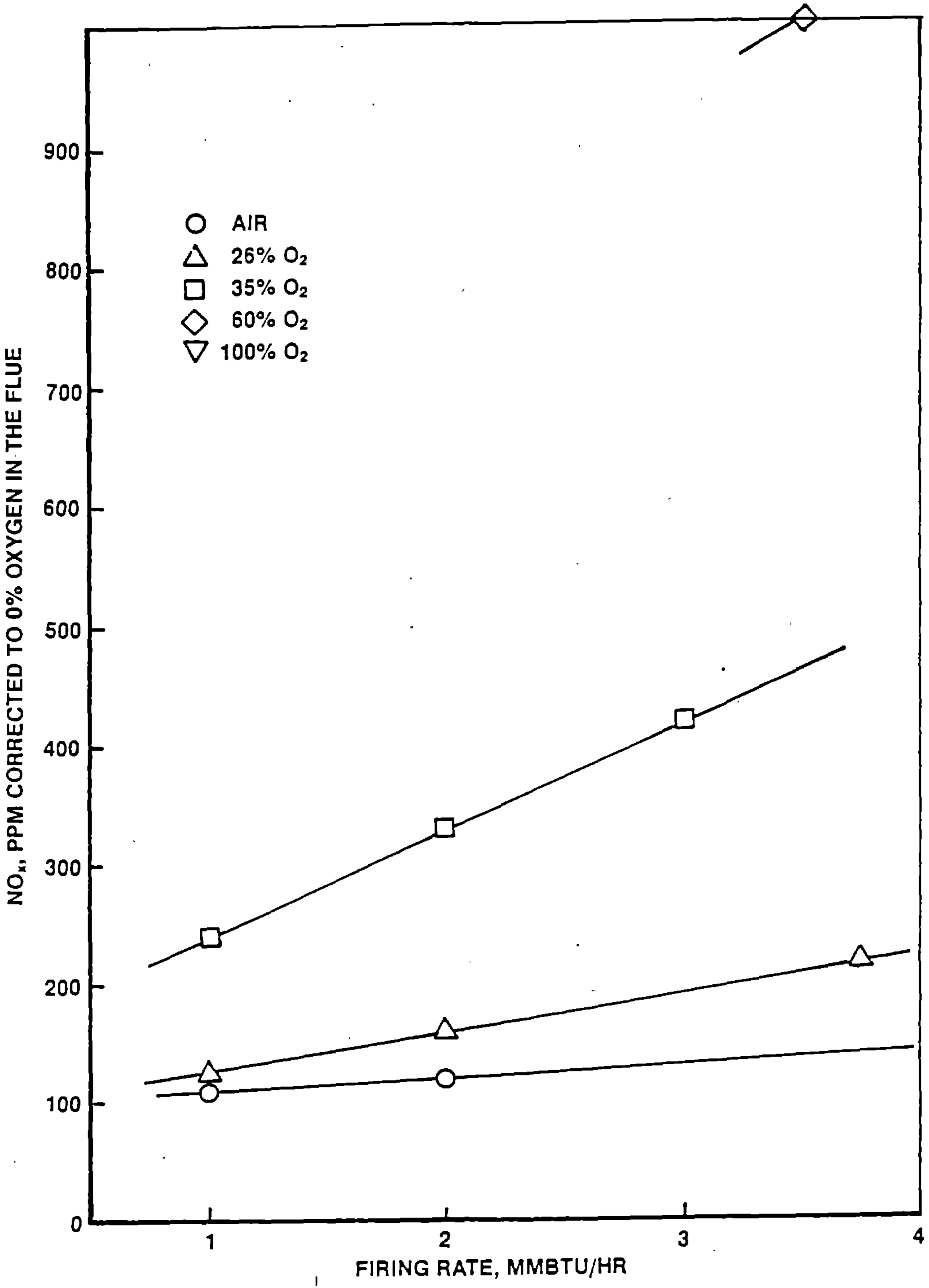
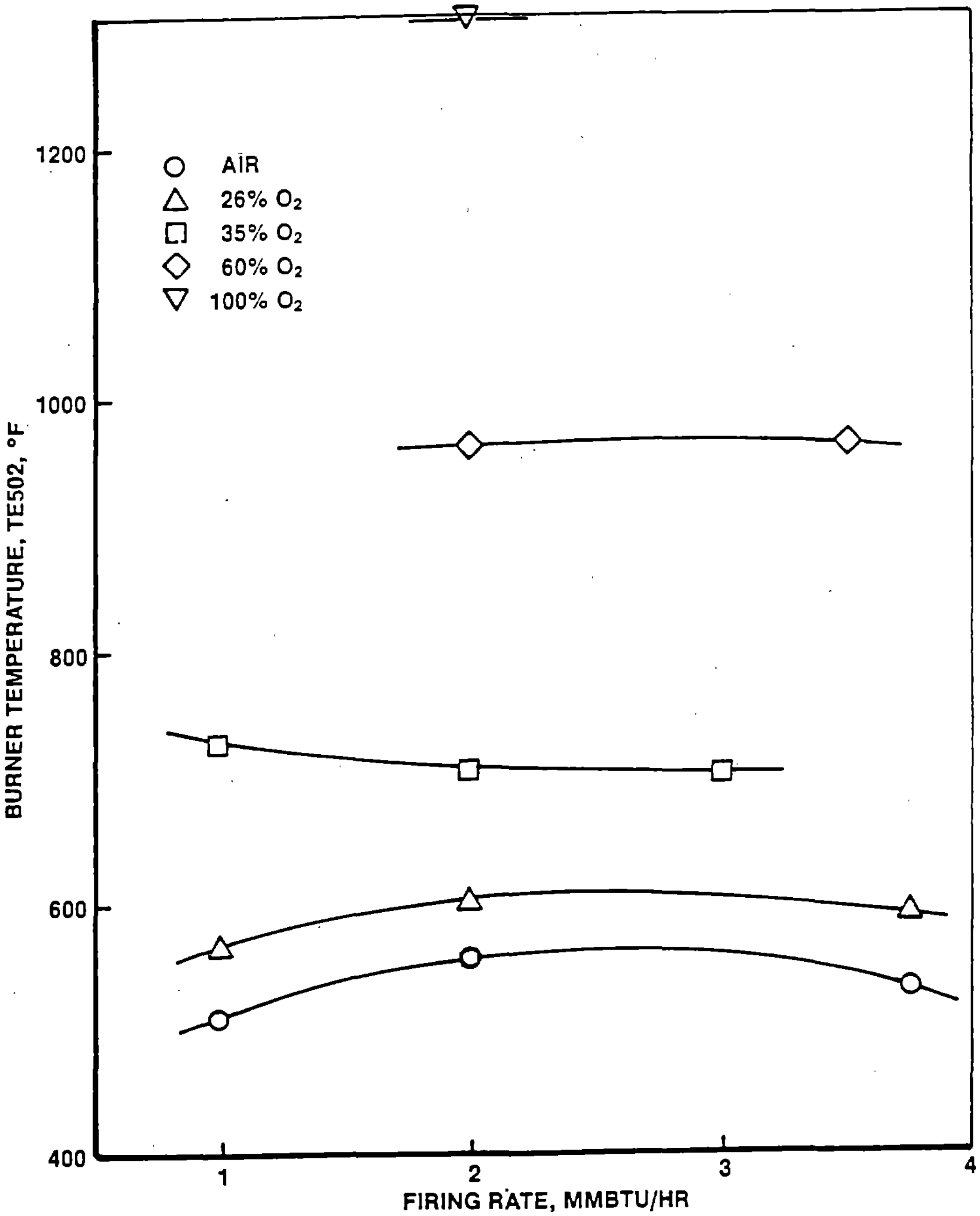


FIGURE 6: BURNER TEMPERATURE
ECLIPSE MVTA 248



BURNER EVALUATION WITH OXYGEN ENRICHMENT

NORTH AMERICAN SERIES 6514

23 DECEMBER 1985

Rated Capacity:	7 MM BTU/hour @ 1 psig Air Pressure
Range of Firing Rates Tested:	1 to 3.75 MM BTU/hour
Range of O_2 Concentration in Air Tested:	21 to 35%
Test Period:	4 November - 7 November 1985

ANALYSIS OF TEST DATA

For a summary of the experimental procedure, see Appendix A. Due to the configuration of cooling panels used, the maximum firing rate was limited to 3.75 MM BTU/hour, 54% of rated capacity at 1 psig air pressure.

1. Furnace Temperature (Figure 1)

Equilibrium furnace temperature as measured by a thermocouple in the center of the roof is shown in Figure 1 as a function of the firing rate and the oxygen concentration in air. As expected, the furnace temperature increased sharply with increasing firing rates. Also, the higher the enrichment level, the higher was the furnace temperature.

2. Temperature Uniformity (Figure 2)

The difference between the temperature at the center of the roof and the temperature at the center of the hearth is taken as an indication of temperature uniformity. The furnace temperature uniformity was improved with increasing firing rates and appeared to be affected little by oxygen concentration in the range of 21 to 35%.

3. Gas Temperature Profiles (Figure 3)

The data obtained by suction pyrometer are reduced to isothermal contours presented in Figure 3. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the combustion air, increased firing rates led the contours as well as the core of the flame to move away from the burner. Increasing the level of enrichment at a constant firing rate appeared to have no significant effect in the range of variables tested.

4. Total Heat Flux Profiles (Figure 4)

The data obtained by the total heat flux meter are reduced to iso-heat flux contours presented in Figure 4. Appendix B briefly describes the data reduction procedure.

At a constant oxygen concentration in the air, increased firing rates led to substantial longitudinal movement.

At a constant firing rate, increasing the oxygen concentration led to significant longitudinal movement and some broadening of the contours.

5. NO_x Emissions (Figure 5)

Data collected by infrared analyzer are corrected to 0% oxygen in the flue and are plotted as a function of the firing rate and the oxygen concentration in the combustion air.

Figure 5 indicates that NO_x emissions increased strongly with increasing O_2 concentration in air and only weakly with increasing firing rates.

6. Fuel-Air Mixing

CO level could be maintained below 100 ppm with only 1% excess oxygen when firing with up to 35% oxygen in air indicating adequate fuel-enriched air mixing.

The color of the flame changed from blue to yellow as the enrichment level was increased from air to 35% O_2 in air. Some sooting was observed on the probes at high enrichment levels and low firing rates.

7. Burner Survival at High Enrichment Levels

The burner was instrumented with a thermocouple through the pilot hole close to the tip of the gas nozzle.

The temperature appeared insensitive to the firing rate, but increased with increasing level of oxygen enrichment. Based on the data shown in Figure 6, the burner is not expected to survive when firing with more than 30% oxygen in the combustion air. When the burner internals were examined for damage, air plate showed bluish oxidation on the upstream face.

PROCESS IMPLICATIONS

Oxygen enrichment is used in a number of high temperature furnaces to reduce the firing rate while maintaining the rate of production. Based on the data in this report, the following may be predicted if oxygen enrichment is used with North American series 6514 burner without any modifications.

1. The burner will be physically damaged if operated with more than 30% oxygen in air.
2. The flame will be more yellow. The gas temperature profile would be more concentrated toward the burner end.
3. The heat flux profile would be more concentrated at the burner end.
4. The temperature uniformity will not suffer.
5. NO_x emissions will increase with low levels of enrichment.

SUGGESTED BURNER MODIFICATIONS

Based on the data collected, the burner is not considered suitable for operations involving high enrichment levels. The modifications that reduce the intensity of air-fuel mixing may result in improved life at higher enrichment levels.

FIGURE 1: FURNACE TEMPERATURE

NORTH AMERICAN 6514

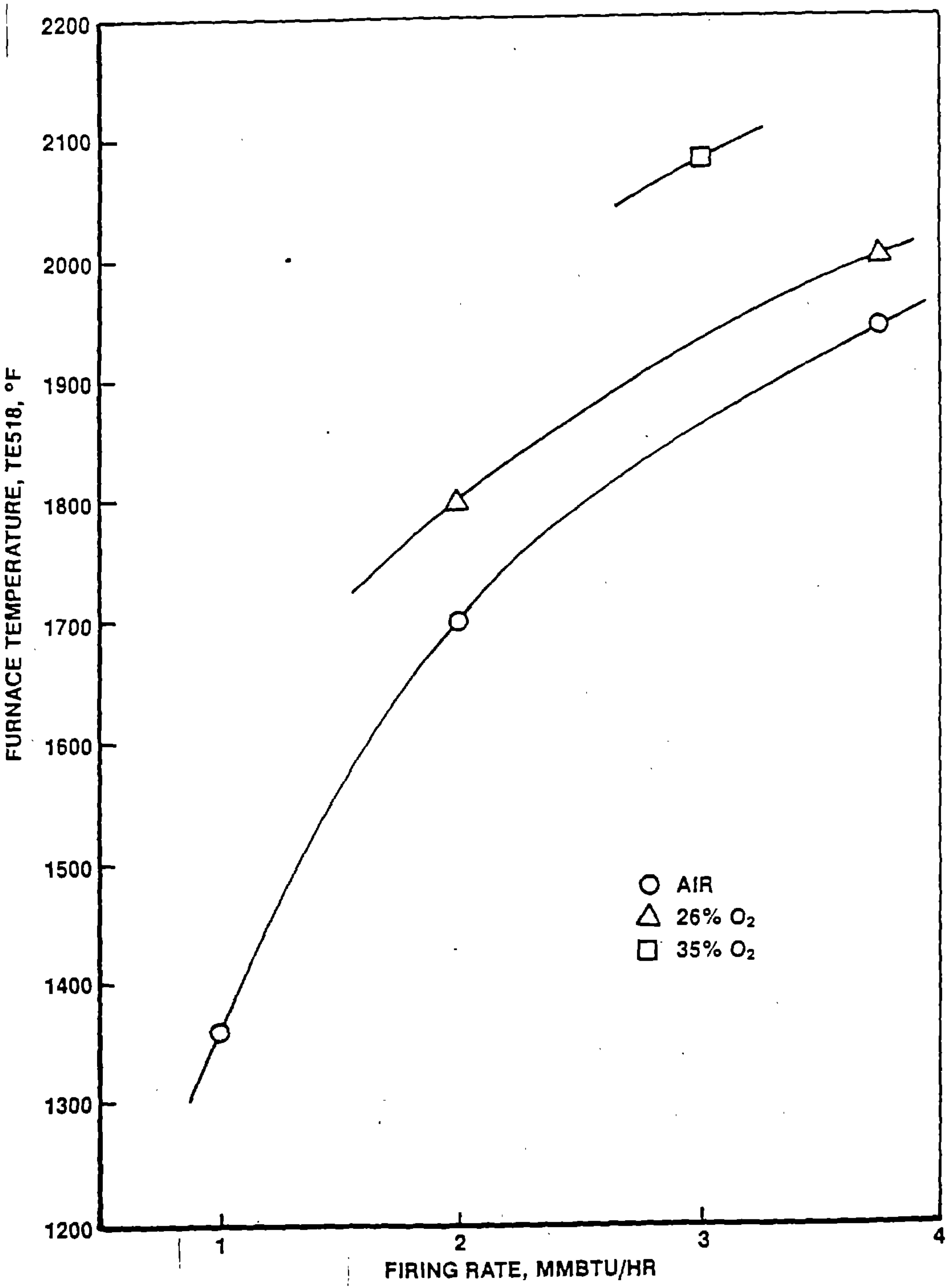
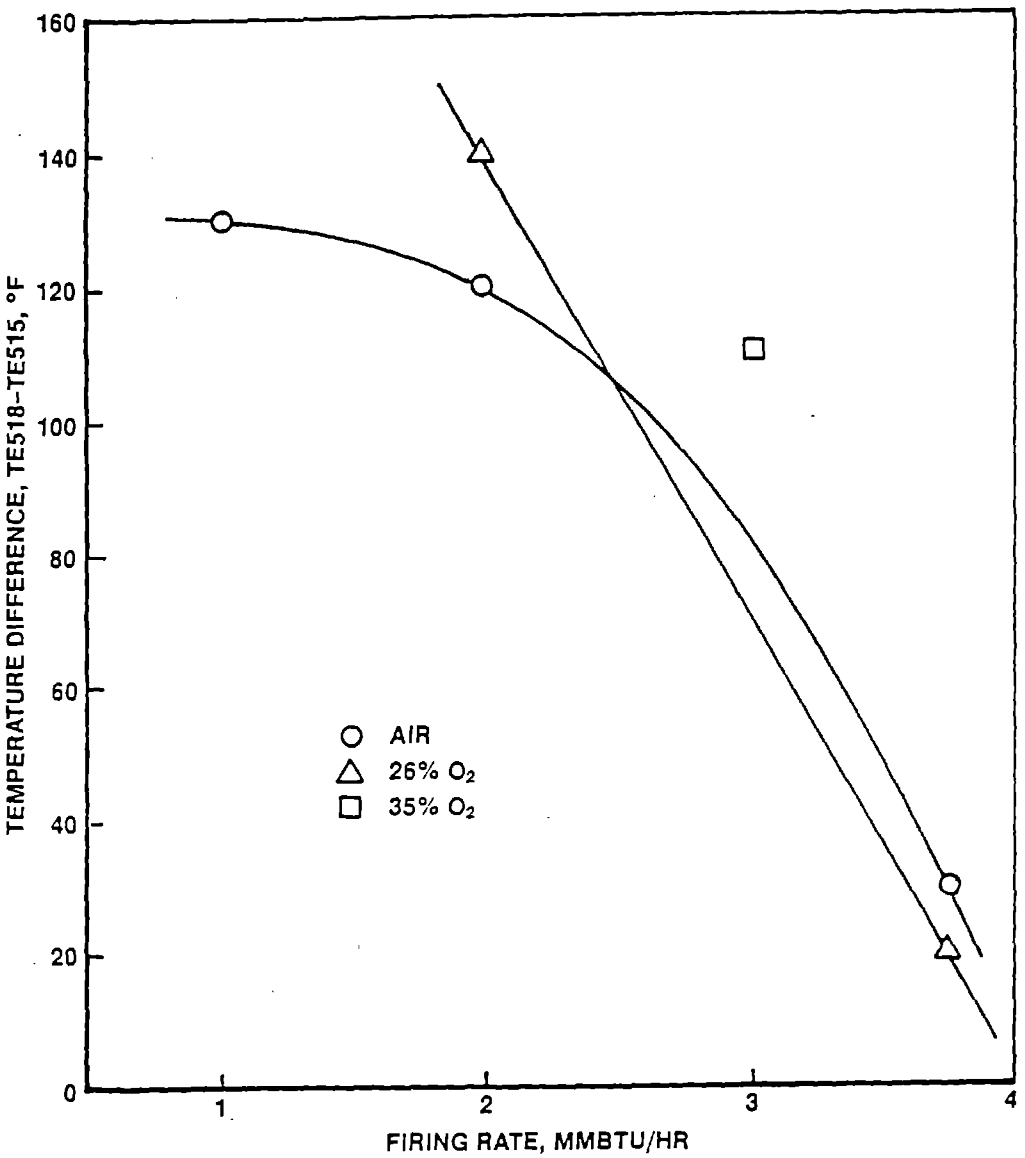
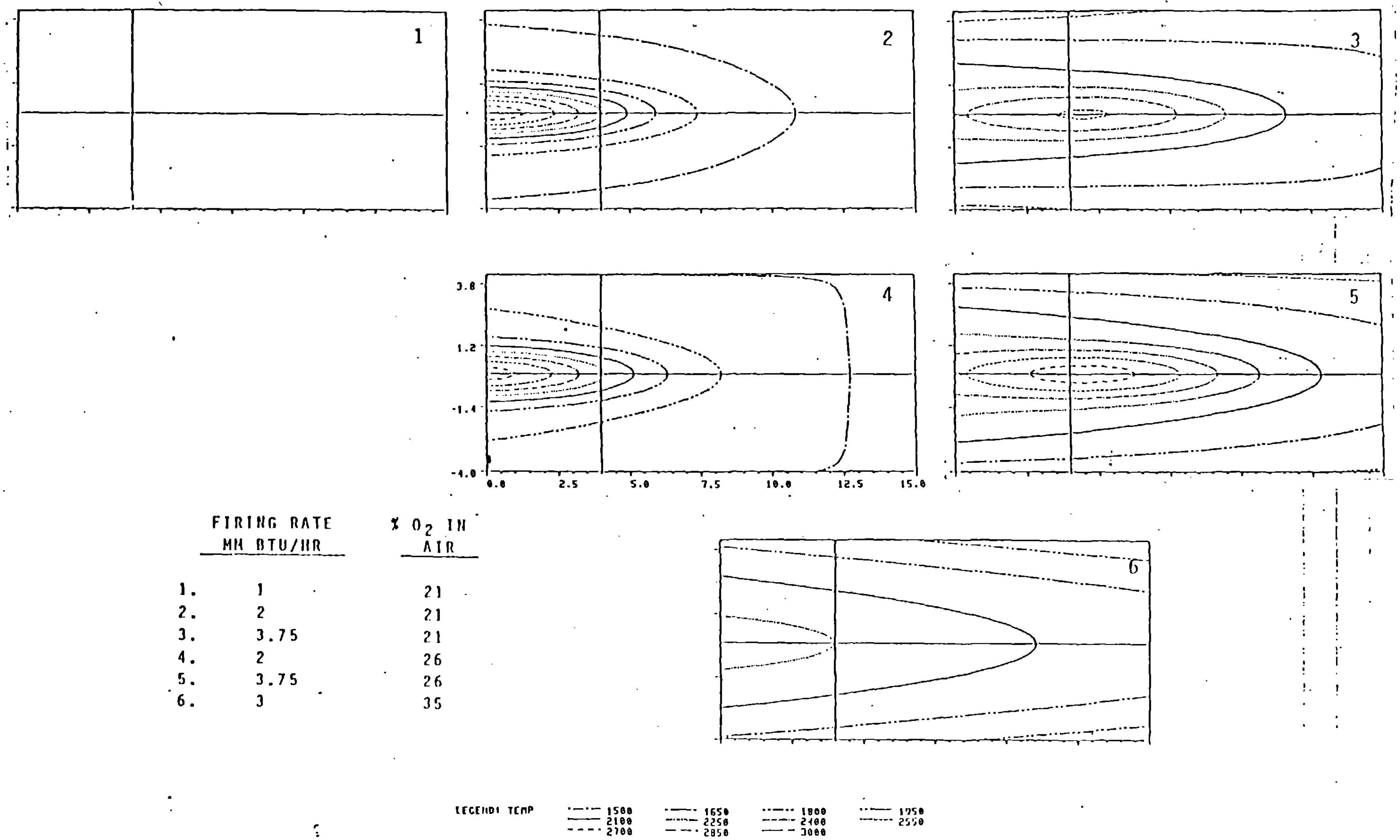


FIGURE 2: TEMPERATURE UNIFORMITY
NORTH AMERICAN 6514



NORTH AMERICAN BURNER 6514

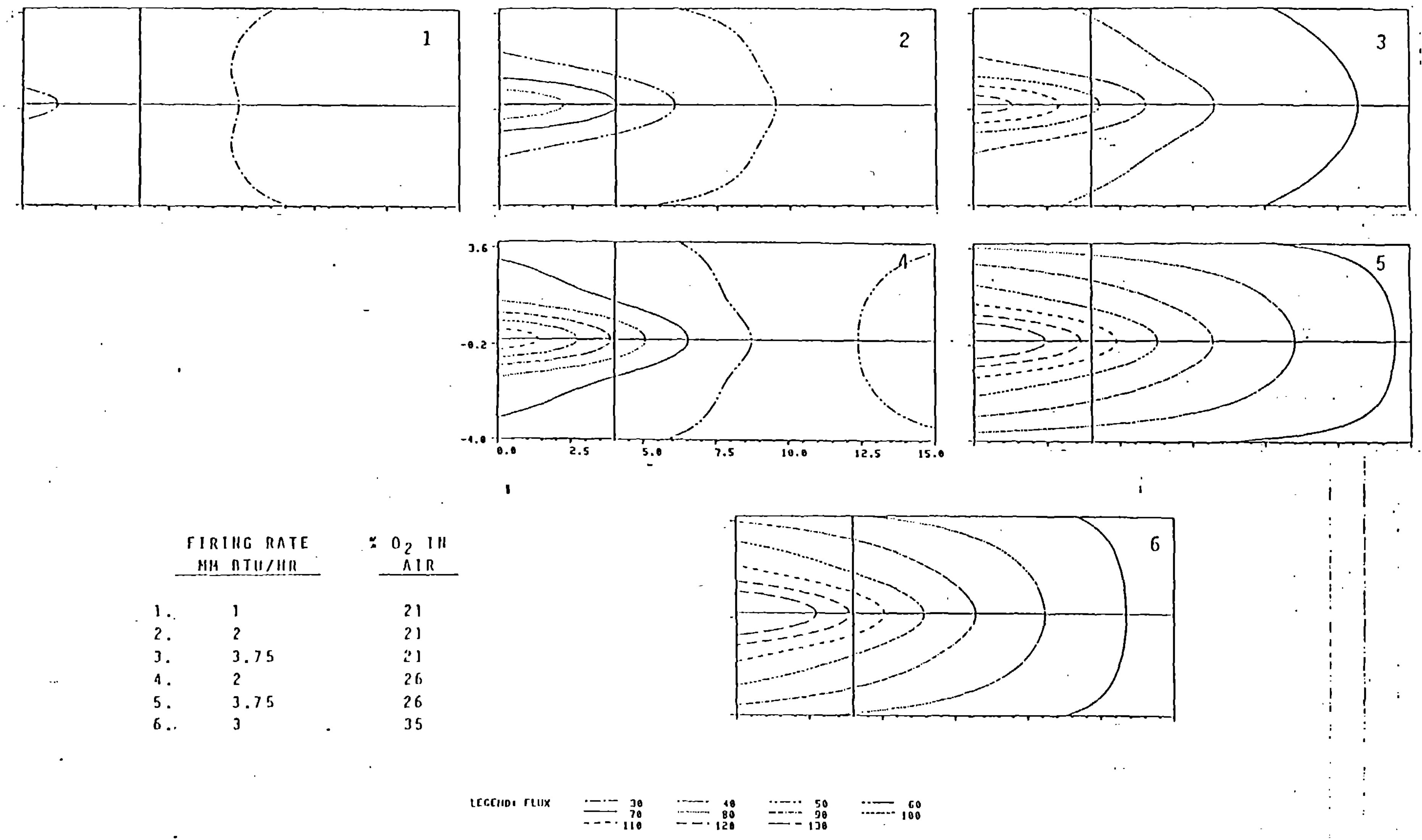
GAS TEMPERATURES BY SUCTION PYROMETER, DEG F



	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	1	21
2.	2	21
3.	3.75	21
4.	2	26
5.	3.75	26
6.	3	35

NORTH AMERICAN BURNER 6514

TOTAL HEAT FLUX BY HEAT FLUX METER, MBTU/FT2/HR



	FIRING RATE MM BTU/HR	% O_2 IN AIR
1.	1	21
2.	2	21
3.	3.75	21
4.	2	26
5.	3.75	26
6.	3	35

FIGURE 5: NO$_x$ EMISSIONS
NORTH AMERICAN 6514

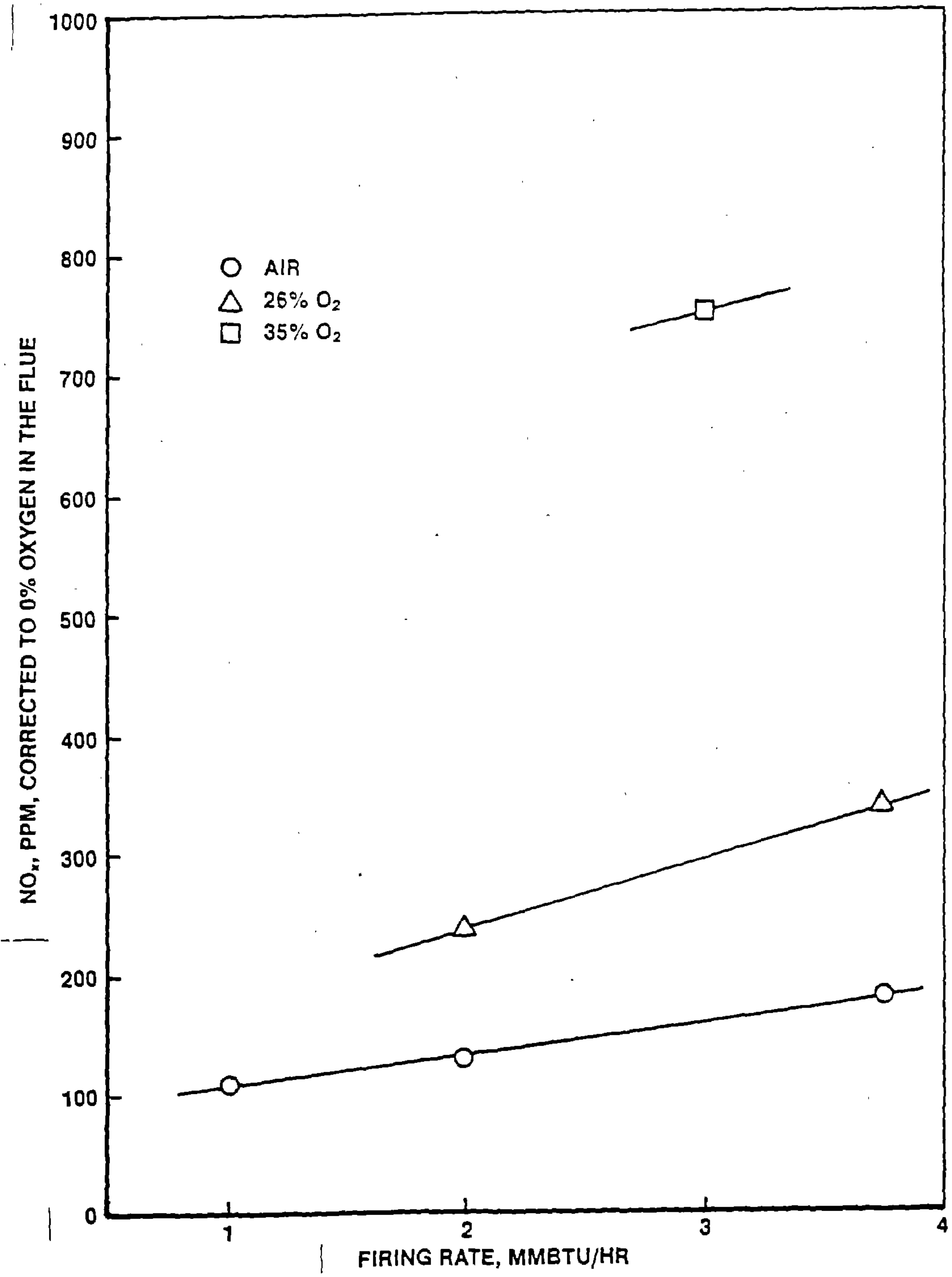


FIGURE 6: BURNER TEMPERATURE
NORTH AMERICAN 6514