CONF-960535--

*Alzeta Report No. 96-7061-203*

DOE/CE/40918--T1

**FINAL REPORT**

# ADVANCED RADIANT COMBUSTION SYSTEM

*Prepared by*

*Alzeta Corporation*
*Santa Clara, California*

MASTER

U.S. Department of Energy
Albuquerque Field Office
Albuquerque, New Mexico

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

September 1996

# ADVANCED RADIANT COMBUSTION SYSTEM

## FINAL REPORT

Prepared by

John D. Sullivan, Martin G. Carswell, and Forrest S. Long

Alzeta Corporation
2343 Calle del Mundo
Santa Clara, California 95054

Alzeta Report 96-7061-203

Prepared for

U.S. Department of Energy
Albuquerque Operations Office
P.O. Box 5400
Albuquerque, New Mexico 87185-5400

Contract DE-AC04-89CE40918

September 1996

## TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

## SECTION 1

## EXECUTIVE SUMMARY

Results of the Advanced Radiant Combustion System (ARCS) project are presented in this report. This work was performed by Alzeta Corporation as prime contractor under a contract to the U.S. Department of Energy Office of Industrial Technologies as part of a larger DOE program entitled Research Program for Advanced Combustion Systems. The goals of the Alzeta ARCS project were to:

- Improve the high temperature performance characteristics of porous surface ceramic fiber burners
- Develop an Advanced Radiant Combustion System (ARCS) that combines combustion controls with an advanced radiant burner
- Demonstrate the advanced burner and controls in an industrial application.

Prior to the start of this project, Alzeta had developed and commercialized a porous surface radiant burner, the Pyrocore™ burner. The product had been commercially available for approximately 5 years and had achieved commercial success in a number of applications ranging from small burners for commercial cooking equipment to large burners for low temperature industrial fluid heating applications. The burner was not recommended for use in applications with process temperatures above 1000°F, which prevented the burner from being used in intermediate to high temperature processes in the chemical and petroleum refining industries. The interest in increasing the maximum use temperature of the burner was motivated in part by a desire to expand the number of applications that could use the Pyrocore product, but also because many of the fluid sensitive heating applications of interest would benefit from the distributed flux characteristic of porous surface burners. Background information on porous surface radiant burners, and a discussion of advantages that would be provided by an improved product, are presented in Section 2.

The first goal of the ARCS project was to develop the improved Pyrocore product. This product, referred to as the Advanced Radiant Burner (ARB) in this report, was developed and is now being sold by Alzeta as Pyrocore HT™. The development of the ARB, from an initial materials investigation, through small scale laboratory life tests, and eventually to a prototype-scale test at Alzeta, is discussed in Section 3. As a result of this work, an improved product was developed. This product has increased the operating range of the porous surface burner and has had the additional benefit of increasing the life of the product in lower temperature applications. Applications for the ARB were identified that included thermal oxidizers for the chemical and semiconductor industries and process heater burners for steam methane reformers. The thermal oxidizer field test is discussed in Section 4. The steam-methane reformer field test is discussed in Appendix B.

As described in the opening paragraph, one of the goals of the ARCS project was to complete a commercial demonstration of the new technology. The end-use application selected for the demonstration, thermal oxidation of volatile organic compounds (VOCs) did not exist as an Alzeta product at the start of this project. However, Alzeta's entry into this growing market led to a need by Alzeta for the improved high temperature radiant burner. To increase the effectiveness of the thermal oxidation process, Alzeta developed the inward-fired, or adiabatic, radiant burner. This burner design has the unique advantage of allowing a premixed stream of fuel, air, and VOCs to be stably combusted at excess air levels of 80 to 100 percent at a gas temperature that approaches the adiabatic flame temperature of the mixture. This concept has now been demonstrated to provide very high destruction levels of VOCs, particularly of hard to destroy halogenated compounds. The results of VOC thermal destruction tests are described in greater detail in Section 4.

The main disadvantage of the adiabatic burner concept is that it requires that the burner operate in a more severe thermal environment. The ceramic fiber burner that was manufactured by Alzeta prior to the development of the Pyrocore HT product was demonstrated to have limited life in high temperature applications, and this limitation necessitated the development of the high temperature burner. This product, the Pyrocore HT has been demonstrated to provide the required performance for the adiabatic thermal oxidizer application.

An assessment of the market for the advanced radiant burner is provided in Section 5. Currently, the most successful high temperature use of the product is in thermal oxidizers. Alzeta market research indicated that oxidizers that incorporate the Pyrocore HT burner provide better thermal destruction of halogenated compounds than competing oxidizers, and this market niche has been targeted by Alzeta. The Alzeta product is sold by Alzeta directly to end users for the destruction of combined flow streams for a complete plant or building (known as "end-of-pipe" oxidizers), and is also incorporated into a point-of-use oxidizer of fluorinated compounds that is manufactured by a supplier of semiconductor equipment. Other successful industrial applications of the Pyrocore HT product include direct heating of drying drums for paper manufacturing, and use in small industrial boilers.

The marketing focus for this product in industrial applications has shifted to the use of the burner in new applications designed from the start to work with a radiant burner (such as the thermal oxidizer products). Retrofit applications do not receive full benefit from the radiant burner product, since most process heaters were designed to work with a conventional flame burner, and therefore were sized to match gas volume and gas-phase radiation to process requirements.

# SECTION 2

# TECHNICAL BACKGROUND AND PROJECT OBJECTIVES

The fundamentals of operation of porous surface radiant burners are described in Section 2.1. This is followed in Section 2.2 by a discussion of industrial applications that could benefit from the use of the advanced radiant burner. Project objectives specific to the development of the advanced radiant burner are presented in Section 2.3.

## 2.1 FUNDAMENTALS OF OPERATION

Radiant heating systems are used in applications where high intensity uniform energy transfer to a process or workpiece is required. The fundamental distinction between radiant and conventional flame burner systems is that a large fraction of radiant burner heat is transferred directly from the burner surface to the process as infrared thermal radiation, instead of by convection or conduction. Radiant flux from a solid surface increases proportionally with $T^4$, where T is the absolute temperature of the surface, while convective and conductive heat transfer mechanisms scale in a nearly linear manner. Because of this, radiant heat transfer becomes the dominant mode of energy transfer in most, if not all, industrial applications operating at temperatures above 1000°F. Porous surface burners provide an effective means of transferring radiant energy to the load due to the relatively high emissivity of the burner surface and the ability to shape the burner surface to conform to the heat transfer requirements of the load.

Industrial boilers and process heaters equipped with more traditional flame burners also transfer a substantial amount of energy by the radiant transfer mechanism. However, this energy must be transferred directly from the combustion products, which have a much lower emissivity than that of a solid surface. As a result, higher gas temperatures and larger furnace volumes (to increase gas path length and emissivity) are required to achieve an energy flux equivalent to that of the radiant burner. These heaters also rely heavily on refractory surface separate from the burner, such as refractory walls, to generate the required energy transfer. In addition, since radiant flux in these conventional systems is proportional to both the gas temperature and the gas path length, it is more difficult to selectively control heat transfer to the process.

Radiant burners are designed so that the combustion reactions occur on or in close proximity to a surface. This surface is heated to incandescence and the surface, not the combustion products, is the primary source of radiation. Furthermore, since up to 30% of the energy of the combustion reaction is radiated from the burner surface, peak gas temperatures are lower than in conventional flames. The effect of radiation from the burner surface on gas temperature is particularly significant if low $NO_x$ emissions are required, since thermal $NO_x$ formation increases with gas temperature.

Types of radiant burners used in moderate to high temperature industrial process can be classified into three groups: indirect fired burners, direct-fired impingement burners and direct-fired porous surface burners. The indirect fired and direct fired impingement burners have the following characteristics:

- **Indirect fired burners** - Typical designs place a conventional burner inside of a nonporous tube made from a ceramic material or high temperature metal alloy. The tube is heated internally by both the flame and the exhaust gas, transfers this energy through the tube wall by thermal conduction, and radiates energy from the outside tube wall to the load. Because the burner itself is not a source of radiation, flame temperatures are high resulting in high $NO_x$ emissions and limited life of the radiant tube. Due to material limitations, indirect fired burners are typically limited to sizes of several million Btu/hr or smaller.
- **Direct-Fired Impingement Burners** - A premixed flame impinges onto a solid refractory surface or quarl, heating the surface to incandescence. This type of burner requires a relatively high pressure drop through a flow limiting orifice to achieve proper flame shape and a high impingement velocity on the refractory quarl. At high throughputs, the flame can actually extend out from the burner surface, creating high temperature zones and limiting proximity of the burner to the load if overheating and flame impingement are to be avoided. Further, due to the large thermal mass of the quarl, it is not possible to respond quickly to changes in process conditions.

The third type of radiant burner, the **direct-fired porous surface burner**, overcomes the limitations of the burners described above and represents a method of simultaneously delivering high radiant heat flux, uniform energy transfer, and low gas phase temperatures. Figure 2-1 shows a schematic representation of this burner. In this system, premixed gaseous fuel and air flow through a porous media and combust in close proximity to the burner surface. The combustion reactions occur in intimate contact with this surface (typically within 0.5 inch), heating it to

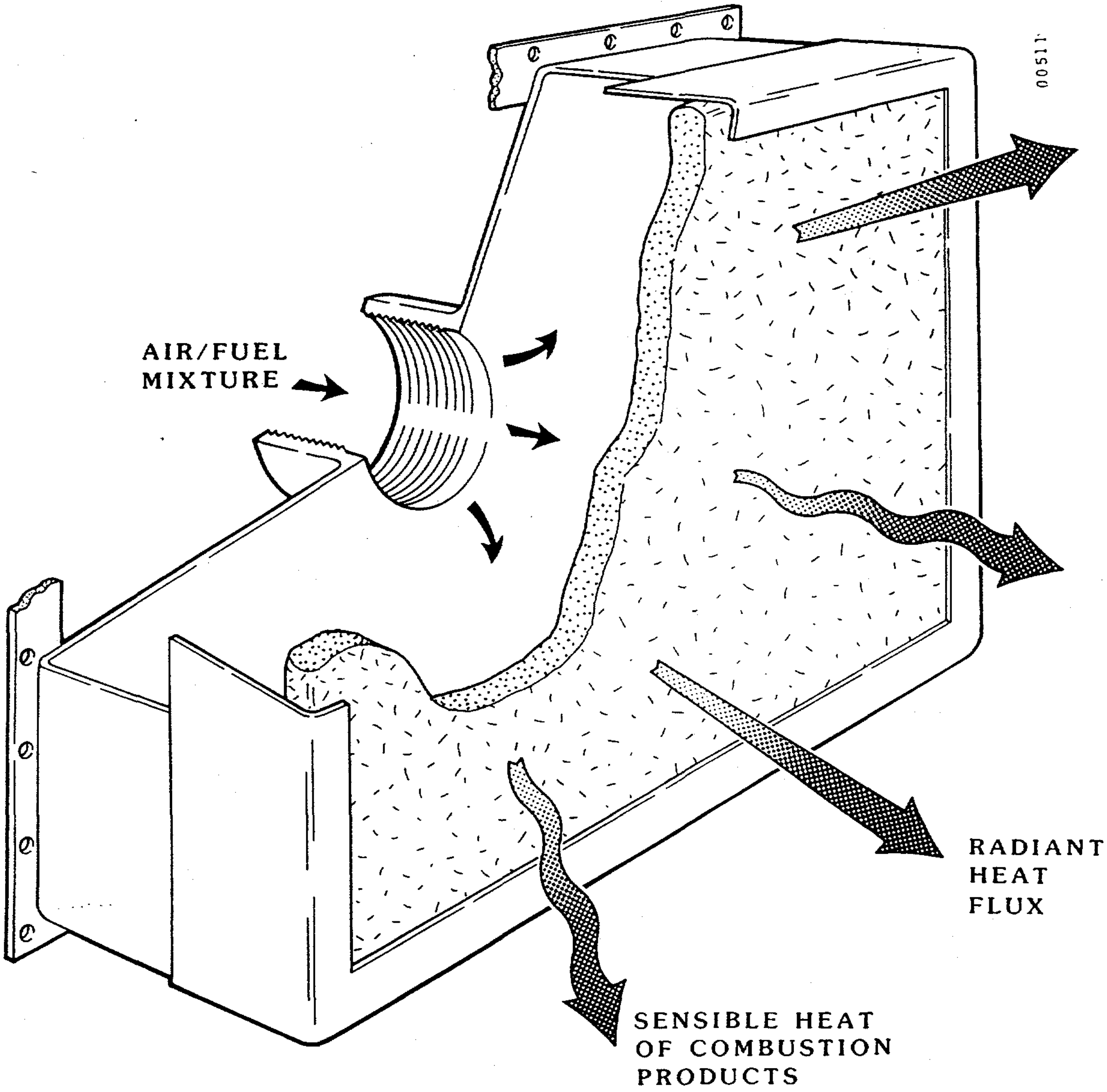


Figure 2-1. Radiant and Sensible Heat Flux from Porous Surface Radiant Burner

incandescence at 1500°F to 2100°F under normal operating conditions, with $NO_x$ emissions typically under 20-25 ppm. See Figure 2-2 for typical emissions data. Under normal operating conditions, the surface glows incandescently to release 15 to 30% of the heat of combustion as direct radiant energy.

Porous surface radiant burners require the use of clean gaseous fuels for proper operation, but, having met this restriction, almost any gaseous fuel can be used. While the most common gaseous fuel used by industry is natural gas, burners used in refineries must be able to burn other byproducts of the refinery process. The byproduct gases contain a mixture of combustible and non-combustible components. As an example, the gas burned in a typical steam-methane reformer is a mix of natural gas, hydrogen, carbon monoxide and carbon dioxide. Radiant burners manufactured by Alzeta have been operated on fuels ranging from propane (with a relatively high volumetric energy content) to waste gases with energy contents of 50 to 100 Btu per standard cubic foot. In refinery applications, Alzeta burners have burned process purge gases containing predominantly methane, but which included varying amounts of hydrogen and other gases. In laboratory demonstrations, successful operation has been demonstrated with vaporized methanol, qualifying the use of methanol as a backup fuel.

A more detailed view of the temperature and energy exchange features of a porous surface radiant burner can be seen in Figure 2-3. The temperature profile shows that the combustion reactions occur only at the very outer surface of the burner, with the peak gas temperature occurring above the burner surface. The interior of the porous material remains at the temperature of the incoming reactants, allowing stability over a wide range of operating conditions. Materials used for these types of burners are highly porous matrices of ceramic or high temperature metal fibers. Since the mixture flows uniformly through all parts of the matrix, combustion and, hence, radiant output are extremely uniform over the entire burner surface. In addition, the high porosity gives the burner a low thermal mass with the capability to respond quickly to rapidly changing process conditions. The burner surface can be shaped to meet process requirements.

Porous surface radiant burners are supplied by Alzeta and other burner manufacturers for a variety of industrial applications, including:

- Process heaters
- Low temperature drying
- Heat transfer fluid heaters/vaporizers
- Water and steam boilers

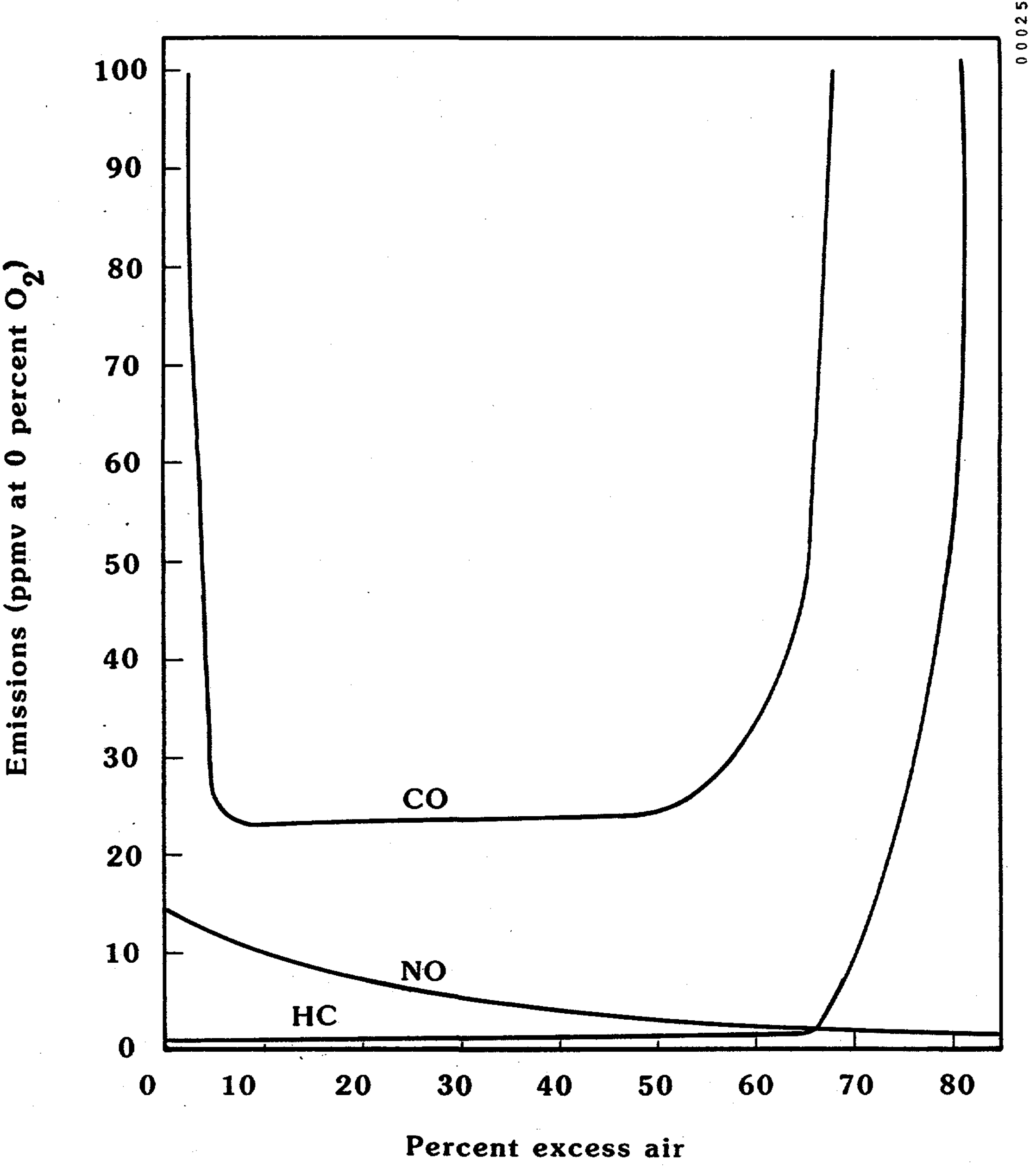


Figure 2-2. Porous Surface Burner Emissions Characteristics

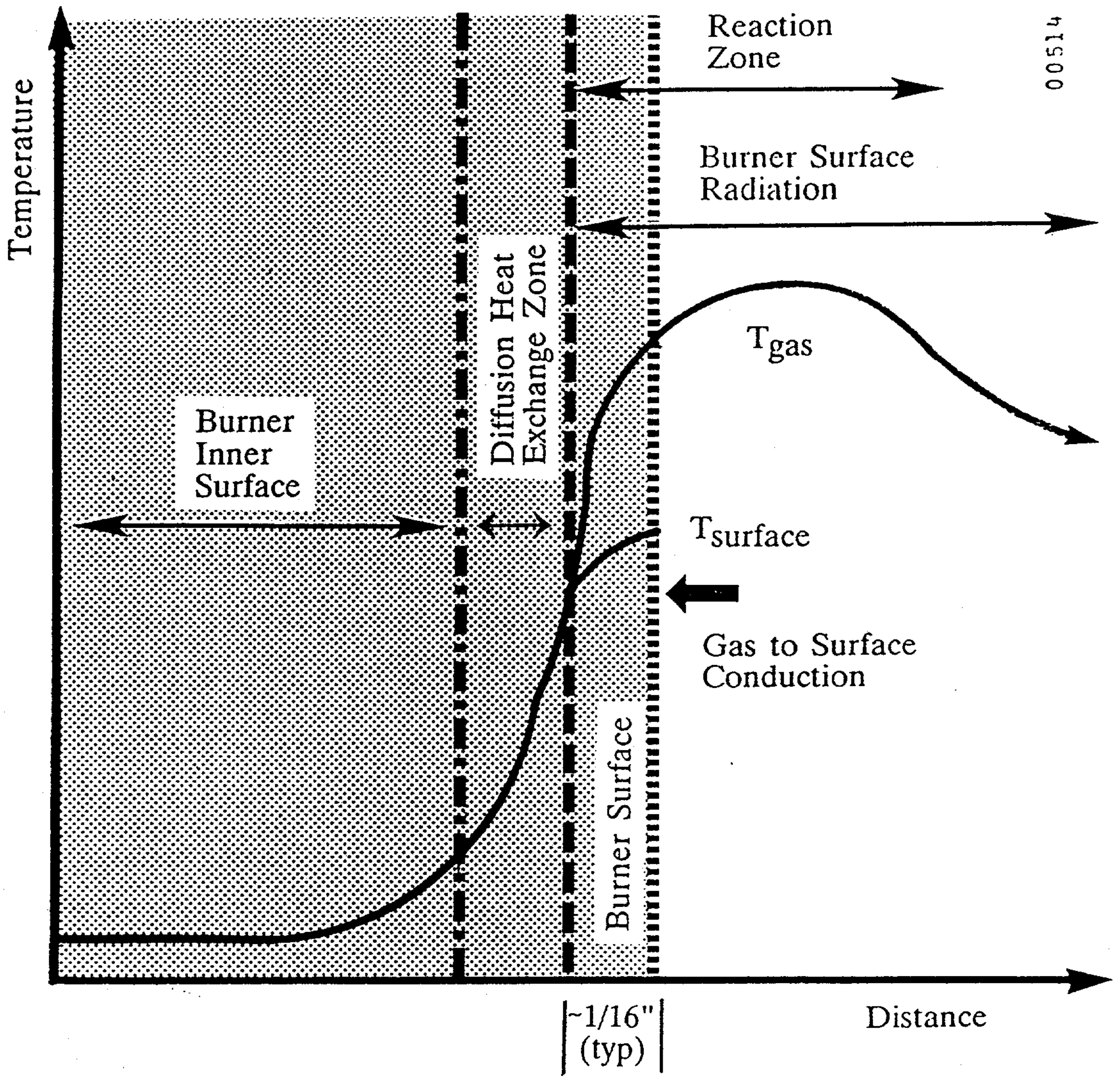


Figure 2-3. Temperature Profile and Energy Exchange Phenomena In Porous Radiant burners

Characteristics of porous radiant burners which make their use preferable in these applications are:

- Uniform, controllable, and compact radiant heating
- Stable and safe operation over a wide range of operating conditions
- Clean combustion – simultaneous low $NO_x$ and low CO emissions
- Scalability to various sizes (250 to 1)
- Low combustion noise
- Compact equipment design

A typical burner assembly is shown in Figure 2-4. It consists of multiple segments connected to make a single larger burner which is connected to a fuel/air supply and ignited by a pilot. These burner assemblies are designed to various size specifications. Burner inputs range from 2 to 15 MMBtu/hr, with lengths up to 20 feet and heights of up to 40 inches.

Porous surface burners are most commonly used in lower temperature industrial applications, and this was particularly true at the start of this project. Higher process or load temperatures lead to an increase in the required operating temperature of the burner surface, and this, in turn, has an adverse effect on the life of typical materials of burner construction. Increasing the temperature handling capability of the porous surface burner through the use of better materials increases the number of industrial applications that can benefit from this product. The primary goal of the ARCS project was to improve the performance of porous surface burners at high temperature. A more detailed description of the objectives of the project are provided in the following section.

## 2.2 INDUSTRIAL APPLICATIONS TARGETED BY THE HIGH TEMPERATURE RADIANT BURNER

Advanced radiant burners can be used in a broad range of industries where processes require uniform high heat flux and precise temperature control of the process or working fluid. Applications that could benefit significantly from the use of radiant burners include:

- Thermal oxidation of volatile organic compounds (VOCs) or other gaseous wastes
- Drum heating or direct drying of paper or textiles

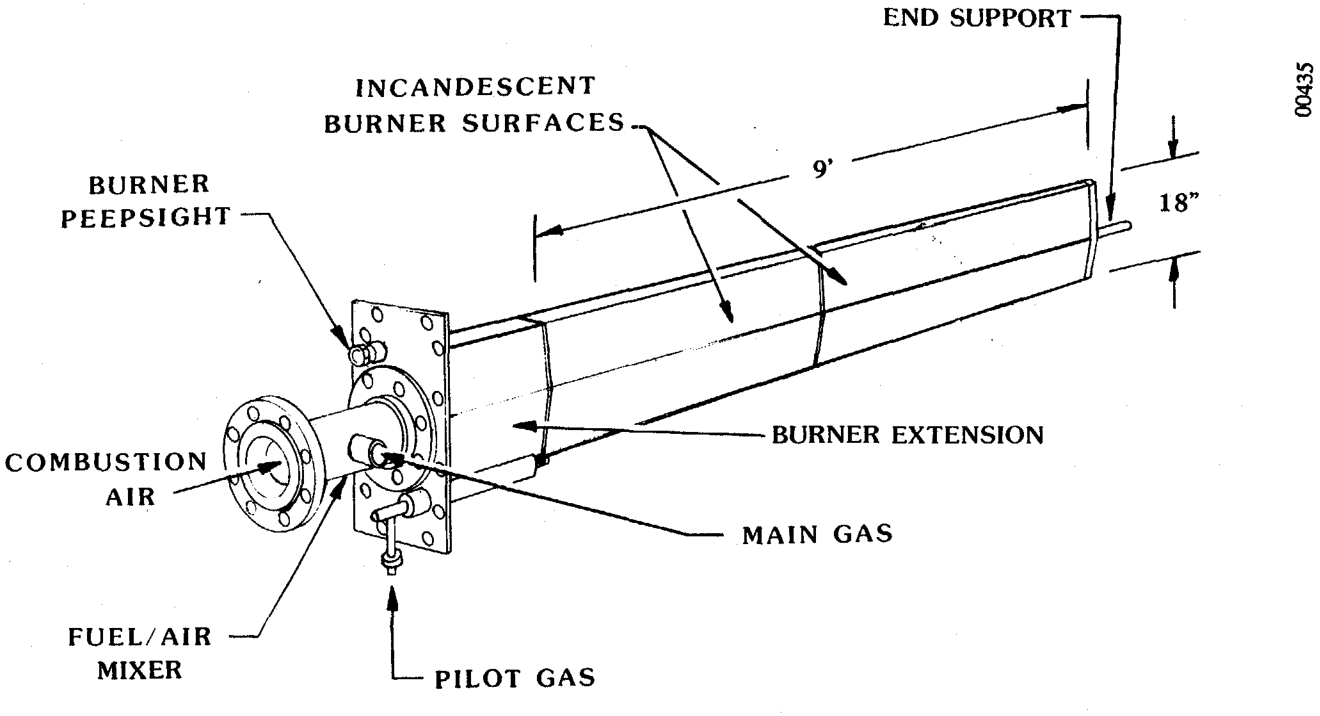


Figure 2-4. Diamond Shape Radiant Burner Assembly

- Refinery and chemical processes, where either a fragile fluid (such as petroleum, heat transfer oil, glycol, etc.) or a catalyst bed is to be heated
- Metals processing applications where loads are heated directly

The operating characteristics of radiant burners that would be used in the thermal oxidizer and refinery applications are described below.

## Thermal Oxidation of Volatile Organic Compounds

The release of volatile organic compounds (VOCs) into the environment comes from a wide variety of stationary and mobile sources. The stationary sources can be broadly categorized as either industrial fumes (such as printing, polymer production, and metal coating processes) or soil remediation (largely from leaking underground storage tanks.) EPA studies estimate over 5 million tons of VOCs were released from stationary sources in nonattainment cities in 1985. VOCs have been identified as a public health hazard in two ways:

- Most VOCs photochemically react with $NO_x$ to form ozone, a constituent of smog.
- Some VOCs (such as benzene and vinyl chloride) are highly toxic by themselves.

To reduce the amount of VOCs released into the atmosphere, soil, and ground water, government regulations have been implemented on the federal, state, and local level. The primary regulatory agencies include: the federal Environmental Protection Agency, state agencies such as the California Department of Health Services (DHS), and local management districts for air and water quality control. Regulations from these agencies are the main market drivers for promoting the use of VOC abatement equipment, and have spawned a VOC treatment industry comprised of environmental clean up firms, equipment manufacturers, and consultants.

Methods to control VOC emissions include emissions reduction, resource recovery, and incineration. For industrial VOC sources, the first two options can be the most cost effective, particularly when the value of the VOC is high. For soil remediation treatment, small mobile package fume incinerators with vacuum extraction systems are used frequently for light hydrocarbons and solvent spills.

Because the VOC treatment market is driven by government regulations and permit rules, a fume incinerator that provides high destruction and removal efficiency (DRE) of the VOC and low emissions of $NO_x$ and CO is seen as a key market need, particularly in soil treatment. This perception led to the development of a low $NO_x$, high DRE radiant thermal oxidizer.

Thermal oxidation of VOCs is a fairly new field. The Alzeta approach to thermal oxidation is a new process within this field. Inward-fired VOC thermal oxidation technology is an outgrowth of Alzeta Pyrocore technology. In concept, the inward-fired design is an "inside-out" porous surface radiant burner in which the ceramic fiber burner surface is cast into the interior of a cylinder and fired inwardly so that the burner surface radiates to itself. This offers the benefit of stable operation with very high levels of excess air (over 100%) which reduces gas phase temperatures and inhibits the formation of thermal and prompt $NO_x$. Laboratory experiments have demonstrated that exceptionally high levels of Destruction Removal Efficiency (DRE) in the range of 99.99%+ can be routinely achieved simultaneously with $NO_x$ emissions well below 10 ppm (referenced to 3% $O_2$) and low emissions of carbon monoxide and unburned hydrocarbons.

In the inward-fired burner, the fuel air mixture is fed to the burner surface through an annular supply plenum that surrounds the burner. As a consequence, there is minimal radiant heat loss to the surroundings and no need for external insulation. The absence of external insulation means that heavy refractory and associated supporting structure are eliminated, resulting in a package having light weight and lower cost when compared to outward-fired Pyrocore burners used in the same applications. Thermal oxidation systems have been assembled using both outward and inward-fired arrangements, and the inward-fired units have proven to have lower cost, better customer acceptance, and broader applications than outward fired units requiring refractory lined combustion chambers. Additionally, inward-fired thermal destruction units have shown that they are capable of nearly instantaneous "on-off" operation because of the absence of dense refractory and large thermal masses. Consequently the technology is uniquely well suited to batch operations in which there is little warning (seconds) of the release of VOCs, and the thermal destruction unit must be operational quickly to destroy the first VOCs that arrive at its inlet.

Variations of the thermal oxidizer process, using preheat, VOC bypass, and adsorption for VOC concentration are described in Reference 1. In all configurations, however, the radiant inward-fired burner is the key component providing complete thermal destruction of the VOCs with low $NO_x$ and CO emissions.

The burner specification for a typical adiabatic thermal oxidizer would have the following characteristics:

| | |
|---|---|
| Maximum burner surface firing rate (fuel input) | 40 to 80 MBtu/hr-ft$^2$ at up to 100% excess air |
| Burner Surface Temperature | 1600-1900°F |
| Maximum Flux to Process | NA - adiabatic operation |
| Burner Element Size | Up to 6-30 in. ID x 2 to 5 ft long typical |
| $NO_x$ emissions | Less than 10 ppm corrected to 3% $O_2$ |

**Refinery and Chemical Industry Applications**

Many intermediate to high temperature refinery and chemical manufacturing processes involve the flow of reactants over a catalyst bed, with a good example of this type of process being steam-methane reforming. Additionally, temperature sensitive heating oils are frequently used as a heat transfer fluid in the 400°F to 800°F temperature range. The performance characteristics of a radiant burner operating in a steam-methane reformer are presented as a "typical" refinery or chemical industry application for the following reasons:

- Steam-methane reforming was originally targeted as the demonstration application for the advanced radiant burner, and as a result of this, many of the performance goals of the advanced radiant burner are consistent with the operating requirements of steam-methane reformers
- While refinery and chemical industry processes span a wide range of operating temperatures, steam methane reforming is a difficult, yet representative, application. The process involves flow of reactants and products over a catalyst bed at temperatures of 1500-1650°F.
- Hydrogen production by the steam-methane reforming process represents one of the largest energy users in the refinery and chemical manufacturing industries.

The most widely used process for hydrogen production by a substantial margin is steam reforming of hydrocarbons over a nickel-based catalyst. The conversion to hydrogen is carried out by reacting the hydrocarbon with steam at temperatures of 1500°F-1650°F and at pressures of several hundred psig. The major process element is the reformer furnace, typically a refractory-lined box in which high temperature alloy tubes are suspended. These tubes are typically 4 to 6 inches in diameter and 30 to 40 feet long. They are suspended vertically in the furnace, with burners located at the top, bottom, or side of the furnace firing in a manner that provides primarily radiant heat transfer while avoiding flame impingement on the process tube walls.

Preheated steam is mixed with natural gas (or other hydrocarbon feedstock) in the ratio of 3 or 4 to 1 and passed down through the process tubes, where the natural gas and steam are converted to hydrogen and CO, and eventually to additional hydrogen and $CO_2$. The hydrogen is then separated from the rest of the process stream. The hydrogen forming reactions are highly endothermic and temperature dependent.

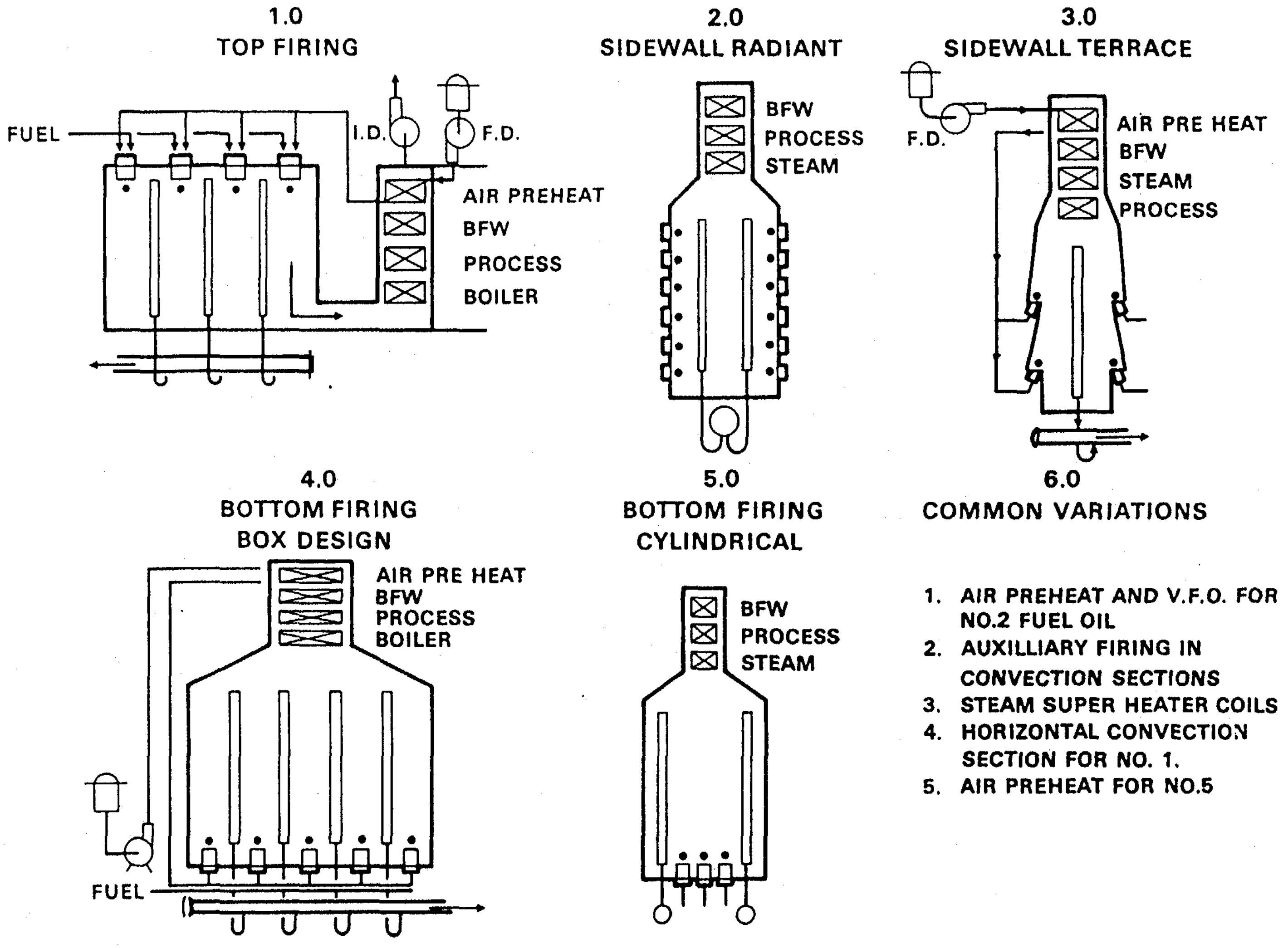
Typical reformer designs are shown schematically in Figure 2-5. The reaction tubes are mounted vertically to minimize mechanical support requirements and to simplify installation and replacement. Wall-mounted direct-fired burners, as well as roof- and floor-mounted flame burners are presented in the schematics. Burners in modern installations use combustion air fans, although some older systems utilize natural draft. The burners are usually fully modulating over a turndown range of about 10:1, but little control exists for varying heat flux along the length of the process tubes. Minor variations of these designs are used for hydrogen plants ranging in size from 0.25 to 500 million standard cubic feet of hydrogen per day (scfd).

A typical modern reformer heater that includes heat recovery equipment can achieve an overall thermal efficiency of 90 to 93% based on fuel lower heating value (LHV). Overall energy consumption for hydrogen production is roughly 400 Btu per standard cubic foot of hydrogen product, divided approximately equally between fuel and feedstock (Reference 2). Typical burner capacities therefore range from 2 MMBtu/hr to 4000 MMBtu/hr, with the larger systems requiring many burners.

As is the case in most combustion applications, the chemical processes used in refineries and in chemical manufacturing are fairly well established. Therefore, heater designs have not changed significantly over the past several decades, with most changes being incremental improvements brought about by improved materials. Therefore, it is critical to the success of the advanced radiant burner that these new burner designs do not require significant heater redesign.

The burner specification for this application would be approximately as follows:

| | |
|---|---|
| Maximum burner surface firing rate (fuel input) | 120 to 150 MBtu/hr-ft$^2$ |
| Burner Surface Temperature | 2000-2100°F |
| Maximum Flux to Process<br>(Includes surface plus gas-phase radiation) | 25-30 MBtu/hr-ft$^2$ |
| Burner Element Size | 2-3 ft dia x 15 ft long typical |
| $NO_x$ emissions | Less than 30 ppm at 3% $O_2$ |
| Burner Life | 3 years minimum |



1. AIR PREHEAT AND V.F.O. FOR NO.2 FUEL OIL
2. AUXILLIARY FIRING IN CONVECTION SECTIONS
3. STEAM SUPER HEATER COILS
4. HORIZONTAL CONVECTION SECTION FOR NO. 1.
5. AIR PREHEAT FOR NO.5

Figure 2-5. Typical Hydrogen Steam Reformer Designs

## 2.3 PROJECT OBJECTIVES

The burner improvement goals of this project were as follows:

- Increase the maximum use temperature of porous surface radiant burners from the typical 1800°F number at the start of this project to 2100°F or higher, with no decrease in burner life
- Increase the maximum load temperature of the burner from the typical 1000°F number at the start of this project to 1600°F-1800°F, again with no decrease in burner life
- Increase the operating life of the burner when operated at 1800°F burner surface temperature and 1000°F or lower load temperatures
- Maintain $NO_x$ and CO emissions levels at less than 30 ppm when operating at 10 to 20% excess combustion air
- Achieve these goals while maintaining the current benefits of: uniform radiant heat transfer with no visible flame, radiant surfaces that can be shaped to process load requirements, and localized control of individual burner elements
- Achieve these burner improvement goals with acceptable cost impact, with a reasonable target at the start of the project being a cost increase of no more than 100%.

Note that increasing the maximum surface temperature of the burner is most directly applicable to the process heater applications encountered in the refinery and chemical industry applications. The inward-fired thermal oxidizer application benefits more from the increased stability of the burner when operated in the presence of a high temperature thermal load (since in the inward-fired configuration the load is the burner surface). New applications such as drum heating for paper drying benefit from the improved life of the advanced burner when operated at relatively low burner surface and load temperatures.

# SECTION 3

# ADVANCED RADIANT BURNER PRODUCT DEVELOPMENT

The performance characteristics of the Alzeta porous surface radiant burner at the start of this project, and the product improvement goals of this project, are discussed in Section 3.1. Approaches to meeting the project objectives are also discussed. The results of the development effort are presented in Section 3.2. Burner performance tests with a low-Btu "purge gas" fuel are discussed in Section 3.3.

## 3.1 PRODUCT IMPROVEMENT APPROACH

At the start of this project, the Alzeta Pyrocore radiant burner had the following: performance specifications:

| | |
|---|---|
| Surface heat release rate | 120 MBtu/hr-ft$^2$ |
| Maximum load temperature | 1000°F |
| Preheat temperature | 400°F |
| Typical excess air | 15-25% |
| Fuel | Typically natural gas, any gaseous fuel |

Within these guidelines, burner life was known to be a strong function of burner surface temperature, with burner surface temperature being a function of variables including surface heat release rate, load temperature, preheat temperature, excess air, and fuel composition. So while burner surface temperature may be the single most critical operating parameter affecting burner life, burner surface temperature is so application specific as to make it nearly impossible to make general statements concerning projected burner life. Within this limitation, it was believed that in a typical application with a burner surface temperature of about 1800°F, burner life would be on the order of 3 years of continuous service.

The goal of the advanced radiant burner development was to maintain or improve upon the performance specifications of the existing product (in existing applications), while increasing the life of the product at high temperature. Assuming that the standard product would operate for 3 years at a surface temperature of 1800°F, the goal was to develop an improved product that would operate for 3 years at a surface temperature of 2100°F or higher. This higher surface temperature would allow the burner to be used in applications with maximum load temperatures of 1600°F-1800°F (as compared to the previous maximum of about 1000°F).

The product improvement approach used in this project was as follows:

- Assume that the current manufacturing approach (vacuum casting from a slurry of burner constituents) provided the best method of fabricating relatively low cost porous surface burners, and therefore would be used in manufacturing the advanced radiant burner
- Similarly, the current approach of using fine fibers in a highly porous mat provides the best combination of high radiant output, low heat transfer back through the pad, and resistance to thermal shock, and therefore primarily fibrous materials (and some fiber coatings) would be investigated. Fibrous materials with oxidation resistance at high temperature and high emissivity provide the best performance. Burner performance improvements would most likely come from the incorporation of materials with these properties into the burner

Reviewing these steps, it was felt from the start that the burner improvement project was primarily a materials effort. Therefore, most of the technical work performed during Phase I and the first task of Phase II involved a systematic investigation of different burner materials and a selection of the most promising materials and burner formulations for more extensive burner evaluation. The material selection and evaluation process is summarized in the following section and presented in detail as Appendix A.

## 3.2 PRODUCT DEVELOPMENT SUMMARY

The primary steps in the burner development task were a first-cut screening of a large number of fibers and additives, a more rigorous statistical test program to optimize the new burner formulation, and a long duration test of a 5 ft' burner at simulated reference conditions. The goal of this work was to increase burner lifetime under current normal operating conditions and to increase the maximum use temperature of the burner. Alzeta's efforts focused on two areas, increasing the emissivity of the burner through additives, and utilizing fibrous materials with a higher maximum use temperature in burner construction.

Burner emissivity increases were achieved through the use of several different material additives and surface treatments. These increases had the dual effect of raising the radiant energy output and lowering the burner surface temperature required to achieve this output, according to the gray body radiation mechanisms described in Appendix A. Some of these materials produced significant gains in emissivity but only at the expense of decreased life of the burners, due to the destruction of the emissivity agent in the combustion environment. The only treatment that appeared to provide increased emissivity and equivalent or increased life of the burner was the addition of the HT fibers. This formulation became the primary target of the continued Alzeta statistical investigation.

Increasing the temperature rating of the structural fibers of the burner was found to add little value to the product. The inclusion of high temperature fibers resulted in increased surface temperatures and subsequently decreased lifetime due to increased oxidative destruction rates. A few of these fiber types were investigated as additives in the later studies

Based on the first-cut screening, a more rigorous statistical analysis was conducted on the best performing fibers, additives, and surface treatments. The various burner formulations were studied according to a standard Analysis of Variance (ANOVA) statistical method. This allowed direct comparison between the different formulations, and further, an optimization of the burners' performance. The testing focused on the HT fibers (the most promising high temperature fibers) and one emissivity agent, testing their effect on burners at different concentrations and in different sizes. Many different mixtures of fibers, emissivity agents, and treatments were examined to determine the optimally performing combination. In each round of testing, the effect of the various components could be examined and the best performing combination would be used as the basis for the next round.

The optimized result of the analysis was the Alzeta Pyrocore HT™ burner formulation. This formula was then tested at a larger scale by Alzeta, for further confirmation of the small scale results, before use in the host-site and other commercial products. The HT formulation was found to significantly enhance both the emissivity and the lifetime of the burner. Burners were observed to have a near doubling of their usable life compared to standard formulation burners fired under the same conditions. The enhanced burners also exhibited reduced $NO_x$ emissions, even in the elevated temperature environments which are the target applications for the HT burner. This benefit is believed to result from the reduced operating temperature of the burner, relative to the standard Pyrocore™, even when operating at the same input energy, excess air, and furnace temperature conditions, due to enhanced emissivity. The Pyrocore HT™ burner was therefore used in the field demonstration.

## 3.3 PURGE GAS TESTS

The ARCS host site reformer operated with natural gas as fuel, and tests conducted at Alzeta to develop the high temperature burner also used natural gas as fuel. Most new reformers, and refinery process heaters in general, burn refinery gas which can include hydrogen and other gases in the fuel mixture. The effect of fuel composition on the performance of a premixed burner should not be overlooked, and was investigated as part of this project.

Subscale testing was done to evaluate the performance of the ARCS burner on low Btu purge gas, a mixture of natural gas and reformer process off-gases. Based on information provided by Air Products, a typical purge gas contains approximately 22% natural gas, 35% hydrogen, 35% carbon dioxide and 8% carbon monoxide by volume. A gas with this composition has a gross energy content of approximately 360 Btu/ft$^3$, slightly more than one-third that of natural gas. Despite this low Btu content, it was believed that the presence of hydrogen in purge gas could pose difficulties for radiant surface combustors, primarily because of hydrogen's higher flame speed ( 9.3 ft/s in air vs. 1 ft/s for natural gas and 1.7 ft/s for CO ). At elevated firing rates and sink temperatures, the presence of hydrogen in the fuel might create an increased potential for burner flashback.

To investigate the effect of purge gas operation on burner performance, a 20 MBtu/hr burner was operated over a range of surface firing rates, combustion air preheats, and excess air levels with both natural gas fuel and purge gas. The tests were conducted in a test fixture that allowed control over the sink temperature. A test gas which contained 23% natural gas, 39% $H_2$ and 38% $CO_2$ was used to simulate the reformer purge gas. It was decided not to include CO in the test gas because of cost and safety concerns and because of its negligible contribution to the purge gas heat input. At each operating point, the following measurements were made:

- Burner surface temperature
- Sink surface temperature
- Flue gas exit temperature
- Flue gas unburned hydrocarbon (UHC), CO, and $NO_x$ emissions

## Flue Gas $CO_2$ and $O_2$ Concentrations

Burner surface temperature measurements were made with a two-color pyrometer directed at the burner surface through a 1 inch sight port installed in the heat sink. Sink temperatures were measured with type K thermocouples attached circumferentially on the sink surface. Flue gas temperature measurements were made with a shielded/aspirated thermocouple which also served as an emission probe support.

The burner was tested initially on natural gas at nominal surface firing rates of 100 and 150 Mbtu/hr-ft$^2$, combustion air preheats of 250°F and 450°F and excess air levels of 15 and 30 percent. Nominal sink temperatures were on the order of 1500°F at the low fire condition and 1700°F at the high fire condition. These tests were then repeated using the purge gas at the same operating conditions. Tests performed at the low fire condition were done at low and high sink temperature conditions of approximately 750°F and 1500°F. High fire purge gas tests were conducted at low and high sink temperature conditions of 1000°F and 1700°F.

The results of the purge gas testing indicated that the use of purge gas does not adversely affect the burner in terms of its potential for flashback or in terms of its radiant output and emissions performance. At similar operating conditions, the burner performed as well or better on purge gas than on natural gas fuel. This determination was made based on the following:

- During testing, there was no evidence of burner flashback or any indication that a flashback condition was imminent. This included several episodes where the flow of $CO_2$ to the purge gas mixture was momentarily interrupted, sending burner surface temperatures well above 2400°F. Therefore, the safe operating envelope of the burner was determined to not be reduced by the use of purge gas.
- Emissions of $NO_x$ and CO were observed to be lower with purge gas than had been observed in a similar environment with natural gas as fuel.
- Energy transferred by the burner to the test apparatus (an indication of burner and combustion system thermal efficiency) was calculated based on flue gas temperature and composition and was determined to be similar for the two gas compositions

The results of the purge gas testing are summarized in Figures 3-1 through 3-6. Figure 3-1 compares the measured combustion efficiency obtained using natural and purge gas as a function of excess air for the 250°F combustion air preheat case. Inspection of the figure shows that efficiency is a stronger function of sink temperature and surface firing rate than fuel composition. The 100 and 150 MBtu/hr-ft$^2$ low sink temperature purge gas tests had calculated efficiencies near 50 percent. Purge gas tests conducted at elevated sink temperatures produced efficiency results below 45 percent. Figure 3-1 also shows little difference between efficiency values for natural gas and purge gas tests conducted at comparable surface firing rates. Figure 3-2 shows the same data for tests conducted using 500°F preheated combustion air. A comparison of Figures 3-1 and 3-2 shows that increased combustion air preheat had little effect on the combustion efficiency. Heat input for the efficiency calculation was based only on energy content of the fuel, and did not include the effect of combustion air preheat on the enthalpy of the premixed fuel and air.

Figures 3-3 and 3-4 compare burner surface temperature data for the natural and purge gas tests conducted with 250°F and 500°F preheat, respectively. Figure 3-3 shows that natural gas produced slightly higher burner surface temperatures than purge gas at comparable sink temperatures and surface firing rates. Thirty-eight percent of the purge gas is $CO_2$, which remains basically inert during the combustion process and acts to further dilute the air/fuel mixture and reduce the flame temperature. Lower purge gas test sink temperatures resulted in corresponding reductions in burner surface temperature. Comparison of Figures 3-3 and 3-4, which presents the same data for the 500°F preheat case, shows near identical results. The only change related to the increase in preheat temperature was 50°F-100°F increase in burner temperature.

The lower burner surface temperatures obtained using purge gas resulted in $NO_x$ emissions that were significantly lower than those measured using natural gas fuel. Figures 3-5 and 3-6 show $NO_x$ emissions vs. excess air for the 250°F and 500°F preheat tests. In both figures, the corrected purge gas $NO_x$ emissions at each test point are found to fall below 10 ppm. Inspection of the figures shows that these values are typically one-half of the emissions produced at comparable firing rates and excess air levels when using natural gas. As in the case of the combustion efficiency and burner surface temperature results, there appears to be little effect associated with increased combustion air preheat.

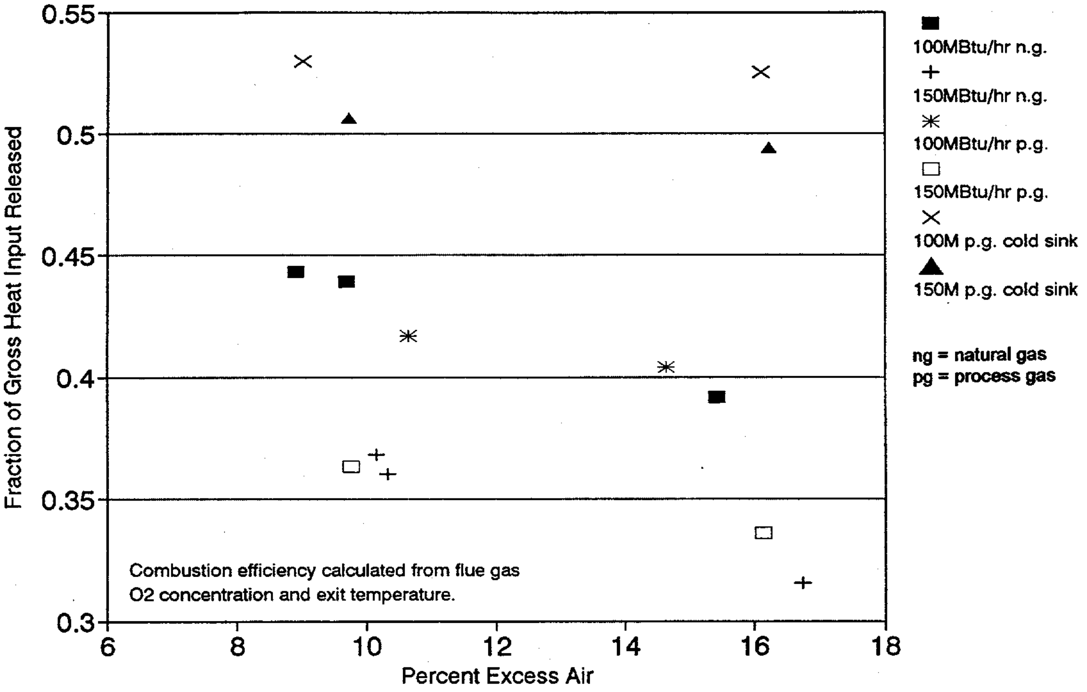


Figure 3-1. Combustion Efficiency as a Function of Excess Air and Fuel Composition with 250°F Preheat

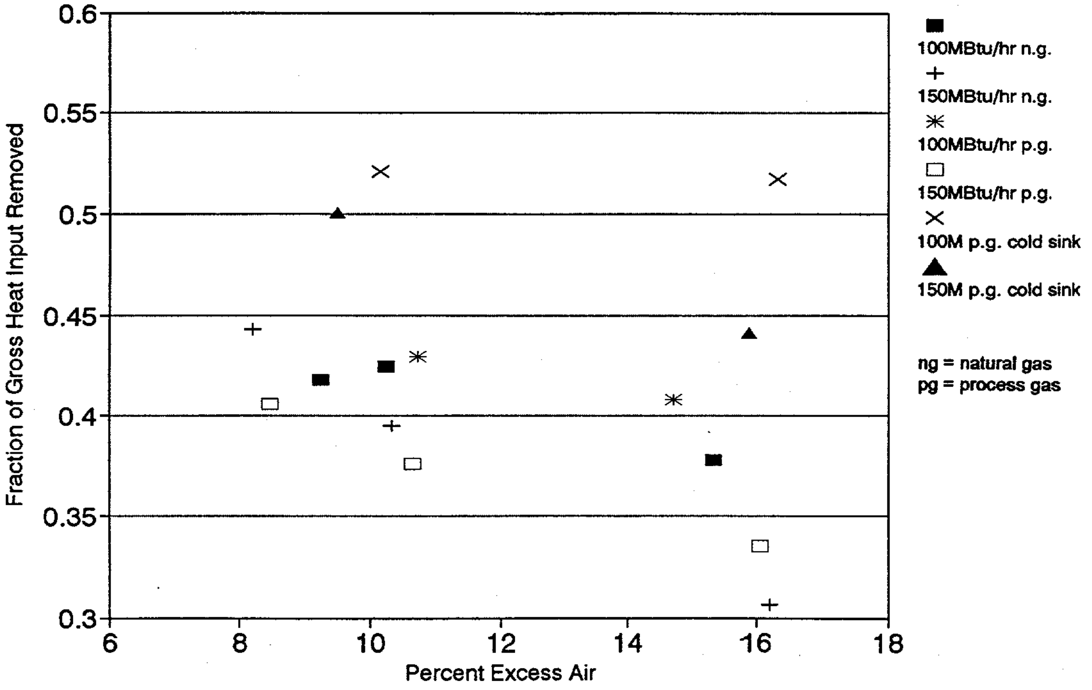


Figure 3-2. Combustion Efficiency as a Function of Excess Air and Fuel Composition with 500°F Preheat

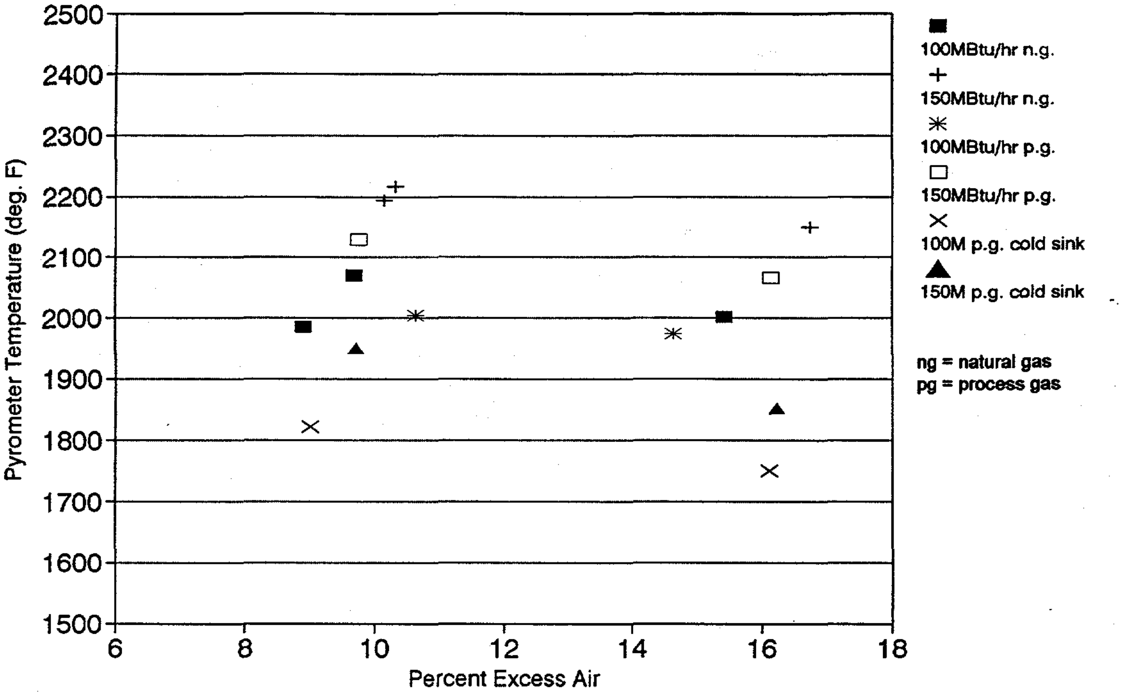


Figure 3-3. Burner Surface Temperature as a Function of Excess Air and Fuel Composition with 250°F Preheat

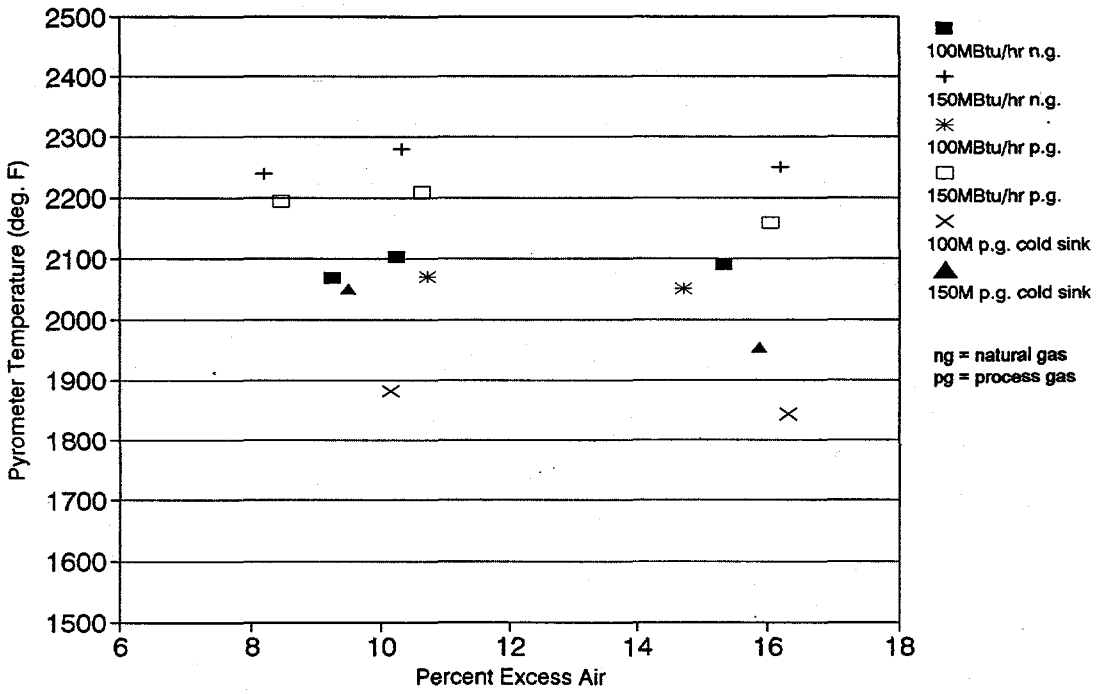


Figure 3-4. Burner Surface Temperature as a Function of Excess Air and Fuel Composition with 500°F Preheat

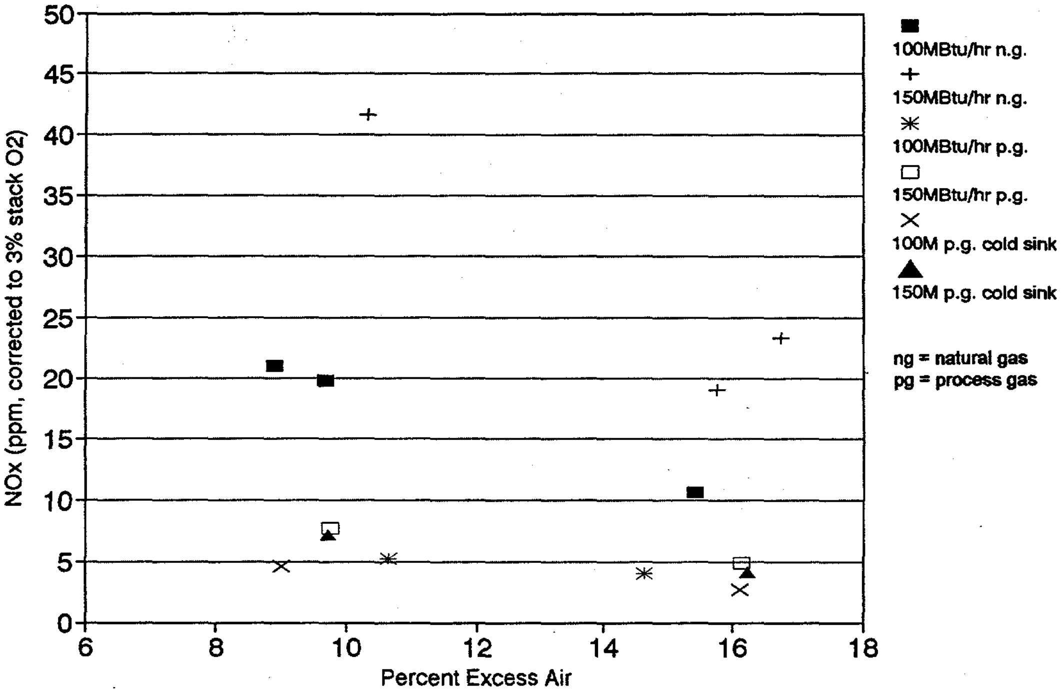


Figure 3-5. $NO_x$ Emissions as a Function of Excess Air and Fuel Composition with 250°F Preheat

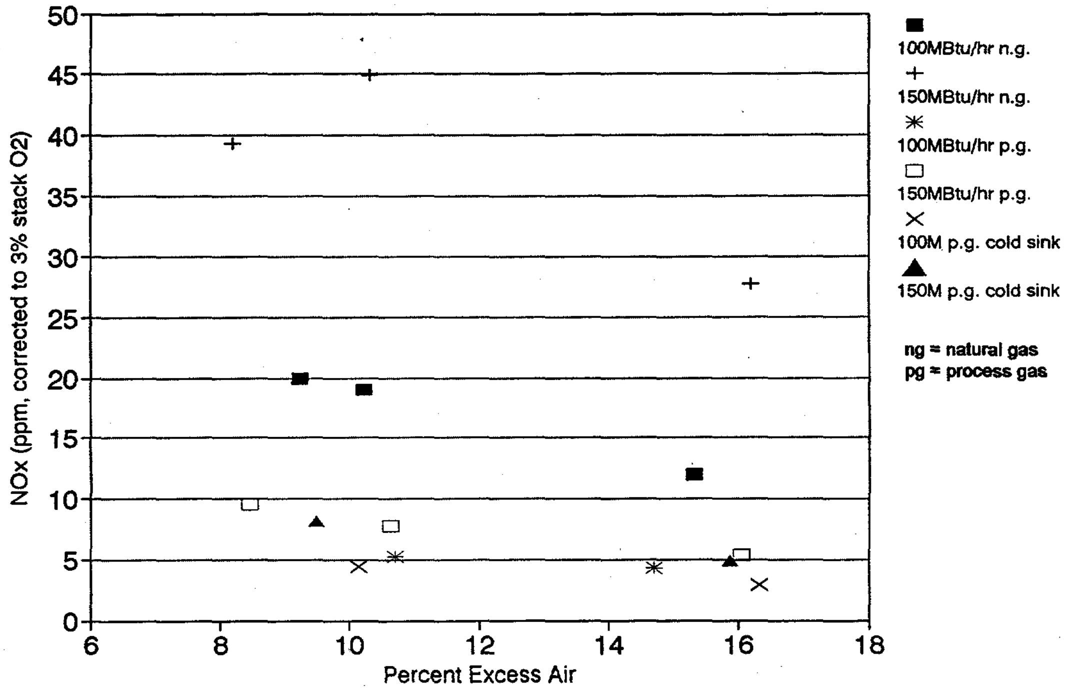


Figure 3-6. $NO_x$ Emissions as a Function of Excess Air and Fuel Composition with 500°F Preheat

# SECTION 4

# THERMAL OXIDIZER FIELD TEST

To verify field operation and performance of the advanced radiant burner, an inward fired VOC thermal oxidizer was selected as the host site. The specific oxidizer application was for batch operation of a photolithography process using xylene for silicon wafer circuit printing. The host site was ECI Semiconductor in Santa Clara, California (now Semtech). Described below are system specifications, design features, lab test results, a discussion of source test results, and a summary of system performance 6 months after startup.

## 4.1 SYSTEM REQUIREMENTS AND SPECIFICATIONS

Semtech is a small manufacturer of processed semiconductor wafers, with annual sales of $7 million. They are restricted by Rule 30 of the Bay Area Air Quality Management District to emit less than 24 gallons per month of xylene from batch development processes. Semtech planned to expand their manufacturing capacity and considered VOC abatement with carbon bed adsorption and thermal incineration. The development processes are done in batch mode, typically operating from 30 to 60 minutes on, and 30 minutes off. Although usage can vary, during most of the host site demonstration the facility was operated during weekdays only, in three 8-hour shifts per day. Operating costs of the competing carbon bed system were high and uncertain due to the mixture of other compounds with poor adsorptivity, such as acetone. Semtech had received a quote for a competitor's thermal incinerator that was large, expensive, and, because of the refractory lining, was required to operate continuously. Therefore, the adiabatic Alzeta system with the advanced radiant burner was selected by the customer.

Design and fabrication of all system components except for the burner and some monitoring instrumentation was completed as part of a Gas Research Institute funded project (Reference 3). As part of the design process, Alzeta reviewed Semtech's ventilation flow requirements and developed four configurations of the inward fired burner. Table 4-1 lists the operating parameters (including flowrate, Q, and duty cycle, DC) and burner configurations. To reduce fuel costs, we recommended reducing the ventilation air flow from 800 to 200 scfm and taking advantage of the batch mode operation. Semtech preferred configuration B, with a variable air flow design.

## TABLE 4-1. ECI FUEL COSTS AND EQUIPMENT COSTS

| Configuration | A1 | A2 | B1 | B2 | C1 | C2 | D1 | D2 |
|---|---|---|---|---|---|---|---|---|
| Units; Quantity | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| Capacity (scfm) | 500 | 500 | 500 | 500 | 250 sink<br>250 fab | 500 sink<br>250 fab | 250 sink<br>250 fab | 500 sink<br>250 fab |
| Air Flow Type | Variable | Variable | Variable | Variable | Var. (sink)<br>Const. (fab) | Var. (sink)<br>Const. (fab) | Var. (sink)<br>Const. (fab) | Var. (sink)<br>Const. (fab) |
| Gas Flow, Control | On (Q,T) | On (Q,T) | On/Off (Q,T) | On/Off (Q,T) | On/Off (Q,T)<br>On (T) | On/Off (Q,T)<br>On (T) | On/Off (Q,T)<br>On/Off (T) | On/Off (Q,T)<br>On/Off (T) |
| $Q_{sink}$ (scfm) | 200 | 350 | 200 | 350 | 200 | 350 | 200 | 350 |
| $DC_{sink}$ | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| $Q_{fab}$ (scfm) | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| $DC_{fab}$ | 1.0 | 1.0 | 0.57 | 0.57 | 1.0 | 1.0 | 0.57 | 0.57 |
| $Q_{eff}$ | 238 | 275 | 173 | 210 | 200 | 238 | 136 | 173 |
| Fuel Cost (k$/yr) | 27.8 | 32.2 | 20.2 | 24.6 | 23.4 | 27.8 | 15.9 | 20.2 |
| Notes | Easiest to permit (always on) | | | | | | Lowest fuel use | |
| Budgetary Cost k$ | 65 | 65 | 65 | 65 | 85 | 105 | 85 | 105 |

$$\text{Fuel Cost} = \frac{\left[\Sigma\,(Q_{air})\,(DC)\right](374.4)\,(HV)\,(GC)}{(AFR)\,(1+EA)} \qquad (\text{k\$/yr})$$

AFR = 9.6
EA = 100%
$(DC)_{fab,B1} = (2/3)(.80) + (1/3)(.10) = 0.57$
HV = 1000 Btu/ft$^3$
GC = \$.60/10$^5$ Btu

Specifications for the thermal oxidizer are shown in Table 4-2. As noted, VOC concentrations were expected to be low, but the quick response of the unit would reduce fuel cost for the low levels of duty cycle.

Air flowrate measurements were made at the Semtech facility. Figure 4-1 shows a simple schematic of the ventilation air circuit; three existing silicon wafer photolithography (fab) machines operate, and a solvent rinse sink is used. Two additional fab units are planned for the future. As shown, the measured flowrates exceeded the design flows. To reduce the ventilation air flows, the following modifications were made:

a) Enlarge the 1½ diameter vent line to 4 inches on machine 2; this reduced the system pressure drop and blower suction pressure, resulting in less air leakage.

b) Reduce the blower speed (belt and pulley adjustment) and balance air flow with existing duct dampers to achieve design flowrate.

c) Reduce the sink hood frontal area to reduce volume flowrate requirement to 200 scfm.

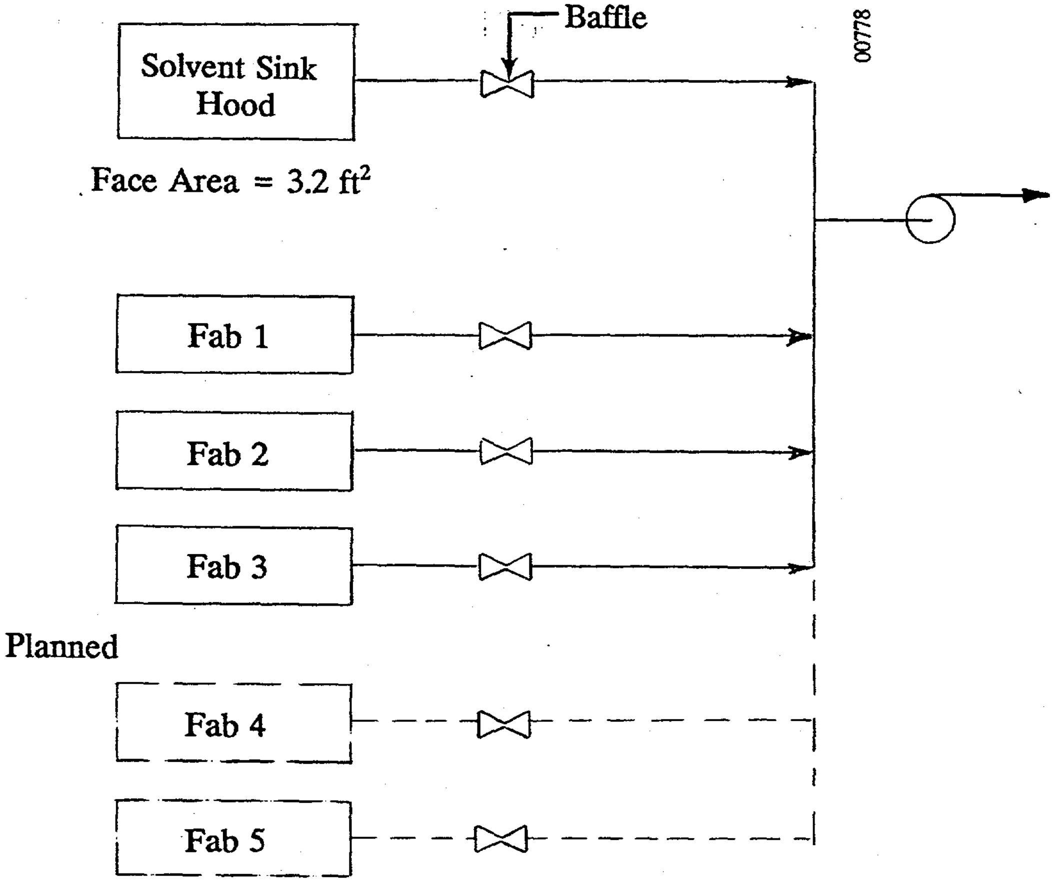
## 4.2 DESIGN SPECIFICATIONS

A conceptual design of the system is given in Figure 4-2. Key elements of the design include:

- Burner size is 29 inch diameter x 36 inches long. (22.8 $ft^2$) This provides a maximum face velocity of 22 sfpm at 500 scfm flowrate. The minimum flowrate is 200 scfm (2.5 :1 turndown).
- The burner screen is removable from the end opposite the stack, to allow quick removal and replacement.
- There is no cast refractory, reducing weight and cost. The downstream end of the burner transitions to a sudden contraction from 29 inches to a 12 inch diameter orifice in a fiberboard plate, then an elbow of high temperature alloy to the stack entrance. The stack itself is 304 stainless steel; a dilution air fan maintains stack metal temperatures below $1500^0$F.

## TABLE 4-2. SPECIFICATION FOR THE THERMAL OXIDIZER FOR SEMTECH SEMICONDUCTOR

| VOC Incinerator, Alzeta Model PCI-500 | |
|---|---|
| Application - System Use | Semiconductor Processing VOC Control |
| Air/fume specifications | |
| Location | Incinerator inlet |
| Flowrate, maximum | 500 scfm |
| Hydrocarbon concentration | <100 ppm nominal |
| Oxygen concentration | 21% |
| Pressure, inlet | -0.5 to +2.0 inches water column |
| Inlet temperature | 70°F plus or minus 10°F |
| Inlet air source | Clean room (filtered) |
| Gas supply | 1,500,000 Btu/hr |
| Gas supply pressure min. | 3.0 psig |
| Incinerator operating temperature | |
| Maximum | 1800°F |
| Nominal | 1600°F |
| Minimum | 1450°F |
| Electrical connections | Supply connections by Semtech |
| Power | 240/480 VAC/3 phase/60 Hz |
| Control | 120 VAC/1 phase/60 Hz |



| Source | | Duct Diameter (inches) | Flow rates (scfm) | |
|---|---|---|---|---|
| | | | Design | Measured |
| Fab 1 | | 1 1/2 | 50 | |
| Fab 2 | | 4 | 50 | 100 |
| Fab 3 | | 4 | 50 | 100 |
| Sink | closed | 8 | 50 | |
| | open | 8 | 200 | |
| Total | min. | | 200 | 550 |
| | max | | 350 | |
| Planned | | | | |
| Fab 4 | | 4 | 50 | |
| Fab 5 | | 4 | 50 | |
| Total | | | 300 - 450 | |

Figure 4-1. Fabrication Ventilation Air Circuit

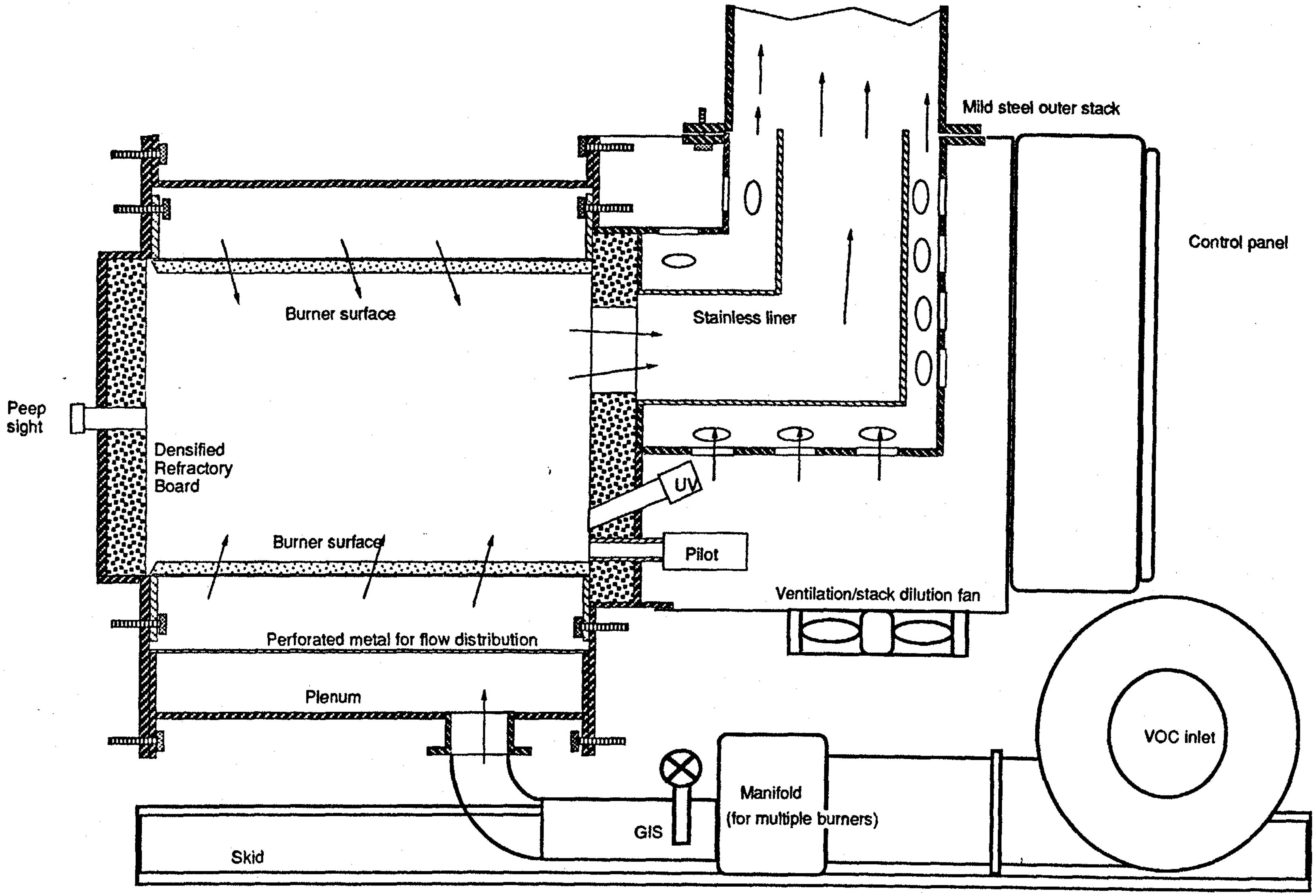


Figure 4-2. Conceptual Incinerator Design

- The air/fuel mixture is distributed to the burner plenum over the 36 inch length of the burner. Low inlet velocities allow uniform distribution over the burner circumference.
- The primary control variable is combustion exhaust temperature measured with a thermocouple, to modulate natural gas delivery. Control requirements are much different for this system than for soil remediation systems. This unit must accommodate batch (on/off) operations of VOC fumes, variable VOC concentrations, and variable air flowrate.

Figure 4-3 shows the general arrangement drawing of the unit. The main blower delivers the VOC stream to the burner, a dilution air fan provides cooling air to the stack to limit exhaust temperatures to 1200°F. Figure 4-4 shows the process instrumentation schematic for the system. Because the process air stream varies from 200 to 500 scfm, variable fuel delivery is required. Testing showed that a venturi-type mixer provided accurate constant excess air control over a two to one turndown in air flow. An alternate control method was tested using a pressure-based control valve provided by Landis and Gyr. Again, excess air levels remained constant, within 3% over a two to one variation in air flowrate. The Landis and Gyr valve arrangement was more compact than the venturi controller, and included positive shut-off when required by the flame safeguard controls. The Landis and Gyr controls are shown in the gas train as FCV 2004, using an air flow meter (FE 1001) as input signal. A trim valve (FCV 4003) was used to adjust fuel to reach the combustion temperature setpoint for variation in VOC energy input from the process flow stream. Tests showed that for stable operation the combustion temperature setpoint should vary linearly with process air flowrate from 1500°F at 200 scfm to 1700°F at 500 scfm.

## 4.3 CHECK-OUT TEST RESULTS

Check-out tests of the unit were made prior to installation at the host site Figure 4-5 shows theoretical air levels of the unit at various air flowrates. At 200 scfm, theoretical air is about 2.46 (or 146% excess air); this corresponds to a fuel/air ratio of 4.2%, compared to about 4.9% at 500 scfm. Fuel use is reduced at lower surface firing rate.

Dynamic response of the system was also tested. Figures 4-6 and 4-7 show open loop (no automatic feedback), response of the system to a step change in fuel rate. The thermal time constant of the system is about 50 seconds for 200 scfm flowrate, 10 seconds for 500 scfm flowrate. The control thermocouple (1/4 inch sheath, ungrounded) provides a less noisy and more sensitive signal, compared to the exhaust gas thermocouple and an optical pyrometer. Figure 4-8

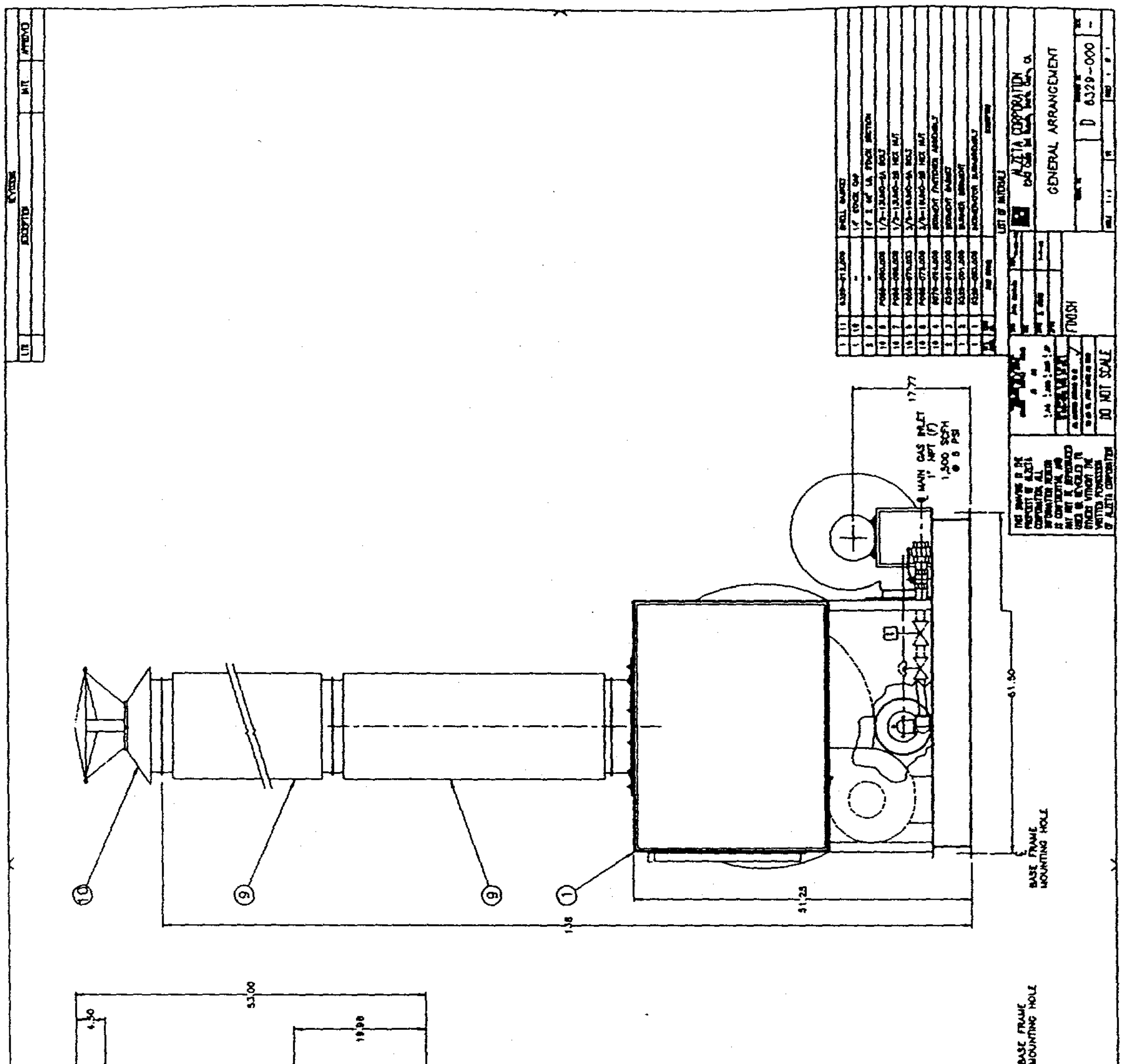


Figure 4-3. General Arrangement of ECI Incinerator

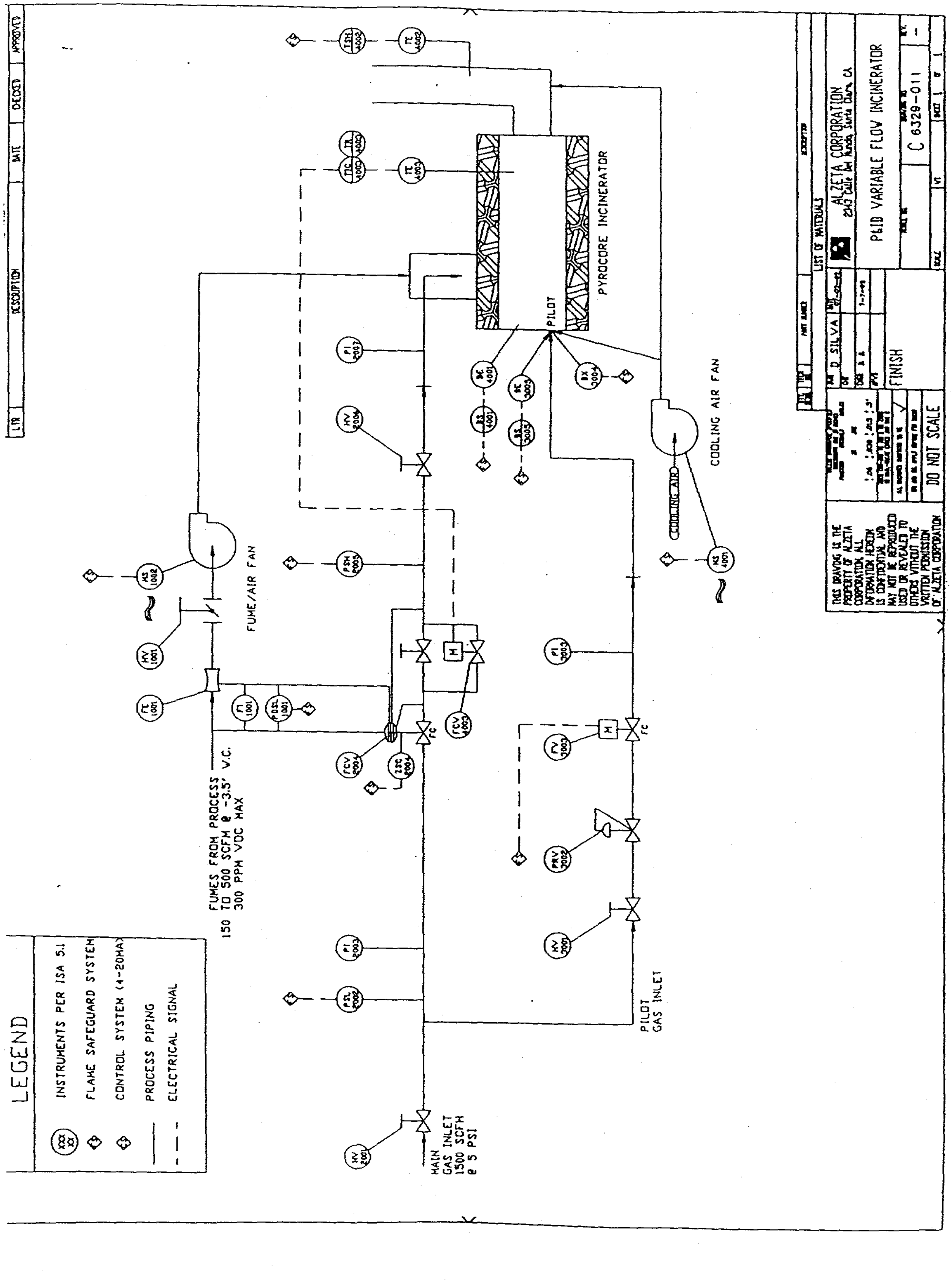


Figure 4-4. P&ID of ECI Incinerator

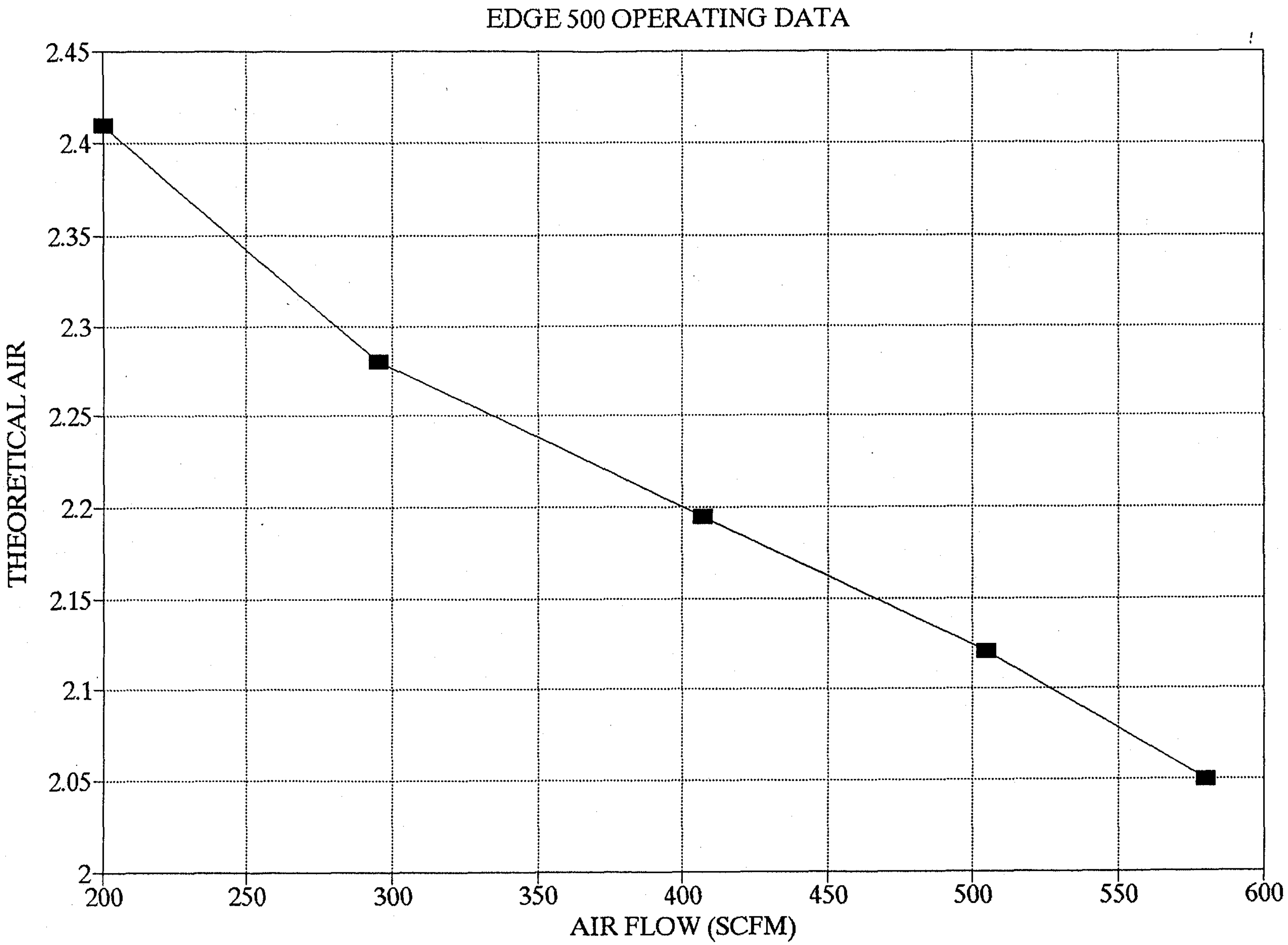


Figure 4-5. EDGE 500 Operating Data

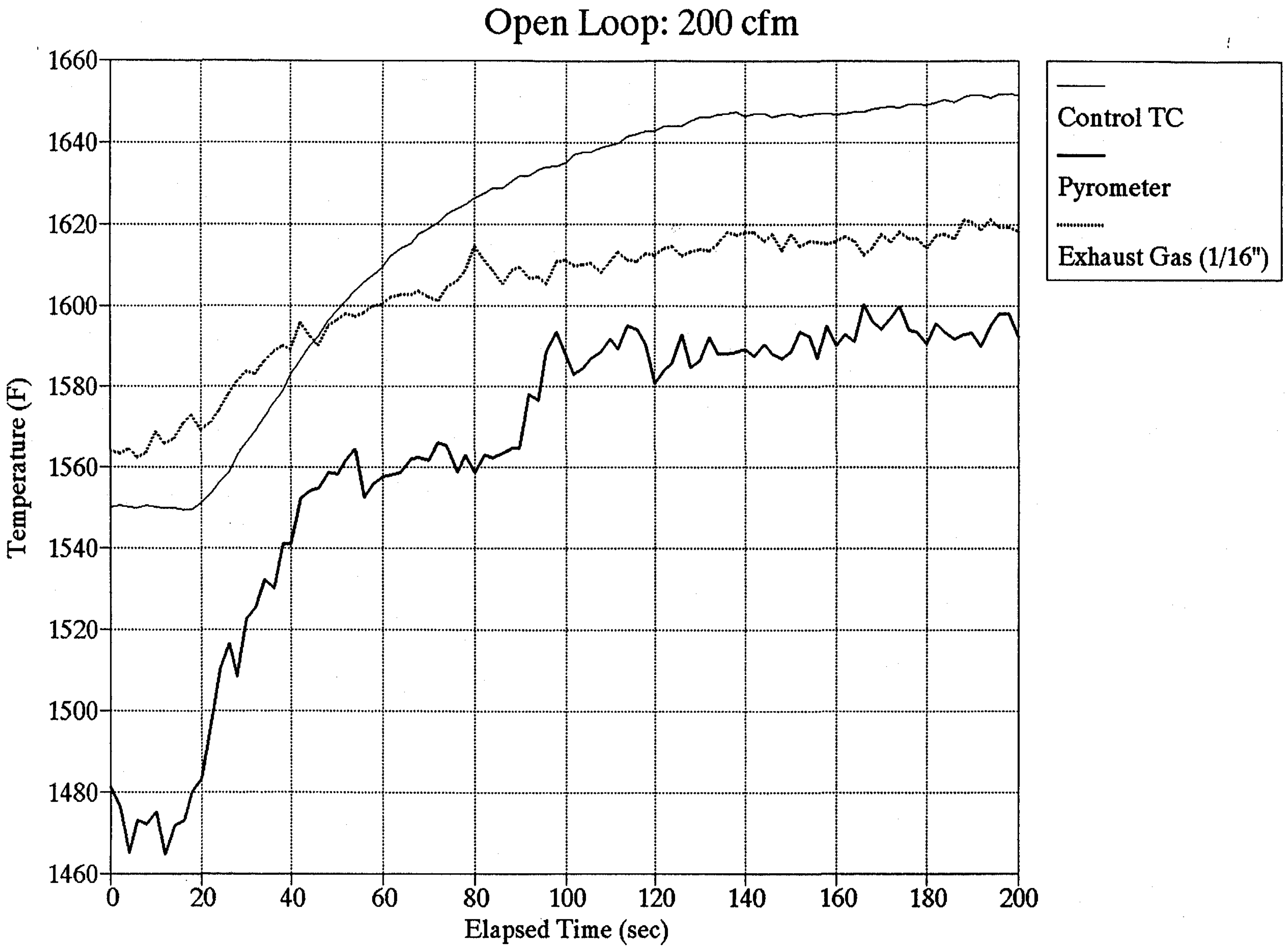


Figure 4-6. Open Loop Response to Step Change in Fuel Input at 200 scfm

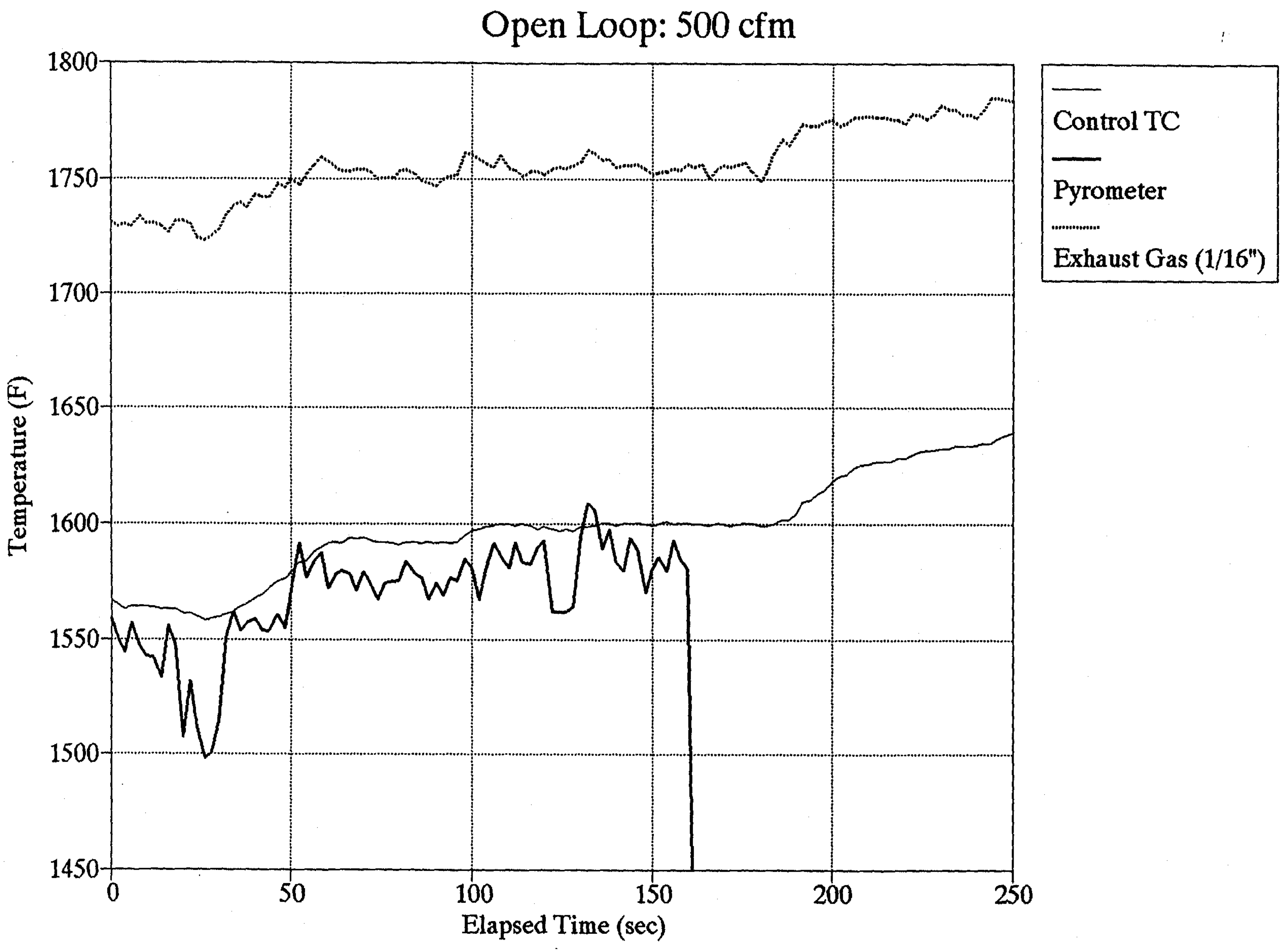


Figure 4-7. Open Loop Response at 500 scfm

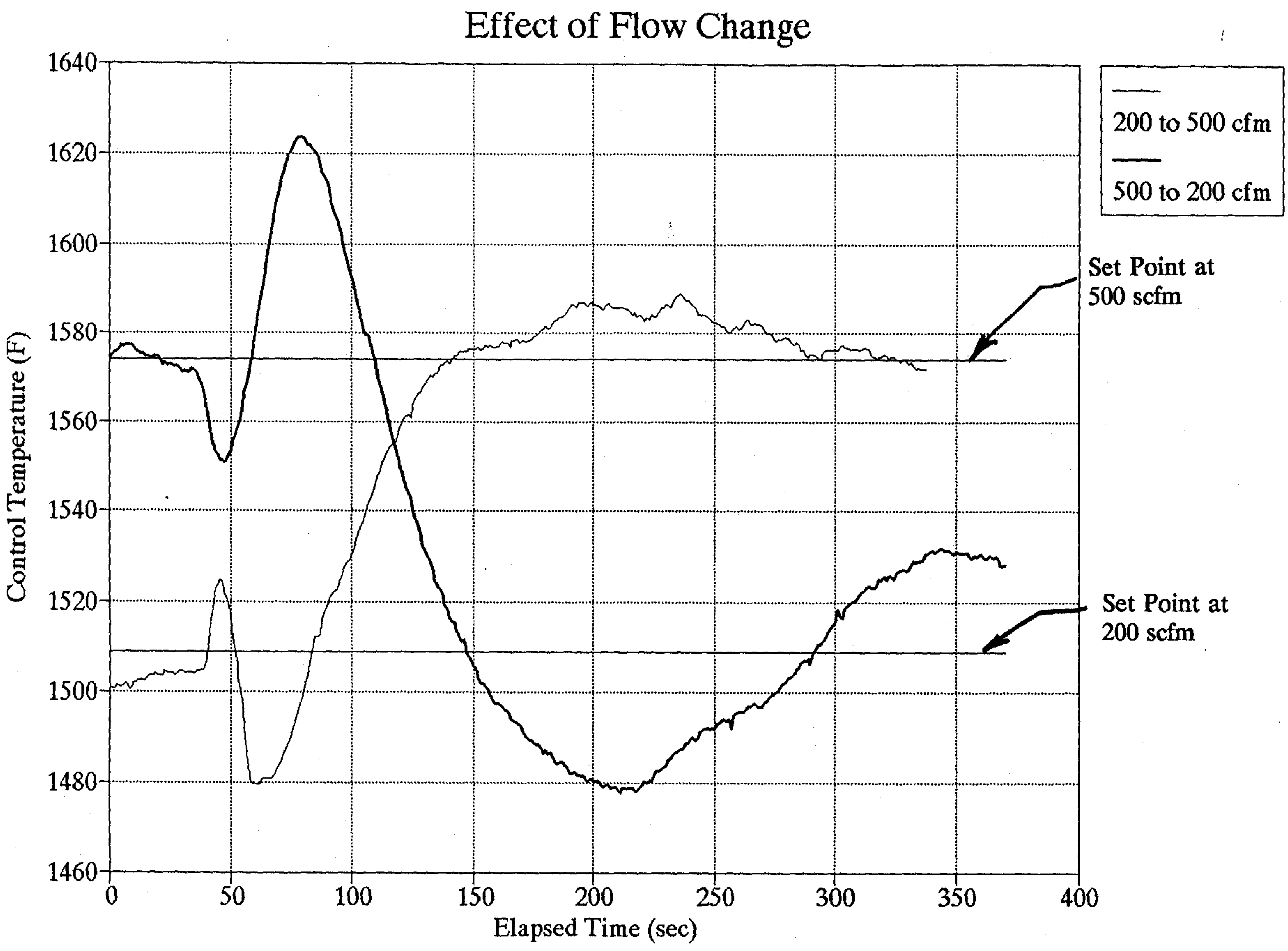


Figure 4-8. Closed Loop Response to Step Change in Flow Rate

shows closed loop response of the system to a step change in flowrate between 200 and 500 scfm. The largest deviation from set point occurs in reducing the flow from 500 to 200 scfm, with an overshoot of about 30°F, due to the longer time constant at 200 scfm. In both tests, however, the control error was reasonably small and gain selection was about right.

## 4.4 SITE PERMITS

Below is a list of permits that were required for installing the field test unit:

BAAQMD

- Authority to construct (granted based on submittal of operation parameters)
- Permit to operate (pending final inspection, source test)

City of Santa Clara

- Planning department approval (granted, based on plan review)
- Building department permit to construct (granted based on licensed structural engineering approval)
- Fire department approval (granted, based on safeguard provisions)

As noted, final permits from BAAQMD were given after installation and source testing with the process VOC stream

## 4.5 DESIGN MODIFICATIONS FOR DOE FIELD DEMONSTRATION

The following modifications were made to the Semtech oxidizer as part of the DOE-sponsored demonstration of the advanced radiant burner

- The adiabatic radiant burner was cast using the Pyrocore HT formulation developed as part of the project
- Six additional thermocouples were installed on in the premix plenum of the burner. Any of the six thermocouples could shut down the system if an overtemperature alarm condition occurred.

The HT burner formulation was described in Section 3.2 and Appendix A.

## 4.6 STARTUP, SHAKEDOWN AND COMPLETION OF SOURCE TESTS

The host site burner was installed on July 29-30 1995 to take advantage of downtime at the facility. Since this was a field demonstration, the ARCS burner was instrumented with six thermocouples on the burner support screen that could shut off the natural gas flow if a screen over-temperature occurred. The thermocouples were attached to a scanning controller. In addition, this controller has a digital display, and screen temperatures were recorded weekly to monitor burner performance.

The system went on-line July 30, 1995 and has been operating since that time. In the typical mode of operation, the system was operated from Sunday evening to Friday evening, and then shut down over the weekend. Alzeta monitored the system at least once per week for the first 6 months of operation.

Field tests were conducted by Alzeta personnel during system startup in July 1995 to quantify system performance. These tests included stack $O_2$ and $NO_x$ measurements using a portable analyzer, and were sufficient to assist Alzeta in tuning the combustion system. Emissions tests to meet Bay Area Air Quality Management District requirements were scheduled by Semtech, and these tests were completed in November 1995. The source test was conducted by Best Environmental, and results of the tests are attached as Appendix D to this report. Bay Area AQMD regulations require 98.5% thermal destruction efficiency of hydrocarbons. As seen in the attached test report, the Alzeta system demonstrated 99.5% thermal destruction.

# SECTION 5

# VOC THERMAL OXIDATION MARKET ANALYSIS

The following sections briefly review the history and status of the technology, and discuss the results of market research evaluating the market opportunities for the inward fired VOC thermal destruction technology, and then discuss the results of initial market introduction activities. Because the markets are driven primarily by rapidly changing government regulations, the discussion includes a review of applicable regulations on the local, state, and federal level.

## 5.1. REGULATIONS: CURRENT AND FUTURE

Destruction technology for volatile organic compounds (vapors and gases) is driven by the need to comply with government regulation. Although some companies are becoming "green" and translating concern about the environment into reduced environmental emissions based on a sense of social responsibility, the markets are predominately driven by regulation.

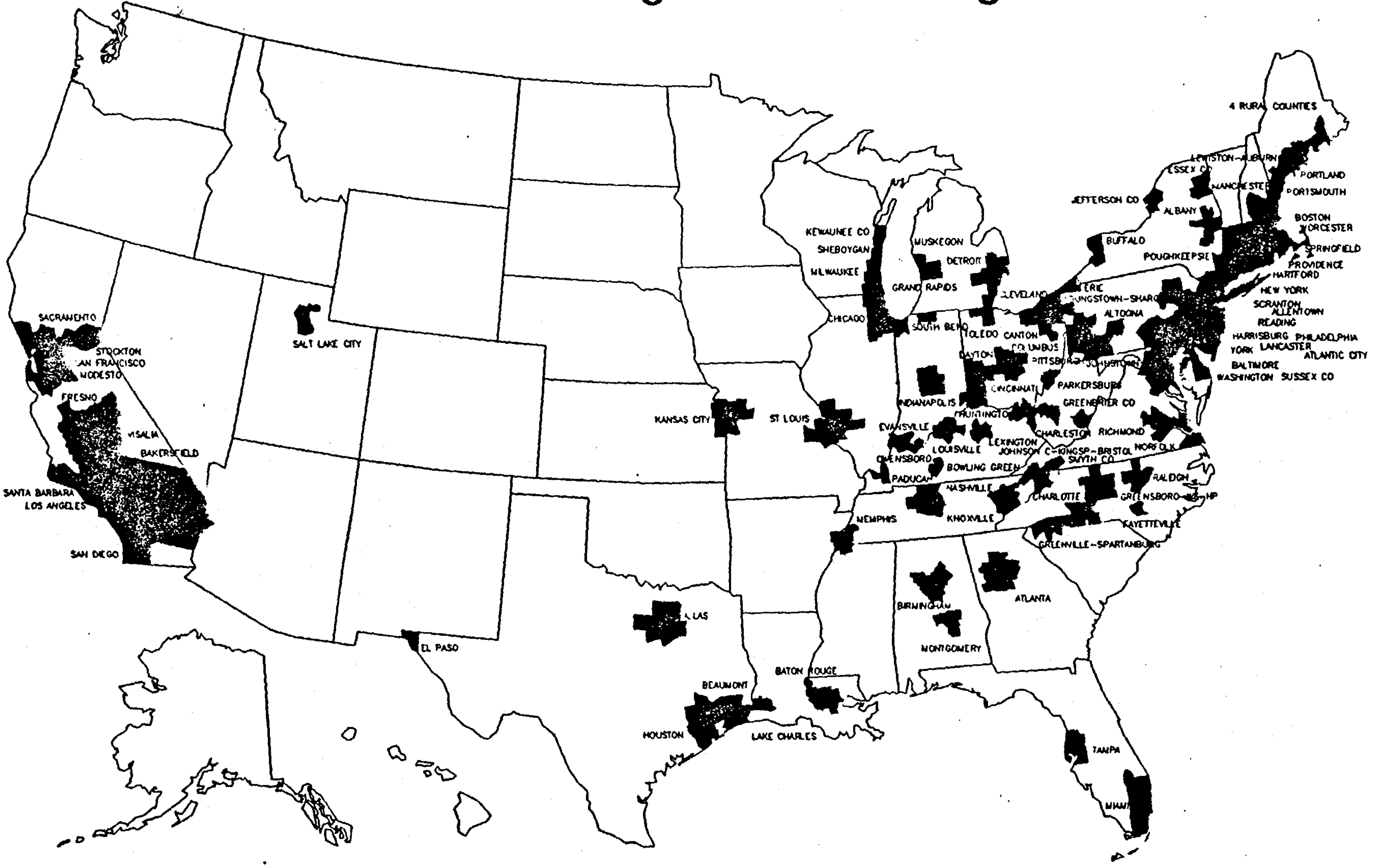
### 5.1.1 Existing Regulations

### VOC Control

Low altitude atmospheric ozone, a key damaging component of smog, is created by the combination of nitrogen oxides (from combustion processes), "reactive" volatile organic compounds (VOCs) and sunlight which causes the formation of ozone in the atmosphere. "Reactive" VOCs are those that participate in the sunlight-$NO_x$ ozone formation chemistry, and typically consist of hydrocarbon vapors ranging from gasoline and some types of paint thinner to complex chemicals that escape industrial processes. Approximately 70% of the U. S. population lives in areas that exceed the national ambient air quality standard for ozone an appreciable portion of the time. Figure 5-1 presents a national map showing the various regions designated as not attaining the federal oxidant air quality requirements. The designations range from extreme (Los Angeles) to moderate. The designation determines the schedule imposed on the region to attain the federal standards.

Ozone control strategies focus on reductions in $NO_x$ and VOC emissions, and the most aggressive actions have been taken in those areas with the worst smog problems. Consequently, local or regional rules have been promulgated which restrict VOC emissions at the source, either

# Ozone Areas Violating Standards During 1987-1989



am79no 8/90

Figure 5-1.  Map of U.S. Nonattainment Areas through destruction, capture, or elimination by changing a process or product (switching to water based paints, for example). VOC abatement products are purchased today largely to comply with existing VOC control rules that seek to reduce ozone and thereby improve air quality. Rules are motivated by poor air quality. As expected, the most aggressive VOC control requirements are in the Los Angeles basin where the South Coast Air Quality Management District (SCAQMD) has taken a national lead in reducing VOC emissions from virtually all sources, and enforces the toughest emissions limits in the nation.

### California Clean Air Act and Offsets

The California Clean Air Act mandated that as of July 1991, there can be no net increases in any criteria air pollutant anywhere in the state (regardless of local air quality). If new sources of pollution are to be constructed, they must be "offset" at a ratio of better than 1 to 1 with the amount of offset depending on details of pollutant, location, amount, and other factors. For example, before increasing capacity which will in turn increase VOC emissions, an industrial plant, even though it is currently in compliance, must reduce VOC emissions to create an offset. Another option is to obtain the offset on the open market or through a "bank" managed by the local air district. Plant operators with expansion plans scrambled to obtain or create the needed offsets, and a strong business recovery in 1993-1994 accelerated this trend. VOC abatement is an attractive option in some circumstances, particularly for those operators that cannot change their process, and who currently have no VOC controls.

### Existing Air Toxics Impacts

Air toxics refer to those vapors and gases that have a known or suspected health impact, whether or not they contribute significantly to ozone formation. With the exception of a few compounds, there are virtually no current direct air toxics control regulations in place, although there is a Federal time line to create such regulations (see section below). However, California has invoked an air toxics review procedure for new emissions sources as part of the formal New Source Review Procedure. It is best demonstrated by an example.

If gasoline is lost from an underground storage tank contaminating nearby soil, a common soil remediation method is to drill wells, pull a vacuum, and thereby pull air through the soil to carry the gasoline away in vapor form. The vapor is commonly disposed of in a thermal destruction unit. Under existing SCAQMD VOC rules driven by ozone control, a thermal destruction unit having 95% destructive removal efficiency will meet existing rules. However, if the gasoline contains (as is frequently the case) benzene, a known carcinogen, then an air toxics assessment is required. This is done by calculating the expected benzene release from the thermal destruction unit, conducting an air modeling study to compute the estimated ground level concentrations downwind where people may be exposed, and estimating the health hazard based on health effects data and assuming a 70 year exposure. If the risk is calculated to result in greater than one additional death per one million population, mitigation measures must be undertaken to reduce emissions, usually by requiring the use of Best Available Control Technology ("BACT"). Therefore, based on the concentration of benzene expected in the gasoline, the amount of vapor being disposed of, the local meteorology, and the nearness of people to the site, higher levels of VOC control may be required than the 95% specified by ozone-driven rules. In Los Angeles, thermal destruction units are being required to provide 99.8% control in some situation, yielding emissions that would be 25 times lower than required by VOC-ozone precursor rules alone.

The procedure above applies to new sources of pollution. Existing sources of air toxics emissions are not covered at this time.

## California AB2588 Air Toxics Inventory

California law AB2588 requires an inventory of all air toxics sources (emitters) above a certain minimum size that emit one of the approximately 600 chemical compounds specified in the legislation. This inventory is on-going, and the results will be published once compiled and verified by the state. Currently, there is no law requiring that heavy air toxics emitters control emissions, but the expectation is that public pressure will cause reductions at the worst sites. If beneficial results are not obtained, the state may follow up by mandating retrofit of technology to existing sources to reduce emissions, although at present there is no plan to do so. Although the result of AB2588 has been to make many air toxics emitters aware of their exhaust streams and to raise consciousness of process and equipment operators, sales of emissions control equipment in response to the legislation and the implied threat of adverse corporate publicity resulting from the publication of the air toxics source inventory have not yet occurred.

## Texas Air Board

After the Los Angeles basin, the greater Houston area is the worst ozone nonattainment area in the U.S. The oxidant-impacted zone extends as far north and east as Port

Arthur/Beaumont. Through 1992 and early 1993 the Texas Air Board formulated new rules concerning $NO_x$ and VOC controls, but at the time this market was completed new rules had not yet been issued. However, discussions with chemical plant operators and consultants active in the area suggested that permit applications for new sources were being postponed until stricter emissions rules were adopted. Additionally, chemical plant operators were advised that uncontrolled releases of VOCs that were previously permissible would no longer be so, and retrofit of VOC controls would be required.

## Federal 1990 Clean Air Act Amendments

The Clean Air Act specified that EPA promulgate regulations controlling the emissions of air toxics. In twenty years EPA succeeded in covering just seven compounds (asbestos, benzene, beryllium, inorganic arsenic, mercury, radionuclides, and vinyl chloride) with rule blockages based on legal challenges of questionable health effects data for the thousands of other compounds potentially targeted. Congress responded in 1990 with the new Amendments to the Clean Air Act which represent a major overhaul of earlier legislation. While the 1990 Clean Air Act Amendments cover many issues including acid rain and regional ozone controls, air toxics received special attention in Title III (Section 3) of the legislation.

## Title III Summary and Implications

Title III replaces the old program with a new program to control air toxics. Section 112 of the Clean Air Act has been renamed "Hazardous Air Pollutants," and has been entirely rewritten. Under the new program, Congress has established a modified approach to regulating hazardous air pollutants. The new program requires emissions control standards to be set for categories and subcategories of sources that emit hazardous air pollutants, rather than the pollutants themselves. For example, air toxics standards will be developed for petroleum refineries, chemical plants, etc. Thus a single set of standards for a source category could conceivably cover all listed hazardous air pollutants which that category emits.

While the rules are complex, the main portion of the air toxics bill which covers hazardous air pollutants can be summarized fairly easily. Congress established an initial list of hazardous air pollutants. EPA is now required to develop a list of source categories that emit these pollutants. The agency must also establish a schedule for issuing maximum available control technology (MACT) standards for the identified categories. Within 8 years of establishing MACT standards for a source category, EPA must promulgate additional risk-based standards, if necessary, to protect human health and the environment. The list of hazardous air pollutants to be regulated currently contains 190 chemical names, most of which are hydrocarbons. On June 21, 1991, EPA published a list of 743 source categories and subcategories of "major sources" and "area sources" of listed hazardous air pollutants that present a threat to human health or the environment.

MACT must first be applied to major sources which are defined as emitting 10 tons per year (2.5 pounds per hour based on 8000 hours per year) of any of the listed pollutants, or 25 tons per year of a combination of the listed pollutants. MACT regulations must be promulgated in four stages: 40 source categories are to be regulated within 2 years of enactment, 25% of all the source categories within 4 years, another 25% in 7 years, and the remainder within 10 years. EPA has released the source categories that it expects to be regulated first:

- Hazardous organic chemical manufacturing (potentially includes several hundred individual source categories)
- Coke ovens
- Dry cleaners
- Commercial ethylene oxide sterilization
- Chromium electroplating
- Asbestos

The act also establishes a significant new program for reducing the risks, particularly in urban areas, resulting from emissions from "area sources." Title III defines an area source as any source that is not a major source. Practically speaking, however, such sources are those sources such as gasoline stations and dry cleaners that are smaller but more numerous than major sources. The goal specified by Congress is to achieve a 75% reduction in the cancer incidence associated with emissions of hazardous air pollutants from these area sources. EPA is to report to Congress within 5 years and recommend a National Strategy to control emissions of hazardous air pollutants from area sources in urban areas. The Strategy is to identify not less than 30 pollutants that present the greatest risks, identify the sources accounting for 90% of the emissions, and provide for actions under any environmental law. The following list presents some of the likely chemicals and source categories that could be included in this new area source program.

## KEY AREA SOURCE CHEMICALS AND SOURCES

| Possible Area Source Chemical | Typical Area Source Category |
|---|---|
| Various organic solvents | Painting and coating |
| Benzene | Service stations |
| | Gasoline distribution |
| Perchloroethylene | Dry cleaners |
| Trichloroethylene | Metal Degreasers |
| 1,1,1-Trichloroethane | Metal Degreasers |
| Ethylene oxide | Sterilizers |
| Methylene dichloride | Degreasers, paint removers |
| Formaldehyde | Combustion |

Title III contains provisions that are to be implemented over a 10 to 15 year period. The legislation will control requirements to a large fraction of the industrial and commercial facilities in the U.S. emitting any of the 190 substances designated as hazardous. By most estimates, 30,000 to 50,000 industrial facilities will be affected along with potentially hundreds of thousands of small industrial and commercial sources that meet the definition of area source. These facilities represent the largest potential market for the new technology and products in the 1990's.

The Administration recently estimated the added cost of Title III at $1.1 billion in 1995 rising to $6.7 billion in 2005. Industry believes that these estimates are a lower bound. To put this in perspective, the Council on Environmental Quality recently reported that air pollution control costs were $30.1 billion in 1987. Title III will thus create incremental additional costs starting at 3% of total air pollution in 1995 rising to 20% in 2005. The Business Roundtable recently estimated that the total cost for residual risk regulation associated with later regulations driven by health effects to range from $7.1 billion (least restrictive interpretation) to $61.9 billion for the most restrictive definition. This added cost will begin to take effect late in this decade.

### 5.1.2 Industry Response, Trends, Expectations

Significant activity has started in industry in preparation for expected Title III regulations. New products have also appeared, and the introduction rate of new products designed specifically to address Title III has accelerated dramatically. As an example, a review of the chemical engineering trade literature shows an explosive growth in the number of "seal-less" (magnetic drive) pumps being offered to eliminate fugitive emissions from pump shaft seal leakage. Chevron's Richmond, California, refinery is considering installing a fugitive emissions capture system that will run a vacuum line to every pump in the refinery to capture VOCs and transport then to modular thermal destruction units. Semiconductor manufacturer Intel is accelerating a program to obtain zero discharge operation to meet its own "good neighbor" policies and to improve its operational flexibility. The trade literature has shown a dramatic rise in the number of vendors offering some form of VOC control technology. Additionally, various European technologies are beginning to be offered in North America. Finally, some consolidation is taking place within the industry. As an example, Engelhard, a manufacturer of catalysts, has acquired Salem Industries, a manufacturer of large regenerative thermal oxidizers and catalytic VOC thermal oxidizers, to improve its reach into the emerging market.

While interest has been high and activity is accelerating, no clearly defined industrial responses have emerged, and some product introductions may be held off until after the final regulations are published. Many prospective customers are delaying decisions as long as possible to conserve capital, while awaiting greater certainty about regulatory enforcement and timing. Consequently, the current activity is largely one of planning, preparation, and positioning in anticipation of expected capital expenditures. Competitive intelligence is relatively sparse as various competitive segments attempt to chart future plans of action. The level of uncertainty is high among equipment manufacturers and process operators, but this also means that a window of opportunity is opening for new technology that correctly addresses future market needs.

## 5.2 THE INDUSTRY

Control of VOCs and air toxics was previously within a business sector that could be called "fume incineration or capture" in the past, but which has fragmented and changed in the last several years, and will continue to change rapidly in the 1990's. The business is diversified, heterogeneous, and highly segmented. The focus of this study is thermal oxidation technologies, and substitutes for thermal oxidation such as carbon absorption.

## Overview, Market Diversity

VOC thermal oxidizers range from massive units of 400,000 cubic feet per minute or more operating continuously on exhaust streams from large painting operations or production lines down to small modular units of 100 cfm which operate in vacuum extraction vapor disposal and air stripping associated with soil and ground water remediation. Table 5-1 presents a brief comparative analysis of several of the most commonly evaluated technologies. Companies range in size from large divisions of global players such as ABB down to start-up operations addressing small, very specific niche applications. Users of VOC control technology range from major auto makers to aerospace companies, chemicals, refining, painting and coating, and in the future could extend down to corner gasoline stations and dry cleaners. Consequently the industry is fairly sizable, involves hundreds of suppliers of highly variable size and capability, dozens of technology variations, thousands of applications, and has little uniformity, consisting instead of a collection of niches. The challenge has been to identify the "best" initial (introductory) market niche for the inward fired ceramic fiber incineration technology, define market characteristics and product requirements, and develop a product introduction strategy in a rapidly changing competitive and regulatory environment.

A useful view of the industry can be obtained from the representation of Figure 5-2 which presents the universe of VOC sources plotted against two axes. The horizontal axis is the total flow rate being treated in cubic feet per minute. The vertical axis is the concentration of the VOC in the air stream. The product of the concentration times the flow rate determines the total VOC emissions in tons per year. Large sources (large tonnages) have been regulated in the past. Thus, regions distant from the intersection of the axes represent high emission rates either due to large flow rates or high concentrations or both. These sources have been regulated in the past, and largely they are now controlled. As a consequence of this long term regulatory impact, there exists a mature industry that addresses this market with technologies such as large catalytic oxidizers, regenerative thermal oxidizers, and recuperative oxidizers. More recent technologies that have emerged are concentration technologies (using adsorbents such as rotary carbon or zeolite wheels) that focus on the large flow rates of lower concentrations. Analysis suggests that the new technology should be targeted at those regions closer to the origin (more dilute and smaller streams) since this segment is largely unoccupied at present.

## TABLE 5-1. COMPARISON OF VOC EMISSIONS CONTROL TECHNOLOGIES

| Technology | Advantages | Disadvantages |
|---|---|---|
| Thermal Oxidation<br>**In Alzeta inward-fired porous ceramic combustion system** | • Ultra-high removal efficiency (99.99%+)<br>• No products of incomplete combustion<br>• Ultra low NOx and CO emissions<br>• Nearly instantaneous on and off; ideal for batch processes<br>• Modular, lightweight, compact<br>• Handles any VOC concentration from zero to saturation; proven in soil remediation<br>• Excellent performance on chlorinated or non-chlorinated VOC's<br>• Simplicity of design; no secondary wastes<br>• Minimal operator attention required | • Currently limited to < 5000 scfm<br>• Maximum 430F preheat (700F in future products) limits heat recovery, can increase supplemtal fuel cost.<br>• HCl generation for chlorinated solvents requires scrubber |
| Thermal Oxidation<br>In conventional direct flame combustors | • Handles any VOC concentration from zero to saturation<br>• Simple units available at low cost | • Potential generation of products of incomplete combustion<br>• Greater than 99% destruction attained only with difficulty<br>• HCl generation with chlorinated solvents requires scrubber<br>• High cost of supplemental fuel |
| Thermal Oxidation<br>In internal combustion engines | • Small compact units<br>• Make on-site power | • Inconsistent operation and efficiency due to variable influent VOC levels<br>• Gumming of engine; high maintnenace demand<br>• Discharge of excessive hydrocarbons<br>• High cost of supplemental fuel<br>• Capacity usually limited to 100-450 scfm |
| Thermal Oxidation<br>In electric heat/ silica bed oxidizers | • Reduces problems associated with maintaining steady flame<br>• Easier to operate than internal combustion engines<br>• Low NOx emissions<br>• Can handle very large volumes of gas (>300,000 scfm) | • Incapable of attaining ultra high destruction removal efficiency; UHC emissions<br>• Frequently emits hydrocarbons and products of incomplete combustion<br>* Large size, very high weight can make siting difficult, installation expensive; not portable<br>• Highest capital cost<br>• Takes days to heat up and cool down<br>• Inappropriate for batch processes |
| Catalytic Oxidation | • Generally simple design<br>• Operates at lower temperatures (500-900F)<br>• Lower fuel cost due to lower temperature | • Fouling of catalyst, life limited, frequently inconsistent performance<br>• Generally incapable of attaining high destruction removal efficiency; UHC emissions<br>• High vapor concentrations (>30%LEL) will cause high-temperature burnout of catalyst bed, system damage, high maintenanc<br>• Low vapor concentrations require excessive auxilliary heating or expensive recuperators |
| Vapor Condensation | • Can be very effective for high VOC concentrations | • High power costs<br>• Disposal of collected liquids<br>• Need for secondary off gas treatment<br>• Can not economically treat VOC's with condensation points < 32F |
| Activated Carbon Adsorption | • Can be effective for removal of a variety of VOC's<br>• Effective for treatment of very low VOC concentrations | • Carbon replacement/regeneration costs<br>• Special non-corrosive materials of construction required if sulfur or chlorine compounds present<br>• Lugging and fouling problems<br>• Potential for fires and explosions |
| Absorption in Wet Scrubbers | • Simple to operate<br>• Minimal operator attention required | • Not efficient for low VOC concentration<br>• Does not operate well with low air volumes (<1000 scfm)<br>• Not suitable for some VOC's<br>• Can not deliver very high removal efficiency<br>• Liquid waste disposal |

Adapted from R. J. Chu as published in "The Air Pollution Consultant," September/October, 1991

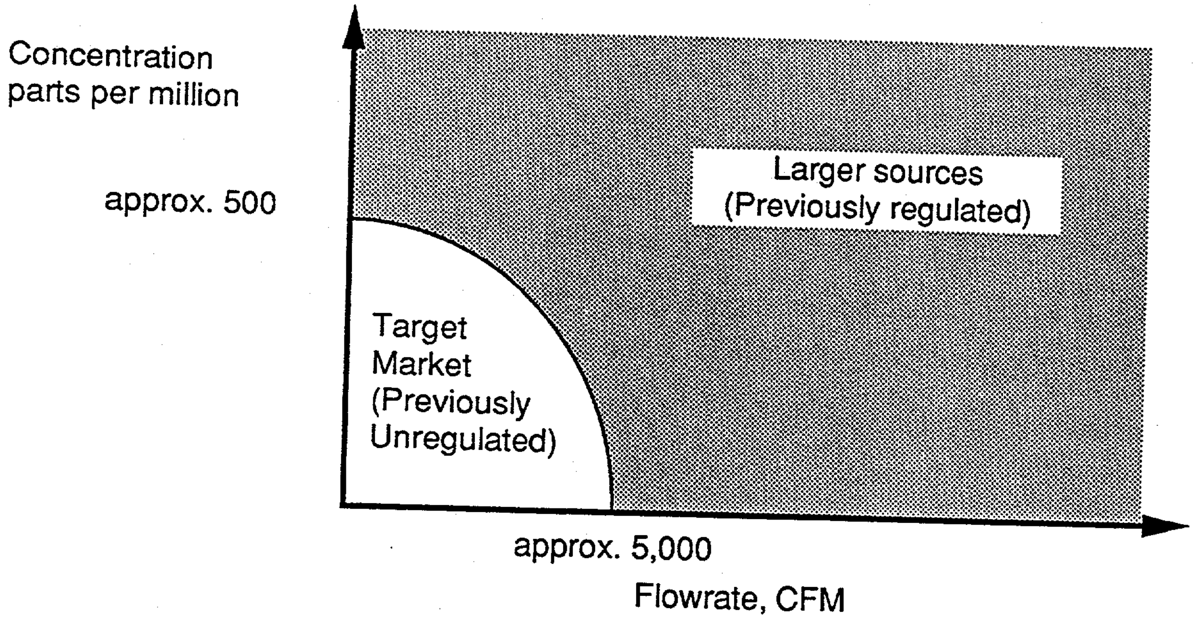


Figure 5.2. Addressable VOC Market and Market Focus

## Summary of Industry Forecasts

Because of the diverse and rapidly changing character of the industry, specifically applicable market size estimates were difficult to obtain, and overall market size estimates were highly variable. However, a survey of some of the major market forecast firms provided the following results.

### Freedonia Group Inc.

The Freedonia Group Inc. issued a report entitled "Business Research Report B242: Industrial Air Pollution Control Equipment" which gave projections for 1995 and 2000. Table 5-2 summarizes the results obtained.

TABLE 5-2. PROJECTED TOTAL CAPITAL EXPENDITURES AND EQUIPMENT SALES FOR AIR POLLUTION CONTROL
(in millions of dollars)

| Item | 1990 | 2000 | Average Annual Growth |
|---|---|---|---|
| Total U. S Capital Expenditures for air pollution control | 4,600 | 7,250 | 9.5% |
| % Air Pollution Equipment | 13.2% | 14.1% | |
| U. S. Equipment Sales | 605 | 1,025 | 11.1% |
| Net Equipment Exports | 85 | 125 | 8.0% |
| Total Equipment Sales | 690 | 1,150 | 10.8% |
| Price deflater (1990 = 100) | 100 | 117.9 | 3.4% |
| Total Inflation Adjusted Sales | 690 | 975 | 7.1% |

Table 5-3 presents a breakdown of projected equipment sales by industry. Power generation is the largest market for air pollution control equipment, and will remain so due to acid rain provisions of the 1990 legislation. Double digit growth is predicted for chemical processing, primary metals, and petroleum refining industries which will be hit hard by the new controls on air toxics.

### TABLE 5-3. PROJECTED EQUIPMENT SALES BY INDUSTRY

(Freedonia Group)

| Industry | 1990 | 1995 | Annual Growth Rate |
|---|---|---|---|
| Power Generation: Utilities | 165 | 320 | 14.2% |
| Power Generation: Industrial | 85 | 140 | 10.5% |
| Pulp and paper mills | 70 | 110 | 13.0% |
| Chemical processing | 65 | 115 | 12.1% |
| Primary metals | 28 | 50 | 12.3% |
| Petroleum refining | 15 | 28 | 13.2% |
| Cement manufacturing | 13 | 17 | 5.5% |
| Other industrial markets | 164 | 245 | 8.4% |
| Net exports | 85 | 125 | 8.0% |
| Total equipment sales | 690 | 1,150 | 10.8% |

Freedonia Group noted that while particulate emissions control devices would comprise the majority of equipment sales, sales of gaseous emissions control devices would grow significantly faster based on required reductions in emissions of $NO_x$ and $SO_x$. Projected equipment sales by technology is summarized in Table 5-4.

### TABLE 5-4. PROJECTED EQUIPMENT SALES BY TECHNOLOGY

(Freedonia Group)

| Technology | 1990 | 1995 | Average Growth Rate |
|---|---|---|---|
| Particulate emissions control devices | 390 | 605 | 9.9% |
| Gaseous emissions control devices | | | |
| Flue gas desulfurization | 140 | 280 | 14.9% |
| Thermal and direct oxidation systems | 50 | 83 | 10.7% |
| Catalytic oxidation systems | 15 | 27 | 12.5% |
| Gas scrubbers | 13 | 23 | 12.1% |
| Gas adsorbers | 7 | 12 | 11.4% |
| Total gaseous emissions control devices | 25 | 425 | 13.6% |
| Other pollution control equipment | 75 | 120 | 13.6% |

The Freedonia Group also noted:

> "In general, successful competitors in the U. S. industrial air pollution control equipment industry stress price competitiveness and strong marketing skills while supplying equipment of systems that are cost-effective, efficient, and reliable. In addition, factors such as product servicing, end-user training, effective distribution, balanced operations,

sound financing and new product development are also of importance. Besides supplying systems that meet emissions requirements, the ability to keep pace and foresee changes in government regulations and policies is also a significant competitive variable."

The study indicated that 150 companies, most relatively small, manufactured air pollution control equipment. Roughly 30% of shipments were attributed to the top four firms: General Electric, Research-Cottrell (Air & Water Technologies), Combustion Engineering (Asea Brown Boveri, ABB), and Babcock & Wilcox (McDermott International). Other major players included Wheelabrator Technologies (Waste Management), American Air Filter (Snyder-General), Air Products & Chemicals, Fuller, and Joy Technologies.

**Frost and Sullivan, Inc.**

The Frost & Sullivan study projected that the air pollution control equipment market would grow from $602 million in 1990 to $1.01 billion in 1994, an average growth rate of 13.8% with most of the growth being associated with electric utilities seeking to reduce acid rain emissions. Other high growth industry segments were predicted to be petroleum refining, chemicals, primary metals, and the municipal market.

Like The Freedonia Group, Frost & Sullivan made projections by technology. These are summarized in Table 5-5.

TABLE 5-5. PROJECTED EQUIPMENT SALES BY TECHNOLOGY
(Frost & Sullivan)

| Technology | 1990 | 1994 | Average Growth Rate |
|---|---|---|---|
| Particulate emissions control devices | 320 | 503 | 12.0% |
| Gaseous emissions control devices | | | |
| Flue gas desulfurization | 76 | 181 | 24.2% |
| Thermal, direct & catalytic oxidation systems | 139 | 233 | 14.4% |
| Solvent recovery, carbon absorption | 37 | 56 | 10.9% |
| Total gaseous emissions control devices | 252 | 470 | 16.9% |
| Other pollution control equipment | 30 | 37 | 5.4% |

**H & W Management Science Consultants**

H & W Management Consultants forecasted that annual expenditures to comply with the amended Clean Air Act would grow from $6.6 billion in 1991 to $10.7 billion in 2005. This is equivalent to 3.5% average annual growth, significantly slower than predicted by other studies. Approximately 60% of the market would be accounted for by stationary sources. Air pollution control expenditures for the petrochemical industry were expected to increase from $465 million in

1991 to $1.35 billion in 2005 as a result of air toxics and nonattainment regulations. The study also projected that by the end of the century over $1 billion per year would be spent on VOC controls such as thermal and catalytic incineration and carbon absorption, far in excess of the amounts projected by the other studies.

### Environmental Business Journal

The April 1991 issue of *Environmental Business Journal* includes 1990 revenue estimates for the environmental industry by industry segment (air pollution control, instrument manufacturing, analytical services, consulting, and asbestos abatement). Growth for air pollution controls was projected to average 16% per year, or $6.3 billion in 1991, rising to $11.1 billion in 1996. The Journal noted that the bulk of the companies pursuing some piece of the air pollution control market are small, privately held firms. Publicly held companies reap 63% of the segment revenues, even though they comprise only 1% of the companies in this segment.

### The McIlvaine Company

The McIlvaine Company has published a comprehensive four volume report, "Air Toxics and VOCs," the only report known to the authors that specifically addresses technology and market forecasts for various aspects of air toxics and volatile organic compounds. The report estimated that more than $19 billion would be spent on compliance analysis, control technology, and measurement of air toxics and VOCs in the U.S. in the 1990's. In the area of incineration and absorption, market forecasts for equipment were as follows (by industry): chemicals, $1.4 billion; surface coating, $420 million; metals, $320 million; petroleum, $570 million; and "other," $2.36 billion.

### The Center for Waste Reduction Technology

The Center for Waste Reduction Technology (associated with AIChE) conducted a survey of users and vendors to generate estimates of the future market character for VOC control. The report was not published as of the time this market assessment was written, but an advance summary was published in the July 1993 issue of Chemical Processing magazine. Significant among the conclusions is the fact that users forecast that 70% of capital expenditures would be for streams of 5000 cfm or lower. Interestingly, the manufacturers did not see this trend to smaller units and continued to forecast that most sales would be for larger equipment. This may reflect a built in bias in the manufacturing community which is comprised mostly of manufacturers of larger units, the most popular products in the past.

## 5.3 PRODUCT POSITIONING ANALYSIS

The initial Alzeta product to be sold was a high performance inward fired ceramic radiant burner thermal oxidizer unit. Care was required to position the product among competing products and substitutes (such as carbon adsorption) and within market segments where competitive advantage was greatest and the company could quickly obtain a foothold.

### Distinguishing Product Characteristics of the Inward Fired Incinerator

- Highly engineered systems
- Modular systems
- Ultra-high DRE performance
- Instant on and off; suitable for batch processes
- Ultra-low $NO_x$ and CO
- Flow rates nominally 100 cfm to perhaps 5000 cfm initially
- Can incinerate flammable or nonflammable vapors (at appropriate concentrations)
- Can handle high or low vapor concentrations
- Can handle chlorinated vapors (but may require scrubbing of exhaust stream depending on exhaust concentrations of HCl)
- Factory assembly as opposed to field construction
- Premium priced product reflecting engineering and technology content, high performance
- Higher fuel consumption than regenerative or highly recuperated conventional thermal destruction units, but lower than high performance unrecuperated units.
- Can be designed for light weight, compact size, small footprint
- Initial low production rates (of the order of one unit per month growing with experience, resources)
- Semi-custom built units (as opposed to standard, built for inventory products)

- Moderate response time for new orders (12-16 weeks, shrinking with increased production and standardization)

## Types of Applications Best Suited for New Technology

Screening of the various VOC abatement segments narrowed appropriate applications to those that had the following requirements:

- Streams of up to perhaps 5,000 scfm with initial applications being preferably somewhat smaller. Larger streams would require major extensions of the technology, primarily addressing uncertainties in the areas of scale-up, and would carry the technology into market areas already served by established and entrenched competitors.
- Inlet temperatures ranging from ambient to about 400°F, the current limit for inlet temperature of the ceramic fiber technology. Higher temperatures may be possible later.
- Inlet concentrations ranging from concentrated (but diluted prior to combustion) to dilute, but preferably outside of explosive concentration limits.
- Chlorinated or nonchlorinated solvents, flammable or nonflammable (in dilute concentrations).
- Particle and droplet free streams, or streams that can be filtered to remove all particles or droplets that could cause plugging of the ceramic fiber matrix.
- Time varying stream concentrations.
- Batch or continuous destruction requirements.

Competitive analysis of the inward fired technology compared with other thermal destruction units and substitutes showed that product/performance competitive advantage could be obtained with applications having the following requirements (either singly or in combination):

- Requirement for very high destruction removal efficiency (DRE), typically above 99.5%. Competitive advantage becomes greatest when DRE>99.8% is required. This is a key competitive benefit of the technology.
- Requirement for quick response in batch processing (quick on and off) where "on-demand" performance is required. Competitive advantage is greatest if the

response time required is measured in seconds rather than minutes or hours. This is a key competitive benefit of the technology.

- Requirement for low $NO_x$ and/or low CO emissions. Low emissions of these pollutants simultaneous with high DRE provides competitive advantage in areas such as the Los Angeles Basin where smog and $NO_x$ are severe problems, but the advantage diminishes outside of these areas.
- Modular compact construction permitting factory assembly and simple installation at the site.
- Moderate fuel usage in batch operations having low utilization (that is, batch process control in which the thermal oxidizer operates less than 20%-30% of the time.

Because the inward fired burner technology cannot currently tolerate air inlet temperatures above about 400°F, such units cannot be operated with high levels of recuperation possible in other technologies, and as a result hourly fuel consumption is higher than highly recuperated units. Consequently, if no heat recovery is possible through some other means, the technology suffers from a competitive disadvantage in continuous operations since operating costs will be higher than for highly recuperated units, all other things being held constant. Consequently, the combination of competitive benefits for the inward fired unit alone is best in batch processes, particularly those requiring high levels of VOC destruction and/or quick response or low $NO_x$ emissions. A smaller but still significant competitive advantage exists in applications (batch or continuous) that require high DRE and/or low $NO_x$. These are predominantly in the Los Angeles basin.

Initial analysis showed the most attractive applications for the technology to be in the following areas:

- High DRE batch processing applications for control of chlorinated and unchlorinated solvent vapors emitted from semiconductor fabrication plants.
- Batch processing operations in single sheet printing operations (now coming under regulation).
- Solvent or gasoline or chemical loading and unloading operations.
- Soil remediation (vacuum extraction) applications requiring very high DRE because of location or toxicity of the solvent contaminating the soil or ground water.

- Possibly smaller area source categories such as dry cleaning that require high DRE performance of potentially carcinogenic chemicals (perchloroethylene in dry cleaning), batch control, compact unit size (for potential roof mounting), and low $NO_x$.

## 5.4 SUMMARY OF INITIAL MARKET FOCUS AND RATIONALE

Because of the diversity, complexity, and rapid change in VOC control markets, a focus strategy was required by Alzeta to avoid diffusion of its resources. The initial focus market segments are described below together with associated rationale.

### Semiconductor Fabrication

VOCs are heavily generated in the photolithography steps of semiconductor fabrication ("chip manufacturing") and in more limited amounts elsewhere in the manufacturing process. In many cases, manufacturers currently operate with no VOC emissions controls, a situation that is rapidly changing. This segment is recommended as the lead market for product introduction for the following reasons:

- Batch operations throughout the manufacturing process seemed to favor quick on and off capability of product
- High DRE performance is allegedly sought by users, although regulations do not yet impose such requirements except in the San Francisco Bay Area (where 98.5% control is required).
- Many potential users operate in $NO_x$-impacted localities
- Some users have plants in Europe where similar emissions restrictions are in force or will be applied, enlarging market.
- High cost of fabrication plants and density of equipment installations places a premium on small footprint and compact size.
- Most common flow rates are in the range of 100 to 5000 cfm, appropriate for the technology, and large enough to permit economies of scale to be obtained in initial, high cost manufacturing periods before economies of production rate are obtained.
- Customers are generally dissatisfied with existing incineration technologies they are now using, or which they have evaluated.

- Customers are accustomed to paying substantial amounts for high margin, highly engineered products, and have large capital expenditure budgets.
- Customers are sophisticated, knowledgeable, and receptive to a technical selling strategy which is appropriate to the product.
- Industry is under heavy pressure from air quality management districts, and will virtually certainly be hit hard by Title III air toxics regulations.
- Industry leaders allegedly tend to be aggressive, rapidly moving, and willing to adopt new technologies. Several of the larger companies have publicly indicated that they seek a zero discharge goal for their operations.
- Alzeta is located in the heart of Silicon Valley, and thus uniquely situated for product introduction and initial local product support.
- Clear competitive advantage, clear market access, and unique fit between product characteristics and customer needs.

## Soil Remediation via Vacuum Extraction

Alzeta has been active in applications of Pyrocore technology to soil remediation to remove gasoline which has leaked from underground storage tanks. Initial units used outward fired technology, and a prototype 100 cfm inward fired unit began operation in Hayward, California, in August 1991. The customer selected the unit for reasons of high performance and low emissions. Because benzene is commonly found in gasoline, stringent air toxics control regulations apply to incineration of gasoline fumes, particularly for installation located in densely populated areas. This segment deserves secondary focus for the following reasons:

- Technology already demonstrated in the application.
- Potentially large market with reportedly 30,000-50,000 gasoline tanks leaking and needing remediation.
- Applicable to soil remediation for soils contaminated with solvents including chlorinated solvents.
- Established linkages with soil remediators (customers).
- Units can meet toughest DRE and $NO_x$ standards in Los Angeles and San Francisco Bay air basins, the most tightly regulated areas for VOC control.

- Company is well established and well known to regulators in the California market where the most stringent rules apply.

However, this market segment suffers from the following disadvantages when viewed in the context of the inward fired incineration technology:

- Many established, lower cost competitors offering lower performance products.
- Smaller sizes of units makes it difficult to make attractive margins at low production rates.
- Substitutes making in-roads into the market (e.g., IC engines for concentrated streams, carbon absorption for dilute streams).
- Continuous operation negates batch operation benefits of the technology.
- Because installations are temporary, regulators do not require very high levels of DRE (in most cases) nor low levels of $NO_x$.

## "Other" Applications

Air toxics regulations will impact many other industries ranging from chemicals and oil refining to dry cleaners. Alzeta has had inquiries from Chevron USA concerning air toxics control in its Richmond, California refinery. While the company has limited current knowledge or presence in these other market segments, they should not be ignored, but viewed as opportunities for future sales once the technology is proven in its initial, chosen market niches. Therefore, activity should continue to focus (at a lower level) on these market segments for the following reasons:

- Very large potential market.
- Likely competitive advantages in applications requiring high DRE, low $NO_x$, and/or batch operation.
- Many possible strategic partners with whom Alzeta can team to address particular market segments. As an example, manufacturers of "concentrators" (rotary wheels that absorb dilute VOCs from large air streams and then release concentrated VOC streams in smaller, heated air streams) have contacted the company to explore use of the incineration technology for applications in $NO_x$ impacted areas. This is discussed in further depth later.

The following sections discuss the character, trends, and outlook of each of the selected market segments.

## Semiconductor Fabrication

### Character

"Chip manufacturing" is at the heart of virtually all high technology industries including computers, communications, aerospace, defense, and consumer electronics. It is an industry that competes on a worldwide basis, is rapidly changing, fiercely competitive, and consumes huge amounts of capital for plant and equipment associated with the manufacturing processes. Economy of scale is pushing suppliers to become larger and larger, but fewer and fewer in number. Increasingly specialized chip vendors subcontract to the large "merchant chip manufacturing companies" for their production needs. Pressure is constantly for performance and chip yield to reduce production costs, but the premiums are obtained by being the first with the best. Consequently, chip manufacturers are motivated to move quickly, maintain flexibility, build competitive advantage through advanced products and early product introductions, and they tend to have limited sensitivity to capital equipment costs.

### Trends

Chip fabrication plants are growing in size and complexity, and are increasingly being targeted by regulators because of their heavy use of chemicals including VOCs. As regulators reduce allowable emissions, manufacturers will be forced to "clean up their act" with regard to VOC emissions if they are to maintain production rates and flexibility in production operations. Additionally, fabrication plants located in Europe and the Far East will be forced to install control equipment similar to that which will be installed in the U. S. The industry seeks high technology solutions, and is dissatisfied with current incineration products.

### Outlook

Growth of the industry, the inability to easily change the chemicals used in fabrication processes, the desire for high performance high technology products, trend of regulations that will impact the use of chemicals employed, and lack of sensitivity to equipment cost all make the outlook excellent for the new technology, particularly in the photolithography sections of chip fabrication plants.

## Soil Remediation

### Character

Soil remediation, particularly using vacuum extraction techniques, has grown explosively in the last 5 years as more and more underground storage tanks are found to be leaking, and property owners are forced to clean up spills before property can be sold. The soil remediation industry is served by a wide variety of vendors ranging from small consulting companies to large engineering companies that offer the service as part of an overall package of environmental remediation and control expertise. Services are generally sold on a cost plus basis because it is impossible to know exactly what steps will be required to clean up a site, how long it will take, and consequently, how much it will cost. Nonetheless, the final users are very sensitive to cost and place considerable down side pressure on pricing from vendors offering cleanup services.

### Trends

Growth in the number of competitors has made soil remediation increasingly competitive, and as the business matures competitors constantly seek improved competitive advantage. From a business perspective, this has resulted in companies growing by acquisition so that they can bundle the full range of consulting, evaluation, analytical laboratory measurement, site drilling, soil clean-up, and final remediation thereby offering "one-stop shopping" to the property owner. Some remediators manufacture their own equipment, while others buy and resell or use under their own brand name.

Specifically in vacuum extraction, there is heavy pressure to minimize gas usage since this is the largest variable cost associated with soil remediation using this methodology. Consequently, users want higher incineration efficiency, but also face increasing demands for high DRE and low $NO_x$. To further reduce costs, some vendors are now dividing the soil remediation process into three phases. Initially they use IC engines to operate on the concentrated well gas stream since the engines can operate without supplemental gas during this phase. As the stream becomes more dilute, they switch to gas fired thermal destruction units. In the final remediation phase when the well stream is very dilute, they switch to carbon absorption when it becomes cost competitive with incineration. All units tend to be skid mounted, and increasingly, they are being trailer-mounted as well to provide maximum flexibility.

### Outlook

Soil remediation is a large and growing business, and the trend for growth is likely to continue as environmental standards continue to tighten. Competitive pressure is rapidly increasing, and an industry shake-out is possible in the near future. Buyers are cost sensitive, but need increasing levels of performance. Therefore, in some segments of the soil remediation market, particularly in California (where regulations are the most stringent) there may remain a significant market opportunity. This must be further defined through additional market research.

## Other Applications

### Character

"Other" applications for the incineration technology are highly varied ranging from chemical and refining plants to dry cleaners, coating and printing, loading and unloading, plastics, and many others. The key characteristic is diversity which means that this segment actually consists of many subsegments having radically different market requirements. Continuing market research will be required to define the best subsegments to target for product introduction.

### Trends

While the growth rate of many of the industries of interest are modest or flat, the impact of air toxics regulations could be enormous. High levels of uncertainty and concern are prevalent in many market segments, particularly oil refining and chemicals. Many equipment suppliers are targeting some or all of these segments, so competition is likely to be fierce, but the level of diversity suggests that there will be niches that can be addressed with the new technology since it provides several competitive advantages that should meet some specific market needs.

### Outlook

The outlook in these other market segments is highly uncertain, but also could be highly promising given the level of diversity and the competitive advantages that the burner may provide in some segments. The key is market research to identify where the first moves should be made. The prospects for substantial growth in these segments in the near future is excellent.

## 5.5 INITIAL COMPETITIVE ADVANTAGE SUMMARY

Assessment of the market and an evaluation of the competitive advantage of the new product are the most crucial areas in the evaluation of the business opportunity. The following subsections discuss the technology in the light of competitive evaluation with other incineration products, and identify the key areas of competitive advantage that must be stressed to achieve market success in the face of a diverse cast of competitors.

### Technology

The inward fired Pyrocore thermal oxidizers are clearly differentiated from the primary competitors, direct flame thermal destruction units, and thermal catalytic units. Direct flame (or "open flame") units use a conventional diffusion flame to directly incinerate the VOCs in the flame envelope, or indirectly through heating of the VOCs to a sufficiently high temperature for a sufficient duration that VOC destruction takes place. Flame thermal destruction unit performance is based on the "three T's of incineration: time, temperature, and turbulence" that all combine to assure that high levels of VOC destruction take place. Higher DRE levels require more time, temperature and turbulence all of which equate with higher capital and operating costs. Higher cost and larger units that operate continuously tend to be recuperated, capturing a portion of the exhaust heat, to reduce gas consumption. Some units (such as pebble bed units) are regenerative meaning that the combustion occurs in a heat transfer media through which flow is cycled forward and backward to capture exhaust energy. Recuperated units are generally capable of capturing 60-90% of the exhaust heat, while regenerative units (which tend to be much larger and heavier) can capture up to 95% of the exhaust heat substantially reducing fuel cost, but at the cost of high capital expenditures. The simplest direct flame units consist of little more than a burner and small combustion chamber, and have low purchase costs. At the other extreme, large highly recuperated or regenerative units can cost over $1 million, have high maintenance costs, and require considerable site preparation and field erection. Sizes range from very small to very large. Direct flame units are the mainstay of VOC incineration in the U. S. today.

Thermal catalytic units rely on a combination of more moderate temperatures together with a catalyst bed to achieve VOC destruction. DRE levels comparable with low performance flame units are achievable at lower operating temperatures so less fuel is needed. Catalytic units thus offer the benefits of regenerative or recuperated direct flame designs, but in a smaller package which can make siting easier. Offsetting the benefits of catalytic oxidation is the fact that catalysts are expensive, frequently life limited, and can be poisoned by contaminants in the VOC stream. Their cost is generally intermediate between the simplest direct flame units, and the most complex regenerative or recuperated direct flame products. Sizes tend also to be intermediate, being larger than the smallest direct flame units, and smaller than the largest units installed at large industrial facilities.

## Performance

The key performance factors for thermal oxidizers are destruction removal efficiency (DRE, percent of incoming VOCs destroyed by the unit), fuel consumption, emissions of other pollutants ($NO_x$ and CO, primarily), and for batch operations, ability to cycle on and off quickly. Key cost factors are installed cost, operating cost (primarily for fuel), and maintenance cost for replacement, refurbishment, spares, down time, etc. Additionally, some markets require extreme reliability and availability, while others (such as soil remediation) can tolerate extended down time and shutdowns because this does not substantially impact other operations. Finally, some market segments place a premium on small size and modular operation because of difficulty in siting units in and around existing industrial processes. In these applications (primarily in semiconductor plants where space is expensive, $1500/square foot, and frequently not available except in small chunks), "small is beautiful."

In these key performance areas, the technologies compare as follows:

- **Destruction Removal Efficiency:** The Alzeta product has a clear competitive advantage. Direct flame units typically achieve 95% DRE in simple units, rising to 99.8% in more complex units having higher operating temperatures, larger combustion chambers, higher fuel consumption, and generally higher $NO_x$. Catalytic oxidation units typically operate in the range of 95-99% with higher levels generally requiring exceptional catalysts or higher temperatures which shorten catalyst life. In contrast, the inward fired technology can routinely achieve 99.9%-99.99%+ DRE without special requirements for time, temperature, and turbulence. Indeed, it appears that the performance of the new technology is largely independent of the traditional "three T's" as long as minimum acceptable operating temperature (about $1500^oF$-$1600^oF$) is maintained.
- **Fuel consumption:** Direct flame units can substantially reduce fuel consumption through application of recuperation or incineration, while catalytic units reduce fuel

consumption through lower operating temperatures. Currently, the ceramic fiber inward fired Pyrocore technology is limited to preheat temperatures of about 430°F permitting only about 30% recuperation. This compares to 60-95% recuperation achievable with direct flame units. Consequently, over some operating regimes, the Pyrocore technology operates at a competitive disadvantage. However, when high levels of DRE are required, direct flame units become sizable, expensive, and operate at higher temperatures which makes materials of construction much more expensive. In these regimes, the Pyrocore technology can begin to compete on life cycle cost basis having lower capital cost, but higher fuel consumption. In batch operations, the benefits of recuperation and regeneration vanish because such units are unable to start and stop, but must operate continuously, constantly consuming fuel. For batch operations that have less than about 30% duty cycle, the Pyrocore units have a fuel consumption advantage.

- **Other Emissions:** In many regions, emissions of $NO_x$ and CO are being increasingly regulated, and $NO_x$ and UHC standards will spread to control atmosphere oxidant formation. In this area, the Pyrocore technology has a clear competitive advantage over direct flame units with $NO_x$ levels well below 10 ppm (corrected to 3% oxygen) compared to 100 ppm for direct flame units, and higher if high levels of DRE are required (which requires higher flame temperatures in direct flame units). Catalytic units tend to have higher levels of UHC and CO emissions that make them unsuitable for use in many tightly regulated air basins. In the future, the low $NO_x$ levels available with the new technology will provide increasing competitive advantage.

- **Batch Operations:** In theory, direct flame units without recuperators can start and stop in several seconds, although in practice several tens of seconds are more typical. Catalytic oxidation units must heat the catalyst bed before becoming effective, and so require minutes to start up. Recuperated and regenerated direct flame units can require many hours to several days to warm up prior to operation. Consequently, in batch operations requiring quick start up, the Pyrocore units offer a clear and nearly overwhelming competitive advantage because of nearly instantaneous effectiveness, and reduced fuel consumption compared to direct flame units which must be unrecuperated, yet burn large quantities of fuel (to attain high temperatures) to achieve the high DREs routinely attainable with the Pyrocore technology. Ability to cycle quickly and without difficulty is a key competitive benefit of the new technology, and must figure prominently in the product introduction strategy.

- **Equipment Pricing:** Evaluation of competitive equipment in soil remediation has shown that the lowest cost direct flame units cost about half what a comparable Pyrocore thermal oxidizer would cost, but when specifications require low $NO_x$ or high DRE (99.8% or higher), equipment costs become comparable. In semiconductor VOC control, the same rule generally applies. Simple, nonrecuperated direct flame units have lower initial cost, but lower performance and generally higher $NO_x$. When high DRE performance is required, and in particular when "on-demand" operation is required for batch processes, Pyrocore units are competitively priced, yet provide superior DRE and lower $NO_x$, frequently with lower fuel consumption. When compared with highly recuperated units or generative direct flame units of comparable size, Pyrocore thermal oxidizer units have a substantially lower installed cost, and for batch operations, generally a lower fuel consumption (life cycle basis) as well. The Pyrocore thermal oxidizer units are therefore a premium priced product, but offer premium performance such that perceived customer value is good and the equipment can be competitively priced in appropriately chosen market niches.
- **Equipment Size, Compactness:** Inward fired Pyrocore thermal oxidizers are comparable in size to the smallest and simplest direct flame thermal destruction units (those consisting of simple duct burners or having small combustion chambers) and are much smaller and lighter than recuperative and regenerative units. The Pyrocore units will be factory assembled on skids, and shipped ready to fire at the customer's site. In applications where space is at a premium (particularly in chip fabrication plants or retrofits cramp factory facilities), the compact systems offer clear competitive advantage because they can be sited close to sources of emissions, or installed on rooftops. Intel seeks units that are easily moved from one location in a plant to another so that changes in factory layouts and operations can be quickly achieved. Units may even be fabricated with integral wheels to facilitate this process. Therefore, in selected market niches, the small size and light weight can offer substantial competitive advantage.

## Product Positioning and Rationale

The analyses above and elsewhere suggest that initial product introduction be guided by the following criteria:

- **Premium priced product for premium applications:** The competitive advantage of the Pyrocore incineration technology is not in low production and sales price, but in offering very high performance for a premium price to customers willing to pay a premium price. This suggests sophisticated customers with large capital equipment budgets, customers that will make repeat buys after a comprehensive selling cycle.
- **Initial focus where there is a clear competitive advantage**: Rather than a frontal assault on entrenched competitors in mature market segments, the approach must be to focus where competitors are weakest, but where customer requirements are stringent. This means initial focus on those segments where there is a combination of competitive advantages. The best market segments for initial penetration are, therefore, those which value some combination of the key product features:
  - Requirement for high DRE
  - Requirement for low $NO_x$ and other pollutant emissions
  - Requirement for batch processing, instant on and off, "on-demand" operation
  - Premium on compact equipment size, light weight, modular construction
  - Stream sizes in the range of up to 3,000-5,000 cfm (at least initially) addressable with factory fabricated systems
  - Minimal downward pressure on equipment capital or operating cost.
  - Preferably sophisticated customers receptive to a highly technical sell, and located (at least initially) close to Alzeta facilities to permit cost effective coordination and site testing.

A match-up of product competitive advantages and company requirements with prospective market segments based on market research accomplished to date suggested that the best initial market opportunities exist in semiconductor fabrication plants starting with those located in California where environmental standards are most severe, and field services can be delivered most cost effectively. (See earlier section for more discussion on initial product positioning.) Secondly, a lesser effort should focus at a lower level in soil remediation applications since the company already has an established position in this market, and the trend of environmental standards is placing increasing pressure on users for improved performance. Finally, additional market research should be conducted to assess potential opportunities in the vast "other applications" market areas including chemicals, refining, and the myriad of other industrial processes that will be impacted by Title III regulations.

## Proprietary Know-how

Currently, Alzeta's proprietary know-how centers on the manufacture and application of the porous ceramic fiber radiant burner technology that is the heart of the inward fired incineration products. This technology is protected through a series of patents, patent applications, and trade secrets. As the product introduction proceeds, additional proprietary information concerning details of various applications will be collected, and will help to improve competitive advantage. Additionally, the company is preparing and will continue to prepare patent applications covering details of the technology, applications, and other features that are identified as protectable as product development and introduction proceeds. Patent protection is and will remain a key element in the maintenance of competitive advantage.

# SECTION 6

# RESULTS AND CONCLUSIONS

A summary of significant results and conclusions based on the work completed in the ARCS project are presented in this section. These results and conclusions are presented under topic headings that reflect the content of Sections 2 through 5 of this report, and are presented in approximately the order that topics are discussed in the text.

## Technical Background

The benefits of porous surface radiant burners have been demonstrated in commercial and industrial applications. These benefits include the ability to provide uniform and well controlled heat flux to a load or process, the ability to shape the burner surface to match load requirements, and the ability to provide low emissions of $NO_x$ and CO while operating at conditions typical of existing boilers and process heaters. A major factor limiting the use of the Alzeta Pyrocore porous surface burner in industrial applications was a maximum load temperature for the burner of approximately 1000°F.

The primary goal of the ARCS project was to develop an improved radiant burner that would extend the operating range of current burners to higher process temperatures. More specific performance targets included:

- Increase the maximum use temperature of the burner from the typical 1800°F limit at the start of this project to 2100°F or higher, with no decrease in burner life
- Increase the maximum load temperature of the burner from the typical 1000°F limit at the start of this project to 1600°F-1800°F, again with no decrease in burner life
- Increase the operating life of the burner when operated at 1800°F burner surface temperature and 1000°F or lower load temperatures
- Maintain $NO_x$ and CO emissions levels at less than 30 ppm when operating at 10 to 20% excess combustion air

Potential applications that could use the improved burner product were identified as:

- Thermal oxidation of volatile organic compounds (VOCs) or other gaseous wastes
- Drum heating or direct drying of paper or textiles

- Refinery and chemical processes, where either a fragile fluid (such as petroleum, heat transfer oil, glycol, etc.) or a catalyst bed is to be heated
- Metals processing applications where loads are heated directly

## Advanced Radiant Burner Development

In order to improve the performance of porous surface burners while maintaining the benefits of existing products, the product improvement approach used in this project was as follows:

- Assume that the current manufacturing process (vacuum casting from a slurry of burner constituents) provided the best method of fabricating relatively low cost porous surface burners, and therefore would be used in manufacturing the advanced radiant burner.
- Similarly, the current approach of using fine fibers in a highly porous mat provides the best combination of high radiant output, low heat transfer back through the pad, and resistance to thermal shock, and therefore primarily fibrous materials (and some fiber coatings) would be investigated. Fibrous materials with oxidation resistance at high temperature and high emissivity provide the best performance. Burner performance improvements would most likely come from the incorporation of materials with these properties into the burner.

Product development was conducted in three steps: a preliminary materials analysis, a more rigorous statistical test program to optimize the new burner formulation, and an extended life test of a larger burner in the Alzeta combustion lab. Significant results and conclusions based on the product development effort are as follows:

- Replacing relatively low cost ceramic fibers in the Pyrocore burner formulation with ceramic fibers with higher use temperatures did not increase burner life in high temperature operation. Most of the high temperature fibers investigated were oxide-based, had relatively low emissivity, and therefore operated at a significantly higher burner surface temperature (to provide equivalent radiant flux), which was believed to accelerate burner aging.
- Burner emissivity increases were achieved through the use of different material additives and surface treatments. These increases had the dual effect of raising the radiant energy output and lowering the burner surface temperature required

to achieve this output. Some of these materials produced significant gains in emissivity but only at the expense of decreased life of the burners, due to the destruction of the emissivity agent in the combustion environment. The only treatment that appeared to provide increased emissivity and equivalent or increased life of the burner was the addition of the HT fibers.

- Following the first-cut screening, over 100,000 burner-hours of testing were completed in an Alzeta test facility capable of testing 16 burners simultaneously. Burner performance and life were analyzed using standard Analysis of Variance statistical methods. The goal of these tests was to determine an optimum burner formulation utilizing the HT fibers. A final burner formulation was developed to meet the project performance and cost goals.
- A final test of the advanced burner formulation was conducted on a 5 $ft^2$ burner in a high temperature Alzeta test facility. Tests were conducted at simulated reformer conditions for 4000 hours of continuous operation. Performance degradation was demonstrated to be minimal over this period. A visual inspection of the burner following the test also indicated that the advanced burner formulation provided improved performance at high temperature.

### Thermal Oxidizer Field Test

To verify field operation and performance of the advanced radiant burner, an inward fired VOC thermal oxidizer was selected as the host site. The specific oxidizer application was for batch operation of a photolithography process using xylene for silicon wafer circuit printing. The host site was ECI Semiconductor in Santa Clara, California (now Semtech).

The system went on-line July 30, 1995 and has been operating since that time. In the typical mode of operation, the system was operated from Sunday evening to Friday evening, and then shut down over the weekend. Alzeta monitored the system at least once per week for the first 6 months of operation.

Emissions tests to meet Bay Area Air Quality Management District requirements were completed in November 1995. The source test was conducted by Best Environmental, and results of the tests are attached as Appendix D to this report. Bay Area AQMD regulations require 98.5% thermal destruction efficiency of hydrocarbons. As seen in the attached test report, the Alzeta system demonstrated 99.5% thermal destruction.

## Thermal Oxidizer Market Analysis

The market for VOC thermal oxidizers is driven by emissions regulations. VOCs are recognized as being ozone precursors, and in the case of a smaller group of VOCs, as air toxics subject to Title III of the Federal 1990 Clean Air Act Amendments. Primary sources of VOCs from industry are chemical manufacturing, surface coating, metals manufacturing, petroleum refining, and semiconductor manufacturing.

The Alzeta advanced radiant burner in the inward-fired adiabatic design provides the following competitive advantages: highest levels of destructive removal efficiency (particularly with difficult to destroy halogenated compounds), very low emissions of $NO_x$ and CO, rapid on-off operation in batch mode, compact equipment size, and the capability of reducing fuel usage by combining the oxidizer with a VOC concentrator in applications where the VOC stream is at a very low concentration.

# APPENDIX A

# BURNER DEVELOPMENT RESULTS

## A.1. FIRST-CUT MATERIALS EVALUATION

After performing some initial materials screening in-house, Alzeta was encouraged by DOE to identify and work with outside materials consultants. The purpose of the consultants was to aid in a broad review of materials opportunities prior to narrowing our focus to a few selected materials for more focused testing. Both the initial Alzeta materials investigation and the results of the consulting work are presented in this appendix. Over the course of the project we met with three consulting sources concerning the development of a high temperature radiant burner. These were Dr. M. Srinivasan of Material Solutions, Grand Island, New York, Timothy Gardner and Frank Gerstle of Sandia Laboratories in Albuquerque, New Mexico, and Dr. Andreas Glaeser of the Materials Department of the University of California at Berkeley.

Dr. Srinivasan's primary contribution to the project was to help investigate the mechanisms of degradation of the existing ceramic fiber burner materials. Based on thermodynamic calculations performed by Dr. Srinivasan, and our laboratory results, we were able to gain a better understanding of the chemical interaction between the fibers, inorganic binders and emissivity agents used in the standard Pyrocore burner. These interactions contribute to fiber degradation that is accelerated as operating temperature of the burner is increased. At lower operating temperatures (say 1800°F or lower), the benefits provided by this chemical interaction of the constituents of the Pyrocore product outweigh the undesired fiber degradation, explaining in part the success of the burner formulation in applications that existed prior to the start of the DOE project.

The work with Tim Gardner at Sandia-Albuquerque suggested alternative emissivity agents (metal alloy powders) and fibers with higher emissivities. These suggestions came about through literature searches and consulting sessions at Sandia.

Dr. Andreas Glaeser's contribution to the project was to help us understand the chemical interactions between the emissivity agents and the ceramic fibers in the Pyrocore product. With Dr. Glaeser we were able to extend our understanding beyond the limitations of thermodynamics and consider the effect of the activities of the species present in the product.

Two basic strategies were considered to increase the temperature capability and the operating life of the burner. One was to increase burner emittance through the use of emissivity agents that would be added to the burner formulation or to the inorganic binder. Similarly, high emissivity fibers could be used to make the burner. The second approach was to utilize commercially available fibers with a higher "temperature rating" that would resist degradation over time. Temperature rating in this context is something more complex than a melt temperature or recommended maximum use temperature, but would be useful in ranking the capability of different fibers to operate for up to 25,000 hours at temperatures above 2000°F. The high temperature fibers investigated included high purity alumina, alumina-silica, alumina borosilicate, and fibers of primarily silicon-carbide composition.

To help understand how an increase in burner emissivity affects burner temperature and increases burner life, consider the basic radiant heat transfer equation for gray bodies:

$$Q_{1-2} = \sigma F_{1-2}(\varepsilon_1 T_1^4 - \varepsilon_2 T_2^4)$$

where $Q$ = energy per unit time

$\sigma$ = Stefan-Boltzmann constant

$F$ = view factor

$\varepsilon$ = emissivity

$T$ = temperature

If the radiant heat transfer from the burner to the process, $Q_{1-2}$ , is to remain constant, and emissivity and temperature of the process remains the same, an increase in the emissivity of the burner will result in a lower burner surface temperature.

To increase burner emissivity, three methods were explored. 1) Modification of the existing inorganic binder by adding a nitrate or a very fine powder to enhance the binder emissivity. 2) Addition of metal powders that would radiate heat at the hot burner surface while reflecting heat outward from the interior of the burner. 3) Use of fibers with a higher emissivity. Table A-1 outlines the materials investigated for improving the emissivity of the burner.

## TABLE A-1. EMISSIVITY MODIFICATIONS TO THE PYROCORE BURNER.

| Binder Modification | Metal Powder | Fiber Modification |
|---|---|---|
| NiO | Cu | Nicalon SiC |
| $Fe_2 0_3$ | Cu-Ni | Nextel 312 with NiO |
| $SiO_2$, (surface coating) | Ni | HT fibers (Alzeta proprietary fiber) |
|  | Zn |  |
|  | Pb |  |
|  | Al-Li |  |
|  | Al-Si |  |

A literature review suggested that NiO should be the most effective binder or fiber additive for increasing burner emissivity. As little as one percent nickel oxide in alumina was shown to significantly increases emissivity of the oxide (Reference A-1). Steps were taken to incorporate NiO in the burner with the intent to keep burner emissivity high after the Pyrocore's conventional emissivity agent degrades.

Two strategies were devised to incorporate NiO in the outer part of the burner. One method involved formulating a binder of an alumina colloid and nickel nitrate. The nitrate decomposes to NiO when the burner is operated. The approach utilized a two layer burner made with a Pyrocore underlayer with a surface layer made up of high-alumina fibers with the nickel nitrate/alumina phase acting as a binder and emissivity agent.

The other method involved incorporating the NiO into the fibers themselves. 3M Corporation has fabricated fibers with 20 wt% NiO in their Nextel 312 product (Reference A-2). 3M agreed to supply Alzeta with enough Nextel 312 fiber with 20 wt% NiO to fabricate several burners. Although the fibers supplied by 3M were larger than the standard fiber used in vacuum forming the burners, (10 µm-20 µm vs. 2 µm-3 µm), it was found that a serviceable burner could be fabricated with the larger diameter fibers.

Two burners with high-alumina fibers and NiO-$Al_2O_3$ binder and two burners with the 3M fibers were fabricated. One of each of the burner types was fired for about 20 minutes for baseline values, and the other burner of each type was fired for 75 hours in simulated reformer conditions. In addition, a sample of the nickel nitrate-alumina colloid binder was calcined at 1832°F for 1 hour to obtain a sample of the binder.

Table A-2 summarizes the radiant performance of the NiO-$Al_2O_3$ binder burner (NiO), the 3M 20 wt% NiO fibers (3M), a Pyrocore burner, and a burner with high-alumina fibers and alumina binder without NiO (fibers only). As may be seen, both NiO burners have radiant emissivities similar to the Pyrocore burner when new. However, the 3M burner and the burner made up of fibers without emissivity agents have temperatures higher than the Pyrocore. It was observed that the flame front receded into these burners along with an increase of temperature. While the radiant efficiency is good, the higher temperatures lead to increased fiber degradation. In contrast, the Pyrocore and burners with the $Al_2O_3$-NiO binder had combustion only at the surface and were cooler.

TABLE 2. SUMMARY OF RADIATION PROPERTIES FOR BURNERS WITH NIO ADDITIONS

| Composition | Time (hrs) | Temp (°F) | Calculated Emissivity |
|---|---|---|---|
| Baseline - Pyrocore, with emissivity agent | 1 | 1920 | 0.37 |
| Pyrocore, no emissivity agent | 1 | 2488 | 0.21 |
| NiO-$Al_2O_3$ binder | 1 | 2250 | 0.41 |
| NiO-$Al_2O_3$ binder (After 75 hours of operation) | 75 | 2087 | 0.22 |
| 3M $Al_2O_3$-NiO Spinel fibers | 1 | 2530 | 0.41 |
| 3M $Al_2O_3$-NiO Spinel fibers (After 75 hours of operation) | 75 | 2360 | 0.16 |

## Oak Ridge National Laboratory HTML Investigation

To help understand the behavior of NiO in the burner, samples were studied at Oak Ridge National Laboratory (ORNL) in the High Temperature Materials Laboratory (HTML) under the Users Program. Samples of burners with the 3M fibers and with NiO added to the binder were taken to ORNL and analyzed. The instruments used at the HTML were the field emission scanning electron microscope, (FE-SEM), x-ray diffraction, (XRD), and scanning auger microprobe, (SAM, or simply auger). In addition, a few samples were investigated with energy dispersive x-ray spectroscopy, (EDS). The following is a very brief summary of the investigation at the HTML.

- XRD revealed the crystalline phases initially present in the NiO-$Al_2O_3$ binder sample to be NiO, (90 wt%), with the spinel structure $NiAl_2O_4$ accounting for the remaining 10 wt%. All of the $Al_2O_3$ formed the spinel structure $NiAl_2O_4$ (crystalline alumina alone was not detected).
- These findings indicate the nickel nitrate is effective with respect to introducing NiO to the burner. The NiO-$Al_2O_3$ residual binder, (20 minutes firing time), starts out nickel-rich through the bulk compared to the surface. However, after firing for 75 hours, considerable Ni depletion is observed, with the surface nickel-rich compared to the bulk.
- Analysis of the 3M fibers with NiO yielded similar results. XRD revealed that a burner with 20 minutes firing time was 98 wt% $NiAl_2O_4$ spinel phase. The remaining phase was $\alpha Al_2O_3$, probably due to the presence of the binder.
- The 3M fiber burner that had 75 hours of firing time in a simulated reformer environment saw a reduction of the $NiAl_2O_4$ spinel phase from 98 wt% to 18% with $\alpha Al_2O_3$ increasing to 82 wt% from 2%.
- Both the 3M fiber with NiO and the binder with NiO added appear to have more Ni at the surface of the fiber relative to the bulk after 75 hours of operation in a simulated reformer environment.

The burners were aged for an additional 155 hours. Observations of the burners indicated that the loss of NiO results in loss of color to the burner. When new, the NiO-$Al_2O_3$ binder and the 3M burners are green. After aging, the green tends to blue, then white. It appears the greatest aging, (whitening), tends to occur in the fired zones. Areas of the burner where the gas flow is the least have greater retention of color and material. After 75 hours, the 3M burner had areas where the fibers had turned white at the surface. These areas were quite weak and friable with some material loss. As aging continued, more patches of fiber were lost. After 230 hours, most of the firing occurred in the zones where the fibers were lost due to a lower pressure drop in these areas. Areas where the 3M fibers remained appeared to be underfired, and the loss of the blue color seemed to stop. The temperature was just about the same as in the fired areas because the burner was enclosed in an insulated tube to maintain 1800°F walls. The lack of further color loss in underfired areas suggested that the loss of NiO was related to the combustion process rather than temperature.

A similar aging process was noted for the NiO-$Al_2O_3$ binder burner. But this burner seemed to have a more uniform flame distribution and aging. After 75 hours, the surface of the burner was white with a blue tint just below the surface. "Islands" of material about 1/8 inch diameter remained while the surrounding surface eroded. After 230 hours, most of the NiO-$Al_2O_3$ layer had ablated away. Around the base of the burner, where the firing rate was the least, the pad remained largely intact and blue in color. Once again, this suggested the NiO loss is related to the combustion process.

It seemed likely that the Ni in the oxide was being reduced at the surface to a suboxide or metal. Any CO present reacted with the nickel to form the carbonyl gas and was lost from the burner. The higher concentration of nickel at the surface was probably due to the rate of carbonyl formation being slower than the rate of nickel reduction. The reduction process caused a build up of nickel and a concentration gradient of NiO, driving the diffusion process transporting nickel oxide to the surface. It appeared that the addition of NiO to the burner was not a good emissivity enhancing material because the exposed NiO would eventually be lost due to combustion zone reaction.

## Investigation of Other Emissivity Additives

Other emissivity agents included $Fe_2O_3$, silica, and various other metal powders. $Fe_2O_3$ was added to surface of the burner by coating the burner with a mixture of binder and $Fe_2O_3$ powder. Emissivity was found to increase, but the life of the burner decreased. It appeared that the iron oxide was reduced in a fashion similar to the NiO and was lost over time in the combustion zone.

Silica additions to the burner were made by way of a colloid and as a precursor that decomposed to $SiO_2$ in the combustion zone. The silica improved the burner performance with respect to radiant efficiency and emissivity. However, a crust developed on the surface of the burner that seemed to make the burner physically less durable as it was prone to cracking. When the quantity of silica was decreased to reduce the crust, the improvement on burner life was also reduced.

None of the metal powders showed improvement with respect to burner life, emissivity, or temperature capability. Copper and its alloys significantly decreased life by forming a low melting point eutectic that created holes in the burner. Nickel was lost over time in the combustion zone, while zinc and lead acted similar to copper by reducing the eutectic melt temperature below the combustion temperature. The aluminum alloys showed initial improvement over the standard emissivity agent(s) in the Pyrocore product, but actually reduced the life of the burner operated in typical reformer conditions.

In summary, most of the emissivity modifications to the standard Pyrocore product had limited benefit to burner life. However, the addition of the HT fibers to the Pyrocore formulation resulted in a significant lifetime increase. While a standard Pyrocore burner operated for 1000 hours transferring heat to hot walls, the addition of metal fibers allowed the burner to operate at the same conditions for more than 6000 hours. At that point, the burner was removed to allow analysis of the surface material. Table A-3 summarizes the effect of the emissivity enhancement techniques investigated.

**TABLE A-3. EMISSIVITY MODIFICATIONS TO THE PYROCORE BURNER.**

| Emissivity Treatment | Material Used | Burner Performance Relative to Standard Pyrocore |
|---|---|---|
| Binder Modification | NiO (from the nitrate) | Worse |
| Binder Modification | $Fe_2 0_3$ | Worse |
| Binder Modification | $SiO_2$, (surface coating) | Improved, however, a burner crust Is developed. |
| Fiber Modification | Nicalon SiC | Worse (fiber degradation) |
| Fiber Modification | Nextel 312 with NiO | Worse (fiber degradation) |
| Fiber Modification | HT fibers added | Much improved |
| Metal Powder | Cu | Much worse |
| Metal Powder | Cu-Ni | Much worse |
| Metal Powder | Ni | Worse |
| Metal Powder | Zn | Worse |
| Metal Powder | Pb | Worse |
| Metal Powder | Al-Li | Worse |
| Metal Powder | Al-Si | Worse |

High emissivity ceramic fibers were not successful in increasing burner life. It appears that fibers such as Nicalon SiC and the 3M Nextel with NiO degrade rapidly and may actually make the burner more susceptible to flashback. The high temperature HT fibers did improve performance, and optimization of a burner formulation that included the HT fibers became the focus of further experimental work described in Section A.2.

## Higher Temperature Ceramic Fibers

The other strategy to increase the temperature capability of the Pyrocore burner was to investigate ceramic fibers that are rated at higher temperatures. The fibers used in the conventional Pyrocore have a recommended application temperature of 2300°F while high-alumina fibers are rated up to temperatures in excess of 2800°F. Table A-4 summarizes the commercial fibers that were investigated during the project.

TABLE A-4. CERAMIC FIBERS AND THEIR TEMPERATURE RATING.

| Fiber | Composition | Manufacturer's Recommended Temperature Rating |
|---|---|---|
| Pyrocore Ceramic Fiber, Carborundum | Natural Alumina-Silica | 2300°F |
| Saffil, ICI | Alumina | 3000°F |
| Alumina-Silica, Rath | Alumina and Alumina-Silica | Up to 3000°F |
| Fibermax, Carborundum | Mullite | 2800°F |
| Nextel 312, 3M | $0.62\ Al_2O_3$, $0.24\ SiO_2$, $0.14\ B_2O_3$ | 2200°F |
| Nextel 440, 3M | $0.7\ Al_2O_3$, $0.28\ SiO_2$, $0.02\ B_2O_3$ | 2500°F |
| Nextel 440 Ultrafiber, 3M | $0.7\ Al_2O_3$, $0.28\ SiO_2$, $0.02\ B_2O_3$, (3μm diameter) | 2500°F |

In all cases, the higher temperature fibers showed significantly shorter lifetimes compared to the standard Pyrocore product when operated in reformer conditions. Alumina fibers caused the burner to operate at high surface temperatures and broke down rapidly, apparently due to grain growth. High purity alumina-silica (mullite and alumina-mullite) fibers behaved similarly with high surface temperatures and reduced lifetimes. The Nextel products also showed increased surface temperatures. After relatively short times at reformer conditions, the Nextel product degraded, apparently due to loss of the $B_2O_3$ and grain growth.

## A.2 STATISTICAL EVALUATION OF MATERIALS AND BURNER FORMULATIONS

The development of the Advanced Radiant Combustion System (ARCS) consisted in large part of investigating the components of the ceramic fiber burner formulation and their contribution to the radiant output and low $NO_x$ emissions performance of the burners. In order to ensure that the testing was done in such a manner as to investigate most of the possible reactions and interactions while still maintaining a manageable scope and sample size, the experiments were planned and executed using statistical design and analysis procedures. Each burner was tested before and at 1000 hour intervals during testing. The data from this testing were input to a computer spreadsheet where they were analyzed using the technique of Analysis of Variance (ANOVA). In the ANOVA technique, the variance between the burners which could be assigned to a specific cause was compared to the variance expected or demonstrated to be due to random variation in burner performance. If the nonrandom variances were significantly larger than the random variance, then the difference is called a real effect. Otherwise, the differences could not confidently be assigned to any one cause, and the effect would be called undetermined or nonexistent. A separate ANOVA analysis was performed on each of the following: $NO_x$ emissions (corrected to 3% $O_2$), radiant efficiency and, in later tests, burner pressure drop data sets.

Experiments were performed using Alzeta's simultaneous, 16-bay, accelerated life-test facility and 0.20 $ft^2$ cylindrical Pyrocore™ style burners. This allowed up to 16 burners of the desired test formulations to be fired under approximately identical conditions. A summary of the formulations tested is presented with each ANOVA table. Screening was performed in a separate facility where the firing rate was kept at a constant value (100 MBtu/hr-$ft^2$ of the average of the surface areas of the array of test burners), and the air/fuel ratio was held at 15% excess air (10.95 to 1). Burner screening consisted of measuring the radiant output (using a radiant power meter), surface temperature (using a two-color infrared pyrometer), and the emissions (enclosed in a quartz tube and sampled by Alzeta's calibrated emissions testing bench).

It was decided that the initial avenues for testing lay in two major directions. One was to replace the current ceramic fiber formulation with a different ceramic which had a higher melt temperature and was therefore able to withstand higher operating temperatures in order to allow increased radiant output with little increase in the $NO_x$ emissions. The other method was to exchange part of the ceramic fibers for a different type of fiber altogether, which would be a more efficient emitter of radiant energy and in that way allow increased radiant output without a large increase in temperature and the correspondingly large $NO_x$ emissions increase.

To this end, lifetime tests were planned using the ANOVA method. These results are described in this section. The first statistical test plan was set up in Lifetime Test #6 (LT6). In this test there were four parameters (factors) varied between two levels. The HT fiber type was varied between two types (suppliers) of fiber. The ceramic fiber was varied between the current fiber and a higher melting fiber. The effect of the emissivity additive and the amount of post-manufacturing surface treatment on the performance of the burners was investigated by making burners at 100% and 0% of nominal additive concentration and with 100% and 50% of a nominal level of surface treatment. The results of the ANOVA analyses are tabulated in Tables A-5 and A-6. The difference between each individual burner's performance at the beginning and after 1000 hours of testing was calculated and analyzed using the ANOVA method as well. This analysis can be used to investigate the aging properties of the formulations and to minimize the possibility of initial casting differences causing erroneous conclusions based solely on the 0 and 1000 hour data. Further results are presented in Table A-7. In all three tables, there are three two-factor interaction effects which are identified as AxB and/or CxD, etc. In the ANOVA method, these are used to account for a combination of two factors having a different effect than either one does by itself (even to the point of having an effect when neither single factor has one in and of itself).

The important trends noted in the analysis of the burners from this test were the effect of the emissivity additive on both the radiant efficiency and the $NO_x$ performance of the burners and the general lack of effect of all of the other factors. Examination of the data, grouped by the presence or absence of the agent, showed that adding the emissivity agent improved both measures of burner performance over time.

While no effects other than a possible interaction between the metal (high emissivity) fiber and the surface treatment, or between the type of ceramic fiber and the emissivity agent were noted in the initial data, there were strong indications of an experimental effect shown in the later test data. The interaction effect was harder to specify because the experiment was run in such a way that the effects of different pairs of interactions appeared in

## TABLE A-5.

**Lifetime 6 initial screening tests**

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber type | A | 8.82E-07 | 1 | 8.82E-07 | 0.029278 | 13% | No discernible effect |
| Ceramic Fiber | B | 7.87E-05 | 1 | 7.87E-05 | 2.612448 | 86% | No discernible effect |
| Emiss. Add. | C | 5.03E-05 | 1 | 5.03E-05 | 1.66971 | 77% | No discernible effect |
| Surface Treat. | D | 4.35E-08 | 1 | 4.35E-08 | 0.001444 | 3% | No discernible effect |
| AxB and/or CxD | | 1.92E-05 | 1 | 1.92E-05 | 0.637344 | 55% | No discernible effect |
| AxC and/or BxD | | 6.81E-06 | 1 | 6.81E-06 | 0.226058 | 35% | No discernible effect |
| AxD and/or BxC | | 3.79E-05 | 1 | 3.79E-05 | 1.258091 | 71% | No discernible effect |
| Random Var. | e | 0.000241 | 8 | 3.01E-05 | | | |
| Total | T | 4.35E-04 | 15 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

n = Degrees of Freedom

V = Variance

## TABLE A-5. CONCLUDED

Lifetime 6 Screening after 1000 hours of run-time

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber type | A | 8.45E-04 | 1 | 0.000845 | 0.756491 | 59% | No discernible effect |
| Ceramic Fiber | B | 9.99E-05 | 1 | 9.99E-05 | 0.089436 | 23% | No discernible effect |
| Emiss. Add. | C | 1.42E-02 | 1 | 0.014158 | 12.67502 | 99.3% | Strong indication of an effect |
| Surface Treat. | D | 2.84E-03 | 1 | 0.002837 | 2.539839 | 85% | No discernible effect |
| AxB and/or CxD | | 2.86E-03 | 1 | 0.002859 | 2.559534 | 85% | No discernible effect |
| AxC and/or BxD | | 1.17E-03 | 1 | 0.001169 | 1.046553 | 66% | No discernible effect |
| AxD and/or BxC | | 1.21E-04 | 1 | 0.000121 | 0.108326 | 25% | No discernible effect |
| Random Var. | e | 0.008936 | 8 | 0.001117 | | | |
| Total | T | 3.10E-02 | 15 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

n = Degrees of Freedom

V = Variance

# TABLE A-6

**Lifetime 6 initial screening tests**

**$NO_x$ Output of burners**

**Analysis of Variance**

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber type | A | 2.44E-02 | 1 | 0.02437 | 0.040461 | 15% | No discernible effect |
| Ceramic Fiber | B | 3.79E-01 | 1 | 0.379386 | 0.629879 | 55% | No discernible effect |
| Emiss. Add. | C | 1.69E-01 | 1 | 0.168748 | 0.280166 | 39% | No discernible effect |
| Surface Treat. | D | 3.28E-01 | 1 | 0.328226 | 0.54494 | 52% | No discernible effect |
| AxB and/or CxD | | 8.01E-01 | 1 | 0.800581 | 1.329172 | 72% | No discernible effect |
| AxC and/or BxD | | 1.63E-01 | 1 | 0.162823 | 0.270328 | 38% | No discernible effect |
| AxD and/or BxC | | 6.44E+00 | 1 | 6.442694 | 10.69655 | 98.9% | Indicates effect |
| Random Var. | e | 4.818523 | 8 | 0.602315 | | | |
| Total | T | 1.31E+01 | 15 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

n = Degrees of Freedom

V = Variance

# TABLE A-6. CONCLUDED

**Lifetime 6 Screening after 1000 hours of run-time**

**$NO_x$ Output of burners**

**Analysis of Variance**

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber type | A | 3.31E+01 | 1 | 33.14335 | 0.8590692 | 62% | No discernible effect |
| Ceramic Fiber | B | 8.55E-01 | 1 | 0.854754 | 0.0221551 | 11% | No discernible effect |
| Emiss. Add. | C | 4.27E+02 | 1 | 426.858 | 11.064076 | 99.0% | Strong indication of an effect |
| Surface Treat. | D | 5.47E+01 | 1 | 54.70428 | 1.4179243 | 73% | No discernible effect |
| AxB and/or CxD | | 7.31E+01 | 1 | 73.09709 | 1.8946623 | 79% | No discernible effect |
| AxC and/or BxD | | 5.54E+01 | 1 | 55.35161 | 1.4347029 | 73% | No discernible effect |
| AxD and/or BxC | | 1.71E+00 | 1 | 1.708628 | 0.0442873 | 16% | No discernible effect |
| Random Var. | e | 308.6443 | 8 | 38.580538 | | | |
| Total | T | 9.54E+02 | 15 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

n = Degrees of Freedom

V = Variance

## TABLE A-7

Lifetime 6 Screening after 1000 hours of run-time

**Difference in Radiant Efficiency of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber type | A | 2.55E-02 | 1 | 0.025537 | 0.9104019 | 63% | No discernible effect |
| Ceramic Fiber | B | 8.12E-04 | 1 | 0.000812 | 0.028948 | 13% | No discernible effect |
| Emiss. Add. | C | 3.76E-01 | 1 | 0.375502 | 13.386761 | 99.4% | Strong indication of an effect |
| Surface Treat. | D | 7.88E-02 | 1 | 0.078793 | 2.8089946 | 87% | No discernible effect |
| AxB and/or CxD | | 6.81E-02 | 1 | 0.0681 | 2.4277858 | 84% | No discernible effect |
| AxC and/or BxD | | 2.86E-02 | 1 | 0.028599 | 1.0195631 | 66% | No discernible effect |
| AxD and/or BxC | | 2.15E-03 | 1 | 0.002148 | 0.0765769 | 21% | No discernible effect |
| Random Var. | e | 0.224402 | 8 | 0.0280503 | | | |
| Total | T | 8.04E-01 | 15 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

n = Degrees of Freedom

V = Variance

## TABLE A-7. CONCLUDED

Lifetime 6 Screening after 1000 hours of run-time

**Difference in $NO_x$ emissions of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber type | A | 1.85E-01 | 1 | 0.184579 | 0.8364846 | 61% | No discernible effect |
| Ceramic Fiber | B | 3.98E-03 | 1 | 0.003978 | 0.0180277 | 10% | No discernible effect |
| Emiss. Add. | C | 2.33E+00 | 1 | 2.33339 | 10.574576 | 98.8% | Strong indication of an effect |
| Surface Treat. | D | 4.32E-01 | 1 | 0.432348 | 1.9593368 | 80% | No discernible effect |
| AxB and/or CxD | | 3.91E-01 | 1 | 0.391328 | 1.7734403 | 78% | No discernible effect |
| AxC and/or BxD | | 3.60E-01 | 1 | 0.359611 | 1.6297036 | 76% | No discernible effect |
| AxD and/or BxC | | 4.17E-02 | 1 | 0.041653 | 0.1887652 | 32% | No discernible effect |
| Random Var. | e | 1.765283 | 8 | 0.2206604 | | | |
| Total | T | 5.51E+00 | 15 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

n = Degrees of Freedom

V=Variance

the same place and were thus indistinguishable one from the other. The fact that the interaction did not appear in the later test data seemed to show that, while it is strongly indicated in the initial test, it was an artificial effect that was actually due to some other random or uncontrollable cause in the testing. It should be noted here that the confidence level presented in the ANOVA tables is neither a measure of the importance nor the magnitude of any effect. It is, instead, the level of confidence that any effect attributed to a cause is a real effect due to that factor. In the case of the interaction effects, the confidence level is most often low, and they have for the most part been included in the random variance pool as the sample for the significance comparison. Given that they are not significant, this increases the accuracy of other confidence levels because the sample is then a better representation of the general burner population.

Because of the importance and magnitude (determined by examining the data, not the ANOVA) of the emissivity agent's effect, a secondary ANOVA analysis of the LT6 burners was performed. This analysis studied only the burners with the emissivity additive. The indications from that analysis were that the rest of the factors examined in the experiment did not seem to have any measurable, real effects. Data are presented in Table A-8.

The conclusions after LT6 were that:

- The higher temperature ceramic fibers did not show conclusive evidence of product improvement,
- The HT fiber types were seemingly identical in effect, and
- The surface treatment did not have a linear relation to performance (no difference between reduced and full loading).

Considering these conclusions, the decision was made to utilize the less expensive supplier (due to volume availability and pricing) for the HT fibers. Additionally, with regard to the HT fibers, a secondary side-by-side test in a different accelerated lifetime environment seemed to support this decision, in that the chosen fibers oxidized away less rapidly than the others.

It was then decided to investigate further the effect of the emissivity agent on the burners' performance. Additionally, the idea was brought up that a denser burner might radiate more effectively and last longer, while maintaining the positive aspects of the flame stabilized system. LT7 was set up to test these properties. There were two factors -- the presence or absence of the emissivity agent, and the full or a reduced amount of the porosity

# TABLE A-8

Lifetime 6 Screening after 1000 hours of run-time

**Radiant Efficiency of burners**

**Analysis of Variance**

Looking only at burners with Emissivity Additive to see if there were any other hidden effects

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber type | A | 1.31E-05 | 1 | 0.0000131 | 0.409375 | 44% | No discernible effect |
| Ceramic Fiber | B | 5.26E-07 | 1 | 5.26E-07 | 0.0164375 | 10% | No discernible effect |
| Surface Treat. | C | 2.10E-08 | 1 | 2.1E-08 | 0.0006563 | 2% | No discernible effect |
| Random Var. | e | 0.000128 | 4 | 0.000032 | | | |
| Total | T | 1.42E-04 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

n = Degrees of Freedom

V = Variance

## TABLE A-8. CONCLUDED

Lifetime 6 Screening after 1000 hours ~~or~~ run-time

**$NO_x$ Output of burners**

**Analysis of Variance**

Looking only at burners with Emissivity Additive to see if there were any other hidden effects

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber type | A | 1.42E+00 | 1 | 1.415975 | 0.2899733 | 38% | No discernible effect |
| Ceramic Fiber | B | 7.32E-02 | 1 | 0.073198 | 0.01499 | 9% | No discernible effect |
| Surface Treat. | C | 6.65E-01 | 1 | 0.665223 | 0.136229 | 27% | No discernible effect |
| Random Var. | e | 19.53249 | 4 | 4.8831225 | | | |
| Total | T | 2.17E+01 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

n = Degrees of Freedom

V = Variance

agent in the burner preparation. ANOVA tables for LT7 and subsequent tests are presented later in this section. The results of an ANOVA analysis on these burners yielded an initial positive radiant efficiency change due to both the emissivity agent (98% confidence) and the reduced porosity agent (97% confidence). This effect was not indicated in either the 1000 hour or the 1000 hour - initial analyses, but reappeared in the 2000 hour (96% confidence level for both factors) and the 2000 hour - initial analyses (approximately 90% confidence level for both factors). Neither factor nor their interaction had any discernible effect on the $NO_x$ emissions performance of the burners in this test in any of the analyses (initial, 1000 hour, 1000 hour - initial, 2000 hour, and 2000 hour - initial). The two factors appeared to be independent of each other, in that they did not interact to produce a different effect than the separate effects of each factor by itself.

These results led to a desire to study the porosity additive level further. The effect of the replacement of the ceramic fibers with higher melting fibers came up again as a possible study, not having been conclusively eliminated as a possible improvement. The surface treatment, while showing benefits to the performance of the burners, had to be abandoned because the compound could pose a significant health hazard if used incorrectly, was difficult to apply, and based on other data might have been implicated in destructive failures of burners. At the same time, the supplier of the HT fibers provided a sample of a different size of fiber which brought up another test factor. This led to LT8, in which those three factors were varied in the manufacture of test burners. The burners were tested over a period of 2000 hours at 1000 hour intervals, and, as with previous data, the actual data and the differences between each 1000 hour segment and the initial data were analyzed using the ANOVA method. In addition, the pressure drop ($\Delta P$) through the burner was analyzed in this and all following tests. The burner pressure drop is an important parameter .for study in that it determines the requirements for combustion air blowers that are to be used with a burner in a functioning application. In this case, as in the $NO_x$ emissions, a lower value is more useful in that it requires less pressure, and thus adds less to the size requirements for the blower.

The results indicated that decreasing the porosity additive had an initial positive effect (92% confidence level) on the radiant efficiency, but by 1000 hours that effect had disappeared. (Hence the effect noted in the 1000 - initial data, at a 96% confidence level.) It also seemed to have an initial positive effect (90% confidence) on the $NO_x$, which disappeared with aging. The effect on $\Delta P$ (detected at a 98% confidence level) was in the expected direction, with a lower porosity causing a higher pressure drop. This effect lasted through the first 1000 hours (94% confidence), but had faded by the time the burners had aged another 1000 hours. The only other effect on $NO_x$ was that of the HT fibers, where the smaller fiber yielded lower emissions. This effect was noted only after 2000 hours (99% confidence), but it was supported by a corresponding effect noted in the 2000 hour - initial data (97% confidence level). The fibers, however, had effects on both the radiant efficiency and the pressure drop. The effects were always in the direction of the lower diameter being an improvement. At 0 and 1000 hours, the smaller fibers gave higher efficiencies (92% confidence for both), showing also a slower rate of change (95% confidence in the 1000 hour - initial data). At the same time, while they never showed an actual performance improvement relative to the other fibers, they seemed to age less over both periods (94% confidence at 1000 hour- initial and 98% at 2000 hour- initial). Finally, the higher melting ceramic fibers continued to show little or no improvement over the regular fibers. They demonstrated an improvement (91% confidence) in the radiant efficiency at 1000 hours which disappeared, but conversely demonstrated an increase of the pressure drop at 0 and 1000 hours (98% and 96% confidence, respectively), though that difference also diminished thereafter, probably due to other aging effects.

It was found during the manufacture of burners at Alzeta that the higher melting ceramic fibers were more expensive, tended to increase pressure drop, and were difficult to use. These additional reasons led to the conclusion that the high melting ceramic fibers should be abandoned as an avenue of burner improvement at this time. The chosen course, then, was to investigate and optimize the effect of the HT fibers in the burners. Theory said that the emissivity of the hot fibers and the emissivity additive cooled the surface through radiant heat transfer away from the burner. On the other hand, the reflective nature of the two when they lay in the interior of the burner kept the radiant heat transfer mostly in an outward direction, thus keeping the inside of the burner cool. Since the effects of the HT fiber and the emissivity additive in the above regard were nearly identical, it was thought that perhaps a balance needed to be struck between the amounts of the two in the burner formulation in order to optimize performance. It was thought that the emissivity agent, which was included in the formulation as a powder, reacted over the life of the burner causing an aging effect of $\Delta P$ increase. Thus an additional benefit of reducing the emissivity agent would be to lower the $\Delta P$ effects and increase the burner useable lifetime. Another effect of the HT fibers was to lower the initial $\Delta P$ of the burners. In order to investigate the effects that such a change would have, it was then decided to adjust the porosity agent loading in test burners.

The LT10 test matrix was devised with the above concerns in mind. It tested burners with four different amounts of the HT fibers in them at levels of 0, 10, 20, and 30 grams per gallon of batch. At each HT fiber load there were specified high and low levels of both emissivity agent and porosity agent. The test was run for 3000 hours in order to more fully specify the performance characteristics and the aging behavior of the different burner formulations.

Analysis showed several positive signs in the behavior of the test burners. With regard to radiant efficiency, results were unambiguous. The primary effect was that of the HT fiber load which, while there was no clear effect in the initial data, demonstrated two important phenomena. The first was that any HT fibers improved the burners performance throughout all of the testing intervals (98% confidence at 1000 hours, 99.8% confidence at 2000, and 99.9998% confidence at 3000 hours) and between intervals the aging effects were reduced (92% confidence at 1000 - initial, 98% at 2000 - initial, and 99.999994% at 3000 - initial). It should be noted here that confidence levels can never be 100% because of the inherent nature of random variation which precludes any sort of total guarantee. The second trend was subordinate to the first, but showed that an increasing loading of the HT fibers had an increasing positive effect on radiant efficiency and an increasing negative effect on age-related degradation in performance. The emissivity agent showed an effect (90% confidence) at the 1000 hour period, at the 3000 hour period (96% confidence), and in the 3000 - initial data (96% confidence) that the lower loadings performed better, supporting the conclusion that the benefit of the emissivity agent was in part counteracted by deleterious aging effects. The porosity agent seemed to have no effects on the efficiency in the levels tested.

The $NO_x$ data showed similar trends with the HT fibers showing the strongest indications of effects in both general and aging categories from the initial data on through 3000 hours (99.6% confidence at start, 98.9% at 1000 hours, 98% at 1000 hours - initial, 99.97% at 2000 hours, 99.89% at 2000 hours - initial, and 99.9998% at 3000 and 3000 hours - initial). Here the trend was again mainly that having any HT fibers improved burner performance, but the effect flattened out or even decreased slightly after the middle loading level. The emissivity agent showed an effect at 2000 hours (93% confidence) and in the 2000 hours-initial data (96% confidence) again seeming to show that the lower loading decreased aging problems. Again, the porosity additive showed no effect on the emissions behavior of the burners in the levels tested.

Pressure drop data demonstrated the only effects of the porosity additive, which as expected showed a dramatic effect in pressure drop at each test point (greater than 99% confidence at all points), with lower porosity yielding higher $\Delta P$. The most important trend for the porosity agent was that the calculated difference data from each test did not show an effect of porosity, indicating that most of the burners aging problems came from other sources. The HT fibers showed an effect in every analysis (greater than 99.9% confidence in all cases). Again, the same trend was observed in these effects such that any fiber was much better than none, and higher loadings aged better. Initially the emissivity agent showed no effect, though at 1000 hours the lower loading seemed better (98% confidence), and in all of the calculated data, the lower loadings aged less (99.9% confidence at 1000 - initial, 99.8% at 2000 - initial, and 93% at 3000 - initial). This was in direct opposition to the trend in the porosity agent effects showing that probably the aging effects stem mostly from the emissivity agent.

Because of the results of LT10, a formulation for the HT Pyrocore™ was selected at the highest HT fiber loading. Because of earlier results (LT6 and LT8), it was decided that eliminating the emissivity agent was a bad idea. The porosity agent data was put to use primarily to confirm that the $\Delta P$ could be adjusted in the burners without significantly affecting most of the other measures of burner performance. An additional benefit of the HT formulation was an improvement in the aesthetic qualities of the product during use that seemed to follow along with the trend in the performance increases, enabling the creation of a much more salable product. This product was then put to use in a preliminary product site in order to begin on-site, customer-monitored product testing.

In order to further increase the product viability, a lower cost option for the Pyrocore HT™ product was then developed for test. The primary adjustment in this formula was to lower the amount of the HT fibers included in the burners to the mid level of the LT10 burner formulae. This level was chosen because it required significantly less HT fiber while still allowing nearly identical performance benefits according to the LT10 data. Additionally, because the HT fiber loading was decreased, the emissivity agent load was decreased as well in order to prevent the aging effects caused by that agent from overwhelming the benefits of the fibers. This reduction also served to reduce the cost further, although the amount of the reduction was much smaller than that allowed by the HT fiber change.

Lifetime 7 initial screening tests

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 7.10E-05 | 1 | 0.000071 | 12.909091 | 98% | Indicates effect |
| Porousity Add. | B | 6.10E-05 | 1 | 0.000061 | 11.090909 | 97% | Indicates effect |
| Interaction Eff. | AxB | 3.40E-07 | 1 | 3.4E-07 | 0.0618182 | 18% | no discernible effect |
| Random Var. | e | 2.20E-05 | 4 | 0.0000055 | | | |
| Total | T | 1.54E-04 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 7 initial screening tests

***NOx Output of burners***

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 1.10E+01 | 1 | 10.9724 | 3.0220753 | 84% | no discernible effect |
| Porousity Add. | B | 1.21E-01 | 1 | 0.12126 | 0.0333981 | 14% | no discernible effect |
| Interaction Eff. | AxB | 4.52E+00 | 1 | 4.52269 | 1.2456627 | 67.3% | no discernible effect |
| Random Var. | e | 14.523 | 4 | 3.63075 | | | |
| Total | T | 3.01E+01 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 7 Screening after 1000 hours of run-time
**Radiant Efficiency of burners**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 2.70E-04 | 1 | 0.00027 | 2.25 | 79% | no discernible effect |
| Porousity Add. | B | 2.70E-04 | 1 | 0.00027 | 2.25 | 79% | no discernible effect |
| Interaction Eff. | AxB | 5.70E-05 | 1 | 0.000057 | 0.475 | 47% | no discernible effect |
| Random Var. | e | 0.00048 | 4 | 0.00012 | | | |
| Total | T | 1.08E-03 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 7 Screening after 1000 hours of run-time
**NOx Output of burners**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 2.71E-02 | 1 | 0.0271 | 0.0034869 | 4% | no discernible effect |
| Porousity Add. | B | 6.58E+00 | 1 | 6.58489 | 0.8472527 | 59% | no discernible effect |
| Interaction Eff. | AxB | 5.69E-01 | 1 | 0.56895 | 0.0732046 | 20% | no discernible effect |
| Random Var. | e | 31.0882 | 4 | 7.77205 | | | |
| Total | T | 3.83E+01 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 7 Screening after 1000 hours of run-time

**Difference in Radiant Efficiency of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 2.52E-03 | 1 | 0.002517 | 0.8259229 | 59% | no discernible effect |
| Porousity Add. | B | 2.87E-03 | 1 | 0.002869 | 0.9414274 | 61% | no discernible effect |
| Interaction Eff. | AxB | 1.90E-03 | 1 | 0.001898 | 0.6228056 | 53% | no discernible effect |
| Random Var. | e | 0.01219 | 4 | 0.0030475 | | | |
| Total | T | 1.95E-02 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 7 Screening after 1000 hours of run-time

**Difference in NOx Output of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 2.40E-02 | 1 | 0.024049 | 3.2805647 | 86% | no discernible effect |
| Porousity Add. | B | 2.34E-02 | 1 | 0.023418 | 3.194489 | 85% | no discernible effect |
| Interaction Eff. | AxB | 1.90E-02 | 1 | 0.018966 | 2.5871841 | 82% | no discernible effect |
| Random Var. | e | 0.029323 | 4 | 0.0073308 | | | |
| Total | T | 9.58E-02 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 7 Screening after 2000 hours of run-time
**Radiant Efficiency of burners**
**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 2.27E-04 | 1 | 0.000227 | 8.990099 | 96% | Indicates effect |
| Porousity Add. | B | 2.10E-04 | 1 | 0.00021 | 8.3168317 | 96% | indicates effect |
| Interaction Eff. | AxB | 4.84E-05 | 1 | 0.0000484 | 1.9168317 | 76% | no discernible effect |
| Random Var. | e | 0.000101 | 4 | 2.525E-05 | | | |
| Total | T | 5.86E-04 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was greater than 90%
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 7 Screening after 2000 hours of run-time
**NOx Output of burners**
**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 9.09E-01 | 1 | 0.909466 | 1.1769663 | 66% | no discernible effect |
| Porousity Add. | B | 2.09E-01 | 1 | 0.209115 | 0.2706218 | 37% | no discernible effect |
| Interaction Eff. | AxB | 2.38E-01 | 1 | 0.238452 | 0.3085876 | 39% | no discernible effect |
| Random Var. | e | 3.090882 | 4 | 0.7727205 | | | |
| Total | T | 4.45E+00 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was greater than 90%
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 7 Screening after 2000 hours of run-time

**Difference in Radiant Efficiency of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 1.85E-03 | 1 | 0.001852 | 4.5033435 | 90% | Effect indicated |
| Porousity Add. | B | 1.84E-03 | 1 | 0.00184 | 4.4741641 | 90% | Effect indicated |
| Interaction Eff. | AxB | 1.54E-03 | 1 | 0.001544 | 3.7544073 | 88% | no discernible effect |
| Random Var. | e | 0.001645 | 4 | 0.0004113 | | | |
| Total | T | 6.88E-03 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 7 Screening after 2000 hours of run-time

**Difference in NOx Output of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| Emiss. Add. | A | 3.06E-02 | 1 | 0.030617 | 1.3810415 | 69% | no discernible effect |
| Porousity Add. | B | 1.83E-03 | 1 | 0.001826 | 0.0823654 | 21% | no discernible effect |
| Interaction Eff. | AxB | 3.36E-02 | 1 | 0.033634 | 1.5171294 | 71% | no discernible effect |
| Random Var. | e | 0.088678 | 4 | 0.0221695 | | | |
| Total | T | 1.55E-01 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

LT8

Lifetime 8 initial screening tests

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | $\nu$ | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 2.11E-08 | 1 | 2.11E-08 | 0.0016015 | 3% | no discernible effect |
| Ceramic Fiber | B | 2.58E-05 | 1 | 0.0000258 | 1.9582543 | 77% | no discernible effect |
| Porousity Add. | C | 6.84E-05 | 1 | 0.0000684 | 5.1916509 | 92% | Indicates Effect |
| Random Var. | e | 5.27E-05 | 4 | 1.318E-05 | | | |
| Total | T | 1.47E-04 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

$\nu$ = Degrees of Freedom

V = Variance

Lifetime 8 initial screening tests

**NOx Output of burners**

**Analysis of Variance**

| Factor | Label | SS | $\nu$ | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 8.12E-01 | 1 | 0.812295 | 2.6745524 | 82% | no discernible effect |
| Ceramic Fiber | B | 9.87E-01 | 1 | 0.986566 | 3.2483549 | 85% | no discernible effect |
| Porousity Add. | C | 1.38E+00 | 1 | 1.375909 | 4.5303009 | 90% | Indicates Effect |
| Random Var. | e | 1.21485 | 4 | 0.3037125 | | | |
| Total | T | 4.39E+00 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

$\nu$ = Degrees of Freedom

V = Variance

Lifetime 8 initial screening tests

**DP Across burners**

**Analysis of Variance**

| Factor | Label | SS | $\nu$ | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 4.05E-03 | 1 | 0.00405 | 1.7802198 | 75% | no discernible effect |
| Ceramic Fiber | B | 2.88E-02 | 1 | 0.0288 | 12.659341 | 98% | Indicates Effect |
| Porousity Add. | C | 3.13E-02 | 1 | 0.03125 | 13.736264 | 98% | Indicates Effect |
| Random Var. | e | 0.0091 | 4 | 0.002275 | | | |
| Total | T | 7.32E-02 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was greater than 90%

SS= Sum of Squares

$\nu$ = Degrees of Freedom

V = Variance

LT8

Lifetime 8 Screening after 1000 hours of run-time

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 8.90E-05 | 1 | 0.000089 | 5.5108359 | 92% | Indicates Effect |
| Ceramic Fiber | B | 7.84E-05 | 1 | 0.0000784 | 4.8544892 | 91% | Indicates Effect |
| Poroussity Add. | C | 4.74E-06 | 1 | 4.74E-06 | 0.2934985 | 38.3% | no discernible effect |
| Random Var. | e | 6.46E-05 | 4 | 1.615E-05 | | | |
| Total | T | 2.37E-04 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 8 Screening after 1000 hours of run-time

**NOx Output of burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 1.16E+00 | 1 | 1.164112 | 0.6634555 | 54% | no discernible effect |
| Ceramic Fiber | B | 4.35E-01 | 1 | 0.435405 | 0.2481478 | 36% | no discernible effect |
| Poroussity Add. | C | 1.03E-04 | 1 | 0.000103 | 5.87E-05 | 0.6% | no discernible effect |
| Random Var. | e | 7.018478 | 4 | 1.7546195 | | | |
| Total | T | 8.62E+00 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 8 Screening after 1000 hours of run-time

**DP Across burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 4.50E-04 | 1 | 0.00045 | 0.1451613 | 28% | no discernible effect |
| Ceramic Fiber | B | 2.65E-02 | 1 | 0.02645 | 8.5322581 | 96% | Indicates Effect |
| Poroussity Add. | C | 2.21E-02 | 1 | 0.02205 | 7.1129032 | 94.4% | Indicates Effect |
| Random Var. | e | 0.0124 | 4 | 0.0031 | | | |
| Total | T | 6.14E-02 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 8 Screening after 1000 hours of run-time

**Difference in Radiant Efficiency of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 2.26E-03 | 1 | 0.002262 | 7.6677966 | 95% | Indicates effect |
| Ceramic Fiber | B | 3.97E-04 | 1 | 0.000397 | 1.3457627 | 69% | no discernible effect |
| Porousity Add. | C | 2.67E-03 | 1 | 0.002672 | 9.0576271 | 96% | Indicates effect |
| Random Var. | e | 0.00118 | 4 | 0.000295 | | | |
| Total | T | 6.51E-03 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 8 Screening after 1000 hours of run-time

**Difference in NOx Output of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 4.03E-02 | 1 | 0.040304 | 2.0561692 | 78% | no discernible effect |
| Ceramic Fiber | B | 3.33E-02 | 1 | 0.033319 | 1.6998189 | 74% | no discernible effect |
| Porousity Add. | C | 2.30E-02 | 1 | 0.022978 | 1.1722572 | 66.0% | no discernible effect |
| Random Var. | e | 0.078406 | 4 | 0.0196015 | | | |
| Total | T | 1.75E-01 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 8 Screening after 1000 hours of run-time

**Difference in DP Across burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 1.87E-02 | 1 | 0.018747 | 6.442268 | 94% | Indicates effect |
| Ceramic Fiber | B | 1.03E-04 | 1 | 0.000103 | 0.0353952 | 14% | no discernible effect |
| Porousity Add. | C | 1.95E-03 | 1 | 0.001945 | 0.6683849 | 54.0% | no discernible effect |
| Random Var. | e | 0.01164 | 4 | 0.00291 | | | |
| Total | T | 3.24E-02 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 8 Screening after 2000 hours of run-time
**Radiant Efficiency of burners**
**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 8.90E-05 | 1 | 0.000089 | 1.5964126 | 72.5% | no discernible effect |
| Ceramic Fiber | B | 6.09E-06 | 1 | 6.09E-06 | 0.1092377 | 24% | no discernible effect |
| Porousity Add. | C | 3.56E-06 | 1 | 3.56E-06 | 0.0638565 | 18.7% | no discernible effect |
| Random Var. | e | 0.000223 | 4 | 5.575E-05 | | | |
| Total | T | 3.22E-04 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 8 Screening after 2000 hours of run-time
**NOx Output of burners**
**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 1.29E+01 | 1 | 12.8807 | 22.375486 | 99% | Indicates Effect |
| Ceramic Fiber | B | 4.27E-01 | 1 | 0.426623 | 0.7411008 | 56% | no discernible effect |
| Porousity Add. | C | 2.54E-01 | 1 | 0.253772 | 0.4408356 | 45.7% | no discernible effect |
| Random Var. | e | 2.30E+00 | 4 | 0.5756613 | | | |
| Total | T | 1.59E+01 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 8 Screening after 2000 hours of run-time
**DP Across burners**
**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 5.93E-02 | 1 | 0.059282 | 1.0105389 | 63% | no discernible effect |
| Ceramic Fiber | B | 1.03E-04 | 1 | 0.000103 | 0.0017558 | 3% | no discernible effect |
| Porousity Add. | C | 2.07E-03 | 1 | 0.002069 | 0.0352688 | 14.0% | no discernible effect |
| Random Var. | e | 0.234655 | 4 | 0.0586638 | | | |
| Total | T | 2.96E-01 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 8 Screening after 2000 hours of run-time
**Difference in Radiant Efficiency of burners from initial screening**
**Analysis of Variance**

| Factor | Label | SS | n | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 2.37E-03 | 1 | 0.002373 | 2.5025046 | 81% | no discernible effect |
| Ceramic Fiber | B | 1.13E-04 | 1 | 0.000113 | 0.1191669 | 25% | no discernible effect |
| Porousity Add. | C | 7.65E-04 | 1 | 0.000765 | 0.8067493 | 58% | no discernible effect |
| Random Var. | e | 0.003793 | 4 | 0.0009483 | | | |
| Total | T | 7.04E-03 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 8 Screening after 2000 hours of run-time
**Difference in NOx Output of burners from initial screening**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 1.41E-01 | 1 | 0.140755 | 10.433252 | 97% | Indicates effect |
| Ceramic Fiber | B | 6.28E-03 | 1 | 0.006282 | 0.4656438 | 47% | no discernible effect |
| Porousity Add. | C | 3.23E-02 | 1 | 0.032282 | 2.3928545 | 80.3% | no discernible effect |
| Random Var. | e | 0.053964 | 4 | 0.013491 | | | |
| Total | T | 2.33E-01 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 8 Screening after 2000 hours of run-time
**Difference in DP Across burners from initial screening**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * | |
|---|---|---|---|---|---|---|---|
| HT Fiber | A | 2.71E-02 | 1 | 0.027131 | 14.707142 | 98% | Indicates effect |
| Ceramic Fiber | B | 1.74E-03 | 1 | 0.001737 | 0.941591 | 61% | no discernible effect |
| Porousity Add. | C | 7.42E-04 | 1 | 0.000742 | 0.4022225 | 44.0% | no discernible effect |
| Random Var. | e | 0.007379 | 4 | 0.0018448 | | | |
| Total | T | 3.70E-02 | 7 | | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 10 initial screening tests

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 1.559E-05 | 3 | 5.196E-06 | 0.2190329 | 11.9% no discernible effect |
| Emiss. Add. | B | 1.01E-05 | 1 | 1.01E-05 | 0.425807 | 47% no discernible effect |
| porosity Add. | C | 2.129E-05 | 1 | 2.129E-05 | 0.8972519 | 63% no discernible effect |
| Random Var. | e | 0.0002372 | 10 | 2.372E-05 | Pool | |
| Total | T | 0.0002842 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 10 initial screening tests

**NOx Output of burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 11.21701 | 3 | 3.7390033 | 8.8773881 | 99.6% Indicates Effect |
| Emiss. Add. | B | 0.0039514 | 1 | 0.0039514 | 0.0093816 | 8% no discernible effect |
| porosity Add. | C | 0.1969341 | 1 | 0.1969341 | 0.4675738 | 49% no discernible effect |
| Random Var. | e | 4.2118281 | 10 | 0.4211828 | Pool | |
| Total | T | 15.629723 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 10 initial screening tests

**DP Across burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.0819187 | 3 | 0.0273062 | 17.434436 | 99.97% Indicates Effect |
| Emiss. Add. | B | 0.0014062 | 1 | 0.0014062 | 0.8978595 | 63% no discernible effect |
| porosity Add. | C | 0.0885063 | 1 | 0.0885063 | 56.509282 | 99.998% Indicates Effect |
| Random Var. | e | 0.0156623 | 10 | 0.0015662 | Pool | |
| Total | T | 0.1874935 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was greater than 90%
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 1000 hours of run-time

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.0036369 | 3 | 0.0012123 | 5.3171191 | 98% Indicates Effect |
| Emiss. Add. | B | 0.0007437 | 1 | 0.0007437 | 3.2616294 | 90% Indicates Effect |
| porosity Add. | C | 5.755E-05 | 1 | 5.755E-05 | 0.2524264 | 37% no discernible effect |
| Random Var. | e | 0.00228 | 10 | 0.000228 | Pool | |
| Total | T | 0.0067181 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

ν = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 1000 hours of run-time

**NOx Output of burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 79.079168 | 3 | 26.359723 | 6.3826664 | 98.9% Indicates Effect |
| Emiss. Add. | B | 9.3401908 | 1 | 9.3401908 | 2.2616066 | 84% no discernible effect |
| porosity Add. | C | 2.452802 | 1 | 2.452802 | 0.5939143 | 54% no discernible effect |
| Random Var. | e | 41.29892 | 10 | 4.129892 | Pool | |
| Total | T | 132.17108 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

ν = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 1000 hours of run-time

**DP Across burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.247875 | 3 | 0.082625 | 26.979592 | 99.996% Indicates Effect |
| Emiss. Add. | B | 0.024025 | 1 | 0.024025 | 7.844898 | 98% Indicates Effect |
| porosity Add. | C | 0.093025 | 1 | 0.093025 | 30.37551 | 99.97% Indicates Effect |
| Random Var. | e | 0.030625 | 10 | 0.0030625 | Pool | |
| Total | T | 0.39555 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

ν = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 1000 hours of run-time

**Difference in Radiant Efficiency of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.209467 | 3 | 0.0698223 | 3.0445564 | 92% Indicates Effect |
| Emiss. Add. | B | 0.042046 | 1 | 0.042046 | 1.8333878 | 79% no discernible effect |
| porosity Add. | C | 0.005345 | 1 | 0.005345 | 0.2330652 | 36% no discernible effect |
| Random Var. | e | 0.229335 | 10 | 0.0229335 | Pool | |
| Total | T | 0.486193 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 1000 hours of run-time

**Difference in NOx Output of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.112621 | 3 | 0.0375403 | 4.8884461 | 98% Indicates Effect |
| Emiss. Add. | B | 0.015205 | 1 | 0.015205 | 1.9799724 | 81% no discernible effect |
| porosity Add. | C | 0.000944 | 1 | 0.000944 | 0.1229263 | 27% no discernible effect |
| Random Var. | e | 0.076794 | 10 | 0.0076794 | Pool | |
| Total | T | 0.205564 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 1000 hours of run-time

**Difference in DP Across burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.201038 | 3 | 0.0670127 | 18.601712 | 99.98% Indicates Effect |
| Emiss. Add. | B | 0.069146 | 1 | 0.069146 | 19.193893 | 99.9% Indicates Effect |
| porosity Add. | C | 0.000276 | 1 | 0.000276 | 0.0766135 | 21.2% no discernible effect |
| Random Var. | e | 0.036025 | 10 | 0.0036025 | Pool | |
| Total | T | 0.306485 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 2000 hours of run-time

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.004983 | 3 | 0.001661 | 9.9223417 | 99.8% Indicates Effect |
| Emiss. Add. | B | 0.000352 | 1 | 0.000352 | 2.1027479 | 82% no discernible effect |
| porosity Add. | C | 2.13E-05 | 1 | 0.0000213 | 0.1272401 | 27% no discernible effect |
| Random Var. | e | 0.001674 | 10 | 0.0001674 | Pool | |
| Total | T | 0.0070303 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 2000 hours of run-time

**NOx Output of burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 87.54679 | 3 | 29.182263 | 17.270268 | 99.97% Indicates Effect |
| Emiss. Add. | B | 7.172031 | 1 | 7.172031 | 4.2444583 | 93% Indicates Effect |
| porosity Add. | C | 0.03092 | 1 | 0.03092 | 0.0182987 | 10% no discernible effect |
| Random Var. | e | 16.8974 | 10 | 1.68974 | Pool | |
| Total | T | 111.64714 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 2000 hours of run-time

**DP Across burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.35922 | 3 | 0.11974 | 12.802994 | 99.9% Indicates Effect |
| Emiss. Add. | B | 0.015625 | 1 | 0.015625 | 1.6706763 | 77% no discernible effect |
| porosity Add. | C | 0.1156 | 1 | 0.1156 | 12.360331 | 99.4% Indicates Effect |
| Random Var. | e | 0.093525 | 10 | 0.0093525 | Pool | |
| Total | T | 0.58397 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 2000 hours of run-time

**Difference in Radiant Efficiency of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.57056 | 3 | 0.1901867 | 5.5990446 | 98% Indicates Effect |
| Emiss. Add. | B | 0.043185 | 1 | 0.043185 | 1.2713548 | 71% no discernible effect |
| porosity Add. | C | 0.006441 | 1 | 0.006441 | 0.1896213 | 33% no discernible effect |
| Random Var. | e | 0.339677 | 10 | 0.0339677 | Pool | |
| Total | T | 0.959863 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 2000 hours of run-time

**Difference in NOx Output of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.141144 | 3 | 0.047048 | 12.254317 | 99.89% Indicates Effect |
| Emiss. Add. | B | 0.021295 | 1 | 0.021295 | 5.546584 | 96% Indicates Effect |
| porosity Add. | C | 0.002103 | 1 | 0.002103 | 0.5477561 | 52% no discernible effect |
| Random Var. | e | 0.038393 | 10 | 0.0038393 | Pool | |
| Total | T | 0.202935 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 2000 hours of run-time

**Difference in DP Across burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.123161 | 3 | 0.0410537 | 25.43125 | 99.995% Indicates Effect |
| Emiss. Add. | B | 0.026718 | 1 | 0.026718 | 16.550827 | 99.8% Indicates Effect |
| porosity Add. | C | 0.002412 | 1 | 0.002412 | 1.4941461 | 75% no discernible effect |
| Random Var. | e | 0.016143 | 10 | 0.0016143 | Pool | |
| Total | T | 0.168434 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 3000 hours of run-time

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.012518 | 3 | 0.0041727 | 53.896495 | 99.9998% Indicates Effect |
| Emiss. Add. | B | 0.000455 | 1 | 0.000455 | 5.8770344 | 96% Indicates Effect |
| porosity Add. | C | 2.42E-05 | 1 | 0.0000242 | 0.3125807 | 41% no discernible effect |
| Random Var. | e | 0.0007742 | 10 | 7.742E-05 | Pool | |
| Total | T | 0.0137714 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 3000 hours of run-time

**NOx Output of burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 421.2522 | 3 | 140.4174 | 53.670049 | 99.9998% Indicates Effect |
| Emiss. Add. | B | 0.019075 | 1 | 0.019075 | 0.0072908 | 7% no discernible effect |
| porosity Add. | C | 0.786579 | 1 | 0.786579 | 0.3006446 | 40% no discernible effect |
| Random Var. | e | 26.163084 | 10 | 2.6163084 | Pool | |
| Total | T | 448.22094 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 3000 hours of run-time

**DP Across burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.496319 | 3 | 0.1654397 | 17.035965 | 99.97% Indicates Effect |
| Emiss. Add. | B | 0.001806 | 1 | 0.001806 | 0.1859708 | 32% no discernible effect |
| porosity Add. | C | 0.154056 | 1 | 0.154056 | 15.863745 | 99.7% Indicates Effect |
| Random Var. | e | 0.097112 | 10 | 0.0097112 | Pool | |
| Total | T | 0.749293 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend

No effect was noted unless the confidence level was 90% or greater

SS= Sum of Squares

v = Degrees of Freedom

V = Variance

Lifetime 10 Screening after 3000 hours of run-time

**Difference in Radiant Efficiency of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 4.493689 | 3 | 1.4978963 | 109.41936 | 99.999994% Indicates Effect |
| Emiss. Add. | B | 0.07274 | 1 | 0.07274 | 5.3135615 | 96% Indicates Effect |
| porosity Add. | C | 0.002955 | 1 | 0.002955 | 0.2158589 | 35% no discernible effect |
| Random Var. | e | 0.136895 | 10 | 0.0136895 | Pool | |
| Total | T | 4.706279 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 3000 hours of run-time

**Difference in NOx Output of burners from initial screening**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 1.973379 | 3 | 0.657793 | 51.678346 | 99.9998% Indicates Effect |
| Emiss. Add. | B | 0.000132 | 1 | 0.000132 | 0.0103703 | 8% no discernible effect |
| porosity Add. | C | 0.012156 | 1 | 0.012156 | 0.9550147 | 65% no discernible effect |
| Random Var. | e | 0.127286 | 10 | 0.0127286 | Pool | |
| Total | T | 2.112953 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 10 Screening after 3000 hours of run-time

**Difference in DP Across burners**

**Analysis of Variance**

| Factor | Label | SS | v | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| HT Fiber | A | 0.451346 | 3 | 0.1504487 | 25.662448 | 99.995% Indicates Effect |
| Emiss. Add. | B | 0.024541 | 1 | 0.024541 | 4.1860267 | 93% Indicates Effect |
| porosity Add. | C | 0.000294 | 1 | 0.000294 | 0.0501484 | 17% no discernible effect |
| Random Var. | e | 0.058626 | 10 | 0.0058626 | Pool | |
| Total | T | 0.534807 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
v = Degrees of Freedom
V = Variance

Lifetime 12 initial screening tests

**Radiant Efficiency of burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 0.0001103 | 1 | 0.0001103 | 3.3642808 | 90.8% Indicates Effect |
| HT Fiber | B | 0.0019099 | 1 | 0.0019099 | 58.233402 | 100% Indicates Effect |
|  | AxB | 2.77E-07 | 1 | 2.767E-07 | 0.0084363 | 7% no discernible effect |
| Random Var. | e | 0.0003936 | 12 | 3.28E-05 | Pool |  |
| Total | T | 0.0024141 | 15 |  |  |  |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 12 initial screening tests

**NOx Output of burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 7.4256524 | 1 | 7.4256524 | 12.294477 | 99.6% Indicates Effect |
| HT Fiber | B | 8.5281943 | 1 | 8.5281943 | 14.11993 | 99.7% Indicates Effect |
|  | AxB | 8.8173493 | 1 | 8.8173493 | 14.598677 | 99.8% Indicates Effect |
| Random Var. | e | 7.2477931 | 12 | 0.6039828 | Pool |  |
| Total | T | 32.018989 | 15 |  |  |  |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 12 initial screening tests

**DP Across burners**

**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 0.003025 | 1 | 0.003025 | 1.5816993 | 77% no discernible effect |
| HT Fiber | B | 0.007225 | 1 | 0.007225 | 3.7777778 | 92% Indicates Effect |
|  | AxB | 0.0016 | 1 | 0.0016 | 0.8366013 | 62% no discernible effect |
| Random Var. | e | 0.02295 | 12 | 0.0019125 | Pool |  |
| Total | T | 0.0348 | 15 |  |  |  |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was greater than 90%
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 12 Screening after 1000 hours of run-time
**Radiant Efficiency of burners**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 1.06E-07 | 1 | 1.056E-07 | 0.0021509 | 4% no discernible effect |
| HT Fiber | B | 0.0064067 | 1 | 0.0064067 | 130.5153 | 99.99999% Indicates Effect |
|  | AxB | 6.21E-06 | 1 | 6.206E-06 | 0.1264232 | 27% no discernible effect |
| Random Var. | e | 0.0005891 | 12 | 4.909E-05 | Pool |  |
| Total | T | 0.007002 | 15 |  |  |  |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 12 Screening after 1000 hours of run-time
**NOx Output of burners**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 11.468888 | 1 | 11.468888 | 0.8607586 | 63% no discernible effect |
| HT Fiber | B | 364.19043 | 1 | 364.19043 | 27.33308 | 99.98% Indicates Effect |
|  | AxB | 4.40053 | 1 | 4.40053 | 0.3302669 | 42% no discernible effect |
| Random Var. | e | 159.88996 | 12 | 13.324164 | Pool |  |
| Total | T | 539.94981 | 15 |  |  |  |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 12 Screening after 1000 hours of run-time
**DP Across burners**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 6.25E-06 | 1 | 6.25E-06 | 0.0232558 | 12% no discernible effect |
| HT Fiber | B | 0.0175563 | 1 | 0.0175563 | 65.325581 | 99.9997% Indicates Effect |
|  | AxB | 0.0001563 | 1 | 0.0001563 | 0.5813953 | 54% no discernible effect |
| Random Var. | e | 0.003225 | 12 | 0.0002688 | Pool |  |
| Total | T | 0.0209438 | 15 |  |  |  |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 12 Screening after 1000 hours of run-time
**Difference in Radiant Efficiency of burners from initial screening**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 7.88E-05 | 1 | 7.876E-05 | 0.4918913 | 50% no discernible effect |
| HT Fiber | B | 3.18E-05 | 1 | 3.176E-05 | 0.1983554 | 34% no discernible effect |
| | AxB | 0.0001124 | 1 | 0.0001124 | 0.7019881 | 58% no discernible effect |
| Random Var. | e | 0.0019214 | 12 | 0.0001601 | Pool | |
| Total | T | 0.0021443 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 12 Screening after 1000 hours of run-time
**Difference in NOx Output of burners from initial screening**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 7.7992725 | 1 | 7.7992725 | 0.1518327 | 30% no discernible effect |
| HT Fiber | B | 16.452536 | 1 | 16.452536 | 0.3202906 | 42% no discernible effect |
| | AxB | 28.238196 | 1 | 28.238196 | 0.5497285 | 53% no discernible effect |
| Random Var. | e | 616.41033 | 12 | 51.367528 | Pool | |
| Total | T | 668.90033 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

Lifetime 12 Screening after 1000 hours of run-time
**Difference in DP Across burners from initial screening**
**Analysis of Variance**

| Factor | Label | SS | ν | V | F statistic | Comments: * |
|---|---|---|---|---|---|---|
| Surf. Treat. | A | 0 | 1 | 0 | 0 | 0.00% no discernible effect |
| HT Fiber | B | 0.0025 | 1 | 0.0025 | 1.2102874 | 70.7% no discernible effect |
| | AxB | 5.63E-05 | 1 | 5.625E-05 | 0.0272315 | 12.8% no discernible effect |
| Random Var. | e | 0.0247875 | 12 | 0.0020656 | Pool | |
| Total | T | 0.0273438 | 15 | | | |

*Percentages are the maximum confidence level which allows this trend
No effect was noted unless the confidence level was 90% or greater
SS= Sum of Squares
ν = Degrees of Freedom
V = Variance

The reduced cost option was then tested in a lifetime test (LT12) to ensure that the benefits of the HT fiber were being maintained. The LT12 test also included a test of Alzeta's surface hardener's effect on burner performance. This hardener is used to give extra resistance to damage in shipment and is designed to burn off at light-off leaving no residual effects.

LT12 demonstrated again, at a 99.98% confidence level or above, that the HT fibers had the effect of lowering $NO_x$, increasing radiant efficiency, and keeping a lower $\Delta P$ in the burners at 1000 hours. The surface treatment had no visible effect in any parameter at 1000 hours, and no unexpected interaction with the HT fibers. This result led to the distribution of the reduced cost option among a wider range of test sites. A further reduced cost option was developed lying between the mid and low level of the LT10 test burners which was to be sold as a lower cost, but lower performance product for customers whose budgetary requirements were more pressing than their performance concerns.

In the time since these tests, Alzeta has continued to test and tried to enhance the Pyrocore HT™ burner. Investigations have been undertaken to test newer and less expensive ways of deriving the same sorts of benefits, such as lower cost HT-like fibers and other burner formula simplifications or adjustments. The HT formulation continues to demonstrate the high efficiency, low emissions behavior for which it was developed across a wide range of customer host sites and commercial sales.

## A.3 EXTENDED OPERATION AT SIMULATED REFORMER CONDITIONS

The tests described in Sections A.1 and A.2 were conducted on burners with 0.2 $ft^2$ of surface area. Typical industrial applications of the advanced radiant burner required burner surface areas of 20 to 100 $ft^2$. Although it would have been best to test burners in the Alzeta combustion lab at full scale, this was not feasible. The maximum burner size that could be tested was determined to be approximately 5 $ft^2$, based on fuel usage, cost of operation, and heat removal capacity of the Alzeta laboratory. An existing facility, the Alzeta Prototype Process Heater (PPH), was modified for use in this project. A description of the facility is provided below, followed by a discussion of burner performance tests during the first month of operation, and finally by a discussion of burner performance and appearance after 6 months of continuous operation.

## Facility Description

A photograph of the PPH furnace is provided as Figure A-1a. The front face of the furnace has external dimensions of 3 ft 4 in. wide by 4 ft 4 in. high, and the furnace is 6 feet deep. The refractory lining inside of the outer sheet metal shell is approximately 6 inches thick, so the internal dimensions of the furnace are 2 ft 4 in. by 3 ft 4 in. by 5 ft deep. Cooling tubes were run along the four side walls of the furnace to simulate the process tubes in a high temperature application.

The cooling tubes have a 4 inch OD and are placed on 6 inch centers in four tube banks of five tubes each. One tube bank is shown in Figure A-1b. The wires attached to the tube walls are sheathed thermocouples. The furnace cooling tubes consist of the 4 inch OD thin-walled stainless steel tubes radiating to concentric inner tubes with a 3.5 inch OD. These inner tubes are water cooled to approximately 100°F to 120°F, and the cooling tubes have a combined heat removal capacity of approximately 300,000 Btu/hr. This arrangement where the outer tube radiated to the water cooled inner tube allowed us to simultaneously achieve high tube wall temperatures (1500°F to 1700°F) and high heat removal rates. The cooling tubes were instrumented with thermocouples mounted to the external tube walls

Figure A-1c shows the radiant burner prior to installation in the furnace. This burner has a surface area of nominally 5 square feet (8 inch OD by 30 inch active length) and a nominal firing rate of 600,000 Btu/hr (120,000 Btu/hr-ft$^2$). The burner was mounted on the front wall of the furnace with the 30 inch dimension running perpendicular to the front wall of the furnace. (The longest dimension of the burner coincides with the longest furnace dimension). Figure A-1d shows a view from the back of the furnace during operation. The burner is radiating to the cooling tubes, and tube wall thermocouples are clearly visible. The furnace exhaust stack is located at the back of the rear view port that provides the view for Figure A-1d.

All PPH tests were performed using natural gas as the burner fuel. Alzeta has refinery experience with process gases with a high hydrogen content, and this type of fuel has not presented operational problems in refinery applications to date. Testing with a representative reformer fuel was to be performed in Phase II, as a large number of reformers operate on process gas.

Testing in the PPH began in April 1993 with a ceramic burner manufactured using the same pad formulation that would be used in a ceramic burner for the host facility test. Tests were performed over the range of surface heat release rates and excess combustion air that are

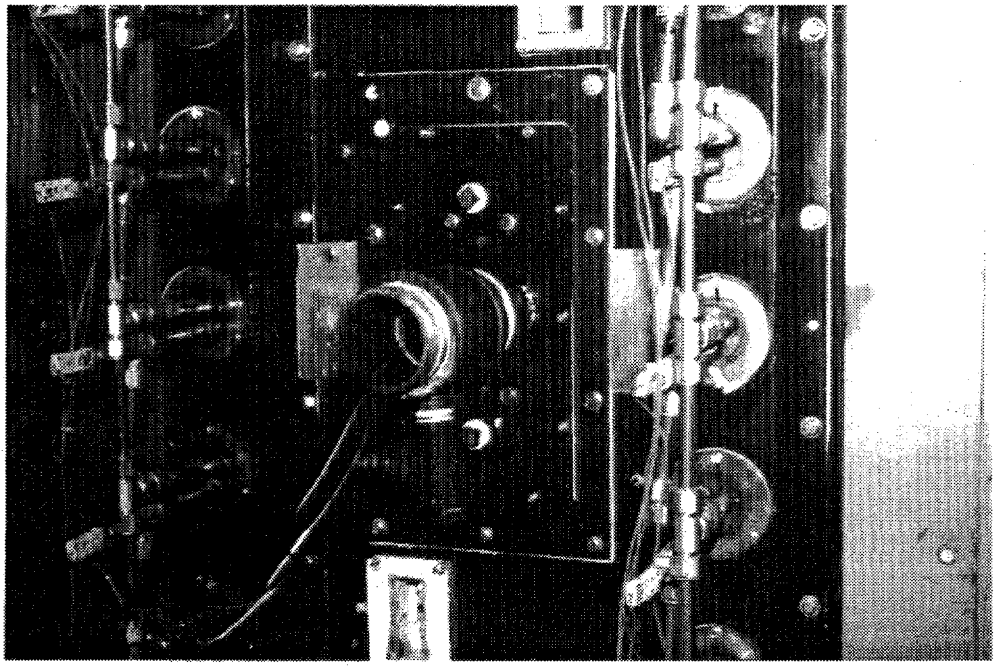


Figure A-1a. Front View of PPH Test Facility

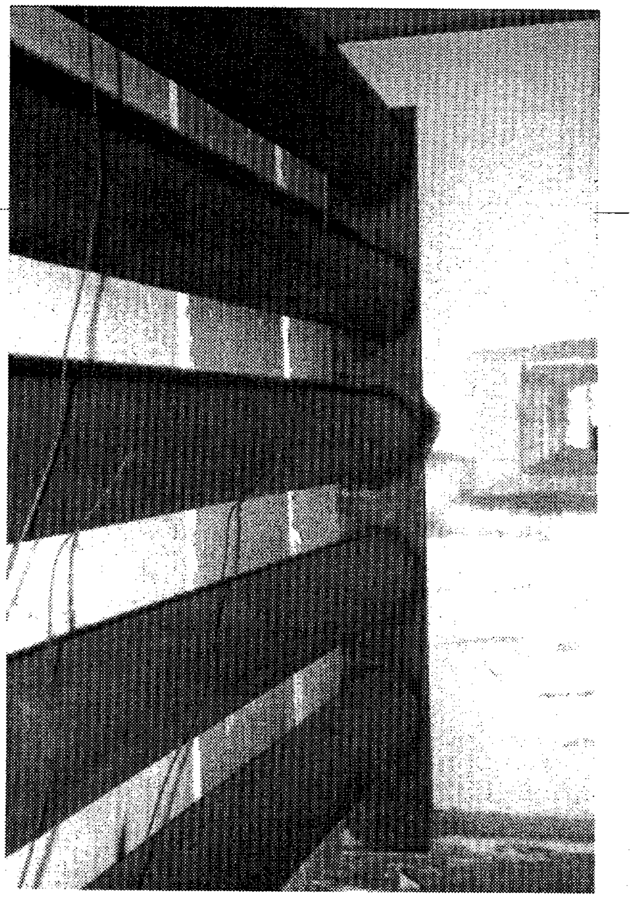


Figure A-1b. PPH Test Facility Cooling Tubes

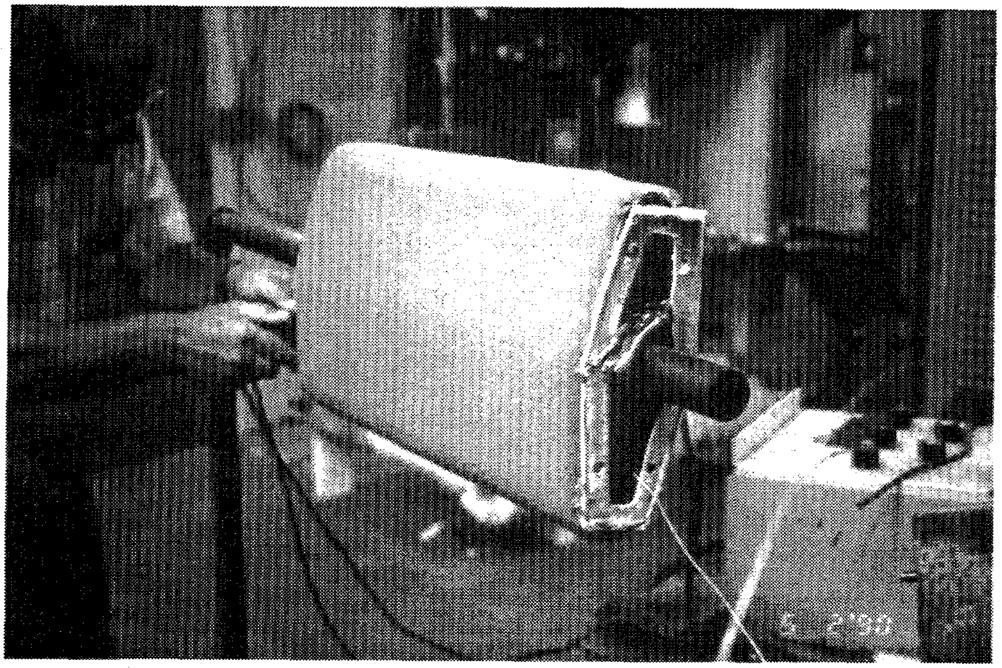


Figure A-1c. Ceramic Fiber Burner Used in PPH Facility

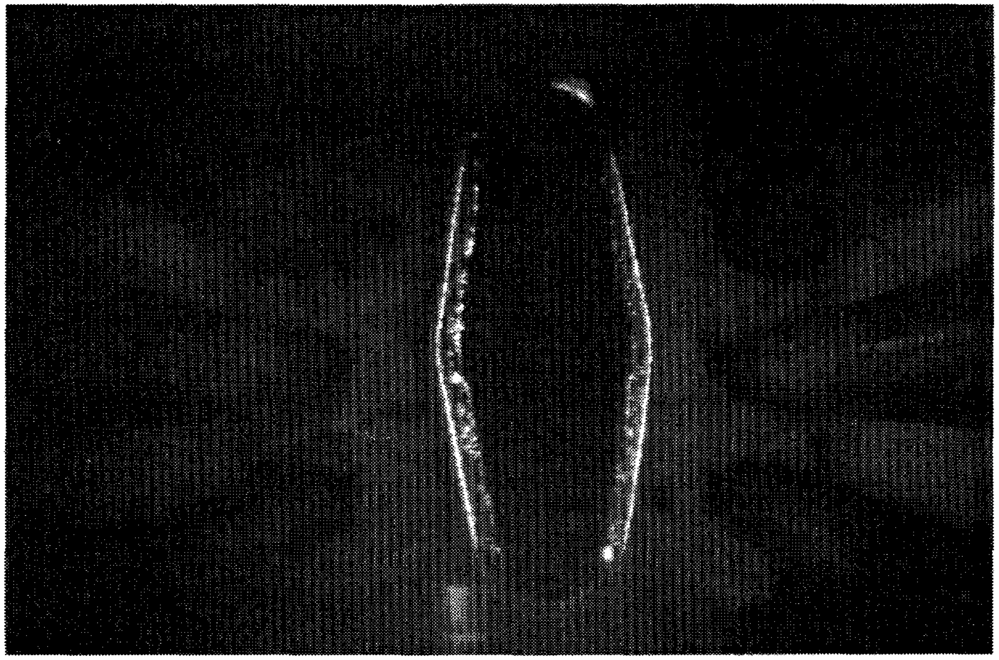


Figure A-1d. PPH Facility During Operation anticipated for the steam-methane reformer host site burner. These tests were completed in May following the installation of a higher capacity induced draft fan. Operating limits of the PPH for ARCS burner tests are presented in Figure A-2.

Results of tests completed during April and May are presented in Figures A-3 and A-4. $NO_x$ emissions are presented in Figure A-3 as a function of heat release rate and excess combustion air. Peak tube wall temperatures for these tests were 1560°F to 1575°F. The process gas temperature at the exit of the host site reformer is approximately 1500°F, which is consistent with the PPH tube wall temperatures. Refractory temperatures in the PPH (and in the host reformer) are probably several hundred degrees higher than the tube wall temperatures, but we have not measured refractory temperatures in the PPH tests.

The data presented in Figure A-3 indicate that at the host site we can expect $NO_x$ emissions of 25 to 30 ppm at a *surface* heat release rate of 120 to 130 $MBtu/hr\text{-}ft^2$ and 15 percent excess combustion air. A higher surface heat release rate of 150 $MBtu/hr\text{-}ft^2$ (due to the installation of a smaller burner) would result in higher $NO_x$ emissions. Based on the available PPH data, $NO_x$ emissions at the higher surface firing rate and 15 percent excess air would be in the range of 40 ppm. The determination of host burner size and surface firing rate required the completion of a material and energy balance of the host site reformer at typical operating conditions.

Radiant section efficiency as a function of heater operating conditions is plotted in Figure A-4. These data followed the expected trends in that efficiency increases as excess air is decreased and decreases as total fired duty is increased. These data were used to generate burner performance curves for use in predicting host reformer performance. Alzeta completed burner modeling at the PPH test conditions to compare with experimental results.

The PPH test burner completed 4000 hours of operation at thermal conditions representative of reformer operation in November 1993. Emissions data were collected at weekly intervals and are presented as Figure A-5. There were no plans for continued testing.

Referring to Figure A-5, during the first 2800 hours of operation the burner was operated at a nominal condition of 3 percent premix $O_2$. During the last 1200 hours of operation, the premix $O_2$ level was gradually decreased to a minimum premix $O_2$ level of 0.4 percent. This had the effect of increasing surface temperature of the burner from 1960°F at 3 percent $O_2$ to 2190°F at lower $O_2$ levels. As expected, $NO_x$ increased as $O_2$ was decreased, but the burner continued to operate well at the higher burner surface temperature. The host reformer burner was operated at a maximum surface temperature of 2100°F.

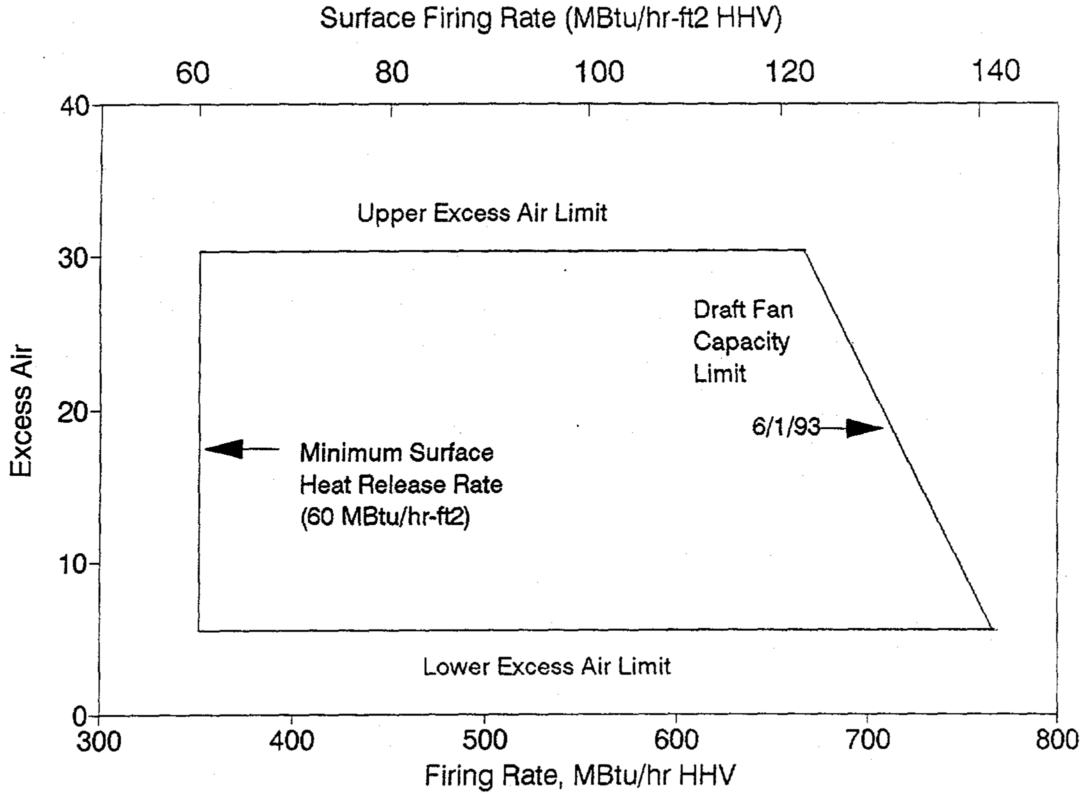


Figure A-2. Operating Envelope for PPH Testing of ARCS Burner

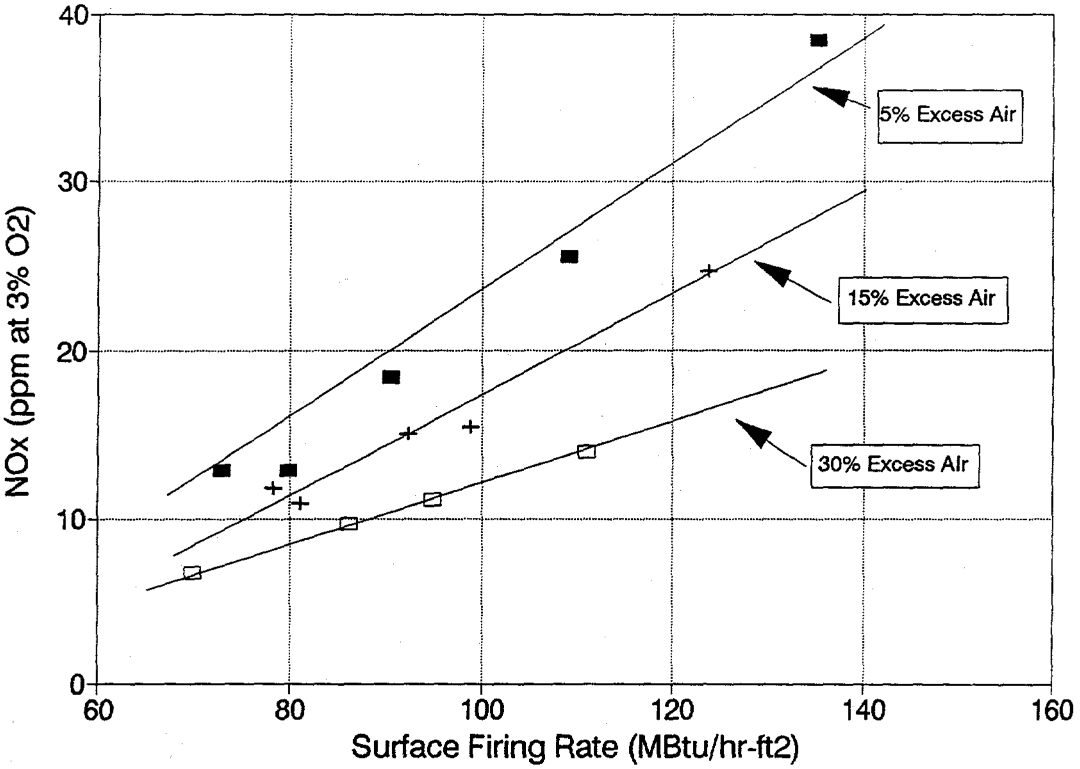


Figure A-3. Heater $NO_x$ Emissions as a Function of Firing Rate and Excess Air

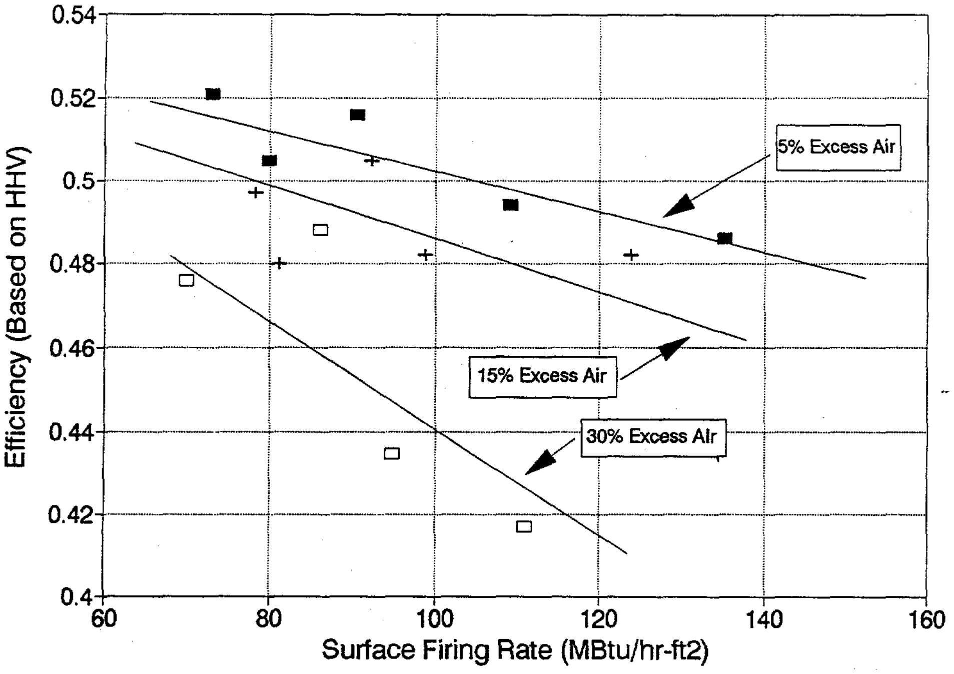


Figure A-4. Heater Efficiency As a Function of Firing Rate and Excess Air

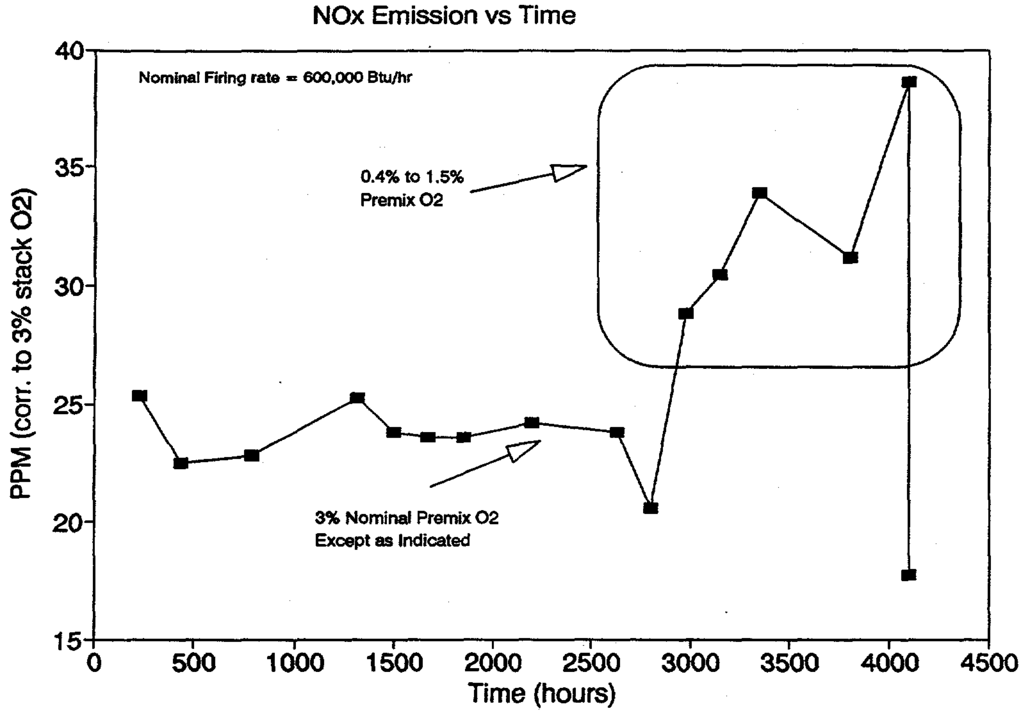


Figure A-5. $NO_x$ Emissions Data from Alzeta PPH

# REFERENCES

A-1. "Thermophysical Properties of Matter," The TPRC Data Series, ed. Y.S. Touloukian, Vol. 8, Thermal Radiative Properties Nonmetallic Solids, pp. 556.

A-2. Sowman, Harold G., "A New Era in Ceramic Fibers via Sol-Gel Technology," Ceramic Bulletin, Vol. 67, Nov. 12, 1988, pp 1911-1916.

# APPENDIX B

# AIR PRODUCTS FIELD DEMONSTRATION

## B.1 PREPARATION FOR FIELD DEMONSTRATION

### B.1.1 System Design and Specifications

The ARCS field demonstration was originally scheduled to take place in an APCI owned and operated reformer. The demonstration site had the following general operating characteristics: vertical cylindrical upfired\downflow geometry, nominal fired duty in the 10 to 20 MMBtu/hr range, natural gas fuel, and no export steam requirement. Retrofit of the ARCS burner into the host reformer presented a number of challenges, with two of the most critical being burner installation and 8:1 turndown capability for system startup.

General System Design - The Alzeta burner was cylindrical in shape with nominal dimensions of 2 foot outside diameter by 17 feet long, with the final 2 feet of burner length having a conical shape. A schematic of the installed burner is provided as Figure B-1. The burner had a surface area of nominally 100 $ft^2$ to provide the necessary fired duty to the heater. The fuel/air delivery system design was based on a design used previously for similarly sized Pyrocore firetube boiler Pyrocore systems.

The burner fabrication process limits maximum single burner "segment" sizes to approximately 3 feet in diameter by 3 feet long. Multiple burner segments were therefore combined to make a single multi-segment burner element. The host site burner design was made up of five cylindrical segments, each 2 feet in diameter by 3 feet long, and one conical "end cap" that has a 2 foot diameter base, a 0.75 foot diameter cap, and is 2 feet long. Segments are typically installed individually and field assembled using mechanical fasteners as part of the burner installation process. As with the fuel/air supply, the burner geometry was typical of what would be supplied in a large Pyrocore firetube boiler installation.

Installation - The upfired heater geometry complicated burner installation by requiring that the burner be installed from below the heater and lifted into place. While it may be possible to install from the top of the heater in some cases (particularly in new installations), it would obviously be desirable to be able to install the burner from the bottom. Due to this

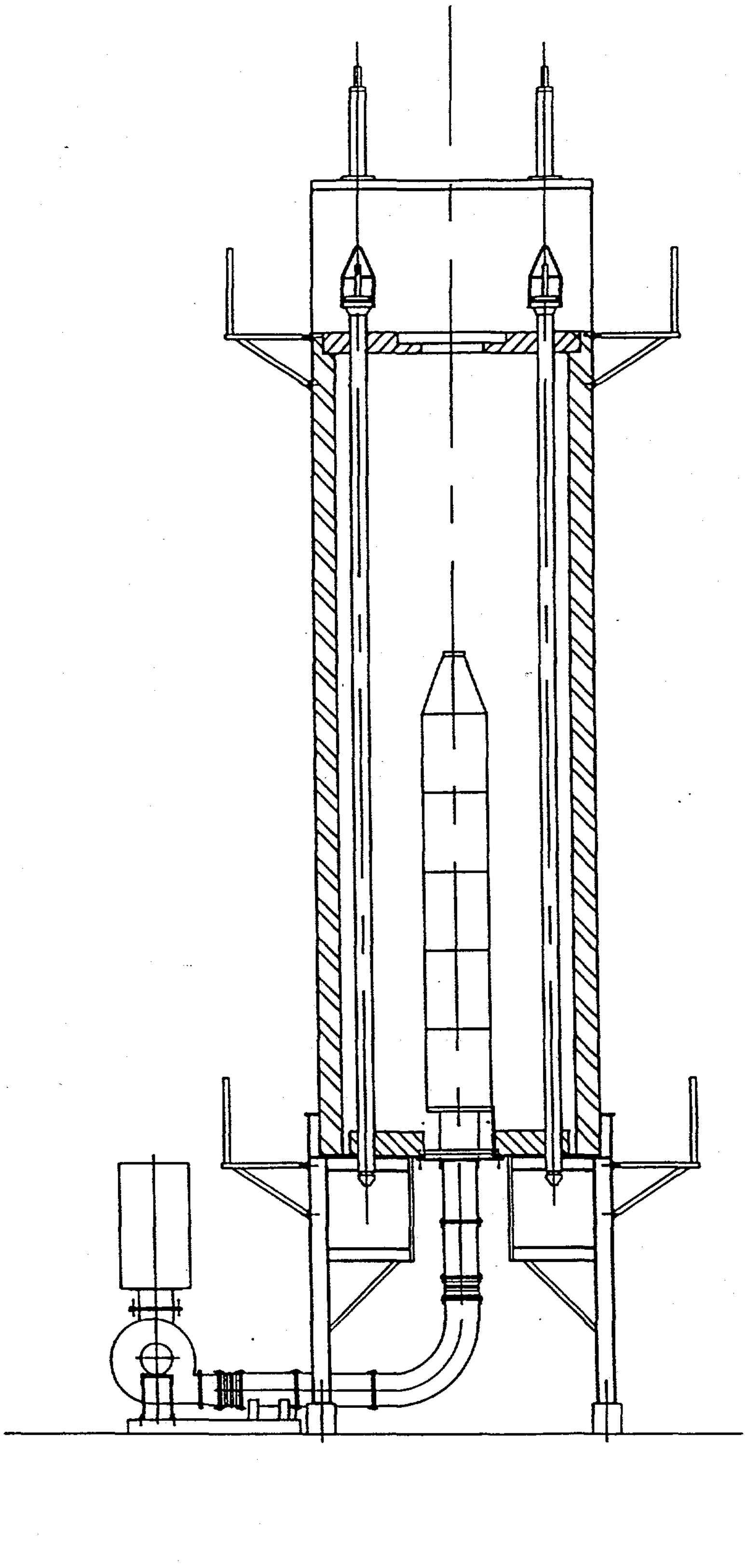


Figure B-1. Schematic of Pyrocore HT Porous Surface Burner Installed in a Vertical Cylindrical Reformer Heater concern, a design constraint for the field test was to devise a means of installation from the bottom of the heater. The segmented burner design is beneficial in this regard, as typical vertical access under a reformer would be at least 6 feet, and the maximum burner segment length is 3 feet. A lifting mechanism was designed that allowed for burner installation. This hardware was demonstrated first at Alzeta and then in the field with the full six segment burner. This, or a similar, installation method would be used in future upfired installations. In downfired reformer installations it is expected that burners would be lowered into place by a crane.

System Turndown - In typical operation, steam-methane reformer heater turndown will not exceed 3:1, and this level of turndown can be easily achieved using a single radiant burner element. During plant startup greater turndown is desired, with 8:1 turndown being the value targeted for the ARCS. This turndown requirement presented a significant challenge in single burner systems, in that burners are typically limited to maximum turndown of 3 or 4 to 1. In multiple-burner Pyrocore systems, such as the 48 MMBtu/hr RCB at the UC Irvine Medical Center, greater turndown was achieved by removing individual burners from service. In a single burner system, this is not an option.

Burner turndown of 8:1 was achieved by inserting an internal baffle into the premixed portion of the burner, with the baffle separating the bottom two segments of the burner (approximately 35% of burner surface area) from the top four segments. The baffle was sized to provide uniform flow of premixed fuel and air to the top and bottom sections of the burner during normal operation. During normal operation, gas injection and mixing occur far upstream of the flow split, so if properly sized the baffle has no effect on flow distribution or stoichiometry.

During startup, the main gas supply line was shut, and a secondary "startup" gas supply line was opened. This startup line injected gas into the flowstream downstream of the baffle inlet, and therefore fed gas only to the bottom two burner segments. Using this technique, the bottom two burner segments (35% of burner surface area) could operate at approximately one-third of maximum fired duty to provide the necessary 8:1 system turndown. At the desired point in the startup sequence, the main gas supply was actuated, the top four burner segments were ignited by the bottom two segments, and then the startup gas line was closed. This sequence was controlled using automatic logic, and was demonstrated to provide the required turndown in preliminary tests.

### B.1.2 Performance Modeling

Reformer modeling was performed during the first year of the ARCS project by Kinetics Technology International, Inc. (KTI) for a downfired cabin-heater design. One goal of the ARCS project was to develop multiple-burner cabin heater combustion systems, but the initial field demonstration targeted a smaller system. A typical "small" reformer has a vertical cylindrical heater and operates with floor mounted burners in an upfired configuration. After the selection of the field demonstration site, additional heater modeling was performed to select appropriate burner dimensions.

This host site heater modeling was performed with assistance from APCI as part of their support of the ARCS project. APCI could use a commercially available code to model conventional flame burner performance in a heater, but no comparable code was available to model radiant burner performance. A zone model was developed by Alzeta that could predict surface-to-surface radiation, gas phase radiation, and convection. The surface-to-surface radiation model used burner surface temperature and emissivity data determined empirically from previous experimental data. Gas phase radiation was calculated using the method developed by Hottel (published in Heat Transmission 3rd edition, by W.H. McAdams, McGraw-Hill Publishing, 1954), and convection was calculated using an empirical convective heat transfer coefficient. The code also assumed nonconstant specific heat for combustion products and the process fluid, and could be used to predict heater performance with radiant or nonradiant burners.

A commercial code, also zone model based, was used to model conventional flame burner performance for a typical cylindrical heater geometry. Commercial code results were used to "calibrate" the Alzeta model at selected operating conditions. This allowed for consistent results to be obtained between the two codes for the selected geometry when modeling conventional burner performance. Using the Alzeta model, comparisons were then made between vertical cylindrical reformer heaters with conventional and radiant burners. The modeling results discussed below assume a fixed rate of hydrogen production, with total fired duty varied to meet this requirement.

The cylindrical reformer heater was broken into seven zones of equal length. Each zone was cylindrical in shape with the diameter of the cylinder being identical the the inside diameter of the heater and the length of the cylinder being one-seventh the total length of the radiant section of the heater. The heater internal dimensions were approximately 8 ft ID by 28 ft long, so the bottom five zones of the seven-zone model included the radiant burner. The last two zones model gas phase radiation and convection to the process tubes.

A comparison of contributions by the different heat transfer mechanisms to total heat flux to the process tubes is presented as Figures B-2 and B-3 for the conventional flame burner and the radiant burner respectively. This information is broken down by zone. As expected, the radiant burner provides a flatter flux profile to the process tubes over the length of the heater. Total flux drops in the conventional burner case as one moves up the heater. In the radiant burner case, the flux is fairly constant in the bottom four zones then drops as the combustion products approach the top of the heater. A comparison of total flux per zone for the two cases is presented as Figure B-4. The model predicted that the radiant burner would increase radiant section efficiency by 5.8% relative to the conventional burner. Modeling performed by KTI for a down-fired cabin heater during the first year of the project predicted a 4% improvement in radiant section efficiency.

A comparison of the average gas temperature per zone for the two different burners is presented as Figure B-5. As expected, the radiant burner operates with significantly lower gas phase temperatures, with the associated benefit that less thermal $NO_x$ will be produced. By radiating combustion energy directly from the burner surface to the process tubes, there is less energy in the combustion products and they leave the burner surface at a lower temperature.

### B.1.3 Baseline Tests

On December 15 and 16, 1993, baseline performance tests were performed at the host site to quantify system thermal and emissions performance prior to installation of the ARCS. Two complete reformer skids are operational at the host site, with only one skid required to produce the hydrogen required by the customer. These skids are referred to as "A skid" and "B skid", with the A skid being the one to be modified to incorporate the ARCS. Although there are only small differences between the two skids, it was determined that any baseline tests would be performed on the A skid.

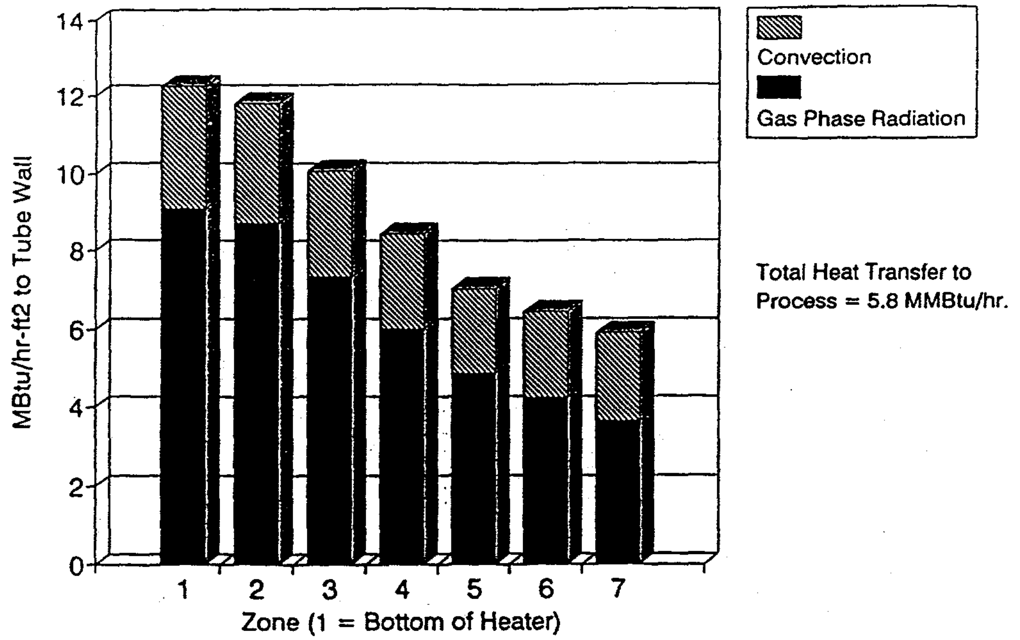


**Figure B-2.** Components of total energy transfer to process tubes as a function of elevation in a vertical cylindrical steam-methane reformer heater with a conventional flame burner.

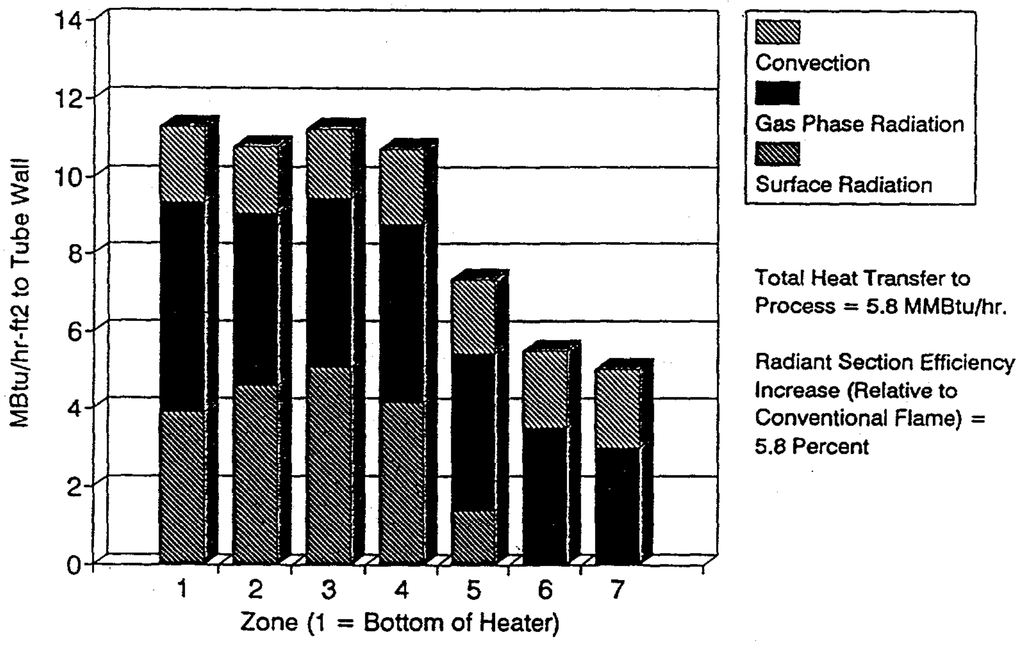
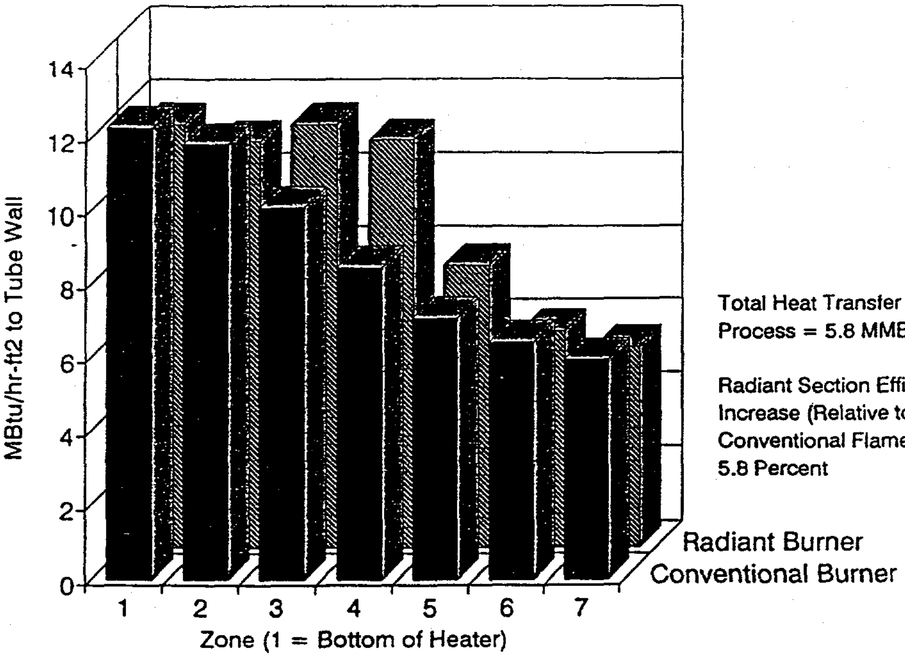


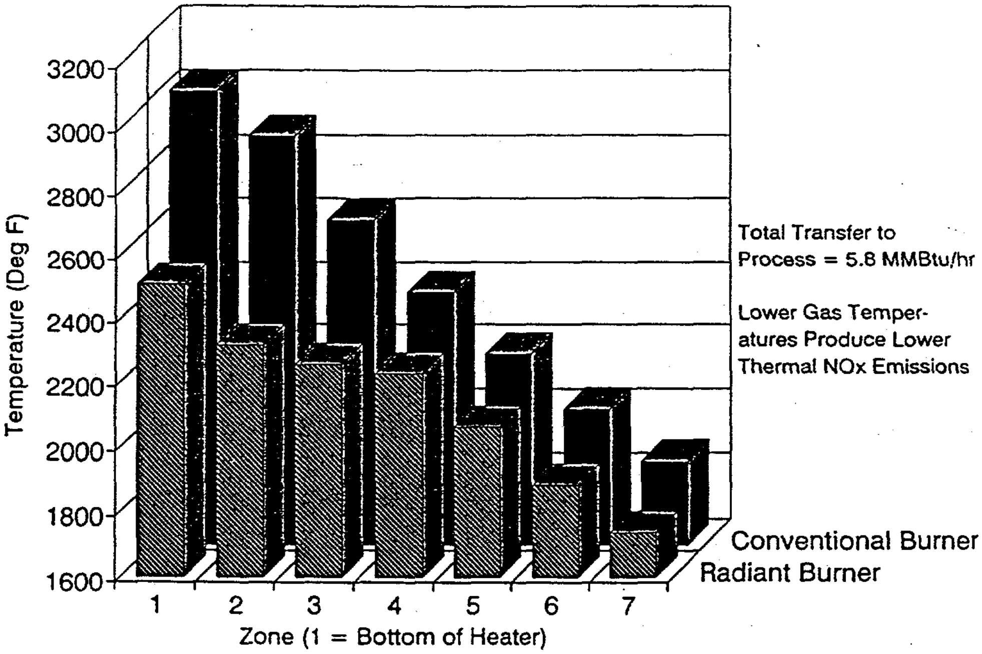
**Figure B-3.** Components of total energy transfer to process tubes as a function of elevation in a vertical cylindrical steam-methane reformer heater with a porous surface radiant burner.



Total Heat Transfer to Process = 5.8 MMBtu/hr.

Radiant Section Efficiency Increase (Relative to Conventional Flame) = 5.8 Percent

Figure B-4. Comparison of flux to process tubes from a conventional flame burner and a porous surface radiant burner for a vertical cylindrical steam-methane reformer heater.



Total Transfer to Process = 5.8 MMBtu/hr

Lower Gas Temperatures Produce Lower Thermal NOx Emissions

Figure B-5. Comparison of average gas phase temperature per zone for a conventional flame burner and a porous surface radiant burner in a vertical cylindrical steam-methane reformer heater.

Over the two days of operation, test data were recorded at seven operating conditions representing a range of hydrogen production rates and excess air levels. APCI had responsibility for recording thermal performance data and process side data. Alzeta performed emissions sampling using a portable emissions analyzer. $NO_x$ emissions corrected to 3% $O_2$ are presented in Figure B-6 in the format used by APCI to correlate $NO_x$ emissions from different reformers. Data are consistent with previously collected data from other facilities.

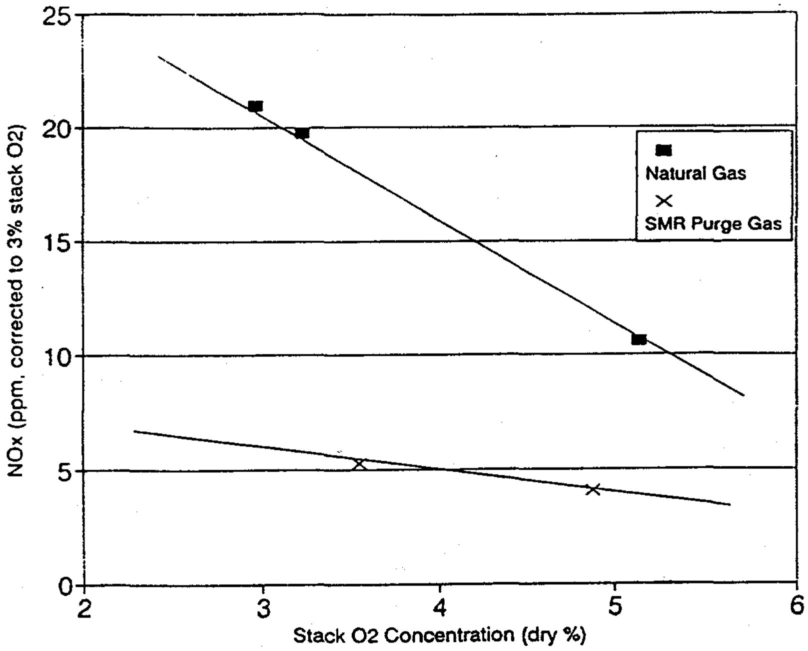


Figure B-6. Comparison of $NO_x$ emissions from a Pyrocore HT burner operating with natural gas and simulated reformer purge gas fuel at 250°F combustion air preheat in a hot-walled test facility.

### B.1.4 Site Permits

APCI was responsible for obtaining site permits for the steam-methane reformer host site. Permitting work was performed by an Environmental Coordinator at APCI. The responsible agency for permitting at Leechburg is the Commonwealth of Pennsylvania Department of Environmental Resources. Based on a review by the state, it was determined that the host site would be exempted from Plan Approval/Operating Permit requirements. Since the purpose of the demonstration was to demonstrate a low $NO_x$ burner, but not to increase the capacity or operating hours of the facility, the impact of the modification would not increase total $NO_x$ emissions from the source. Also, the modifications would not cause the site to be viewed as a new source. Site permitting was therefore straightforward, requiring only that APCI receive a Plan Approval/Operating Permit Application Determination exemption. The letter of exemption was sent by the Department of Environmental Resources on September 23, 1993.

## B.2 FIELD TEST RESULTS

Burner installation and site modifications necessary to operate the ARCS were completed in February 1994. The actual burner installation was completed over a 3 day period, which was about 1 day more than had been planned. The burner installation was completed on February 24. It was expected that some modifications to the Leechburg installation hardware would be made prior to performing additional facility retrofits. None of the burner segments were damaged during installation. There were three spare segments at the host site.

Additional modifications to the host facility included piping, electrical, and control system modifications. These modifications were completed to the point where the burner pilot was operated on February 28, the startup burner segments were operated on March 1, and the full burner was operated on March 2. On February 28 or March 1, it was observed that the system ID fan needed repairs. Rather than risk an unscheduled shutdown due to ID fan failure, it was decided to have the fan fixed prior to switching hydrogen production to the ARCS skid (hydrogen production on the unmodified skid was unaffected by ARCS skid modifications).

The full burner was operated on March 2 for several hours to allow the heater to reach wall temperatures in the 1100°F to 1300°F range. Steam was also generated in the boiler and superheater sections of the skid. However, due to the ID fan problems the system was deliberately shut down prior to passing steam through the process tubes. Based on the limited experience gained during the 3 days of operation, some additional modifications to the facility have been implemented. The facility restart was scheduled for the week of March 14.

Alzeta personnel returned during the week of March 14-18 to continue the shakedown process. On March 16, the system was started at 4 a.m. with the intent of being at full hydrogen production capacity by the end of the day. At about 12:40 p.m., the system was at conditions typical of hydrogen production. The process gas temperature at the exit of the heater was 1500°F. While this is a typical process gas temperature, the target operating point for this heater was 1600°F due in part to the age of the catalyst. Therefore, system operating temperatures were still being ramped up. At 12:40 the plant tripped on loss of flame and high burner internal temperature alarms. All automatic safety shutdown procedures operated correctly with gas flow being shutoff immediately and combustion air flow continuing.

Immediately after the plant trip, it was observed that the ARCS burner had suffered damage that was significant enough to prevent further testing. The system was allowed to cool off overnight, and the burner was removed for inspection on March 17. Initial inspection revealed that all six burner segments suffered some damage, with the second segment from the floor of the heater suffering the worst damage. Based on this and subsequent inspections it is believed that the cause of failure originated at segment 2. All other burner damage probably resulted from the internal pressure pulse generated by the accident. The internal pressure was sufficient to remove ceramic pad from all segments except segment 1, but did no damage to the metal support screens.

## B.3 POST-DEMONSTRATION BURNER INVESTIGATION

### B.3.1 Initial Evaluation

Immediately after the burner failure at the Leechburg host site, a list of possible causes was compiled. This list follows. Failure scenarios investigated were:

1) Flashback at interface between startup separator plate and segment 2 to segment 3 flanges
2) Pad delamination from metal support screen
3) Pad overheating leading to flashback due to nonuniform flow
   Pad overheating leading to flashback due to high flux rate from the surrounding hot gas environment to burner surface
4) Refractory damage
5) Installation damage causing pad to separate from screen prior to operation
   Vertical mounting causes compressive stress leading to screen buckling
6) Bottom two segments ran poorly mixed and possibly rich
   Hot restart on bottom burner doubles gas flow at low fire for 1 minute
7) Poor pad adhesion due to dual-layer screen design leads to loss of pad and failure.
8) Out of spec thermal processing at Alzeta prior to shipment leading to burner failure.

## B.3.2 Alzeta Examination of Leechburg Failure

### PPH Burner Tests

Following the initial review of potential causes of the Leechburg burner failure, Alzeta conducted a series of tests in the Alzeta PPH facility. This facility was selected because it allowed for testing the largest burners possible at Alzeta at thermal conditions that could exceed reformer temperatures. A summary of these tests is provided below:

- Burners failed at surface temperatures of 2430°F or hotter, well above the intended operating temperature of the burner. The burner at Leechburg was believed to be operating at about 2000°F at the time of burner failure based on two-color pyrometer measurements made prior to the failure.
- Burner failure was preceded by a rapid rise in support screen temperature of 25°F to 50°F per minute, allowing time to shut off fuel flow and "save" burners prior to failure if screen temperatures are monitored
- Screen temperature rise was not confined to a single location even though the "spot" indicating imminent failure is highly localized. All screen TC's experienced a rapid temperature rise.
- Maximum screen temperatures of 1000°F did not cause permanent damage on a macroscopic scale. Burners were retested with no observable difference in operation, but there should be a permanent change in burner pad materials due to the high screen temperature that would be observed on a microscopic scale.
- The results of the PPH tests demonstrated two important points. First, burner failures in PPH were not as repeatable as we would have liked. This made it difficult to establish the cause of burner failure. Secondly, PPH burner tests were being run at conditions significantly more severe than what was encountered at the host site prior to failure. This second observation is consistent with the concern that larger burners may be more susceptible to failure that smaller burners due to the increased likelihood of flow nonuniformity as burner size is increased.

### Examination of Full-Scale Host Site Segments

Seven cylindrical burner segments were fabricated for the ARCS field demonstration. Of these, five were installed and fired in the host heater and two were kept as spares. During

December, burner pad material from four of the fired segments and one of the spares was examined to determine variations in burner pad thickness. The results were as follows:

- Of the five segments examined, the pad was 0.125 to 0.188 inches thicker at the bottom of the segment than at the top. The average variation in thickness was 0.150 inches, which represents a 24% variation from top to bottom.
- Circumferential variations were measured to be on the order of .032 inches, much less than the measured longitudinal variation.
- Pad thickness variation from segment to segment was on the order of +/- .050 inches, so variation from segment to segment was less than variation from top to bottom of each segment.
- Three "standard formulation" Pyrocore burners manufactured at Alzeta were also measured in December. The maximum variation in thickness was 0.094 inches, with the average being 0.042 inches. Additional measurements will be made to determine if this smaller thickness variation is "typical."
- Pad pressure drop has been demonstrated to vary approximately linearly with pad thickness. Therefore, it is possible that premix flow would vary by 24% from the top to the bottom of a host site burner segment, with the top of the burner operating at a higher heat release rate then the bottom.

If significant, this variation in pad thickness would be most significant in segmented burners where differences in pad thickness would be most pronounced at the interface between two segments. Pad thickness variation has not been demonstrated to lead to burner failure in any previous field or laboratory tests, and pad thickness variations are not routinely measured at Alzeta.

### 5.3.3 Consultants Report on APCI Burner

At the request of DOE, Alzeta hired a consultant familiar with natural gas burners to provide an independent assessment of probable causes of the Leechburg burner failure. The consultant was Mr. Shyam Singh of Shyam Singh Energy Environmental International, Inc. (SSEEI), of Rockford, Illinois. Mr. Singh's investigation focused on the following areas:

- Flow uniformity through the porous burner surface
- Premix nonuniformity due to inadequate mixing

Additional tests were performed by Alzeta at the completion of the consultant report. These tests did not provide evidence that poor mixing or poor pad uniformity led to the Leechburg failure. Both of these potential causes do become more critical as burner size is increased, and could explain the difference in performance between the Alzeta subscale burner and the full-scale APCI burner.

# APPENDIX C

# MARKET ANALYSIS -- STEAM METHANE REFORMING/REFINERIES

## C.1 STEAM-METHANE REFORMING AND REFINERIES

During Phase I, market research was performed to quantify the benefits provided to U.S. industries by the advanced radiant burner. A survey of the reformer market is provided in Section C.1.1, followed in Section C.1.2 by the results of a cost analysis comparing the ARCS reformer to a conventional unit. A discussion of benefits provided to the general petrochemical market is provided in Section C.1.3. Section C.1.4 provides an estimate of the value of reduced $NO_x$ emissions provided by advanced radiant burner technology.

### C.1.1 Results of Hydrogen Market Studies

Information on the hydrogen market in general, and in particular the steam reforming of hydrocarbons to produce hydrogen, was obtained from two sources. One source was the Chemical Economics Handbook (CEH) study performed by SRI International as part of their Process Economics Program. This report investigates primarily the merchant hydrogen market which includes hydrogen manufactured for pipeline delivery, government use and cylinder delivery in gaseous form. The report intentionally excludes a significant number of hydrogen reformers used in the production of ammonia and methanol. These reformers are covered in separate CEH reports describing the ammonia and methanol industries.

In addition, information more specific to hydrogen reformers was assembled by a consultant to Alzeta, Dr. Ronald Minet. The Minet market study was an attempt to provide data on all hydrogen reformers currently operating in the U.S. and worldwide regardless of industry. The report placed particular emphasis on the refinery market and large chemical users of such products as ammonia and methanol. Industry activity between 1980 and 1990 was reviewed and this information was used to provide estimates of market growth between 1990 and 2010.

A brief review of the uses of hydrogen will help to illustrate its importance to U.S. industry. Hydrogen is required in the production of a large number of intermediate chemicals that end up as both industrial and consumer products. Table C-1 presents a summary of the largest current and potential industrial users, and provides approximate hydrogen requirements to produce given quantities of the tabulated end products. A more complete list of uses of hydrogen is presented as Table C-2. Currently, the United States accounts for 26% of the world's hydrogen production with other significant production capability existing in Western Europe, Canada, and Japan.

The domestic need for hydrogen is projected to grow at approximately 2.7% annually and a breakdown of projected U.S. hydrogen production by end use is presented in Figure C-1. Ammonia currently represents the largest end use for hydrogen, accounting for roughly 50% of domestic hydrogen consumption. This is followed by refinery consumption at 32% and methanol production which accounts for about 9% of total hydrogen usage. Miscellaneous applications such as metals, chemicals, and food processing account for the remaining hydrogen. A comparison of U.S. production with worldwide production in these four categories is presented as Table C-3.

The primary purpose of the Minet study was to define the hydrogen reformer market over the next 20 years, as this is the market we will penetrate with the ARCS. Results of this part of the study are presented as Table C-4. New production capacity required in 5-year windows between 1990 and 2000, and the 10-year window between 2000 and 2010, was estimated by industry. Based on the current size distribution of reformers, future plant sizes were also estimated. These figures do not include replacement units. An average plant life of 20 years implies that in each 5-year window approximately 25% of the existing plants must be replaced or refurbished.

The importance of the U.S. hydrogen industry is apparent from the industry's energy requirements. With U.S. production at approximately 6600 million scf per day and an average energy requirement of 400 to 450 Btu per scf of hydrogen (fuel + feedstock), the U.S. annual energy use by the industry is approximately 1000 trillion Btu. This is a full 20% of the current domestic petrochemical energy use of 5000 trillion Btu, and could grow to near 25% by the year 2000. An estimated 450 billion cubic feet of natural gas are consumed per year by the industry. Since the cost of hydrogen production (and of other petrochemical heating processes) includes approximately 15% to 30% for fuel, a reasonable ARCS goal of a 2% to 5% efficiency gain would have the effect of reducing product prices by 1% to 2% – improving the competitive position of hydrogen as a commodity.

### C.1.2 Conceptual Design Cost Analysis

The conceptual design of an ARCS-based reformer was performed with the assistance of Kinetics Technology International Corporation (KTI) as part of the Phase I program. KTI is

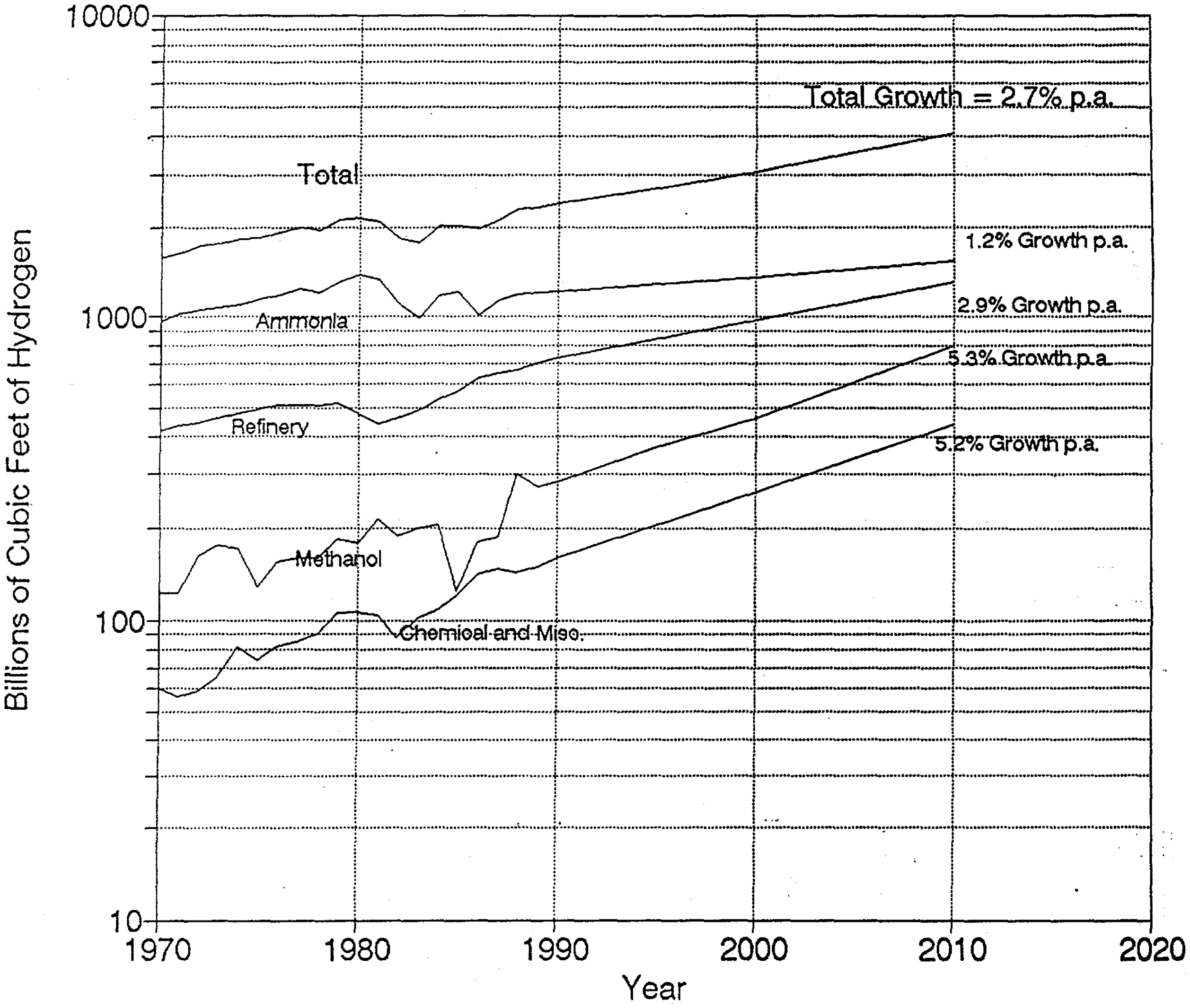


Figure C-1. U.S. Production of Hydrogen

## TABLE C-1. WORLD HYDROGEN PRODUCTIONBY END USE
(billions of cubic feet per year)

| | 1980 | 1990 | 1995 | 2000 | 2010 |
|---|---|---|---|---|---|
| Ammonia - U.S. | 1,376 | 1,218 | 1,290 | 1,350 | 1,530 |
| -- Rest of world | 4,824 | 7,580 | 8,810 | 10,200 | 12,400 |
| -- Total world | 6,200 | 8,798 | 10,100 | 11,550 | 13,930 |
| Refinery - U.S. | 477 | 731 | 845 | 975 | 1,300 |
| -- Rest of world | 480 | 1,288 | 1,850 | 2,655 | 4,325 |
| -- Total world | 957 | 2,019 | 2,695 | 3,630 | 5,625 |
| Methanol - U.S. | 179 | 285 | 370 | 460 | 800 |
| -- Rest of world | 400 | 916 | 1,230 | 1,660 | 2,430 |
| -- Total world | 579 | 1,201 | 1,600 | 2,120 | 3,230 |
| Chem & Other - U.S. | 107 | 160 | 205 | 262 | 440 |
| -- Rest of world | 300 | 500 | 600 | 735 | 1,090 |
| -- Total world | 407 | 660 | 805 | 997 | 1,530 |
| Total U.S.Production | 2,139 | 2,394 | 2,710 | 3,047 | 4,070 |
| -- Rest of world | 6,004 | 10,284 | 12,490 | 15,250 | 20,245 |
| -- Total world | 8,143 | 12,678 | 15,200 | 18,297 | 24,315 |

## TABLE C-2. USES OF HYDROGEN

Petroleum Refining
- Desulfurization
- Hydrocracking
- Demetalization
- Lube Oil

Petrochemical
- Methanol
- Ammonia
- OXO Alcohols

Chemicals
- Nylon
- Polycarbonates
- Plastics
- Dye Stuffs

Metals
- Direct Reduction of Iscon
- Nickel
- Copper
- Tungsten

Chemicals and Glass
- Float Glass
- High Purity Silicon

Electronics
- Polysilicon Production
- Epitaxy
- Etching
- Chemical Vapor Deposition

Space Exploration
- Liquid Hydrogen Fuel
- High Thrust Rocket Fuel

Power Generation
- Fuel Cells
- Direct Hydrogen Fuel

Other Uses
- Food Processing
- Soaps, Detergents, etc.

# TABLE C-3. HYDROGEN REFORMER STUDY

| Ammonia | 1980 | 1990 | 1995 | 2000 | 2010 |
|---|---|---|---|---|---|
| -- US | 1376 | 1218 | 1290 | 1350 | 1530 |
| -- Rest of World | 4824 | 7580 | 8810 | 10200 | 12400 |
| -- Total World | 6200 | 8798 | 10100 | 11550 | 13930 |
| Refinery | | | | | |
| -- US | 477 | 731 | 845 | 975 | 1300 |
| -- Rest of World | 480 | 1288 | 1850 | 2655 | 4325 |
| -- Total World | 957 | 2019 | 2695 | 3630 | 5625 |
| Methanol | | | | | |
| -- US | 179 | 285 | 370 | 460 | 800 |
| -- Rest of World | 400 | 916 | 1230 | 1660 | 2430 |
| -- Total World | 579 | 1201 | 1600 | 2120 | 3230 |
| Chem and Other | | | | | |
| -- US | 107 | 160 | 205 | 262 | 440 |
| -- Rest of World | 300 | 500 | 600 | 735 | 1090 |
| -- Total World | 407 | 660 | 805 | 997 | 1530 |
| Total US Production | 2139 | 2394 | 2710 | 3047 | 4070 |
| Total Rest of World | 6004 | 10284 | 12490 | 15250 | 20245 |
| Total World Production | 8143 | 12678 | 15200 | 18297 | 24315 |

## TABLE C-4. FUTURE HYDROGEN REFORMER REQUIREMENTS – USA

YEAR: 1990

| End Use | $H_2$ Capacity BSCF/yr | No. of Units | Size of Reformer (Million SCFD) <3.5 | 3.5-20 | 20-100 | >100 |
|---|---|---|---|---|---|---|
| Ammonia | 1,160 | 54 | 0 | 6 | 39 | 9 |
| Refinery | 719 | 48 | 5 | 12 | 23 | 8 |
| Methanol | 200 | 9 | 0 | 1 | 5 | 3 |
| Chem & Misc. | 180 | 61 | 39 | 20 | 2 | 0 |
| Total USA | 2,259 | 172 | 44 | 39 | 69 | 20 |

YEARS: 1990-1995

| End Use | New $H_2$ Capacity Req'd BSCF/yr | No. of New Units | Size of Reformer (Million SCFD) <3.5 | 3.5-20 | 20-100 | >100 |
|---|---|---|---|---|---|---|
| Ammonia | 53 | 2 | 0 | 0 | 2 | 0 |
| Refinery | 110 | 7 | 0 | 2 | 4 | 1 |
| Methanol | 68 | 3 | 0 | 0 | 3 | 0 |
| Chem & Misc. | 49 | 13 | 10 | 3 | 0 | 0 |
| Total USA | 280 | 25 | 10 | 5 | 9 | 1 |

BSCF = Billion Standard Cubic Feet
SCFD = Standard Cubic Feet per Day

## TABLE C-4. CONCLUDED

| YEARS: 1995-2000 | | | | | | |
|---|---|---|---|---|---|---|
| End Use | New $H_2$ Capacity Req'd BSCF/yr | No. of New Units | Size of Reformer (Million SCFD) | | | |
| | | | <3.5 | 3.5-20 | 20-100 | >100 |
| Ammonia | 62 | 2 | 0 | 0 | 1 | 1 |
| Refinery | 127 | 7 | 0 | 2 | 4 | 1 |
| Methanol | 74 | 3 | 0 | 0 | 3 | 0 |
| Chem & Misc. | 63 | 16 | 5 | 11 | 10 | 2 |
| Total USA | 326 | 28 | 5 | 11 | 10 | 2 |

| YEARS: 2000-2010 | | | | | | |
|---|---|---|---|---|---|---|
| End Use | New $H_2$ Capacity Req'd BSCF/yr | No. of New Units | Size of Reformer (Million SCFD) | | | |
| | | | <3.5 | 3.5-20 | 20-100 | >100 |
| Ammonia | 147 | 5 | 0 | 0 | 3 | 2 |
| Refinery | 316 | 16 | 0 | 2 | 12 | 2 |
| Methanol | 215 | 7 | 0 | 0 | 4 | 3 |
| Chem & Misc. | 95 | 24 | 6 | 12 | 6 | 0 |
| Total USA | 773 | 52 | 6 | 14 | 25 | 7 |

actively involved in the design of conventional reformer furnaces, and in addition has fabricated low temperature process heaters using Alzeta's radiant burner technology. Due to this experience, it was felt that KTI was ideally qualified to perform the conceptual design of the ARCS-based reformer and to compare the cost of this system to an equivalently sized conventional reformer. KTI recently completed the design of a 5 million scfd conventional reformer furnace, so this design was used as the basis for comparison with the ARCS conceptual design.

The cost breakdown for both the conventional reformer and the radiant-burner-based system is provided as Table C-5. As expected (based on previous design experience), the ARCS design results in a reduced furnace volume. As a result of this, less structural steel and refractory is required for the ARCS system resulting in a lower furnace cost (excluding burners). The costs of the two systems, excluding burners, is $932.3K for the conventional reformer and $878.8K for the radiant-burner-based system. This is for two furnaces with equivalent hydrogen production capacity and equivalent thermal efficiency.

Conventional "low $NO_x$" burners with $NO_x$ emissions of roughly twice that produced by the ARCS would cost $32K based on KTI's previous experience. This brings the cost differential between the competing systems to $85.5K with the conventional system having the higher cost, excluding for the moment the cost of radiant burners. Based on the results presented in Appendix B, the total burner surface area required for the ARCS reformer is 435 square feet (40 MMBtu/hr fired duty based on HHV, with an average surface firing rate of 92 MBtu/hr-ft$^2$). At a nominal burner cost of $100 per square foot (which is accurate to within 20% for the current product) the total cost of radiant burners would be $43.5K. Therefore, the cost of a radiant-burner-based reformer could be $42K less than a conventional system for a furnace with a total cost of roughly $1 million, substantiating the claim in Section 2 of the main report that the use of radiant burners can reduce the capital cost of new furnaces.

This simple cost analysis does not account for three factors. The first is anticipated higher cost of ARCS burners when compared to current burners. It is anticipated that the higher temperature capability required for operation in the reformer environment will result in somewhat higher burner costs. The market penetration predictions presented in Section C.1.1 were done assuming that ARCS burner costs would be twice the current nominal cost, and the results of this analysis were favorable.

Second, the cost comparison presented above did not include an estimate for the cost of the advanced control system that is an integral part of the ARCS. Although this control system is an integral component of the ARCS, it is not a required component of a reformer utilizing radiant

## TABLE C-5. REFORMER FURNACE COST SUMMARY

| DESCRIPTION | BASELINE FURNACE | ARCS FURNACE |
|---|---|---|
| TUBES, FITTINGS & FINS: | | |
| Radiant | $228,300 | $225,800 |
| Convection | $94,800 | $92,900 |
| | | |
| STEEL | | |
| Radiant Section | $61,000 | $42,400 |
| Convection Section | $30,600 | $31,200 |
| Stack | $8,800 | $8,800 |
| Ductwork | $35,100 | $30,000 |
| Ladders & Platforms | $43,100 | $40,000 |
| Support Steel | $15,300 | $15,300 |
| | | |
| REFRACTORY | | |
| Radiant Section | $62,400 | $61,500 |
| Convection Section | $22,700 | $27,500 |
| Stack | $5,200 | $5,200 |
| Ductwork | $23,300 | $20,000 |
| | | |
| ADDITIONAL STEEL | | |
| Peep, Access & Explosion Doors | $8,400 | $8,400 |
| Dampers & Actuators | $70,000 | $70,000 |
| Alloys, Expansion Joints & Misc. Items | $2,100 | $2,100 |
| | | |
| SUPPORTING SYSTEM | | |
| Cast Tubesheets | $11,400 | $13,000 |
| Spring Hangers, Rods & Clamps | $13,400 | $14,000 |
| | | |
| EQUIPMENT | | |
| ID Fan | $3,800 | $4,000 |
| FD Fan | $3,100 | $3,300 |
| Air Preheater | $74,500 | $54,900 |
| Waste Heat Boiler & Steam Drum | $105,000 | $96,500 |
| | | |
| INTERNAL FREIGHT | $10,000 | $12,000 |
| TOTAL COST (EXCLUDING BURNERS): | $932,300 | $878,800 |
| Burner Cost | $32,000 | TBD |
| TOTAL COST: | $964,300 | TBD |

burners. In a real job costing exercise, the cost-benefit analysis of the control system would have to be performed separately from the radiant burners as an additional capital cost that would have to provide an acceptable return on investment. KTI did not have accurate cost information available to estimate control system costs, so their cost-benefit analysis was based only on the decision of whether to use conventional or radiant burners.

The third factor not addressed in this section is the value of reduced $NO_x$ provided by radiant burners. In the KTI cost comparison, the ARCS was compared to a system with conventional "low $NO_x$" burners. These conventional burners have significantly higher $NO_x$ emissions than the ARCS target of 25 ppm (corrected to 3% O2). The conventional low $NO_x$ burners have emissions of 40 to 50 ppm, and standard industrial burners with no $NO_x$ reduction hardware have emissions of 80 to 100 ppm. The cost significance of these different emissions levels is extremely dependent on facility location. In analyses performed to date by both Alzeta and KTI, the initial cost of a Pyrocore-based reformer furnace will be significantly less than the cost of a conventional furnace with a selective catalytic reduction (SCR) unit.

### C.1.3 General Refinery and Chemical Industry Applications

Hydrogen production via steam reforming of hydrocarbons was selected as the initial market application of the ARCS in Phase I of the project. The ARCS concept is general in nature and nearly all high temperature applications will benefit from the concept, with energy intensive processes benefiting most due to the payback associated with reduced fuel consumption. A brief survey of additional markets was performed, with a focus on petrochemical processes.

The petrochemical industries are the single largest category of energy users. They are classified by Standard Industrial Classification (SIC) Codes 28, Chemicals and Allied Products, and 29, Petroleum and Coal Products, and consume over 2300 trillion Btu (2300 billion cubic feet) of natural gas energy in the U.S. annually (Reference C-1). These industries are unique in that many of the processes produce by-product fuel gases that are mixed with purchased gas and burned as fuel. With the industry producing nearly 50% of the energy it consumes, the total energy used in U.S. petrochemical operations is estimated at near 5000 trillion Btu annually.

Alzeta's studies show that relatively inefficient equipment (50% with conventional burners) can realize a significant efficiency improvement of over 10% with radiant burners. At higher existing equipment efficiencies, the gain by radiant burner retrofit is less significant.

From this application experience, known efficiencies in the radiant furnaces of current petrochemical process heaters (55%-65%), and overall equipment efficiencies (75% to 83% based on higher heating values, controlled by convective heat exchangers and additional energy recovery devices), the advanced radiant combustion system is expected to produce a 2% to 5% efficiency gain in process heaters and hydrogen reformers. Therefore, if the technology were applied to the entire industry, total energy savings would amount to 100 to 250 trillion Btu per year. At an average energy cost of $4.00 per million Btu, this represents an annual energy savings of up to one billion dollars to the industry.

Recognizing that the technology will be phased into the industry over a 40-year period, accounting for 5% annual growth, a conservative 2% average efficiency improvement, and a market penetration of 50%, a more realistic projection of energy savings is shown in Table C-6.

### C.1.4 Air Quality Benefits

The petrochemical industry is the two largest domestic energy consumer, so reductions in combustion pollutant emissions from these processes provide a profound benefit to national air quality. The radiant burner system is able to reduce emissions of nitrogen oxides ($NO_x$) by an average of 80% over conventional burners used in these processes. This benefit is achieved while maintaining low emissions of carbon monoxide (CO) and unburned hydrocarbons (less than 30 ppm each). $NO_x$, CO, and organic fractions contribute to acid rain and to ozone -- creating compliance problems for over 100 U.S. metropolitan areas.

The primary air quality benefit of the advanced combustion system is its reduction of $NO_x$. An average emission reduction for processes discussed above will be from 0.14 lb $NO_x$ per million Btu fired duty using conventional burners down to 0.03 lb $NO_x$/MMBtu using the ARCS. Considering the possible capacity to be refit in the target industries of Tables C-6 and C-7, a total annual $NO_x$ reduction is shown in Table C-8. This $NO_x$ reduction is very large primarily due to the quantity of energy consumed in the petrochemical and metals industries.

In recent studies by Alzeta of retrofits of refinery process heaters (Reference C-2), the cost-effectiveness of radiant burner systems has been found to range from $0.77 to $1.43 per pound of NOx reduced. The higher complexity and cost of the advanced system for higher temperature processes is expected to have an average annualized cost-effectiveness of $3.50 per

## TABLE C-6. ESTIMATED PETROCHEMICAL ANNUAL ENERGY SAVINGS PROVIDED BY THE ARCS

| | Year | | | | | |
|---|---|---|---|---|---|---|
| | 1995 | 2000 | 2005 | 2015 | 2025 | 2035 |
| Industry energy consumption ($10^{12}$ Btu) | 6400 | 9100 | 10,400 | 16,900 | 27,600 | 44,900 |
| Percent of capacity retrofit | 4 | 10 | 20 | 30 | 40 | 50 |
| Energy saved ($10^{12}$ Btu) | 5.12 | 16.2 | 41.9 | 101 | 220 | 450 |
| Energy cost ($ million) | 20.5 | 64.8 | 166 | 406 | 884 | 1800 |

## TABLE C-7. ESTIMATED METALS INDUSTRY ANNUAL ENERGY SAVINGS PROVIDED BY ARCS

| | Year | | | |
|---|---|---|---|---|
| | 1995 | 2000 | 2005 | 2015 |
| Industry energy consumption ($10^{12}$ Btu) | 560 | 575 | 595 | 615 |
| Percent of capacity retrofit | 3 | 10 | 25 | 50 |
| Energy saved ($10^{12}$ Btu) | 0.84 | 2.9 | 7.4 | 15.4 |
| Energy cost ($ million) | 3.4 | 11.6 | 29.6 | 61.6 |

## TABLE C-8. $NO_x$ REDUCTION PROVIDED BY THE ARCS

| | Year | | | | | |
|---|---|---|---|---|---|---|
| | 1995 | 2000 | 2005 | 2015 | 2025 | 2035 |
| Petrochemical energy refit ($10^{12}$ Btu) | 256 | 810 | 2,080 | 5,070 | 11,000 | 22,500 |
| Petrochemical $NO_x$ reduction (tons) | 14,080 | 44,500 | 114,400 | 279,000 | 308 | 1,240,00 |
| Metals industry refit ($10^{12}$ Btu) | 17 | 58 | 149 | 308 | 308 | 308 |
| Metals industry reduction (tons) | 935 | 3,190 | 8,200 | 15,900 | 16,900 | 16,900 |
| Total $NO_x$ Reduced (tons) | 15,000 | 47,700 | 123,000 | 296,000 | 622,000 | 1,250,000 |

pound $NO_x$. This compares to the cost-effectiveness of Selective Catalytic Reduction post-combustion cleanup techniques of approximately $4.40 per pound (Reference C-3). For the hydrogen reformer example of Appendix B, with a fired duty of 1.3 trillion Btu per year and NOx reduction of 82 tons per year, this provides an additional advanced combustion system cost benefit of $126,000. This large benefit scales approximately linearly with equipment size; benefits in proportion to system firing rate are expected in the metals industries.

This emissions cost benefit can be achieved without reduction of air quality by poisonous CO, hydrocarbons, amines, or additional particulate matter. In addition, improvements in process efficiencies should reduce the growth of $CO_2$ production currently contributing to global warming concerns from the greenhouse effect. By focusing on the two largest energy use industries, the advanced combustion system will have profound effect on the nation's future air quality.

## REFERENCES

C-1. "Future Gas Consumption in the United States,: Vol. 13, November 1986, American Gas Association Catalog No. F00783, Arlington, Virginia, 1986.

C-2. "The Cost Effectiveness of Using Pyrocore Burner to Reduce $NO_x$ Emissions from Three Chevron/El Segundo Refinery Heaters," Alzeta Report No. 85-711-118, August 1985.

C-3. Farris, Brain, et al., "Draft Supplemental Environmental Impact Report, Rule 1109 Amendment, Control of Oxides of Nitrogen Emissions from Refinery Heaters and Boilers," South Coast Air Quality management District, Diamond Bar, CA 91765.

# APPENDIX D

## BEST ENVIRONMENTAL, INC.
## SOURCE TEST REPORT FOR
## ECI SEMICONDUCTOR

# ECI SEMICONDUCTOR

# SOURCE TEST REPORT
Alzeta Thermal Oxidizer
Compliance VOC DE

Test Date: November 10, 1995

**BEST ENVIRONMENTAL, INC.**
15890 Foothill Boulevard
San Leandro, California 94578
**(510) 278-4011 FAX (510) 278-4018**

December 1, 1995

ECI Semiconductor
975 Comstock Street
Santa Clara, CA 95054

**Attn:** Mr. Bill Schanen

Subject: Compliance control efficiency test of the Thermal Oxidizer (A-1), serving positive and negative photoresist applicators in Fab 1 (Permit Application #10063, Condition 6).

Test Date: November 10, 1995.

Sampling Location: The source is located at the above address. Sampling was conducted at the inlet and outlet of the Oxidizer. Stack gas volumetric flow rates and moisture was measured at the inlet and outlet locations. The outlet sampling location did not meet the minimum port location requirements of 2 & 0.5 diameters.

Sampling Personnel: Sampling was performed by Guy Worthington and Darren Lane of BEST ENVIRONMENTAL, INC.

Observing Personnel: The BAAQMD was notified but did not attend the compliance emissions test.

Process Description: The Alzeta PCI-500 Thermal Catalytic Oxidizer is used as a control device for volatile organic emissions from semi-conductor manufacturing operations. The Oxidizer was maintained at >1450°F.

Test Program: Testing for non-methane hydrocarbons (NMHC) was performed to determine the Oxidizer NMHC destruction efficiency and NMHC emissions.

The inlet was continuously monitored during triplicate 30-min. test runs for non-methane hydrocarbons (NMHC) and carbon dioxide ($CO_2$), using the Bay Area Air Quality Management District (BAAQMD) combustion procedure, Method ST-7. The outlet was simultaneously monitored for carbon dioxide ($CO_2$), oxygen ($O_2$) and non-methane hydrocarbons (NMHC by FID). Inlet $O_2$, CO and methane ($CH_4$) were checked and determined to be ambient since no combustion sources are related to the processes. The stack gas volumetric flow rate and moisture content was measured at the outlet using BAAQMD Method ST-17, 18 & 23. Inlet moisture was determined using wet-bulb/dry-bulb measurements, and flow rate was determined by BAAQMD Methods ST-17 & 18.

Sampling and Analysis Methods: The following Bay Area Air Quality Management District

(BAAQMD) sampling and analytical methods were used:

| | |
|---|---|
| BAAQMD Method ST-5 | Carbon Dioxide, continuous monitoring |
| BAAQMD Method ST-6 | Carbon Monoxide, continuous monitoring |
| BAAQMD Method ST-7 | NMHC, continuous monitoring |
| BAAQMD Method ST-14 | Oxygen, continuous monitoring |
| BAAQMD Method ST-17 & 18 | Volumetric Flowrate |
| BAAQMD Method ST-23 | Moisture Content |
| | Plus wet-bulb/dry-bulb measurements |

<u>Instrumentation</u>: The following continuous emission analyzers were used:

| | |
|---|---|
| THC/$CH_4$ | Beckman Model 400A FID Total Hydrocarbon Analyzer |
| CO | TECO Model 48 GFC Carbon Monoxide Analyzer |
| $CO_2$ % | Horiba PIR-2000 |
| $CO_2$ ppm | Horiba PIR-2000 |
| $O_2$ | Teledyne Model 326RAX Oxygen Analyzer |

<u>Test Results</u>: Emission results for the Oxidizer are presented in Table 1. The Oxidizer efficiency averaged ≥99.46%.

Stratification was present in the exhaust gases due to poor port location at the bend of the chamber exhaust. The second test run was significantly different from 1 and 3 because the probe was moved to a different location during velocity measurements. In future, ports will be re-located.

All supporting documentation; stack gas volumetric flow rate and moisture calculations, field data sheets, strip chart records, emission calculations, equipment calibrations, calibration gas certifications, and the Authority to Construct are appended to this report.

If you have any questions regarding this report, or if BEST ENVIRONMENTAL, INC., can be of any further assistance, please call.

Prepared by
Guy Worthington
Sr. Project Manager

Reviewed by
Dan Cartner
Manager

## TABLE 1

## ECI
## Alzeta Thermal Oxidizer

| RUN # | 1 | | 2 | | 3 | | AVG | | Limit |
|---|---|---|---|---|---|---|---|---|---|
| TEST LOCATION | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet | |
| TEST DATE | 11-10-95 | | 11-10-95 | | 11-10-95 | | | | |
| TEST TIME | 1052-1122 | | 1135-1205 | | 1220-1250 | | | | |
| INCINERATOR TEMP.,°F | 1550±50 | | 1550±50 | | 1550±50 | | | | 1450 |
| FLOW RATE, DSCFM | 494 | 951 | 494 | 951 | 494 | 951 | 494 | 951 | |
| STACK TEMP.,°F | 76.0 | 1265.0 | 76.0 | 1265.0 | 76.0 | 1265.0 | 76 | 1,265 | |
| $H_2O$, % | 2.0 | 5.0 | 2.0 | 5.0 | 2.0 | 5.0 | 2.0 | 5.0 | |
| $O_2$, % | 20.0 | 16.4 | 20.3 | 14.2 | 20.0 | 16.4 | 20.1 | 15.7 | |
| $CO_2$, ppm & (%) | 300 | (2.3%) | 300 | (3.5%) | 300 | (2.4%) | 300 | (2.7%) | |
| CO, ppm | < 1 | 15.1 | < 1 | 19.2 | < 1 | 15.4 | < 1 | N.M. | |
| $CH_4$, ppm | < 1 | 123.0 | < 1 | 40.7 | < 1 | 117.3 | < 1 | 93.7 | |
| THC, ppm | N.A. | 122.0 | N.A. | 41.7 | N.A. | 114.7 | N.A. | 92.8 | |
| TOC, ppm | 2,142 | N.A. | 2,233 | N.A. | 1,917 | N.A. | 2,097 | N.A. | |
| TNMHC, ppm | 1,842 | < 5.0 | 1,933 | < 5.0 | 1,617 | < 5.0 | 1,797 | < 5.0 | 10.0 |
| TNMHC, Lbs/Hr as $CH_4$ | 2.26 | < 0.01 | 2.37 | < 0.01 | 1.98 | < 0.01 | 2.20 | < 0.01 | |
| TNMHC D.E., % | > 99.48 | | > 99.50 | | > 99.40 | | > 99.46 | | 98.5 |

**WHERE,**

CO = Carbon Monoxide (M.W. = 28)
$CO_2$ = Carbon Dioxide
$O_2$ = Oxygen
$CH_4$ = Methane (M.W. = 16)
TOC = Total Oxidizable Carbon as $CH_4$
THC = Total Hydrocarbon as $CH_4$
TNMHC = Total Non-Methane Hydrocarbon as $CH_4$
TNMHC = THC - $CH_4$, or TOC - $CO_2$ - CO - $CH_4$

Lbs/hr = Pounds Per Hour Emission Rate
DSCFM = Dry Standard Cubic Feet Per Minute
D.E. = Destruction Efficiency
N.M. = Not Measured
N.A. = Not Applicable
ppm = Part per Million
Tstd = 70.0 °F

**CALCULATIONS,**

D.E. = 100 * (Inlet TNMHC Lbs/hr - Outlet TNMHC Lbs/hr) / Inlet TNMHC Lbs/hr
Lbs/hr = ppm * DSCFM * M.W. * 8.223E-5 / (Tstd + 460)

# APPENDICES

# CALCULATIONS

# CEM SUMMARY

| | | | |
|---|---|---|---|
| **Facility:** | ECI | **Date:** | 11-10-95 |
| **Location:** | Alzeta Thermal Oxidizer | **Barometric:** | 30.45 |
| **Personnel:** | GW, DL | **Leak Check:** | Y |
| **Cyl. #s:** | SA6966 (THC), CC86018 (TOC), SA 8536 (MIX) | | |

| | INLET | | | | | OUTLET | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **TOC** | **$CO_2$** | **$\%O_2$** | **CO** | **$CH_4$** | **$\%O_2$** | **$\%CO_2$** | | **THC** | **$CH_4$** | **CO** | **Comments** |
| **Analyzer** | PIR | PIR | 326RAX | TECO 48 | 400A | 326RAX | PIR | | 400A | 400A | TECO 48 | |
| **Range** | 10,000 | 10,000 | 25.0 | 50.0 | 250.0 | 25.0 | 5.0 | | 250.0 | 250.0 | 50.0 | |
| **Span Gas Value** | 8,487 | 8,487 | 20.26 | 42.5 | 84.0 | 20.26 | 1.86 | | 84.0 | 84.0 | 42.5 | |
| **Run 1** | 0.0 | 0.0 | | | | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | zero (initial), $Z_i$ |
| | 8,487 | 8,487 | | | | 20.26 | 1.86 | | 84.0 | 84.0 | 42.5 | upscale cal (initial). $S_i$ |
| **1052-1122** | 2142 | 300 | 20 | <1 | <2.5 | 16.35 | 2.3 | | 122 | 123 | 14.9 | TEST AVG |
| | 0.0 | 0.0 | | | | 0 | 0 | | 0 | 0 | 0 | zero (final), $Z_f$ |
| | 8,487 | 8,487 | | | | 20.1 | 1.86 | | 84 | 84 | 41.5 | upscale cal (final). $S_f$ |
| | 0.0% | 0.0% | | | | 0.0% | 0.0% | | 0.0% | 0.0% | 0.0% | zero drift |
| | 0.0% | 0.0% | | | | -0.6% | 0.0% | | 0.0% | 0.0% | -2.0% | cal drift |
| | 2,142 | 300 | 20 | <1 | <2.5 | 16.4 | 2.3 | | 122.0 | 123.0 | 15.1 | CORRECTED AVG |
| **Run 2** | 0.0 | 0.0 | | | | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | zero (initial), $Z_i$ |
| | 8,487 | 8,487 | | | | 20.26 | 1.86 | | 84.0 | 84.0 | 42.5 | upscale cal (initial), $S_i$ |
| **1135-1205** | 2233 | 300 | 20.25 | <1 | <2.5 | 14.2 | 3.5 | | 41 | 40 | 19.1 | TEST AVG |
| | 0.0 | 0.0 | | | | 0 | 0.05 | | 0 | 0 | 0 | zero (final), $Z_f$ |
| | 8,487 | 8,487 | | | | 20.26 | 1.88 | | 81.2 | 81.2 | 42 | upscale cal (final). $S_f$ |
| | 0.0% | 0.0% | | | | 0.0% | 1.0% | | 0.0% | 0.0% | 0.0% | zero drift |
| | 0.0% | 0.0% | | | | 0.0% | 0.4% | | -1.1% | -1.1% | -1.0% | cal drift |
| | 2,233 | 300 | 20.25 | <1 | <2.5 | 14.2 | 3.5 | | 41.7 | 40.7 | 19.2 | CORRECTED AVG |
| **Run 3** | 0.0 | 0.0 | | | | 0.0 | 0.0 | | 0.0 | 0.0 | 0.0 | zero (initial), $Z_i$ |
| | 8,487 | 8,487 | | | | 20.26 | 1.86 | | 84.0 | 84.0 | 42.5 | upscale cal (initial). $S_i$ |
| **1220-1250** | 1917 | 300 | 20 | <1 | <2.5 | 16.37 | 2.35 | | 114.7 | 117.3 | 15.4 | TEST AVG |
| | 0.0 | 0.0 | | | | 0 | 0 | | 0 | 0 | 0 | zero (final), $Z_f$ |
| | 8,487 | 8,487 | | | | 20.26 | 1.86 | | 84 | 84 | 42.5 | upscale cal (final). $S_f$ |
| | 0.0% | 0.0% | | | | 0.0% | 0.0% | | 0.0% | 0.0% | 0.0% | zero drift |
| | 0.0% | 0.0% | | | | 0.0% | 0.0% | | 0.0% | 0.0% | 0.0% | cal drift |
| | 1,917 | 300 | 20 | <1 | <2.5 | 16.4 | 2.4 | | 114.7 | 117.3 | 15.4 | CORRECTED AVG |
| AVERAGE: | 2,097 | 300 | | | | 15.7 | 2.7 | | 92.8 | 93.7 | 16.6 | |

$$\text{CORRECTED VALUE} = \left\{\text{Test Avg.} - \frac{(Z_i + Z_f)}{2}\right\} * \frac{\text{Span Gas Value}}{\frac{(S_i + S_f)}{2} - \frac{(Z_i + Z_f)}{2}}$$

$$\text{ZERO DRIFT \%} = 100 * (Z_f - Z_i) / \text{Instrument Range}$$

$$\text{SPAN DRIFT \%} = 100 * (S_f - S_i) / \text{Instrument Range}$$

# BEST ENVIRONMENTAL, INC
# STACK VOLUMETRIC FLOW RATE DETERMINATION
## Method 2

## ECI
## Alzeta Thermal Oxidizer
## Inlet

| | | | | | |
|---|---|---|---|---|---|
| Date: 11-10-95 | | RUN | | 1 | |
| | | Time | | 1210 | |
| 1. Temperature of Stack (Ts) | | | | 76 | °F |
| 2. Std Temperature (Tstd) | | | | 70 | °F |
| 3. Square Root of ΔP (SQRTΔP) | | | | 0.231 | "$H_2O$ |
| 4. Barometric Pressure (Pb) | | | | 30.45 | "Hg |
| 5. Static Pressure (Pstatic) | | | | −2.00 | "$H_2O$ |
| 6. Stack Pressure (Ps) | | | | 30.30 | "$H_2O$ |
| 7. Stack Gas: | Moisture ($H_2O$) | M.W.= | 18 | 1.98 | % |
| | Oxygen ($O_2$) | M.W.= | 32 | 20.10 | % |
| | Carbon Dioxide ($CO_2$) | M.W.= | 44 | 0.03 | % |
| | Carbon Monoxide (CO) | M.W.= | 28 | 0.00 | % |
| | Other: | M.W.= | | 0.00 | % |
| | Nitrogen ($N_2$) | M.W.= | 28 | 79.87 | % |
| 8. Mol. Weight of Stack Gas (MWs) | | | | 28.59 | g/g−mol |
| 9. Area of Stack (As) | | | | 0.546 | $ft^2$ |
| 10. Pitot Tube Factor (Cp) | | | | 0.99 | |
| STACK GAS VELOCITY (Vs) | | | | 15.38 | ft/s |
| ACTUAL CUBIC FEET PER MINUTE | | | | 504 | ACFM |
| DRY STANDARD CUBIC FEET PER MINUTE | | | | 494 | DSCFM |

CALCULATIONS,

MWs = MWd * (1−Bwo) + 18 (Bwo)
MWd = .44(%$CO_2$) + .32(%$O_2$) + .28(%CO+%$N_2$) + (%Other*M.W./100)
Ps = (Pstatic / 13.6) + Pb
Vs = 85.49 * Cp * SQRTΔP * SQRT((Ts + 460) / (Ps * MWs))
ACFM = 60 * Vs * As
DSCFM = 60 (1−Bwo) * Vs * As * (Tstd + 460)/(Ts + 460) * (Ps/29.92)

WHERE,

Bwo = % Moisture / 100
MWs = Molecular Weight of Stack Gas (wet−basis)
MWd = Molecular Weight of Stack Gas (dry−basis)
ΔP = Pitot Differential Pressure

# BEST ENVIRONMENTAL, INC
# STACK VOLUMETRIC FLOW RATE DETERMINATION
## Method 2

## ECI
## Alzeta Thermal Oxidizer
## Outlet

| | | | | |
|---|---|---|---|---|
| Date: | 11-10-95 | RUN | | 1 |
| | | Time | | 1145 |

| | | | | |
|---|---|---|---|---|
| 1. Temperature of Stack (Ts) | | | 1265 | °F |
| 2. Std Temperature (Tstd) | | | 70 | °F |
| 3. Square Root of ΔP (SQRTΔP) | | | 0.436 | "$H_2O$ |
| 4. Barometric Pressure (Pb) | | | 30.45 | "Hg |
| 5. Static Pressure (Pstatic) | | | −0.16 | "$H_2O$ |
| 6. Stack Pressure (Ps) | | | 30.44 | "$H_2O$ |
| 7. Stack Gas: Moisture ($H_2O$) | M.W.= | 18 | 5.02 | % |
| Oxygen ($O_2$) | M.W.= | 32 | 15.70 | % |
| Carbon Dioxide ($CO_2$) | M.W.= | 44 | 2.70 | % |
| Carbon Monoxide (CO) | M.W.= | 28 | 0.00 | % |
| Other: | M.W.= | | 0.00 | % |
| Nitrogen ($N_2$) | M.W.= | 28 | 81.6 | % |
| 8. Mol. Weight of Stack Gas (MWs) | | | 28.50 | g/g−mol |
| 9. Area of Stack (As) | | | 1.026 | $ft^2$ |
| 10. Pitot Tube Factor (Cp) | | | 0.99 | |
| STACK GAS VELOCITY (Vs) | | | 52.03 | ft/s |
| ACTUAL CUBIC FEET PER MINUTE | | | 3,203 | ACFM |
| DRY STANDARD CUBIC FEET PER MINUTE | | | 951 | DSCFM |

**CALCULATIONS,**

MWs = MWd * (1−Bwo) + 18 (Bwo)
MWd = .44(%$CO_2$) + .32(%$O_2$) + .28(%CO+%$N_2$) + (%Other*M.W./100)
Ps = (Pstatic / 13.6) + Pb
Vs = 85.49 * Cp * SQRTΔP * SQRT((Ts + 460) / (Ps * MWs))
ACFM = 60 * Vs * As
DSCFM = 60 (1−Bwo) * Vs * As * (Tstd + 460)/(Ts + 460) * (Ps/29.92)

**WHERE,**

Bwo = % Moisture / 100
MWs = Molecular Weight of Stack Gas (wet−basis)
MWd = Molecular Weight of Stack Gas (dry−basis)
ΔP = Pitot Differential Pressure

M2

# FIELD DATA SHEETS

# CONTINUOUS MONITORING DATA SHEET

| | | |
|---|---|---|
| **CLIENT:** ECI Semiconductor | **TEST #:** 1, 2, 3 | **DATE:** 11-10-95 |
| **Personnel:** GW, DL | **Barometric:** 30.45 | **Stratification Check:** |
| **Sample location:** Inlet / Outlet | **Leak Check:** ✓ | **Cyl. #'s:** SA 8536(MIX), CC86018(TOC) |
| **Observers:** | | **Cyl. #'s:** SA 6966(THC) |

| | **INLET** | | | | | | | | | **OUTLET** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10K | | 50 | 250 | | | 25 | 6 | 50 | | | 250 | | |
| **TIME** | **TOC, ppm** | **CO2, ppm** | **CO, ppm** | **CH4, ppm** | ~~**VOC, ppm**~~ O2% | | **O2, %** | **CO2, %** | **CO, ppm** | **NOx, ppm** | **NOx, @3%O2** | **THC, ppm** | **CH4, ppm** | **TNMHC ppm** |
| | 8487 | | 42.5 | 84.0 | | | 20.26 | 1.86 | 42.5 | — | | 84.0 | 84.0 | |
| 1052 | 2500 | | | | | 1052 | 16.4 | 2.3 | 16 | | | 51 X | 2.5 | |
| 1057 | 2200 | | | | | 1057 | 16.3 | 2.3 | 13 | | | 45 X | 2.5 | |
| 1102 | 1950 | 300 | | | | 1102 | 16.4 | 2.3 | 14.5 | | | 50 X | 2.5 | |
| 1107 | 1700 | | | | | 1107 | 16.4 | 2.3 | 15.5 | | | — | 50 X | 2.5 |
| 1112 | 2100 | | | | | 1112 | 16.3 | 2.3 | 15.0 | | | — | 47 X | 2.5 |
| 1117 | 2400 | | | | | 1117 | 16.3 | 2.3 | 15.5 | | | — | 51 X | 2.5 |
| CAL | 8487 | | | | | CAL | 20.1 | 1.86 | 41.5 | | | 84 | 84 | |
| ZERO | 0 | | | | | ZERO | 0 | 0 | 0 | | | 0 | 0 | |
| AVG | 2142 | 300 | <1 | <2.5 | 20 | AVG | 16.35 | 2.3 | 14.9 | | | 122 | 123 | <2.5 |
| | | | | | | | PROBE MOVED!! | | | | | | | |
| 1135 | 2000 | | | | | | 15.0 | 3.1 | 21 | | | 44 | | |
| 1140 | 1950 | | | | | | 14.2 | 3.6 | 21 | | | 38 | | |
| 1145 | 2600 | 300 | | | | | 14.0 | 3.6 | 17.5 | | | — | 38 | |
| 1150 | 2500 | | | | | | 13.9 | 3.6 | 18 | | | — | 38 | |
| 1155 | 2050 | | | | | | 14.0 | 3.6 | 18 | | | — | 38 | |
| 1200 | 2300 | | | | | | 14.2 | 3.6 | 19 | | | — | 45 | |
| CAL | 8487 | | | | | | 20.26 | 1.88 | 42 | | | 81.2 | 81.2 | |
| ZERO | 0 | | | | | | 0 | .05 | 0 | | | 0 | 0 | |
| AVG | 2233 | 300 | <1 | <2.5 | 20.25 | | 14.2 | 3.5 | 19.1 | | | 41 | 39.8 | <2.5 |
| 1220 | 1700 | | | | | | 16.4 | 2.35 | 15 | | | 112 | | |
| 1225 | 2050 | 300 | | | | | 16.3 | 2.35 | 16 | | | 117 | | |
| 1230 | 2450 | | | | | | 16.2 | 2.35 | 15 | | | 115 | | |
| 1235 | 1550 | | | | | | 16.3 | 2.35 | 16.5 | | | — | 117 | |
| 1240 | 1800 | | | | | | 16.5 | 2.35 | 15 | | | — | 115 | |
| 1245 | 1950 | | | | | | 16.5 | ~~2.35~~ | 15 | | | — | ~~120~~ | |
| **AVG** | 1917 | 300 | <1 | <2.5 | 20 | | 16.37 | 2.35 | 15.4 | | | 114.7 | 117.3 | <2.5 |

**COMMENTS:** (i.e., Operating Conditions/Load/Fuel Usage/Serial #'s ...)

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CAL | 8460 | | | | | | 20.26 | 1.86 | 42.5 | | | 84 | 84 | |
| ZERO | 0 | | | | | | 0 | 0 | 0 | | | 0 | 0 | |

#1 N

#2 N

#3 N

# BEST ENVIRONMENTAL

## Stack Gas Volumetric Flowrate Determination

| | | | |
|---|---|---|---|
| **Facility:** EC I | | | |
| **Date:** 11-10-95 | | **Time:** | 1210 |
| **Pitot Factor (Cp):** 0.99 | | **Pitot #:** | 2' Std. |
| **Assumed %O2:** | | **Actual** | 20.9 |
| **Assumed %CO2:** | | **Actual** | .05 |
| **Assumed %CO:** | | **Actual** | |
| **Assumed %H²O:** | 0.5 | **Actual** | |

**Location:** INLeT

**Run#:** 1

**Personnel:** G.W / D.C

**Barometric (Pb):** 30.45

**Static Pressure (Pstatic):** -2.0

**Stack Diameter, in:** 10"

**Stack Area, ft² (As):** 0.546

**Port Dia:** - **Port Depth:** -

**Downstream Distance:** 4 diam

**Upstream Distance:** 15 diam.

**Pitot Leak Chk. (15secs@>3"):** ✓

| Port ID & Point # | Point Location Inches | Delta P (^P) | Stack Temp °F, (ts) | SQRT ^P | Ø Avg<20° |
|---|---|---|---|---|---|
| 1 | 1.0 | 0.05 | 76 | 0.224 | |
| 2 | 1.5 | 0.05 | | 0.224 | |
| 3 | 3.0 | 0.06 | | 0.245 | |
| 4 | 7.0 | 0.06 | | 0.245 | |
| 5 | 8.5 | 0.05 | | 0.224 | |
| 6 | 9.0 | 0.05 | | 0.224 | |
| | | | | | |
| 1 | 1.0 | 0.05 | 76 | 0.224 | |
| 2 | 1.5 | 0.05 | | 0.224 | |
| 3 | 3.0 | 0.06 | | 0.245 | |
| 4 | 7.0 | 0.06 | | 0.245 | |
| 5 | 8.5 | 0.05 | | 0.224 | |
| 6 | 9.0 | 0.05 | | 0.224 | |
| /ERAGES | | | 76 | 0.231 | |

3B

## CALCULATIONS

**Molecular Weight of Dry Gas, g/g.mole (MWd)**

MWd = 0.44(%CO2)+0.32(%O2)+0.28(%CO+N2)

MWd =

**Water Vapor Fraction, (Bwo)**

Bwo = 0.0473*ml/(DSCF + 0.0473*ml)

Bwo =

**Molecular Weight of Stack Gas, g/g.mole (MWs)**

MWs = MWd*(1-Bwo)+18(Bwo)

MWs = 28.911

**Stack Pressure, "Hg (Ps)**

Ps = Pb + (Pstatic/13.6) =

**Stack Gas Velocity, actual feet per sec (Vs)**

Vs = 85.49*Cp*(SQRT ^P)avg*SQRT[(ts+460)/(Ps*MWs)]

Vs = 15.292

**Stack Area, ft² (As)**

As = (Diameter/24)² * 3.1416

As =

**Stack Gas Flow Rate, DSCFM**

DSCFM = 60(1-Bwo)*Vs*As*528/(ts+460)*Ps/29.92

ACFM =

DSCFM = 499.567

**Comments: (i.e.: diag. or process info.)**

WB = 68°F

## BEST ENVIRONMENTAL

## Stack Gas Volumetric Flowrate Determination

**Facility:** ECI

**Date:** 11-10-95 **Time:** 11 45

**Pitot Factor (Cp):** 0.99 **Pitot #:** 2' STd.

**Assumed %O2:** **Actual** 15.2

**Assumed %CO2:** **Actual** 2.3

**Assumed %CO:** **Actual**

**Assumed %H$^2$O:** **Actual** 5.0

**Location:** outlet

**Run#:** 1

**Personnel:** G.W / DL

**Barometric (Pb):** 30.45

**Static Pressure (Pstatic):** - 0.16

**Stack Diameter, in:** 13.75

**Stack Area, ft$^2$ (As):** 1.026

**Port Dia:** - **Port Depth:** -

**Downstream Distance:** ¼ diam.

**Upstream Distance:** 12+ diam

**Pitot Leak Chk. (15secs@>3"):** ✓

| Port ID & Point # | Point Location Inches | Delta P (^P) | Stack Temp °F, (ts) | SQRT ^P | Ø Avg<20° |
|---|---|---|---|---|---|
| 1 | 1.0 | 0.20 | 1265 | 0.447 | |
| 2 | 2.0 | 0.23 | | 0.480 | |
| 3 | 4.1 | 0.23 | | 0.480 | |
| 4 | 9.7 | 0.18 | | 0.424 | |
| 5 | 11.7 | 0.18 | | 0.424 | |
| 6 | 12.75 | 0.18 | | 0.424 | |
| | | | | | |
| 1 | 1.0 | 0.18 | 1265 | 0.424 | |
| 2 | 2.0 | 0.18 | | 0.424 | |
| 3 | 4.1 | 0.18 | | 0.424 | |
| 4 | 9.7 | 0.23 | | 0.480 | |
| 5 | 11.7 | 0.23 | | 0.480 | |
| 6 | 12.75 | 0.10 | | 0.316 | |
| ERAGES | | | 1265 | 0.436 | |

3 B

# CALCULATIONS

**Molecular Weight of Dry Gas, g/g.mole (MWd)**

MWd = 0.44(%CO2)+0.32(%O2)+0.28(%CO+N2)

MWd =

**Water Vapor Fraction, (Bwo)**

Bwo = 0.0473*ml/(DSCF + 0.0473*ml)

Bwo =

**Molecular Weight of Stack Gas, g/g.mole (MWs)**

MWs = MWd*(1-Bwo)+18(Bwo)

MWs = 28.427

**Stack Pressure, "Hg (Ps)**

Ps = Pb + (Pstatic/13.6) =

**Stack Gas Velocity, actual feet per sec (Vs)**

Vs = 85.49*Cp*(SQRT ^P)avg*SQRT[(ts+460)/(Ps*MWs)]

Vs = 52.102

**Stack Area, ft$^2$ (As)**

As = (Diameter/24)$^2$ * 3.1416

As =

**Stack Gas Flow Rate, DSCFM**

DSCFM = 60(1-Bwo)*Vs*As*528/(ts+460)*Ps/29.92

ACFM =

DSCFM = 948.811

**Comments: (i.e.: diag. or process info.)**

# BEST ENVIRONMENTAL,INC.
## Isokinetic Sampling Data Sheet

Facility: ECI  Date: 11-10-95  Method: 4  Run #: 1  Personnel: G.O/D.L

| Facility Information | | Equipment | | Sampling Data | |
|---|---|---|---|---|---|
| *Location:* OUTLET | | *Meter #:* 8558 | Pitot #: – | *PBar:* 30.45 | P Static: – |
| *Port Dia.* – | *Depth:* – | *Meter Yd:* 0.9776 | Pitot Cp: – | %$O_2$ Ass. | %$O_2$ Actual: 15.2 |
| Fitting Type: – | Length: – | ΔH@: 2.439 | Noz. #: – | %$CO_2$ Ass. | %$CO_2$ Actual: 2.3 |
| Stack Dia. | Area: | Filter Box # – | Noz. Dia. – | %$H_2O$ Ass. | Pitot LC: — |
| Upstream Dist. – | | Probe #: – | Mag # – | Test Mins. 30 | Filter #: – |
| Downstream Dist. – | | Temp. Meter # | Umb.# – | | |

Initial LC: .010 CFM @ 25 "Hg
Final LC: .005 CFM @ 18 "Hg

| Point | Clock Time | Gas Meter Vol. Ft³ | Meter Temp °F | | Stack Temp°F | ΔP | ΔH | Meter CFM | SQRT ΔP | Temperatures °F | | | Vac. "Hg | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Inlet | Outlet | | | | | | Probe | Filter | Imp | | |
| | 1050 | 683.700 | 63 | 66 | 1265 | | | | | | | ≤45 | 6 | |
| | 1055 | 686.6 | 68 | 68 | | | | | | | | | | |
| | 1100 | 690.9 | 70 | 68 | | | | | | | | | | |
| | 1105 | 694.7 | 73 | 68 | | | | | | | | | | |
| | 1110 | 698.1 | 75 | 68 | | | | | | | | | | |
| | 1115 | 701.7 | 77 | 69 | | | | | | | | | | |
| | 1120 | 705.235 | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| | | <21.535> | <69.4> | | | | | | | | | | | |

### MOISTURE DATA

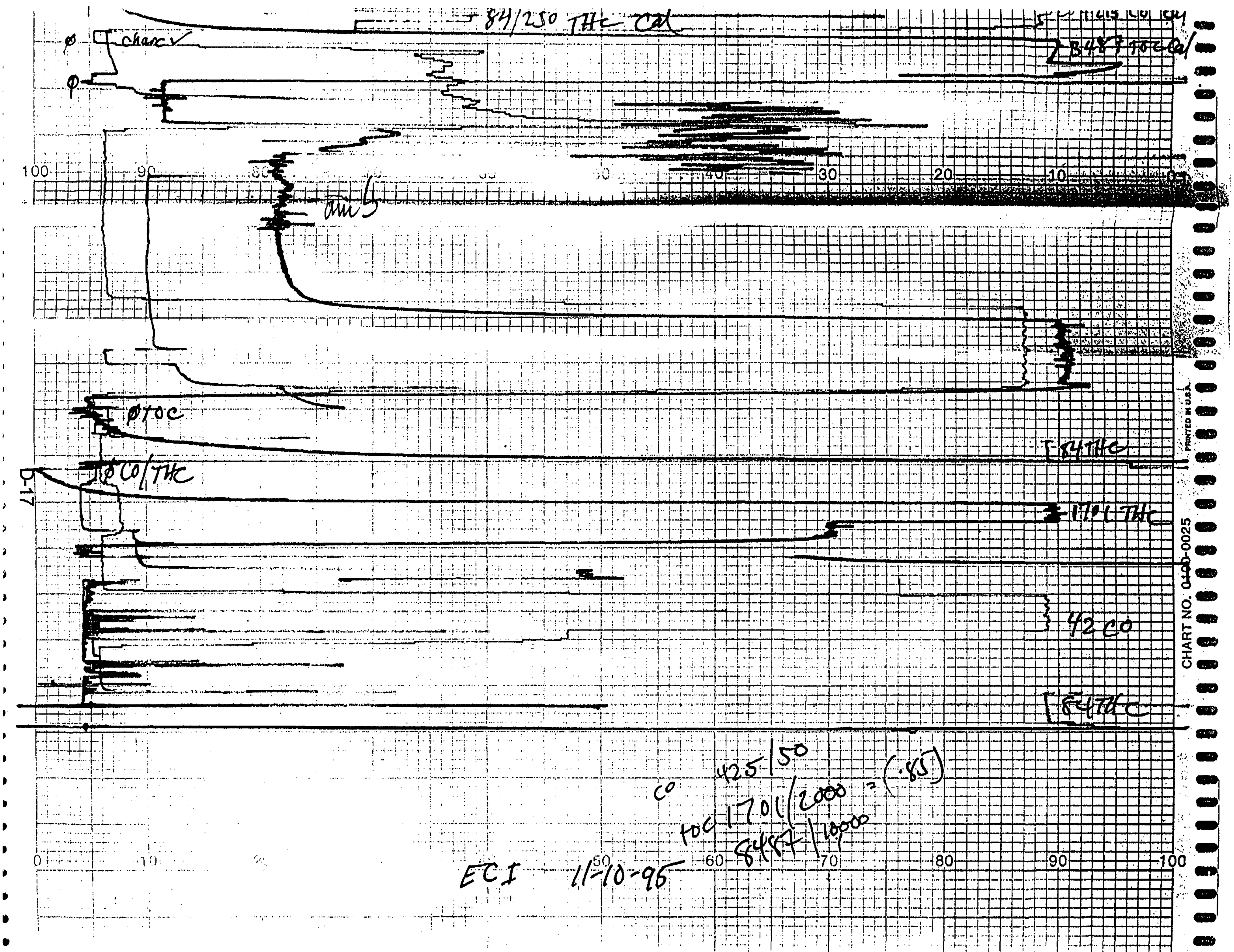
| | Initial | Final | Net |
|---|---|---|---|
| Impinger #1 | 100 | 115 | 15 |
| Impinger #2 | 100 | 104 | 4 |
| Impinger #3&4 | | | |
| Silica Gel | 200 | 205 | 5 |
| Rinse Vol. = | | | |
| TOTAL NET = | | | 24 |
| TOTAL SAMPLE VOL. = | | | |

### CALCULATED VALUES

| | |
|---|---|
| Sample Vol. scf = | 21.498 |
| % $H_2O$ = | 4.995 |
| MWs = | |
| Stack Vel.(ft/s) = | |
| Flowrate(acfm) = | |
| Flowrate(dscfm) = | |
| Isokinetics (%) = | |

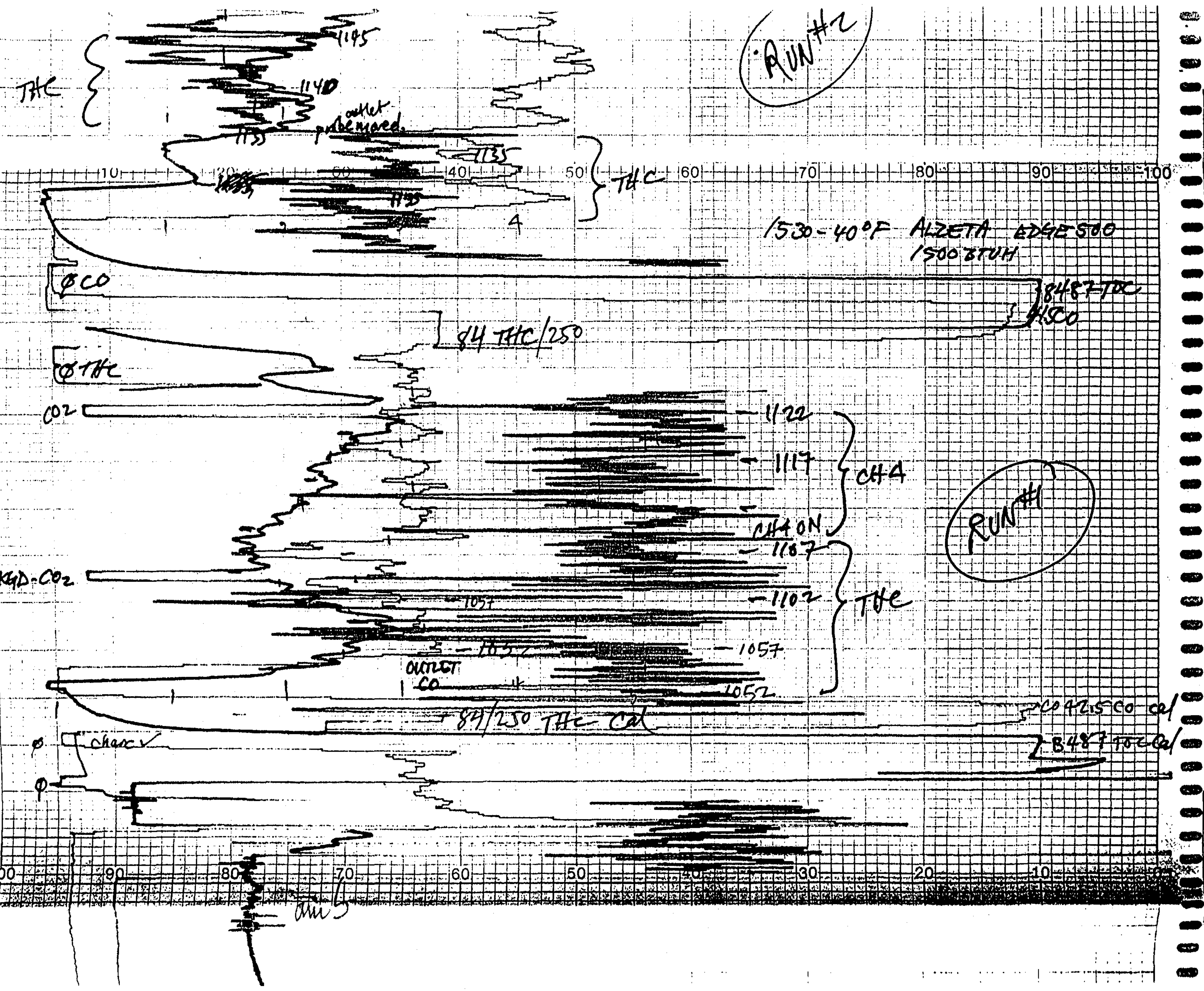
COMMENTS:

# STRIP CHART RECORDS



CO 425/50
TOC 1701/2000 = (.85)
8487/10000

ECI 11-10-96


RUN #2
THC
1145
1140
outlet probe moved.
1135
1135
THC
1135
4
1530-40°F ALZETA EDGE 500
1500 BTUH
ØCO
8487 TOC
4150
84 THC/250
ØTHC
CO2
1122
1117
CH4
CH4 ON
RUN #1
1107
1102
THC
1057
1052
BKGD-CO2
1057
1052
OUTLET CO
84/250 THC Cal
CO 4215 CO cal
8487 TOC Cal
Ø chan ✓
Ø
0
10
20
30
40
50
60
70
80
90
100

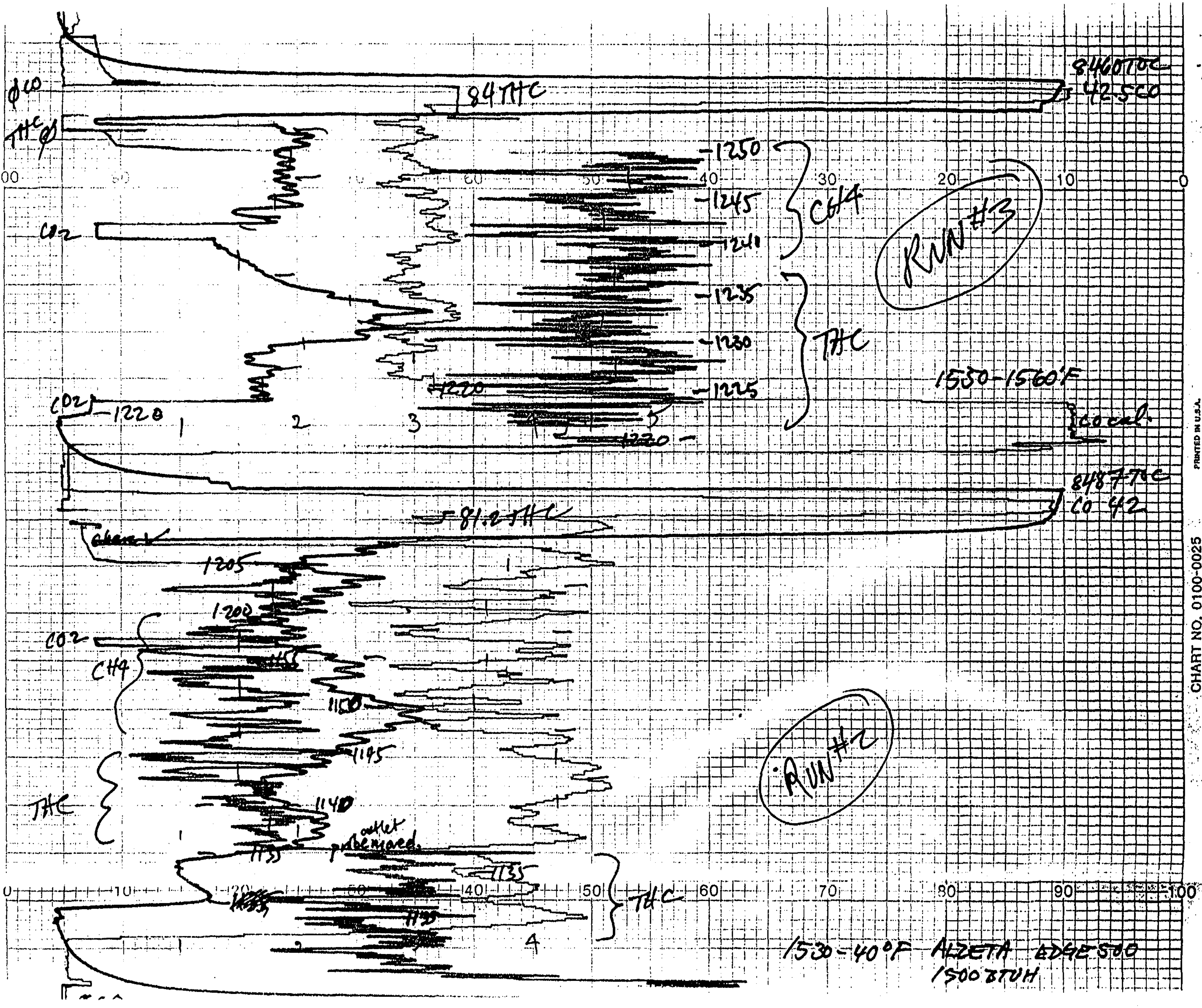
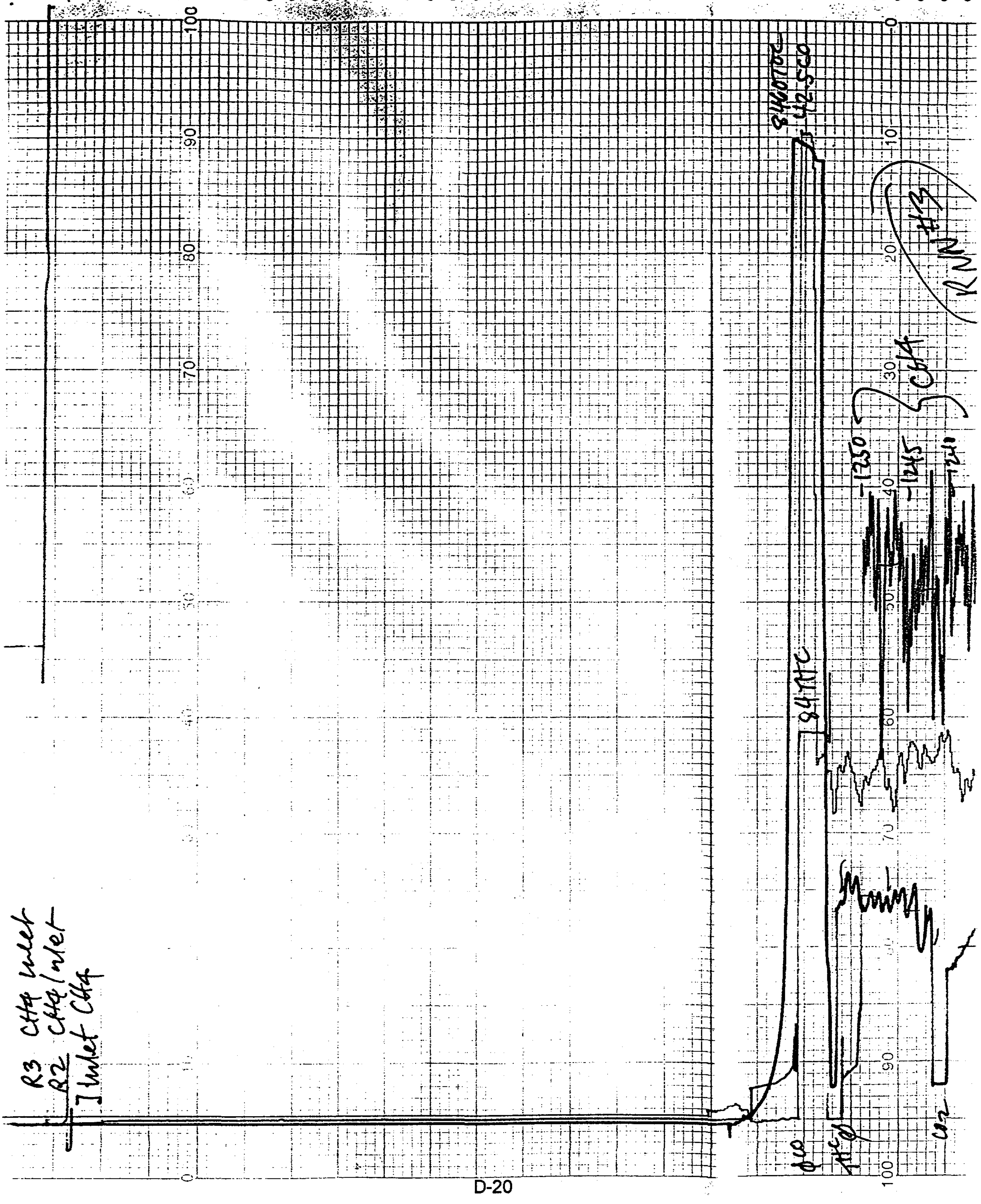
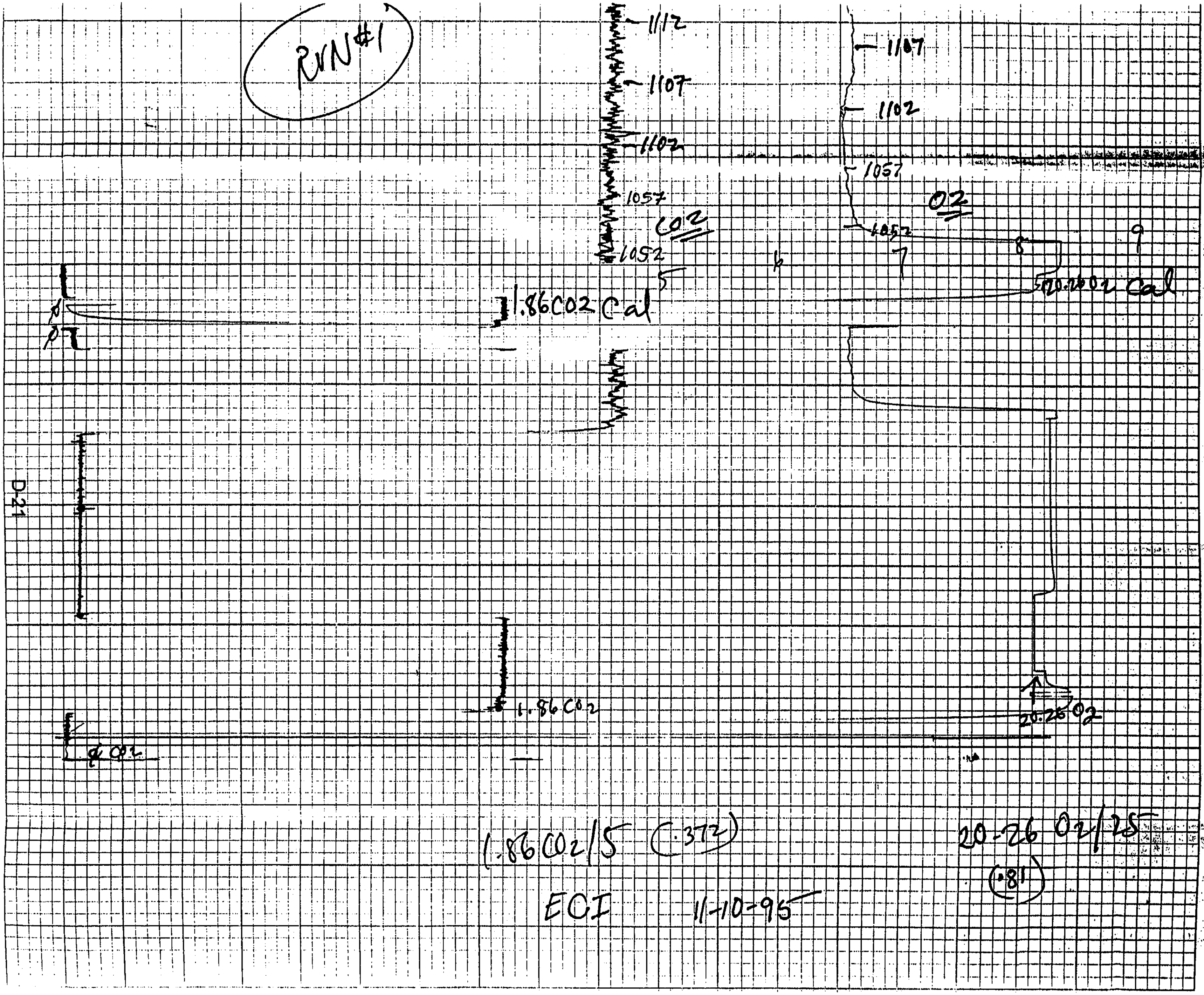


CHART NO. 0100-0025
PRINTED IN U.S.A.
8460 THC
42.5 CO
84 THC
ϕ CO
THC ϕ
CO2
-1250
-1245
-1240
-1235
-1230
-1225
-1220
-1220
CH4
THC
RUN #3
1530-1560°F
CO cal.
CO2
1220
8487 THC
CO 42
81.2 THC
clean
1205
1200
1155
1150
1145
1140
1135
1135
1135
1130
CO2
CH4
THC
THC
outlet probe moved.
RUN #2
1530-40°F ALZETA EDGE 500
1500 BTUH
1
2
3
4
5
100
90
80
70
60
50
40
30
20
10
0


R3 CH4 inlet
R2 CH4 Inlet
I Inlet CH4
100
90
80
70
60
50
40
30
20
10
0
8460TOC
8425CO
RUN #3
CH4
-1250
-1245
-1240
84THC
CO
H2O
CO2

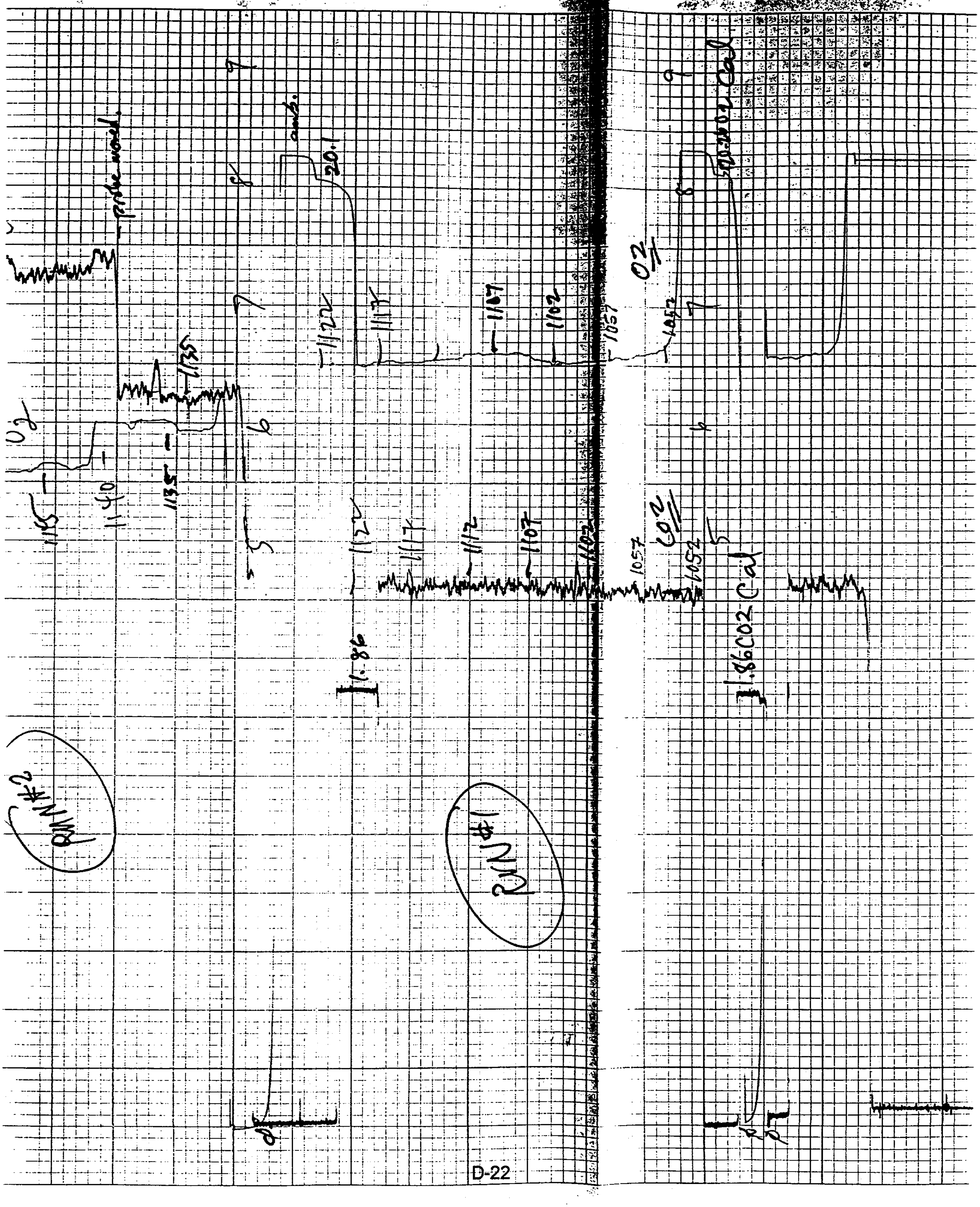
RUN#1

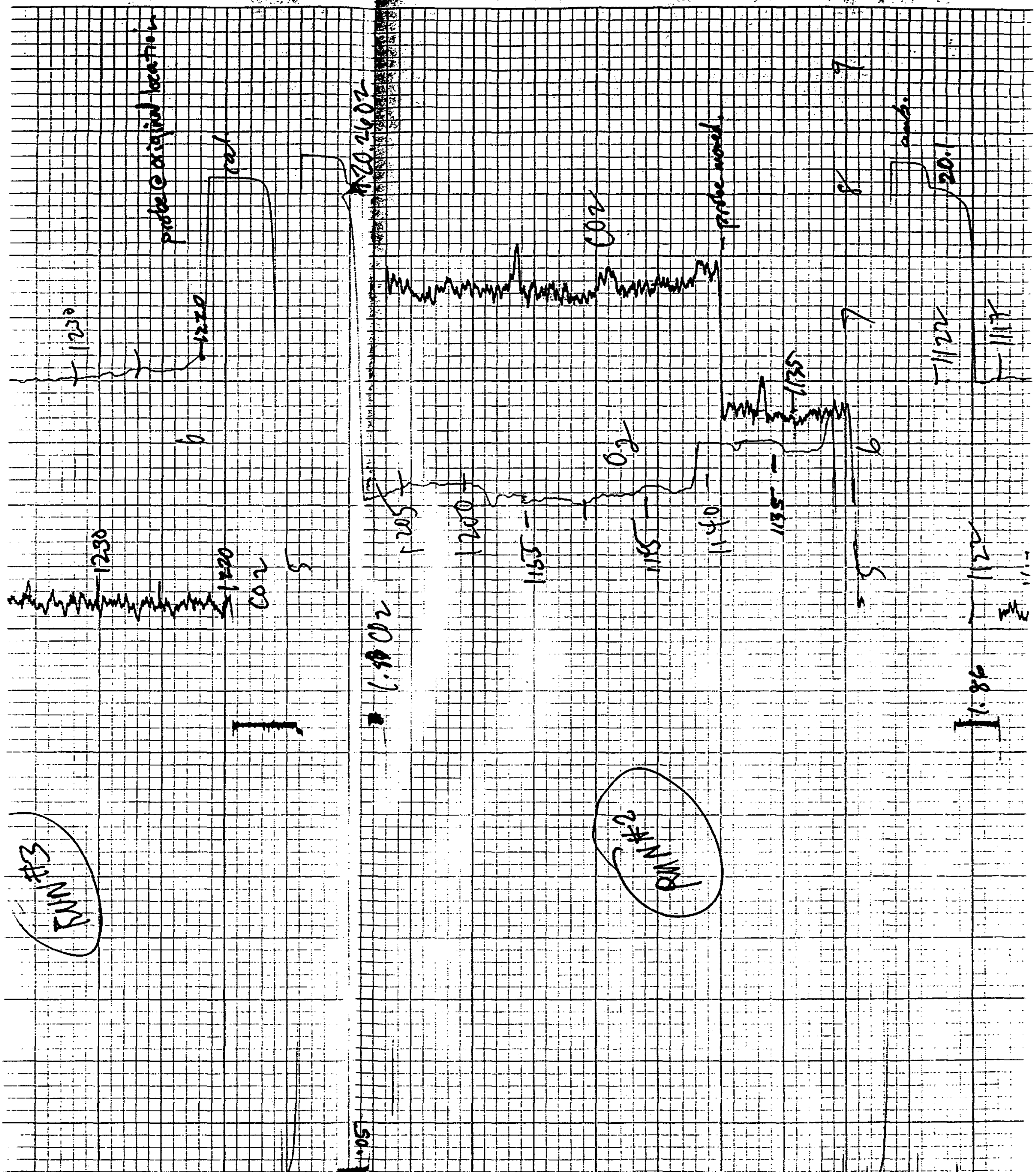


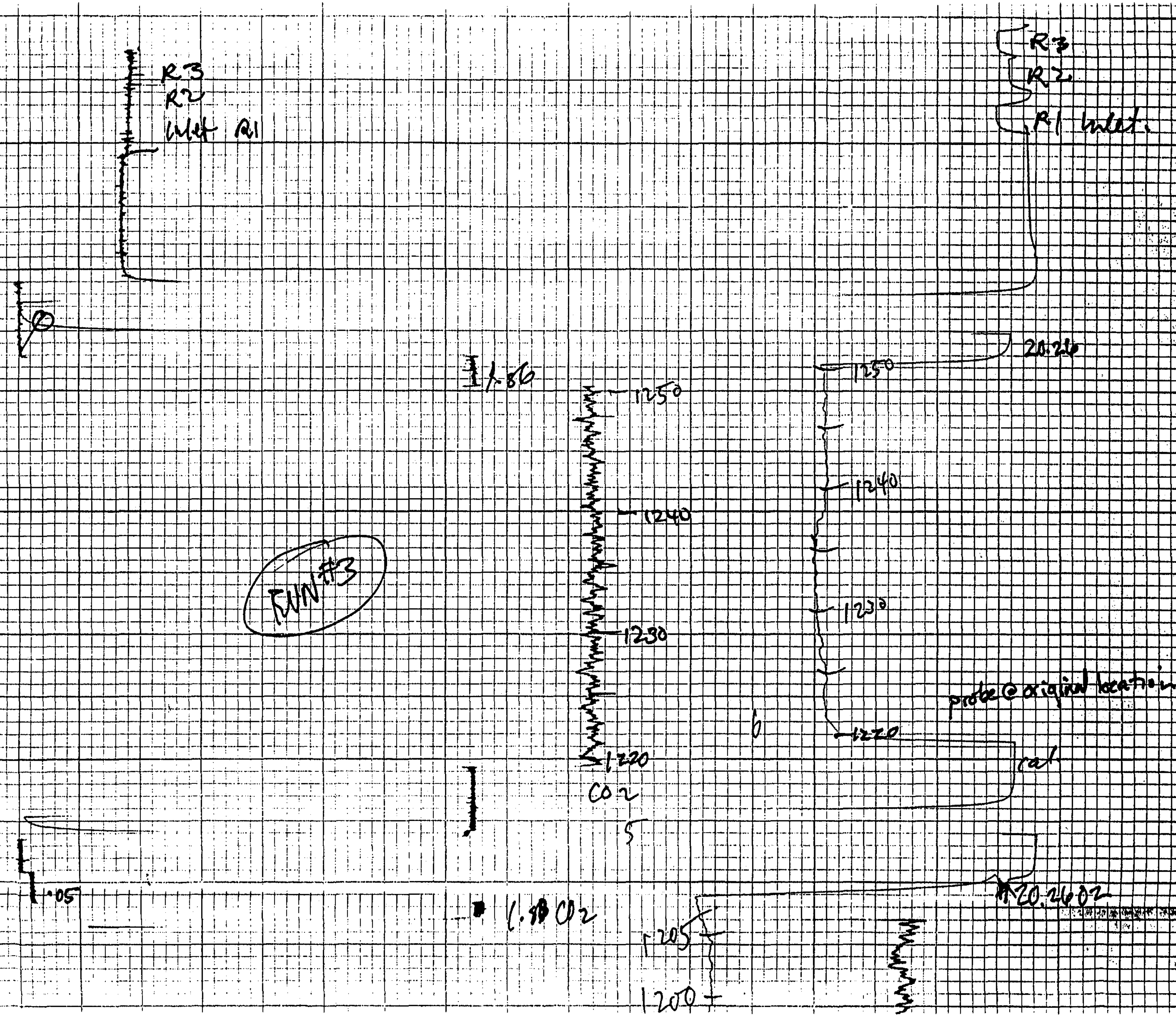
1.86CO2/5 (.372)

20-26 O2/25 (.81)

ECI 11-10-95


RUN #2
RUN #1
O2
CO2
probe moved
amb.
20.1
20.2% O2 Cal
1.86
1.86 CO2 Cal
1115
1140
1135
1135
1127
1122
1117
1112
1107
1102
1057
1052
5
6
7
8
9
0
0
0
0


probe @ original location
cal
1230
1221
1220
6
1230
1220
CO2
5
20.24 O2
1.80 CO2
1205
1200
1155
1150
1140
CO2
O2
probe moved
1135
1135
9
8
7
6
5
amb.
20.1
1122
1117
1122
1117
1.88
.05
0
RUN #3
RUN #2


R3
R2
R1 Inlet.
20.26
1250
1240
1230
1220
probe @ original location
cal
6
20.26 O2
1205
1200
R3
R2
Inlet R1
1.86
1250
1240
1230
1220
CO2
5
1.8 CO2
.05
RUN #3

# CALIBRATION GAS CERTIFICATIONS

**LIQUID CARBONIC**

CYLINDER GAS PRODUCTS

5700 SOUTH ALAMEDA STREET • LOS ANGELES, CA 90058

213-585-2154
FAX# 213-585-0582

# CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

**CUSTOMER** BEST ENVIRONMENTAL **P.O NUMBER** SG131713 RE:8845

## REFERENCE STANDARD

| COMPONENT | NIST SRM NO. | CYLINDER NO. | CONCENTRATION |
|---|---|---|---|
| CARBON MONOXIDE GMIS | vs 1678c | CC 50893 | 50.6 ppm |
| CARBON DIOXIDE sam# 33-07-C | 2622a | FF26726 | 1.9349 % |
| OXYGEN GMIS | vs 2659a | TT 46544 | 21.11% |

## ANALYZER READINGS

*R=REFERENCE STANDARD* *Z=ZERO GAS* *C=GAS CANDIDATE*

1. **COMPONENT** CARBON MONOXIDE GMIS **ANALYZER MAKE-MODEL-S/N** Siemens Ultramat 5E S/N A12-729

**ANALYTICAL PRINCIPLE** NDIR **LAST CALIBRATION DATE** 04/15/95

**FIRST ANALYSIS DATE** 05/05/95 **SECOND ANALYSIS DATE** 05/12/95

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Z 0.0 | R 50.6 | C 42.6 | CONC. 42.6 ppm | Z 0.0 | R 50.6 | C 42.4 | CONC. 42.4 ppm |
| R 50.6 | Z 0.0 | C 42.6 | CONC. 42.6 ppm | R 50.6 | Z 0.0 | C 42.4 | CONC. 42.4 ppm |
| Z 0.0 | C 42.6 | R 50.6 | CONC. 42.6 ppm | Z 0.0 | C 42.4 | R 50.6 | CONC. 42.4 ppm |
| U/M ppm | | | MEAN TEST ASSAY 42.6 ppm | U/M ppm | | | MEAN TEST ASSAY 42.4 ppm |

2. **COMPONENT** CARBON DIOXIDE sam# 33-07-C **ANALYZER MAKE-MODEL-S/N** Siemens Ultramat 5E S/N A12-730

**ANALYTICAL PRINCIPLE** NDIR **LAST CALIBRATION DATE** 05/10/95

**FIRST ANALYSIS DATE** 05/12/95 **SECOND ANALYSIS DATE**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Z 0.000 | R 1.933 | C 1.854 | CONC. 1.86 % | Z | R | C | CONC. |
| R 1.932 | Z 0.000 | C 1.852 | CONC. 1.86 % | R | Z | C | CONC. |
| Z 0.000 | C 1.853 | R 1.933 | CONC. 1.86 % | Z | C | R | CONC. |
| U/M % | | | MEAN TEST ASSAY 1.86 % | U/M % | | | MEAN TEST ASSAY |

3. **COMPONENT** OXYGEN GMIS **ANALYZER MAKE-MODEL-S/N** Siemens Oxymat 5E S/N A12-839

**ANALYTICAL PRINCIPLE** Paramagnetic **LAST CALIBRATION DATE** 04/15/95

**FIRST ANALYSIS DATE** 05/12/95 **SECOND ANALYSIS DATE**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Z 0.00 | R 21.10 | C 20.25 | CONC. 20.26 % | Z | R | C | CONC. |
| R 21.10 | Z 0.00 | C 20.25 | CONC. 20.26 % | R | Z | C | CONC. |
| Z 0.00 | C 20.25 | R 21.10 | CONC. 20.26 % | Z | C | R | CONC. |
| U/M % | | | MEAN TEST ASSAY 20.26 % | U/M % | | | MEAN TEST ASSAY |

**THIS CYLINDER NO.** SA 8536
**HAS BEEN CERTIFIED ACCORDING TO SECTION** EPA-600/R93/224
**OF TRACEABILITY PROTOCOL NO.** Rev. 9/93
**PROCEDURE** G1
**CERTIFIED ACCURACY** ± 1 **% NIST TRACEABLE**
**CYLINDER PRESSURE** 1650 **PSIG**
**CERTIFICATION DATE** 05/12/95
**EXPIRATION DATE** 05/12/98 **TERM** 36 MONTHS

| CERTIFIED CONCENTRATION | |
|---|---|
| CARBON MONOXIDE | 42.5 ppm |
| CARBON DIOXIDE | 1.86 % |
| OXYGEN | 20.26 % |
| NITROGEN | BALANCE |

Values not valid below 150 psig

*ANALYZED BY* Maria MARIA ROCHON

*CERTIFIED BY* DOUG GRANT

**LIQUID CARBONIC**

CYLINDER GAS PRODUCTS

5700 SOUTH ALAMEDA STREET • LOS ANGELES, CA 90058

213-585-2154
FAX# 213-585-0582

# CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

**CUSTOMER** BEST ENVIRONMENTAL **P.O NUMBER** 8878

## REFERENCE STANDARD

| COMPONENT | | NIST SRM NO. | CYLINDER NO. | CONCENTRATION |
|---|---|---|---|---|
| PROPANE | GMIS | vs 1667b | 579140 | 29.8 ppm |

## ANALYZER READINGS

*R=REFERENCE STANDARD* *Z=ZERO GAS* *C=GAS CANDIDATE*

1. **COMPONENT** PROPANE GMIS **ANALYZER MAKE-MODEL-S/N** HP 5890 SERIES II S/N 3310A48533

**ANALYTICAL PRINCIPLE** GC/ FLAME IONIZATION **LAST CALIBRATION DATE** 06/19/95

**FIRST ANALYSIS DATE** 07/13/95 **SECOND ANALYSIS DATE**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Z 0 | R 132471 | C 124876 | CONC. | 28.1 ppm | Z | R | C | CONC. | |
| R 133177 | Z 0 | C 125149 | CONC. | 28.0 ppm | R | Z | C | CONC. | |
| Z 0 | C 124956 | R 133072 | CONC. | 28.0 ppm | Z | C | R | CONC. | |
| U/M uV-s | | | MEAN TEST ASSAY | 28.0 ppm | U/M uV-s | | | MEAN TEST ASSAY | |

Values not valid below 150 psig

| | | | |
|---|---|---|---|
| THIS CYLINDER NO. | SA 6966 | CERTIFIED CONCENTRATION | |
| HAS BEEN CERTIFIED ACCORDING TO SECTION | EPA-600/R93/224 | PROPANE | 28.0 ppm |
| OF TRACEABILITY PROTOCOL NO. | Rev. 9/93 | ULTRA ZERO AIR | BALANCE |
| PROCEDURE | G1 | | |
| CERTIFIED ACCURACY | ± 1 % NIST TRACEABLE | | |
| CYLINDER PRESSURE | 2000 PSIG | | |
| CERTIFICATION DATE | 07/13/95 | | |
| EXPIRATION DATE | 07/13/98 TERM 36 MONTHS | | |

*ANALYZED BY* MARIA ROCHON

*CERTIFIED BY* KUAN YOUNG

SCOTT-MARRIN, INC.
6531 BOX SPRINGS BLVD. • RIVERSIDE, CA 92507
TELEPHONE (909) 653-6780 • FAX (909) 653-2430

# REPORT OF ANALYSIS
# EPA PROTOCOL GAS MIXTURES

BEST01

TO:

CRAIG THIRY
BEST ENVIRONMENTAL INC.
15890 FOOTHILL BLVD
SAN LEANDRO, CA 94578-2101

DATE : 07/11/94

CUSTOMER ORDER NUMBER: 8727

PAGE 1

| COMPONENT | CONCENTRATION (v/v) | REFERENCE STANDARD | ANALYZER MAKE, MODEL, S/N, DETECTION | EXPIRATION DATE | REPLICATE ANALYSIS DATA |
|---|---|---|---|---|---|
| CYLINDER NO.: | CC86018 | | | | |
| | | | Varian Model 1860 | | 07/08/94 |
| Propane | 2829 ± 28 ppm | GMIS | S/N None | 07/08/97 | 2829 ppm |
| | | Cylinder # | Flame Ionization | | 2828 ppm |
| Zero Air | Balance | CAL5249 | Gas Chromatography | | 2831 ppm |
| Cylinder Pressure: 2000 psig | | @ 2479 ppm | Last Cal Date: 07/08/94 | | Mean: 2829 ppm |

ppm = umole/mole          % = mole-%

The above analyses were performed in accordance with EPA-1987 Traceability Protocol # 1, Section 3.0.4, Procedure G1.

Analyst: M.S. Calhoun

Approved: J.T. Marrin

# EQUIPMENT CALIBRATION RECORDS

## THERMOMETER CALIBRATION (Spring Type)

**Reference Thermometer: ASTM Mercury in Glass**
**Method Reference: EPA QA Handbook Vol. III: Stationary Source Specific Methods, Sect. 3.5.2.2**
**Tolerance Limits: ±5.4°F at ambient temp and in hot water bath.**

| Thermometer ID | Reference Thermometer °F | Test Thermometer °F | °F Difference |
|---|---|---|---|
| Therm. # 9B | 34.2 | 36 | −1.8 |
| | 82.5 | 84 | −1.5 |
| Meter # 8558 | 109.0 | 108 | +1 |
| Therm # 11A | 34.2 | 35.5 | −1.3 |
| | 81.2 | 85 | −3.8 |
| Meter # 8558 | 108.4 | 110 | −1.6 |
| Therm # 18A | 32.5 | 35 | −2.5 |
| | 70.9 | 69.5 | +1.4 |
| Meter # 3502 | 109.9 | 112 | −2.1 |
| Therm. # 18B | 32.5 | 34 | −1.5 |
| | 71.7 | 68 | +3.7 |
| Meter # 3502 | 109.4 | 113 | −3.6 |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

**ANALYST:** BoB GAllagher
**DATE:** 9-7-95

USED NIST Potentiomter # T-134449

# METER BOX FULL TEST CALIBRATION

Date: 9/6/95
Operator: BG
Signature:

Meter Yd: 0.9776
Meter Box ΔH@: 2.439
Calibrated with: Lab Orifice

Meter Box #: 8558
Bar. Pressure (Pb): 30.00 in. Hg

| | | | Standard Meter Gas Volume (ft³) | | | Meter Box Gas Volume (ft³) | | | Std. Meter Temp. | Meter Box Temperature | | | Time (Min.) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ΔH | ΔP | Yds | Initial | Final | (Vds) Net | Initial | Final | (Vd) Net | (Tds) Avg. | In | Out | (Td) Avg. | Θ | ΔH@ | Yd | Q |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| 0.50 | −0.05 | 1.000 | 5.000 | 10.000 | 5.000 | 356.142 | 361.412 | 5.270 | 77.0 | 91.0 | 93.0 | 92.0 | 14.61 | 2.357 | 0.9740 | 0.337 |
| 0.50 | −0.05 | 1.000 | 10.000 | 15.000 | 5.000 | 361.412 | 366.683 | 5.271 | 78.0 | 94.0 | 94.0 | 94.0 | 14.59 | 2.350 | 0.9755 | 0.337 |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| 1.50 | −0.08 | 1.000 | 25.000 | 35.000 | 10.000 | 377.432 | 387.961 | 10.529 | 79.5 | 100.0 | 95.0 | 97.5 | 17.16 | 2.437 | 0.9777 | 0.572 |
| 1.50 | −0.09 | 1.000 | 35.000 | 45.000 | 10.000 | 387.961 | 398.491 | 10.530 | 81.0 | 101.0 | 95.0 | 98.0 | 17.17 | 2.451 | 0.9757 | 0.570 |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| 3.00 | −0.12 | 1.000 | 56.275 | 66.678 | 10.403 | 411.024 | 421.888 | 10.864 | 82.0 | 104.0 | 94.0 | 99.0 | 12.80 | 2.522 | 0.9801 | 0.794 |
| 3.00 | −0.12 | 1.000 | 66.678 | 76.688 | 10.010 | 421.888 | 432.296 | 10.408 | 82.5 | 103.0 | 94.0 | 98.5 | 12.29 | 2.518 | 0.9826 | 0.795 |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |

Variables:

Q = Flow rate (cfm)
ΔH = Orifice pressure differential (in. $H_2O$)
ΔP = Inlet pressure differential standard meter (in. $H_2O$)
Yds = Standard meter correction factor (Unitless)
Yd = Meter box correction factor (unitless)
ΔH@ = Orifice pressure differential that gives 0.75 DSCFM of air at 68°F and 29.92 in. Hg (in. $H_2O$)

$Yd = (Yds)(Vds)/(Vd)(Td+460)/(Tds+460)(Pb+(\Delta P/13.6))/(Pb+(\Delta H/13.6))$

$\Delta H@ = 0.0317\ (\Delta H)/(Pb(Td+460))((Tds+460)\Theta/(Vds*Yds))^2$

$Q = 17.647(Vds)(Pb)/((Tds+460)\Theta$

1. Tolerance Yd ($Yd_{AVG}-Yd$) ≤ ±0.02 ref. Fig 5.6 in EPA method 5
2. Tolerance ΔH@ ($\Delta H@_{AVG}-\Delta H@$) ≤ ± 0.20 ref. fig 5.6 in EPA method 5

8817-895

# AUTHORITY TO CONSTRUCT

# BAY AREA AIR QUALITY MANAGEMENT DISTRICT

April 6, 1993

Bill Schanen
ECI Semiconductor
975 Comstock Street
Santa Clara, CA 95054

**Application Number:** *10063*
**Equipment Location:**
*Same as above*

Gentlemen:

This is your Authority to Construct the following:

**S-1** Fab 1
**The equipment permitted at Source S-1 includes a maximum of: 1 Solvent Station, having an aggregate holding capacity of 5 gallons; 8 Wet Chemical Stations, having an aggregate holding capacity of 80 gallons; 1 Siliconizing Reactor; 1 Chemical Vapor Deposition Chambers; 30 Diffusion, Oxidizing, Alloying, and/or Annealing Furnaces; 4 Negative Photoresist Applicator; 4 Negative Photoresist Developer; 1 Positive Photoresist Applicator; 1 Ion Implantation Chamber.**

**A-1** **VOC Fume Thermal Oxidizer, Alzeta, Model PCI-500; to abate S-1 Fab 1.**

Operation of this equipment will be subject to the attached specific conditions.

## Notification

Please notify the District by letter at least **three days** before the initial operation of the equipment is to take place so that we may observe the equipment in operation and verify conformance with the Authority to Construct. Operation includes any **start-up** of the source for testing or other purposes. Operation of equipment without prior written notification to the District or beyond the start-up period without a Permit to Operate may result in enforcement action.

## Start-Up Period

10/12/95 ready to go

**After *receipt of the start-up letter*** required above, this Authority to Construct authorizes operation during the start-up period from the date of initial operation noted in your start-up letter until the Permit to Operate is issued, up to a maximum of 60 days. **All conditions (specific or implied) of the Authority to Construct are in effect during the start-up period.**

9/6

8/6 [illegible]

939 ELLIS STREET • SAN FRANCISCO, CALIFORNIA 94109 • (415) 771-6000 • FAX (415) 928-8560

## Fees

District Regulation 3 requires a fee for each new Permit to Operate. You will be *invoiced* upon receipt of your start-up letter. No permits will be issued until all outstanding fees are paid.

## Implied Conditions

In the absence of specific permit conditions to the contrary, the throughputs, fuel and *material* consumptions, capacities, and hours of operation described in your permit application will be considered maximum allowable limits. A new permit will be required before any increase in these parameters, or change in raw material handled, may be made.

## Expiration

In accordance with Regulation 2-1-407, this Authority to Construct expires two years from the date of issuance unless substantial use of the authority has begun.

## Correspondence

Please include your application number with any correspondence with the District regarding this matter. If you have any questions on this matter, please call **M.K. Carol Lee, Air Quality Engineer II at (415) 749-4689.**

Very truly yours,

Milton Feldstein
Air Pollution Control Officer

by John A Swanson
Permit Services Division

JAS:MCL:ryr

COND# 9313 -----------------------------------------------

1. The maximum gross usage of solvents containing Precursor Organic Compounds at solvent stations in S-1 shall not exceed 4,000 gallons during any consecutive 12-month period.

2. The maximum gross usage of Trichloroethane shall not exceed 90 gallons during any consecutive 12-month period. No other Non-Precursor Organic Compounds shall be used without written approval from the District.

3. The maximum gross usage of positive photoresist maskant shall not exceed 200 gallons during any consecutive 12-month period.

4. The maximum, gross usage of negative photoresist maskant shall not exceed 400 gallons during any consecutive 12-month period.

5. The maximum, gross usage of negative photoresist developer shall not exceed 2400 gallons during any consecutive 12-month period.

6. The owner/operator of this source shall enclose the photoresist tracks and spinners and vent their organic emissions to A-1 VOC Fume Incinerator with a capture/destruction efficiency greater than or equal to 98.5% or a VOC outlet concentration less than or equal to 10 ppm.

7. The owner/operator of this source shall enclose the solvent stations and vent their organic emissions to A-1 VOC Fume Incinerator with a capture/destruction efficiency greater than or equal to 90% or a VOC outlet concentration less than or equal to 10 ppm.

8. A continuous recorder, approved by the District, shall be installed and maintained to monitor the oxidation temperature of the thermal oxidizer. The incineration temperature shall be maintained at 1450oF or higher as necessary to meet the required destruction efficiency. Records shall be retained for a period of at least two years from the record date and made readily available to District staff upon request.

9. The collection systems for this source shall be designed and operated to achieve maximum collection of fugitive emissions for destruction by the thermal oxidizer. The APCO shall approve these collection systems prior to issuance of the Permit to Operate.

10. Within 60 days of initial start-up of the thermal oxidizer, the operator/owner shall perform a

source test, approved by the District's Source Test Manager, of the abatement device, to determine the destruction efficiency and demonstrate compliance with conditions 6 and 7. The operator/owner shall receive prior approval from the District's Source Test Manager for installation of testing ports, platform and source testing procedures. The operator/owner shall notify the Permit Service Division and Source Test Manager at least two weeks prior to any source test. Complete reports of source test results shall be submitted to the District's Source Test Section and Permit Services Division within thirty (60) days of the source test.

11. Operator/owner shall apply for a change of permit conditions in the case of a change in solvent, solvent quantity, photoresist, or photoresist quantity.

12. Operator/owner shall apply for a change of permit conditions if a toxic air contaminant that is not listed in these conditions is used in quantities that trigger a Toxic Risk Assessment.

13. Operator/owner shall keep monthly records of type and amount of all materials used at this sources.

All records shall be retained for a period of two years from the date of entry, and be made available to District Staff on request.

14. A-4 and A-8 Scrubber shall be properly maintained and kept in good operating condition at all times. A-4 and A-4 Scrubber shall be operating whenever emissions are generated at this source.

ist condition NUMBER >>

TOTAL P.05

# APPENDIX E

# INVESTIGATION SCENARIOS FOR THE LEECHBURG FIELD TEST DEMONSTRATION

| SCENARIO | SUPPORTING EVIDENCE | CONTRADICTING EVIDENCE | STATUS |
|---|---|---|---|
| 1) Flashback at interface between startup separator plate and segment 2 to segment 3 flanges | a) Close proximity to area of most severe damage<br>b) Gaskets seemed unusually hard, binder appeared to have completely baked out<br>c) Field modifications provided non-metal path to premix<br>d) New design, not used before, particularly in hot environment | a) No evidence of scorched or oxidized paint on separator plate or flanges of segments in contact with plate<br>b) Tops of segments 1 and 2 are distorted in a similar fashion (indicating that failure at segment 2 could also have happened at segment 1)<br>c) Damage to segment 2 appears to have occurred about 1 inch below flange | a) Examination of plate and flanges showed no evidence of overheating. This scenario has been eliminated from consideration. |
| 2) Pad delamination prior to installation related to dual-screen design | a) After the accident, pad reported to have "poor" adhesion to outer screen<br>b) "Bowing" of pad observed at top of segments 1 and 2<br>c) Limited data on dual-screen in field use plus different dual-screen design than used previously | a) No evidence during fabrication, post shipping, or during installation of poor pad adhesion<br>b) Concerning "bowing", only bottom 2 segments are bowed indicating that bowing occurred during operation<br>c) Air damper forced to full-closed position at time of failure. Resulting high temperatures could have caused poor pad adhesion in installed segments | a) April 21 inspection and scraping of pad from burners determined that pad adhesion was poor, but it is suspected by Alzeta that this is a result of the failure, not a cause. Unfired segments had significantly better adhesion.<br>b) Pad adhesion will be quantified by duplication pull tests performed earlier with standard burner material. |
| 3)Pad overheating leading to flashback due to non-uniform flow | a) Examination in field indicated that pad felt "powdery," "not very strong," and had poor pad adhesion<br>b) Non-uniform flow at tops of segments 1 and 2 could have caused "bowing" at both locations<br>c) Flow distribution problem could have been most severe at separator plate causing local failure at top of segment 2<br>d) Outer screen paint is white over large areas, indicating overheating<br>e) No center bodies. This is not typical for cylindrical Pyrocore of this diameter<br>f) New pad formulation and hotter than normal environment are unique to this application | a) Scans of surface with 2-color pyrometer indicated temperature of 1900 to 1950°F 1/2 hour before failure. Scans included interface between segments 1 and 2, and periodically 2 and 3.<br>b) Pad properties such as "powdery" description could have been caused after the accident by air damper failing at full-closed position.<br>c) White paint on screen could also have been caused after the accident.<br>d) Pad pressure drop was 1 in w.c. prior to accident. This, combined with low flow velocities should minimize flow non-uniformity<br>e) Operating at 35% EA and well mixed (visual indication) at time of failure<br>f) Tests of this pad formulation at high temperature in lab have been successful | a) Consultant to study flow non-uniformity issue<br>b) Alzeta and APCI have reviewed flow-splitter sizing calculation and have determined flow split to be uniform (to within 2-3 percent accuracy). |

| SCENARIO | SUPPORTING EVIDENCE | CONTRADICTING EVIDENCE | STATUS |
|---|---|---|---|
| 4) Pad overheating leading to flashback due to high flux rate from environment to burner surface | a) Examination in field indicated that pad felt "powdery," "not very strong," and had poor pad adhesion<br>b) Sink radiation back to burner has been duplicated in lab at PPH scale. Gas phase radiation has not been duplicated. Three foot thick hot gas layer calculated to radiate on order of 10 $MBtu/hr\text{-}ft^2$ to burner surface<br>c) 2-color pyrometer would indicate temperature of surface fibers. Would not distinguish if flux from environment to surface had increased the thickness of the hot layer at surface of burner<br>d) Outer screen paint is white over large areas, indicating overheating<br>e) No center bodies. This is not typical for cylindrical Pyrocore of this diameter<br>f) New pad formulation and hotter than normal environment are unique to this application | a) Scans of surface with 2-color pyrometer indicated temperature of 1900 to 1950°F 1/2 hour before failure. Scans included interface between segments 1 and 2, and periodically 2 and 3 (see item c in "SUPPORTING EVIDENCE".<br>b) Pad properties such as "powdery" description could have been caused after the accident by air damper failing at full-closed position.<br>c) White paint on screen could also have been caused after the accident.<br>d) Burners in lab have been operated at more severe conditions including high preheat with no incidence of flashback.<br>e) Operating at 35% EA and well mixed (visual indication) at time of failure<br>f) Tests of this pad formulation at high temperature in lab have been successful (4000 hrs in PPH) | a) Gas phase radiation effects calculated. Tests run at small scale have not resulted in burner failure.<br>b) Larger scale (PPH) tests with fully insulated walls have led to failure, but this is not "flux from the environment" scenario. We do know that failure is related to operating temperature.<br>c) 4000 hr old PPH burner did not have chalking of paint. Failed PPH burners do have chalked paint under areas where pad is in place.<br>d) Consider full-scale multiple segment test prior to reinstallation |
| 5) Refractory Damage | a) Large piece of refractory found on floor of heater after accident. Partially covered with Pyrocore pad<br>b) Refractory piece was of sufficient size to cause observed screen damage at segment 2<br>c) No photos were taken of heater roof prior to Pyrocore installation, but there was no "mention" of refractory on floor.<br>d) We could have caused refractory to fall with heater overpressure at time of failure | a) No evidence of contact with burner cone section<br>b) Refractory block was found 90° away from contact point according to Phil DaPrato and John. Duane thinks refractory location was much closer to point of burner damage. | a) Tests of PPH burner with multiple 3"x3" sections of outer pad removed did not result in failure. Test with pad lifted from screen but left attached did result in failure.<br>b) Refractory damage seems unlikely given location of failure. |
| 6) Installation damage causing pad to separate from screen prior to operation | a) On bottom or second from bottom segment connection, the burner dropped 3 inches to mate<br>b) Bottom screens both bowed at top<br>c) Impact loading could have loosened pad from bottom screens | a) Difficult to calculate impact loading | a) No evidence from photos or examination that pad was loose prior to operation.<br>b) PPH tests have shown that loose pad will lead to failure similar to that observed at host site. |

| SCENARIO | SUPPORTING EVIDENCE | CONTRADICTING EVIDENT | STATUS |
|---|---|---|---|
| 7) Vertical mounting causes compressive stress leading to screen buckling | a) Bowing of screens observed at tops of segments 1 and 2<br>b) Non-standard design to mount vertically | a) Design calculations performed during design indicated that we were far from buckling design limits, but may not adequately consider thermal expansion effects | a) Buckling calculations show that vertical mounting is not a problem. Buckling of outer screen could be related to thermal expansion |
| 8) Bottom 2 segments ran poorly mixed and possibly rich | a) Operated in this mode for 12.5 of 18.5 hrs of operation<br>b) Orifice plate for startup gas incorrectly drilled. Conditions at startup close to stoichiometric | a) PPH burner operated rich for several days with no apparent damage | a) Tests at Alzeta suggest that start-up operation did not lead to failure. Consultant may address this further. |
| 9) Hot restart on bottom burner doubles gas flow at low fire for 1 minute | a) Unplanned mode of operation<br>b) Low flow and hot sink condition should be most prone to flashback<br>c) Bottom segments operate at approx 70% theoretical air for 10 seconds | a) Failure did not occur until approximately 45 minutes after startup<br>b) Damage may have caused hot shutdown, so damage would already have occurred | a) Tests in PPH indicate that rich vs lean operation over short term does not lead to burner failure. Conditions that maximize burner surface temperature cause burner failure. |
| 10) Poor pad adhesion due to dual-layer screen design leads to loss of pad and failure. | See Scenario 2 supporting evidence. Supporting evidence is the same. | See Scenario 2 contradicting evidence. | a) Pad adhesion tests completed and compared to standard batch adhesion. |
| 11) Out of spec thermal processing at Alzeta prior to shipment leading to burner failure. | a) Out of spec thermal processing has been demonstrated in other burner configurations to lead to failure.<br>b) Effect of new pad formulation on thermal processing requirements is unknown. |  | a) PPH tests are incomplete. Tests with longer processing times will be completed in July. |

APPENDIX F

# EVALUATION OF ALZETA PYROCORE BURNER FAILURE AT AIR PRODUCT & CHEMICAL STEAM REFORMER LEECHBURG, PA

Prepared By

Shyam N. Singh

SSEEI, Inc
129 S. Phelps Avenue
Suite #406
Rockford, Illinois 61108

Prepared for

Dr. Gideon Varga Jr
Program Manager, CE-221
U.S Department of Energy
Washington, DC 20585

1. OBJECTIVE: SSEEII was asked by Dr. Gideon Varga (DOE) to determine the failure mechanism of the Pyrocore burner system design used in the air products process heater and recommend the proper actions to be taken to correct this failure problems. SSEEII will limit its efforts to the tasks listed in this proposal.

## 2. RESULTS OF EVALUATION:

### 2.1 System Description:

This burner system is a fully-premixed porous radiant burner with a maximum rated capacity of 15 million BTU/hr. This gas-air mixing system, apparently Alzeta's design, is termed a "Gas Injection Spool". It can best be classed as a mixing tee. Air and gas, both under positive pressure, are fed to a cylindrical mixing chamber. The chamber, which is in line with the combustion air piping, contains an array of radial gas jets and a stationary propeller to accelerate the process of mixing. Gas-air mixture leaving the gas injection spool immediately enters a 14" pipe size, long radius (21"), 90° elbow and then a 102" long vertical run of 14" pipe before exiting into the burner proper.

Gas and air flows are controlled and proportioned by a linked valve arrangement, consisting of a butterfly disc in the bore of the mixing chamber (controlling the air flow) and an external Maxon "Q" gas valve. The later is a butterfly valve with an eight point adjustable gradient cam. Use of the cam allows the Q valve's characteristic flow curve to be altered to match that of the fixed port air butterfly. The two valves are mechanically linked to a pneumatic actuator so that a change in positon of one valve is matched by an equivalent change in the other.

Combustion air is supplied by a 7 1/2 hp Chicago Blower type SQAD 13 1/2 centrifugal fan. Depending upon the wheel used in this fan it develops a static pressure of about 6.5" to 8.8 " w.c. at the full firing capacity of the system. Details of the natural gas supply system are unknown.

### 2.2 Analysis of System Components and Design:

This analysis was conducted using Alzeta drawings D7061000, D7061-046, B6209-051.XXX, two un-numbered layout drawings of the burner and gas injection spool and operating data and remarks from ARCS. Dimensions were scaled from the drawings. Gas-air mixture pressures, flows, and velocities were calculated making the following assumptions:

-Stoichiometric Air-Gas ratio is 10:1

-The nominal combustion ratio of 35% excess air was held at all flows over the turndown range of the burner.

-The burner and its associated mixture piping behave like a fixed orifice; i.e., their discharge coefficient doesn't change with firing rate or temperature, so it's possible to extrapolate a single flow and mixture pressure reading to higher and lower capacities by using the square root law of flow. We have assumed a discharge coefficient of 0.62 for these calculations.

-The natural gas fuel has a gross heating value of 1000 BTU/Cu.Ft. and a specific gravity of 0.6.

-The discharge coefficient of the holes in the gas spud (drawing B6209-051.XXX) is 0.62.

-The combustion air temperature is 70°F, and its density is 0.75 lb/cu.ft.

## DIMENSIONAL ANALYSIS - BURNER

Overall length of radiant section: 17'
Outside diameter of radiant section: 24 " for five cylindrical sections, 24" tapering to 10.62" for conical cap.
Total outside surface area (radiating surface): 103.31 sq. ft.
Inside cross-sectional area of radiant section: 2.82 sq.ft, not allowing for internal flanges and hardware.
Outside diameter of baffle tubes: 10.5"
Cross-section of baffle tubes: 0.60 sq.ft.
Net burner cross section: 2.22 sq.ft.

## DIMENSIONAL ANALYSIS - GAS INJECTION SPOOL

Overall length of spool: 33.86"
Inside diameter of spool: 13.69"
Inside cross-sectional area of spool, excluding internal componets: 1.022 sq.ft
Outside diameter of air butterfly disc: 11.92"
Cross-sectional area of butterfly disc: 0.775 sq.ft
Gas line pipe size: 3"
Holes in gas spud, number, size, and area: 12 @ 0.625" diameter, 3.682 sq.in. total.

## DIMENSIONAL ANALYSIS - MIXTURE PIPING

Nominal pipe size: 14"
Inside diameter of pipe: 13.69"
Straight run of piping -
- between mixer and first elbow: 0
- between elbow and entrance of burner: 102" (7.45 pipe diameters)

## 2.3 Calculation of Operating Parameters from Data and Dimensions:

Table I contains key burner operating parameters as a function of firing rate. We were told that the burner was operating at a mixture pressure of 1.05" wc at an input of 7.0 million BTU/Hr. The remaining flows and pressures were calculated from these values using the square root law and the assumptions stated above.

TABLE I. Burner Operating Parameters at Various Firing Rates

| Firing Rate x $10^6$ Btu/hr | Mixture Flow @ 35% Ex Air, scfh | Mixture Pressure, inches wc | Mixture Velocity in Burner, ft/sec bottom 2 segments* | Firing Rate, Btu/hr per sq. ft. of Radiant surface |
|---|---|---|---|---|
| 2.0 min | 29,000 | 0.09 | 3.63 | 19,360 |
| 3.0 | 43,500 | 0.19 | 5.44 | 29,040 |
| 4.0 | 58,000 | 0.34 | 7.25 | 38,720 |
| 5.0 | 72,500 | 0.54 | 9.07 | 48,400 |
| 6.0 | 87,000 | 0.77 | 10.89 | 58,080 |
| 7.0 | 101,500 | 1.05 | 12.70 | 67,760 |
| 8.0 | 116,000 | 1.37 | 14.52 | 77,440 |
| 10.0 | 145,000 | 2.14 | 18.14 | 96,800 |
| 15.0 | 217,500 | 4.82 | 27.21 | 145,194 |

*These segments contain baffle tubes. Mixture velocities are highest in this part of the burner.

Compared to prevailing industry practice, mixture pressures are below the accepted minimum firing rates up to 3 million BTU/hr. The mixture velocity in the lower part of the burner is well below that corresponding to the accepted minimum.

TABLE II. Gas Injection Spool & Mixture Piping Parameters @ Various Firing Rates.

| Firing Rate, x $10^6$ BTU/hr | Mixture Velocity, in Mixture Pipe, ft/sec | Calculated Gas Spud Press. Drop, " wc |
|---|---|---|
| 2.0 | 7.88 | 0.17 |
| 3.0 | 11.82 | 0.38 |
| 4.0 | 15.76 | 0.67 |
| 5.0 | 19.71 | 1.04 |
| 6.0 | 23.65 | 1.50 |
| 7.0 | 27.59 | 2.05 |
| 8.0 | 31.53 | 2.67 |
| 10.0 | 39.41 | 4.18 |
| 15.0 | 59.12 | 9.40 |

Up to inputs of 8 million BTU/Hr, the mixture pipe velocity is below the commonly-accepted industry minimum.

The design of the gas injection spool deserves comment. This mixer does not resemble most of the gas-air mixer designs offered by other burner manufacturers, so a direct comparison of their performance and merits can't be made. However, we believe this mixer can not be as effective as the air-aspirated venturi mixers in common use. Venturi mixers have greater length-to-pipe diameter ratios and require higher air pressure drops to create the energy required for mixing the air and gas, yet tests have shown that even they do not produce a fully homogeneous mixture at their outlets. This is why some manufacturers require a minimum length of mixture piping - to allow mixing to complete before the burner is reached.

On the basis of our experience with gas mixing and burner equipment, we doubt that the four-armed mixing blade can generate enough tubulence to create a homogeneous mixture at the mixer outlet, especially at lower flow rates, when the incoming air velocity is low. Its performance is likely to be further compromised by its proximity to the air control butterfly disc. At low to medium flows, the partially-open disc will mask off flow over a large part of the mixing blade. Further, we do not believe there is sufficient length or induced turbulence in the mixture piping to finish the task of mixing. Consequently, we expect the mixture reaching the burner to be highly non-uniform in composition.

This has some strong implications for the tendency of the system to flashback. At a nominal gas-air ratio of 35% excess air, the burning velocity of the mixture is considerably lower than that of a stoichiometric mixture and should make the Alzeta burner system more resistant to flashback; however, if the incoming mixture is not uniform, it probably contains strata or pockets of stoichiometric composition. If a flame front moves into one of these pockets, flashback can occur as easily as if the entire mixture were uniformly stoichiometric.

## 2.4 Conclusions:

An analysis of the dimensional and operating parameters of this burner system does reveal that flashback could have occurred for one of three reasons:

1. Perforation of the porous matrix, allowing the flame to pass into the cavity.
2. Operation at such low flows that the flame front advanced through the much lower velocity mixture and began burning inside the burner cavity.
3. Overheating of the porous medium to the point where its entire thickness became hot enough to act as a combustion stabilizer. This would allow the gas-air mixture to auto-ignite on the inner most surfaces of the porous matrix.

Regardless of the cause of flashback, the situation would have been aggravated by several design factors which, in view of common industry practice, can be considered marginal at best:

1. The gas-air mixture line is a 14" nominal pipe size and lacks any backfire protection devices. Industry custom is to limit the size of such lines to 8", and some manufacturers are uncomfortable even with that size, preferring not to exceed line sizes of 4" or 6". Larger sizes are discouraged because of their increased susceptibility to flashback. Where such lines sizes can't be avoided, such as in plantwide premix systems, they are usually protected by firechecks, flame arrestors, and safety blowouts.

2. The diameters of the burner and its mixture feed piping, in addition to allowing flow velocities lower than customary practice, also created a large reservoir for unburned mixture. In the event of a flashback explosion, this large volume of mixture will contribute to its violence.

3. The gas-air mixing tee, termed as a Gas Injection Spool, does not appear to have the requisite qualities to produce a homogeneous gas-air mixture at the burner inlet connection. Consequently, the mixture flow entering the burner probably contains pockets of near-stoichiometric composition, which have a higher inherent flame velocity than the average mixture composition, which contains 35% excess air.

## 3. ESTIMATE OF GAS PHASE RADIATION:

Estimates of the radiation flux incident on the ceramic pad surface were attempted and for this purpose the methodology presented by Viskanta and Menguc(5) was used. But, after the analysis has been developed, it immediately became apparent that the results obtained depended strongly on the assumptions which had to be made (i.e., burner surface temperature, mean combustion products temperature, refractory wall temperature of the steam reformer, and radiation surface properties of the pad, steam/methane carrying tubes, refractory walls, etc.). Therefore, it was decided to use an effective surroundings temperature, $T_{sur}$, in a parametric way to estimate the radiation flux incident on the ceramic pad, $G_{pad} = \sigma T^4_{sur}$, where $\sigma$ is the Stefan-Boltzmann constant.

Two mathematical models were developed for predicting the temperature distribution in the pad:

1. Steady-state advection and conduction heat transfer with heat generation in a porous one-dimensional solid.
2. Steady-state advection, conduction and radiation with a chemical reaction inside the porous matrix to account for combustion in the ceramic pad.

An exact analytical solution was obtained with Model 1, but the mathematical details are not presented here. Numerical solutions were generated with Model 2 by modifying the GRI-Eclipse porous burner-radiant heater program. The computational details are not very interesting and are omitted here. The results obtained with Model 2 appear to be more realistic and are only ones presented and discussed here.

Figure 1 shows the influence of the effective surroundings temperature, $T_{sur2}$, on the solid and gas temperature distributions in the porous solid. The thermophysical properties (particularly the effective thermal conductivity) and the radiative properties (absorption and scattering coefficients) are highly uncertain and were estimated. For example, the effective thermal conductivity used in the calculations was taken to be 1.0 W/mK. This is consistent with the value used by Sathe et al.(2). The convective heat transfer coefficient between gas and solid matrix was estimated from existing empirical correlations for a reticulated ceramic having a PPI of 65. An effective surroundings temperature, $T_{sur2} = 1100$ K, corresponds to an incident radiation flux on the pad,

$$G_{pad} = 1.714 \times 10^{-9}(1100 \times 1.8)^4 = 2.6343 \times 10^4 \text{BTU/hr ft}^2$$
$$= 5.6688 \times 10^{-8}(1100)^4 = 8.2997 \times 10^4 \text{ W/m}^2$$

We note from Figure 1 that for $T_{sur2}$ = 1000 K and $T_{sur2}$ = 1300 K there is no combustion taking place inside the fibrous solid (i.e., the flame is located in front of the solid) matrix. However, for $T_{sur2}$ = 1400K and $T_{sur2}$ = 1500 K combustion is apparently occurring at approximately 6 mm and 5 mm from the back face of the pad, respectively. This is indicated by the maximum gas temperature. Ahead of the "flame" the temperature of the gas is very close to the solid, because of very effective convective heat transfer between the solid matrix and the gas. As expected, behind the "flame" the solid matrix temperature is higher than the gas temperature. The "flame front" is not sharp (as in gas combustion) but is rather "diffuse". The corresponding net radiative fluxes for the four simulations are shown in Figure 2. Because of the sign convention adopted, the net radiative flux is negative and has a maximum at the front face of the pad.

The effect of the fuel flow rate on the temperature distribution in the porous solid is shown in Figure 3. It is clear from the temperature distributions presented that the temperature of the solid matrix is significantly higher for the lower fuel burning rate of 50,000 BTU/hr $ft^2$. This is the consequence of the combustion inside the matrix as already discussed. For the higher fuel burning rate of 120,000 BTU/hr $ft^2$ the flame is apparently in front of the pad. The effect of the fuel burning rate on the net radiative heat flux is shown in Figure 4. The trends revealed in the figure are consistent with expectations.

## 3.1 Conclusion:

Based on the models used, thermophysical and radiative properties estimated for the fibrous matrix of the burner, and the operating conditions employed, the results obtained suggest the following:

- The back-radiation (reradiation) from the combustion products and hot refractory walls can have a significant effect on the temperature in the pad.

- At sufficiently high effective surroundings temperatures, the results show that combustion can occur inside the porous matrix and the flame "sinks" into the matrix. The consequences of combustion and high temperatures inside the matrix on the integrity of the pad are uncertain as the model used for the calculations is not intended to predict the mechanical integrity of the structure.

- The results obtained suggest that the pad is more likely to be overheated at low rather than at high specific fuel firing rates.

- The results reported is based upon estimated thermophysical and radiative properties of the fibrous matrix and the operating conditions.

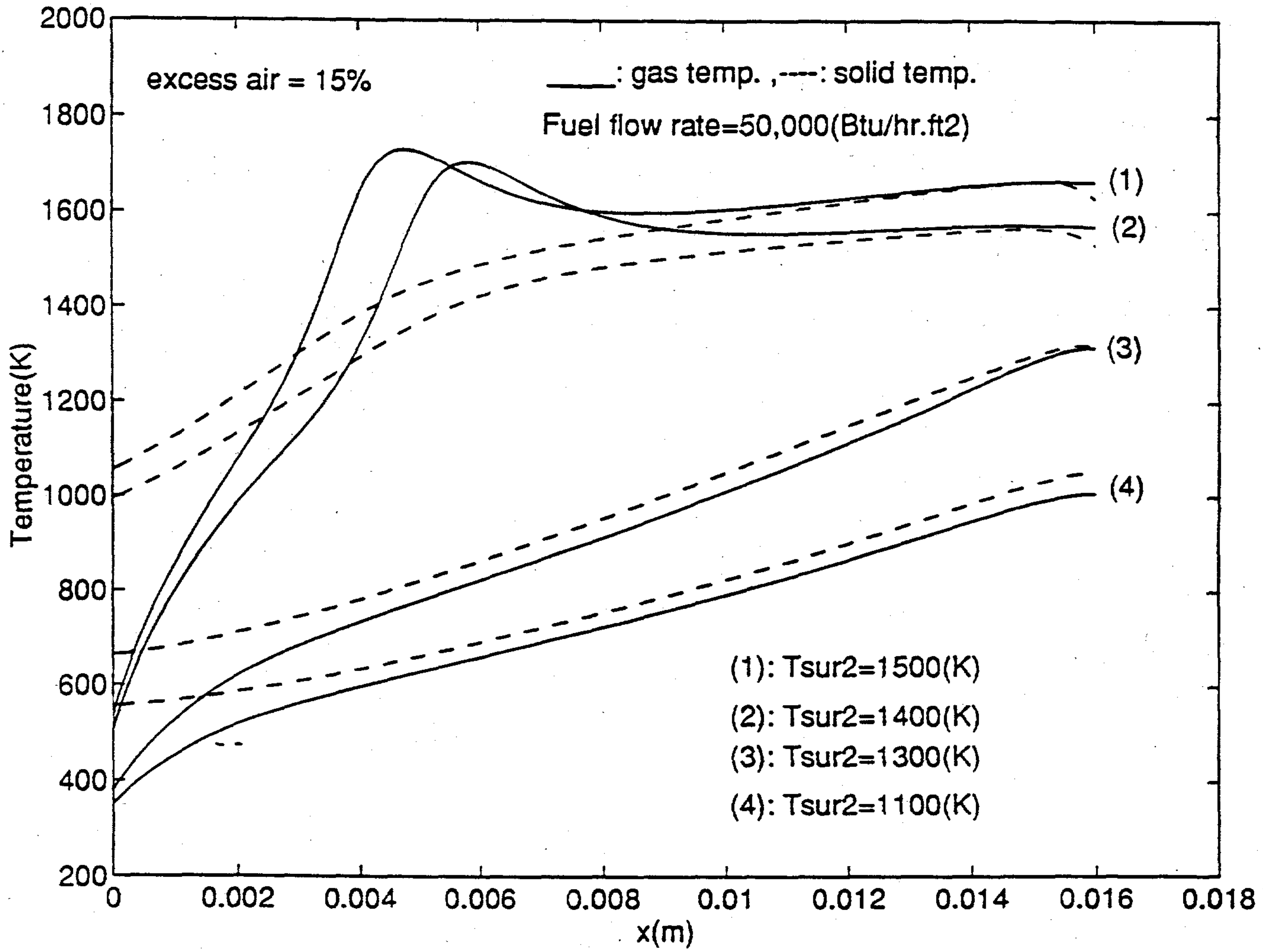

excess air = 15%
____: gas temp. ,----: solid temp.
Fuel flow rate=50,000(Btu/hr.ft2)
(1)
(2)
(3)
(4)
(1): Tsur2=1500(K)
(2): Tsur2=1400(K)
(3): Tsur2=1300(K)
(4): Tsur2=1100(K)
Temperature(K)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
x(m)

Figure 1

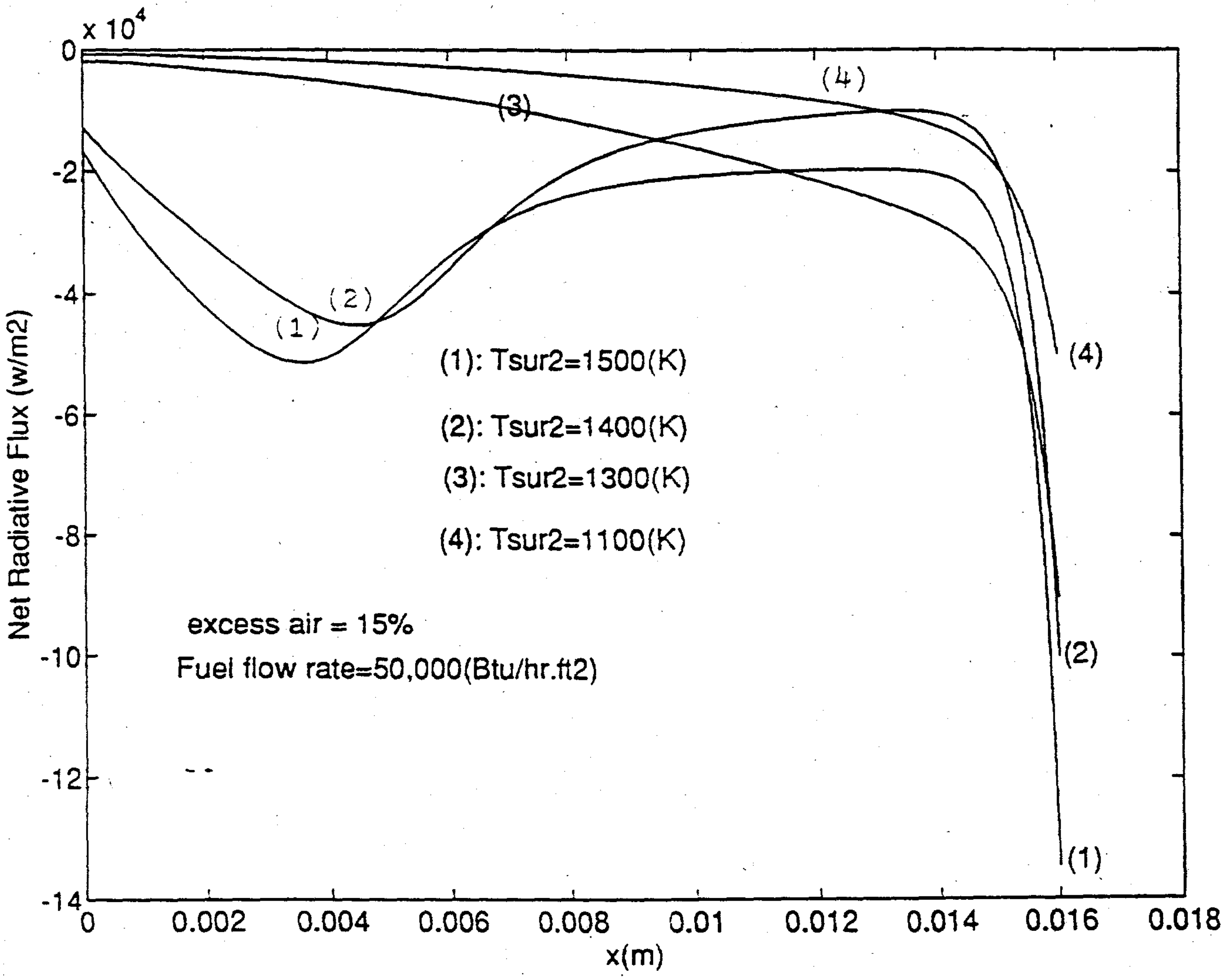

x 10^4
0
-2
-4
-6
-8
-10
-12
-14
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
x(m)
Net Radiative Flux (w/m2)
(1)
(2)
(3)
(4)
(1): Tsur2=1500(K)
(2): Tsur2=1400(K)
(3): Tsur2=1300(K)
(4): Tsur2=1100(K)
excess air = 15%
Fuel flow rate=50,000(Btu/hr.ft2)
(4)
(2)
(1)

Figure 2

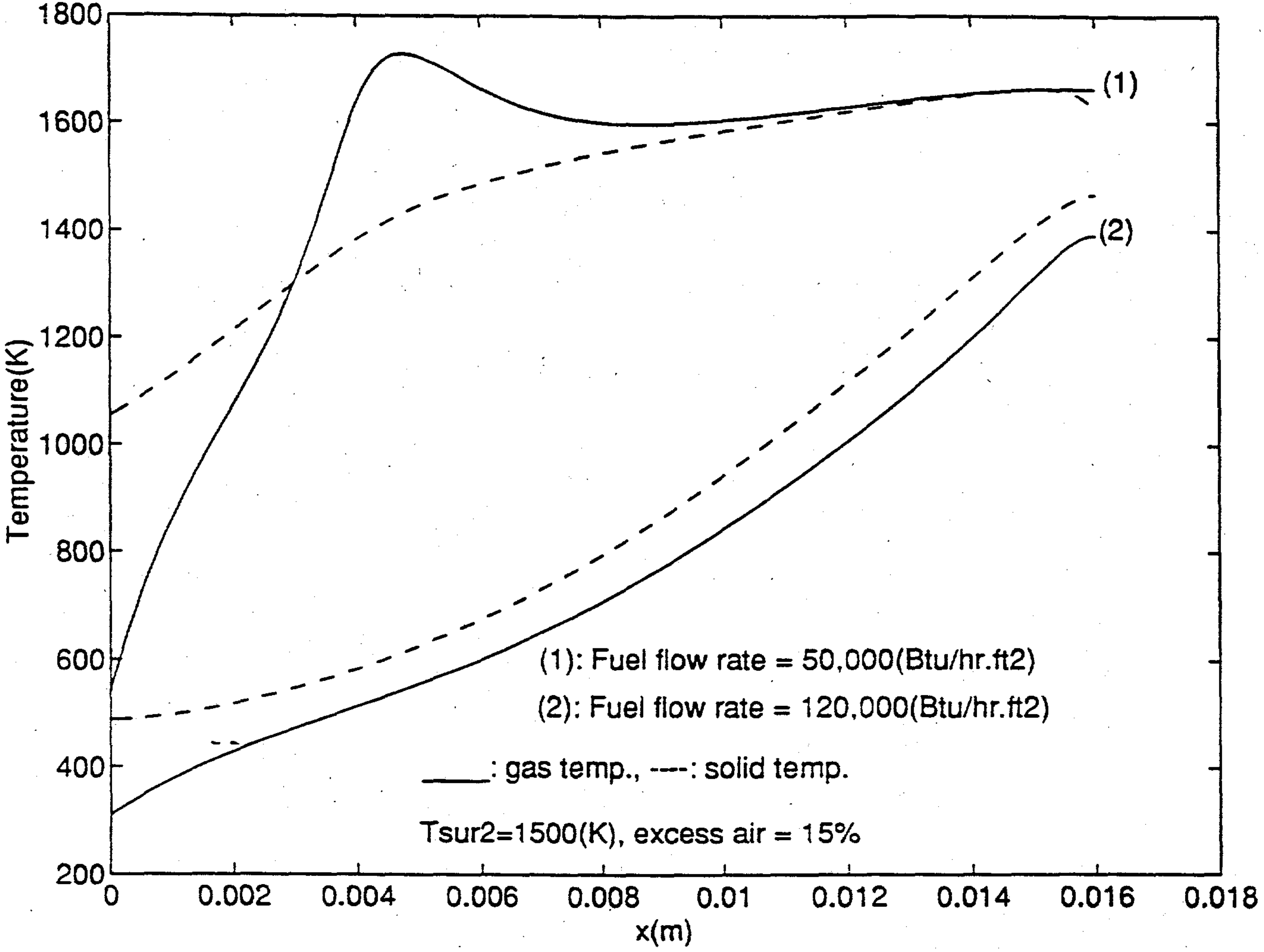

1800
1600
1400
1200
1000
800
600
400
200
Temperature(K)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
x(m)
(1)
(2)
(1): Fuel flow rate = 50,000(Btu/hr.ft2)
(2): Fuel flow rate = 120,000(Btu/hr.ft2)
____: gas temp., ----: solid temp.
Tsur2=1500(K), excess air = 15%

Figure 3

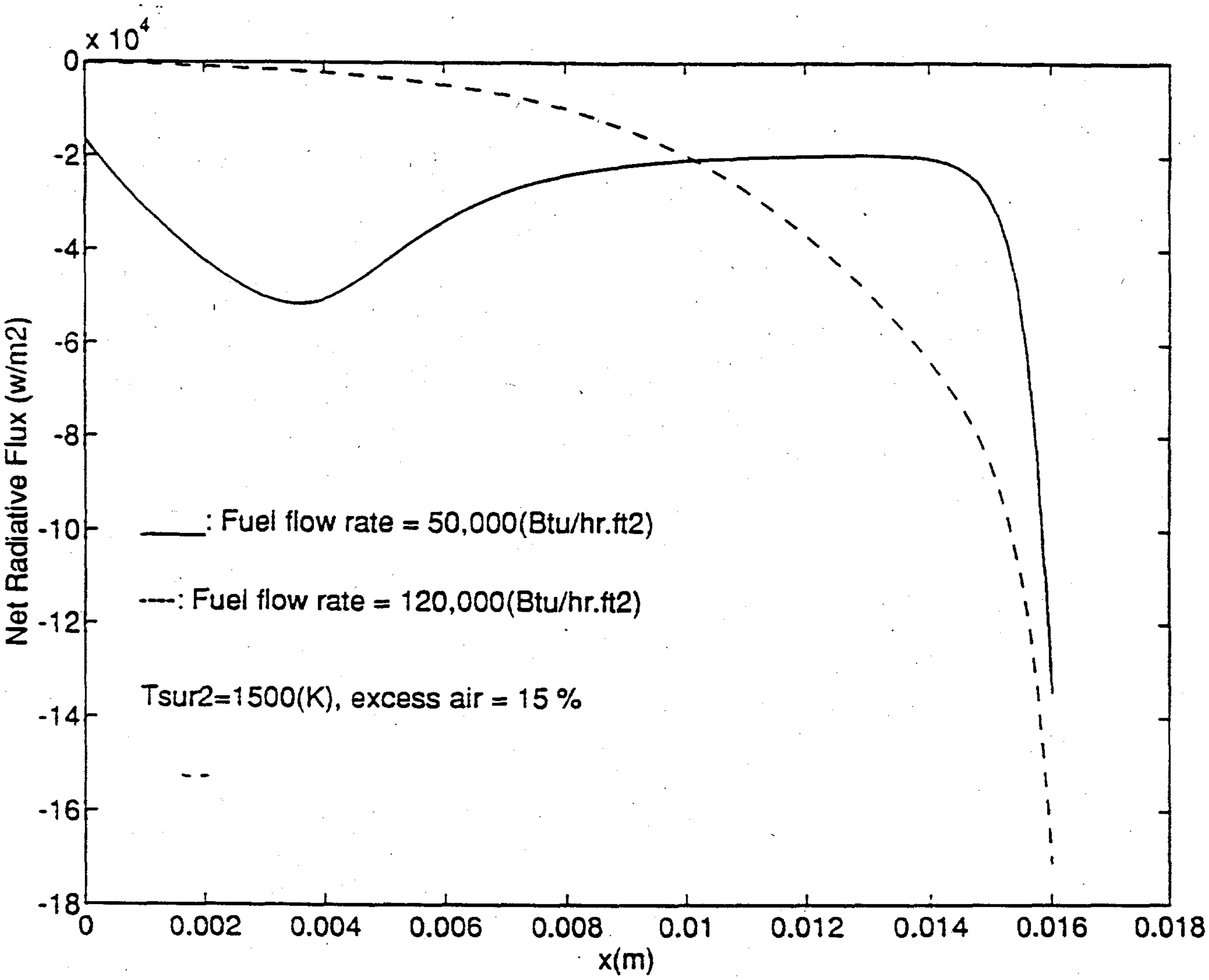

x 10^4
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Net Radiative Flux (w/m2)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
x(m)
____: Fuel flow rate = 50,000(Btu/hr.ft2)
----: Fuel flow rate = 120,000(Btu/hr.ft2)
Tsur2=1500(K), excess air = 15 %

Figure 4

## 4. ESTIMATE OF PRESSURE RISE DUE TO AUTO-IGNITION:

The auto-ignition of natural gas (approximated as methane) in the plenum chamber of a two feet diameter, 14 feet long radiant burner was considered using homogeneous chemical kinetic calculations. The inflow of reactants was assumed to be shut off leading to auto-ignition conditions due to the reactant velocity not being sufficient to prevent overheating of the stream prior to the burner surface. The outflow of products was also prevented to simulate back pressure conditions that would be conducive to auto-ignition. Based on the estimated range (1900 to 2180 F) of the burner surface temperature, a range of temperatures (1340 F or 1000 K to 2060 F or 1400 K) for the mixture that may auto-ignite was considered. Excess air between 10 and 30% was considered. The mass of the reactants that may auto-ignite was determined by the fixed volume of the plenum chamber and the initial pressure (1 atm.) and temperature. The reaction rate expression was taken from Westbrook and Dryer (Combustion Science and Technology, Vol. 27, pp. 31-43, 1981) assuming methane combustion. Thus the overall reaction is first order and has a negative exponent in methane mole fraction due to the endothermic nature of this fuel. Ordinary differential equations for the conservation of mass, species, and energy in the plenum chamber were written. These equations were solved using Euler's method with adaptive time stepping selected to control the rise in temperature during a time step to be less than 0.5%.

Figure 5 shows the temperature, pressure and fuel mass fraction profile for an initial temperature of 1100 K and an excess air of 20%. The temperature increases very slowly at first (note the logarithmic time axis) and then takes off as expected for auto-ignition conditions. The time taken for reaching the rapid increase is 1.4 seconds and the final pressure is 253 kPa. A rise of over a factor of 2 in pressure is observed over a short period after the long induction.

If the initial temperature was near the higher end of the operating range (1400K), the mixture would auto-ignite in less than 2/1000 seconds (compared to 1.4 seconds at 1000K) as seen in Figure 6. In both cases a rapid heat release period follows a relatively long induction period. However, the induction period at 1400K is more than two orders of magnitude shorter than that at 1000K.

Several initial temperatures and two excess air levels (10% and 30%) were considered. Figure 7 shows the variation of final pressure and auto-ignition delay time with initial temperature. The change in excess air did not affect the auto-ignition delay time and the final pressure significantly. The final pressure decreased by approximately 50 kPa with increase in initial reactant temperature. This is due to the lower mass of reactants available for the combustion process with lower initial density caused by higher temperature at fixed plenum chamber volume.

The pressure rise to over two atmospheres occurs in a very short time for the higher initial temperatures. The bottom portion of Figure 7 shows the reduction in delay time with increase in temperature. The delay time decreases from 1.4 seconds at 1000K to 0.002 seconds at 1400K. The change in excess air from 10 to 30% has very little influence on ignition delay as seen in Figure 7. This observation is subject to flammability limits consideration and can not be extended far from the present range of excess air.

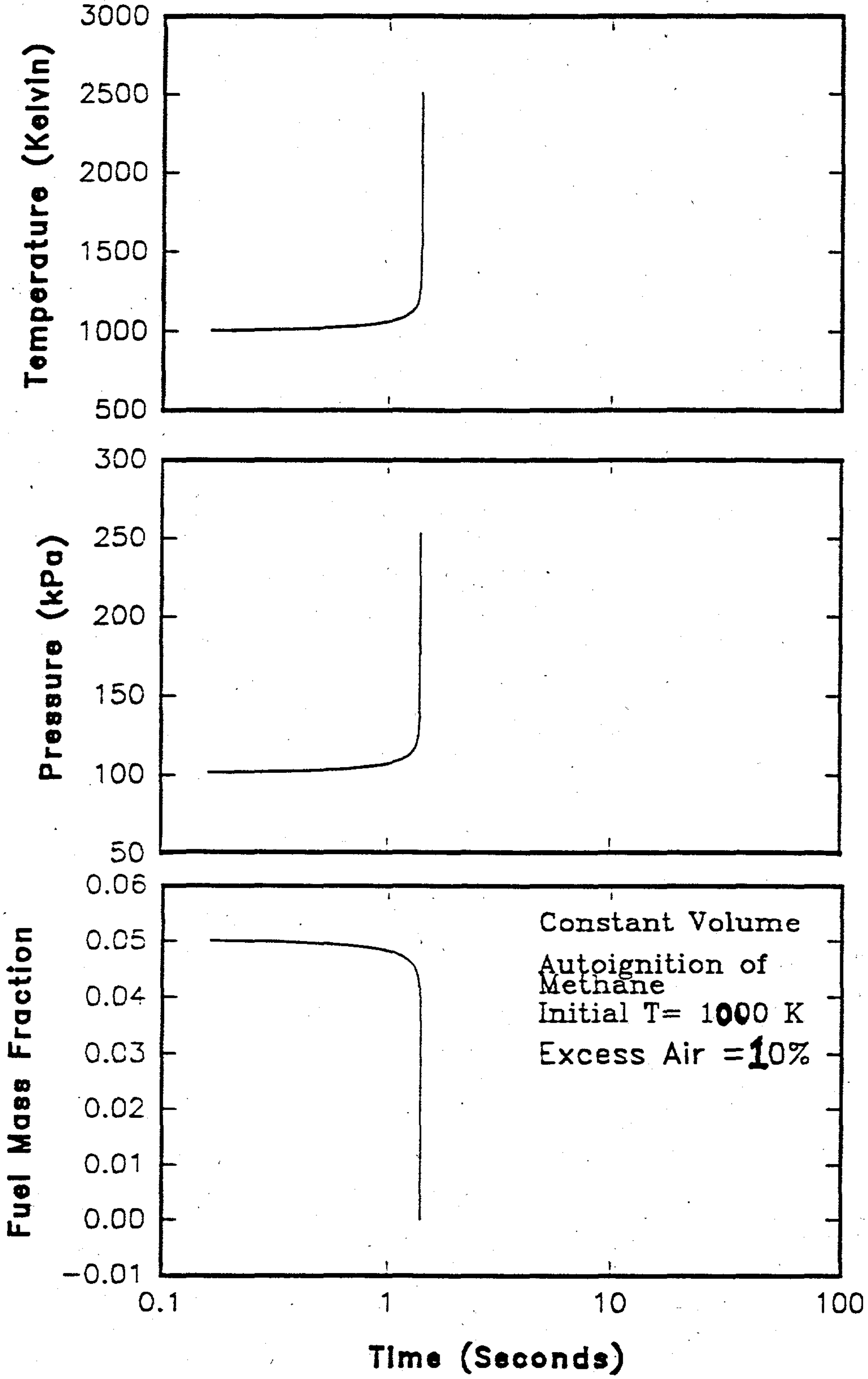

3000
2500
2000
1500
1000
500
Temperature (Kelvin)
300
250
200
150
100
50
Pressure (kPa)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
Fuel Mass Fraction
Constant Volume
Autoignition of Methane
Initial T= 1000 K
Excess Air =10%
0.1
1
10
100
Time (Seconds)

Fig. 5

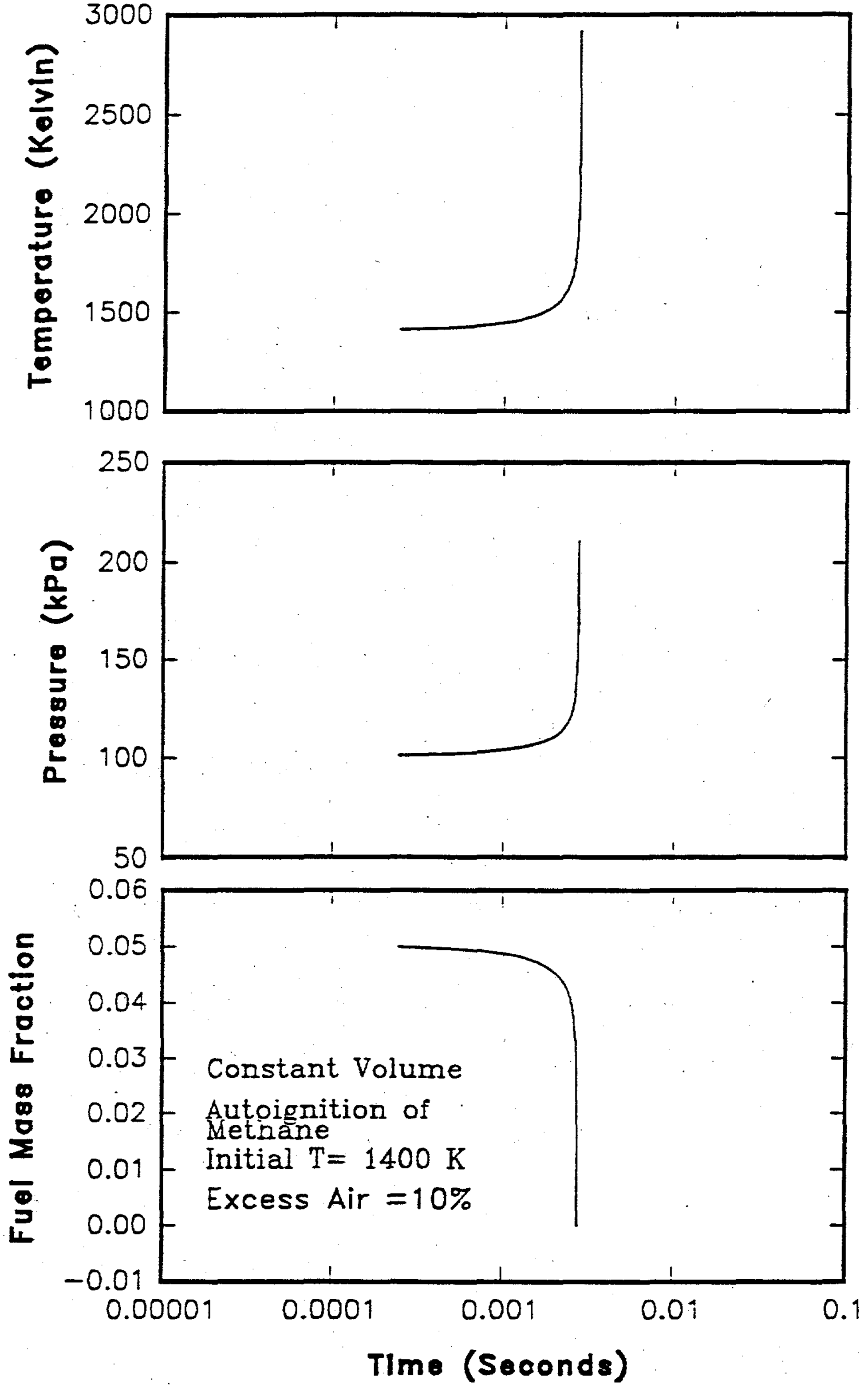

3000
2500
2000
1500
1000
Temperature (Kelvin)
250
200
150
100
50
Pressure (kPa)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
Fuel Mass Fraction
Constant Volume
Autoignition of
Methane
Initial T= 1400 K
Excess Air =10%
0.00001
0.0001
0.001
0.01
0.1
Time (Seconds)

Fig. 6

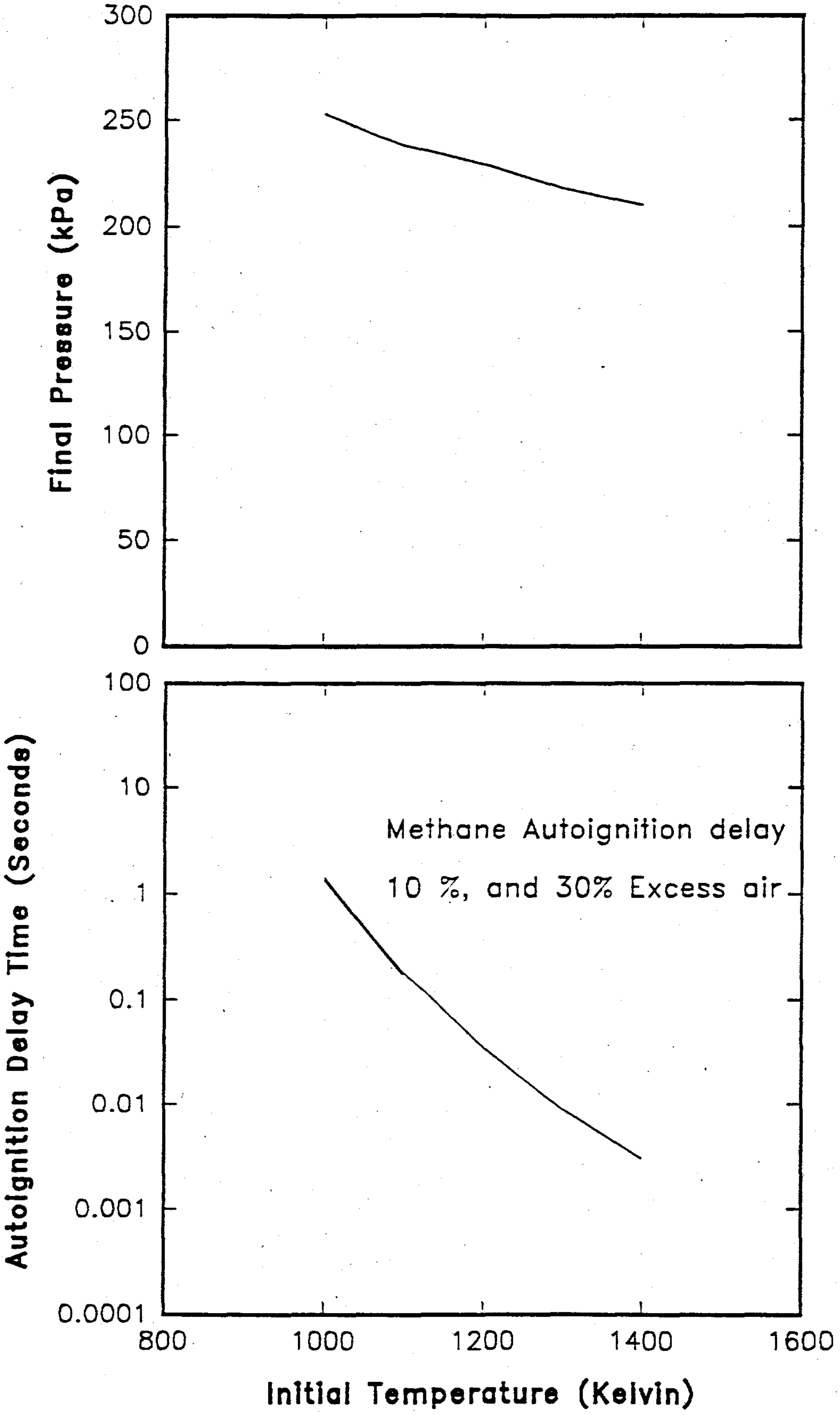

300
250
200
150
100
50
0
Final Pressure (kPa)
100
10
1
0.1
0.01
0.001
0.0001
Autoignition Delay Time (Seconds)
Methane Autoignition delay
10 %, and 30% Excess air
800
1000
1200
1400
1600
Initial Temperature (Kelvin)

Fig 7

## 4. Conclusion:

In conclusion, for the given conditions in the plenum chamber of an infra-red burner:

- Auto-ignition can increase the pressure by over a factor of 2 in as little as 2 milliseconds time.

- The auto-ignition condition is very sensitive to the initial reactant temperature and hence this may serve as a very convenient monitoring and control variable.

- The changes in excess air within flammability limits are not of significance to the present problem.

## 5. Recommendations:

In addition to the detail study of the probable failure mechanisms, following recommendations are made to diagnose and to overcome the problems encountered with the burner system.

1. Use a commercially-available premixing machine in place of gas injector spool. Test the laboratory scale burner and compare the combustion and thermal performance with the previous design. Our concern is, however, that the the current mixer may work with smaller units and not with a larger unit. Follow the NFPA 86 and NFPA 54 rules when designing a system. Consider a flame arrestor in mixture piping upstream of the burner.

2. Fire the scaled down burner at 3:1 turndown ratios for eight hours, measure the axial and radial temperatures of the matrix surface, turn off the burner and cut three (3) 1" square pieces of the fiber pad, analyze them under scanning electron microscope to determine physical and chemical composition, compare the results with the unfired fiber samples to examine any changes in the original structure.

3. As a control, a second burner should be run at full fire for the same length of time as described earlier, cut a few samples and examine under scanning microscope, compare with the results obtained at high fire.

4. Using thermocouples at six locations inside the plenum and underneath the fiberpad, monitor the temperature as a function of burner length and time to see how the temperature varies.

All the above tests must be conducted under identical surrounding thermal environment simulating the steam reformer temperature regime.

### 5.1 General Recommendations:

Minimum Gas-Air Mixture Pressure: Most manufacturers' literature specifies that burners be run at natural gas-air mixture pressures no lower than 0.25" w.c. except for few specific types of burners, which are permitted to operate as low as 0.1"w.c. Eclipse generally specified a minimum of 0.2" w.c. Reference 3 state 0.25" w.c., and reference 4, 0.25" to 0.30"w.c. All these assume near-stoichiometric premix entering the burner. A mixture pressure of 0.25" w.c. corresponds to a pipe velocity of 33.9 ft/sec.

Maximum Mixture Line Size: Very few firm statements are made, although none of the manufacturers offer a venturi or tee-type mixer larger than 8" pipe size. North American cautions that their high pressure gas injector mixers should not be used to feed multiple burners if the mixture pipe is larger than 3", because of the hazard of flashback. Eclipse recommends avoiding mixture line sizes 6" or larger for the same reason, and NFPA 54 requires a safety blowout or backfire preventer if piping downstream of a gas-air mixing machine exceeds 2 1/2" size. No such requirement is imposed on simple venturis or mixing tees, so we presume part of their rationale may be to prevent damage to the more expensive mixing machines.

Minimum Mixture Piping Runs: Eclipse calls for at least 9-10 pipe diameters between the mixer outlet and the first downstream pipe fitting. North American accepts a minimum of 4 between the mixer and burner. If there is a fitting in the mixture line, they specify at least 2 pipe diameters upstream and two downstream of that fitting. The IHEA manual specifies a minimum of 4. None of the other sources discuss this subject.

REFERENCE:

1. National Fire Protection Association Code NFPA 86. Ovens and Furnaces

2. NFPA 54, National Fuel Gas Code

3. IHEA Combustion Technology Manual, Fourth Edition

4. Gas Engineers Handbook

5. R. Viskanta and M.P. Manguc, "Principles of Radiative Heat Transfer in Combustion Systems," in HandBook of Heat and Mass Transfer - Volume 4: Advances in Reactor Design and Combustion Science, N.P. Cheremisinoff, editor, Gulf Publishing Co., Houston (1990), Chapter 22.

6. S.B. Sathe, M.R. Kulkarni, R.E. Peck, and T.W. Tong, "An Experimental and Theoretical Study of Porous Radiant Burner Performance," Twenty-third Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA (1990), pp. 1011-1018.