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DEVELOPMENT OF THE RADIATION STABILIZED DISTRIBUTED FLUX BURNER

Phase 2 Final Report

A. Webb
J. D. Sullivan

June 1997

Work Performed Under Contract No. DE-FC07-95ID13332

For
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC

By
Alzeta Corporation
Santa Clara, CA 95054

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PHASE II FINAL REPORT

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EXECUTIVE SUMMARY

This report covers progress made during Phase 2 of a three-phase DOE-sponsored project to develop and demonstrate the Radiation Stabilized Distributed Flux burner (also referred to as the Radiation Stabilized Burner or RSB) for use in industrial watertube boilers and process heaters. The goal of the DOE sponsored work is to demonstrate an industrial boiler burner with NO_x emissions below 9 ppm and CO emissions below 50 ppm (corrected to 3 percent stack oxygen). To be commercially successful, these very low levels of NO_x and CO must be achievable without significantly affecting other measures of burner performance such as reliability, turndown, and thermal efficiency.

Phase I of this project demonstrated that sub-9 ppm NO_x emissions and sub-50 ppm CO emissions (corrected to 3 percent oxygen) could be achieved with the RSB in a 3 million Btu/hr laboratory boiler using several methods of NO_x reduction. During Phase 1 the RSB was also tested in a 60 million Btu/hr steam generator used by Chevron for Thermally Enhanced Oil Recovery (TEOR). In the larger scale tests, fuel staging was demonstrated, with the RSB consistently achieving sub-20 ppm NO_x and as low as 10 ppm NO_x. Large scale steam generator tests also demonstrated that flue gas recirculation (FGR) provided a more predictable and reliable method of achieving sub-9 ppm NO_x levels.

The Phase 1 market evaluation showed that participation in the industrial burner market will require that Alzeta have the capability of supplying both a sub-30 ppm low NO_x burner and a sub-9 ppm very low NO_x product. The primary objective of Phase 2 was to demonstrate and test a full scale burner design at the sub-9 ppm NO_x level. The opportunity to test at full scale was accomplished by the sale of a 125 million Btu/hr burner as a retrofit in a watertube package boiler. This sale provided Alzeta with a full scale site at which to demonstrate the sub-9 ppm burner without having to guarantee sub-9 ppm performance (This customer has a sub-30 ppm NO_x requirement).

Due to a relatively small boiler firebox and higher than typical volumetric heat release rate in this particular boiler, we had difficulty in meeting all of our Phase 2 test

objectives. Following this installation, it was decided to do additional tests in the 60 million Btu/hr Chevron-owned steam generator used for Phase 1 tests. All Phase 2 test objectives were met by the completion of the additional steam generator tests.

Based on the results of tests at SF Thermal and Chevron, the near term approach selected by Alzeta for achieving low NO_x is to utilize FGR. This decision was based on a number of factors, with the most important being that FGR has proved to be an easier approach to transfer to different facilities and boiler designs. In addition, staging has proved difficult to implement in a way that allows good combustion and emissions performance in a fully modulating system. Minimum system turndown of 6:1 is a typical expectation of industrial package boiler operators.

Additional objectives of the Phase 2 work included final host site selection for the Phase 3 field demonstration and a continuing effort to reduce burner costs in order to be commercially competitive with other very low NO_x burners or other NO_x reduction techniques.

All Phase 2 project goals were met as follows:

- The full-scale burner demonstration was completed at San Francisco Thermal in San Francisco, California. The burner is currently tuned to operate at sub-30 ppm NO_x at 50% excess air with no staging. Soot formation, due primarily to the small furnace size of the Zurn boiler, made staging a undesirable option for this customer.
- Two new materials were identified as a means to further reduce the cost of the burner. Both materials have now been tested in commercial installations at small scale (less than 10 million Btu/hr) and are discussed in greater detail in Section 3.
- The single burner retrofit market was redefined to include 50,000 to 150,000 lb/hr boilers (62 million to 185 million Btu/hr). The marker for multi-burner installations is still defined as 50,000 to 250,000 lb/hr.
- Alzeta teamed with Chevron and Babcock & Wilcox to demonstrate a sub-9 ppm NO_x burner in a TEOR steamer in Bakersfield, California using FGR. These tests were successful in that the targeted emissions levels were achieved at approximately 3 percent stack oxygen.

- B&W and Alzeta have used this information in the design of the sub-9 ppm NO_x Phase 3 demonstration boiler. This new boiler design will utilize additional heat transfer surface in the boiler firebox to more rapidly cool the combustion products. Although new boilers can utilize an intermediate row of water tubes, retrofit installations will probably add extended tube surface to the existing firebox water tubes to increase heat transfer. This tradeoff is dictated by the relatively high cost of field modifications to installed boilers.

With all Phase 2 technical goals met, Alzeta is beginning work on Phase 3. In Phase 3, the RSB will be demonstrated as a very low emissions burner product suitable for continuous operation in a commercial installation. As such, the Phase 3 field demonstration will represent the first installation in which the RSB will be operated continuously with a sub-9 ppm guarantee.

SECTION 1

INTRODUCTION

The Radiation-Stabilized Burner (RSB) was developed to overcome limitations of traditional radiant porous surface burners. Large-scale industrial applications of radiant porous surface burners have been limited because the low surface heat release rate (less than 150,000 Btu/hr-ft^2) of radiant burners can result in large burner sizes and relatively high costs. The development of the RSB in 1994 dramatically reduced the size requirement and cost of the burner element while maintaining the benefits of controlled flame shape and low emissions traditionally found in radiant burners.

The RSB, commercialized under the name Pyromat CSB, is a premixed, semi-radiant, natural gas burner that uses a patented technique to form radiant and blue-flame zones adjacent to each other on the surface of a cylindrical porous metal mat. The burner offers surface heat release rates that are up to ten times higher than traditional radiant burners. References 1 and 2 discuss the development and application of the RSB in more detail. Figure 1-1 is a photograph of a 60 MMBtu/hr Pyromat CSB operating in a 50,000 lb/hr oil field steamer.

Currently the RSB can achieve 30 ppm NO_x at moderate levels of excess air and 9 ppm NO_x at high levels of excess air. The goal of this project is to simultaneously reduce NO_x emissions to sub-9 ppm levels at moderate excess air levels and to extend the application of the RSB into larger multi-burner systems.

Extending the burner into larger boiler applications will require designing larger burner elements and applying multiple burner elements into a single furnace. The size of the largest single burner element manufactured by Alzeta has increased from 62 MMBtu/hr in 1994 to 180 MMBtu/hr in 1997, with the 180 MMBtu/hr single burner element being large enough to provide the total heat requirement of a 150,000 lb/hr boiler. Thus, boilers over 150,000 lb/hr capacity will require multiple burner elements.

The RSB uses a patented technique, combining radiant and blue-flame surface zones, to lower NO_x emissions relative to fully perforated burners. This selectively perforated technique offers several advantages over fully perforated burners:

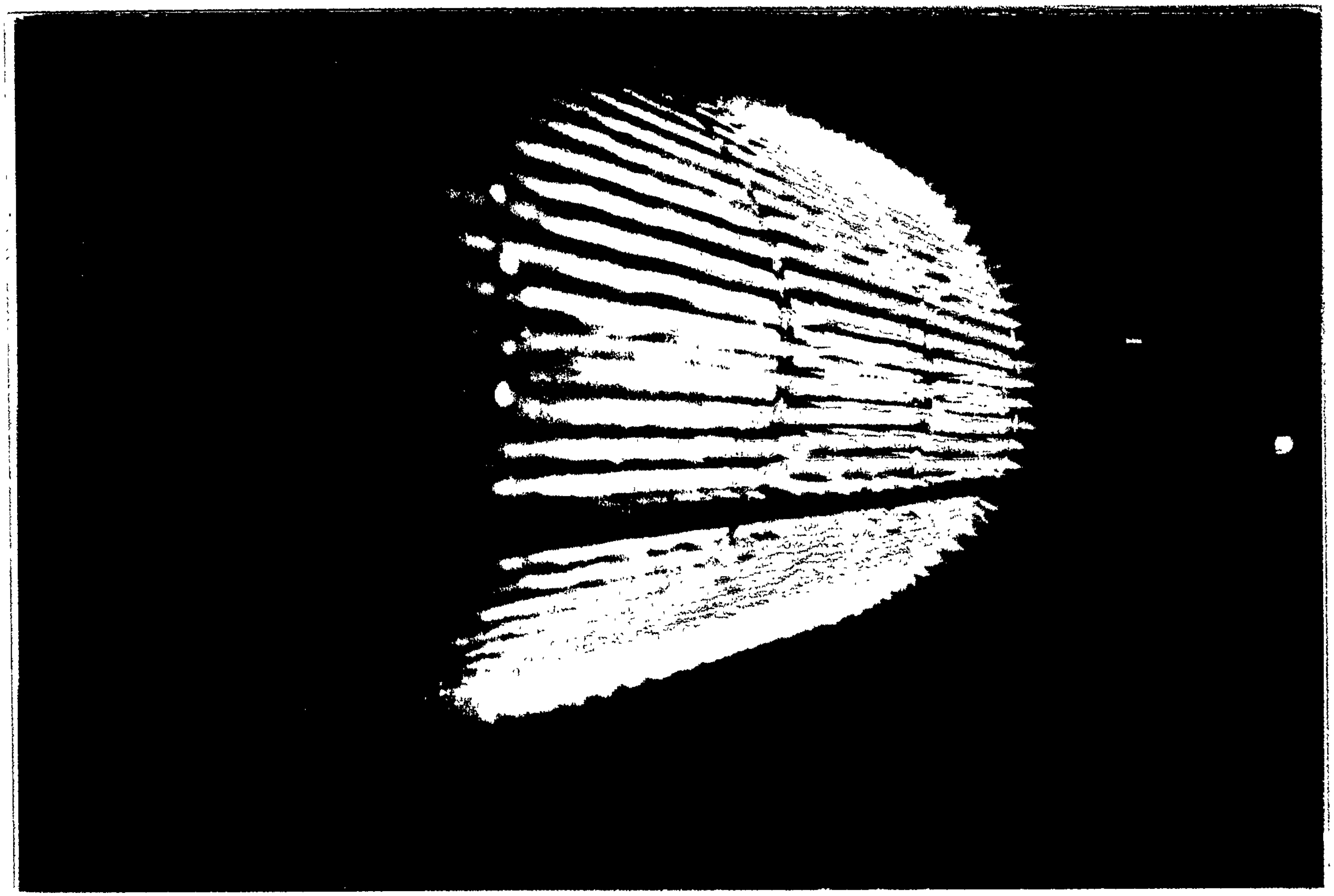

Figure 1-1. Radiant and Blue Flame Zones are Present on the Burner Surface

- Lower NO_x emissions at a fixed excess air level
- Greater flame stability allowing operation with high flue gas recirculation (FGR) levels or low Btu fuels
- Greater operating range without combustion-induced noise

This "striped" perforation pattern is shown in Figure 1-2. Two mechanisms contribute to the NO_x reduction in the RSB. The first mechanism is a more rapid post-flame cooling of each blue-flame zone via the gas phase radiation mechanism. By spreading the flame over a larger surface, the gas layer thickness at any specific location on the burner is thin (relative to that of a conventional burner) and can more rapidly transfer energy to the process.

A second effect is the direct "flue gas recirculation" effect produced by the entrainment of the products of combustion from the adjacent radiant zones into the blue flame. In the radiant zone, the combustion reaction is completed a few millimeters downstream of the burner surface. The combustion products initially serve to stabilize the attachment of the blue flame above the perforated portion of the burner as well as introduce their somewhat lower energy gases into that blue flame. Both of these effects reduce the flame temperature and the corresponding NO_x formation rate.

1.1 PROJECT ORGANIZATION

The project is divided into three phases that allow an orderly scale up of the burner technology. The phases are summarized below:

- **Phase 1: Laboratory Demonstration.** To accomplish this task, Alzeta used a combination of testing and analysis. Laboratory testing was conducted in Alzeta's 3 MMBtu/hr watertube boiler and a 50,000 pound per hour (62 MMBtu/hr) oil field steamer operated by Chevron USA in Bakersfield, California. Alzeta also used its PROF (PRemixed One dimensional Flame) code to verify the experimental NO_x performance of the burner in both the laboratory and the field. Phase 1 laid the ground work for Phases 2 and 3 by defining the market for new and retrofit burners, developing new boiler concepts that take advantage of the RSB, and locating a host site for the Phase 3 demonstration.

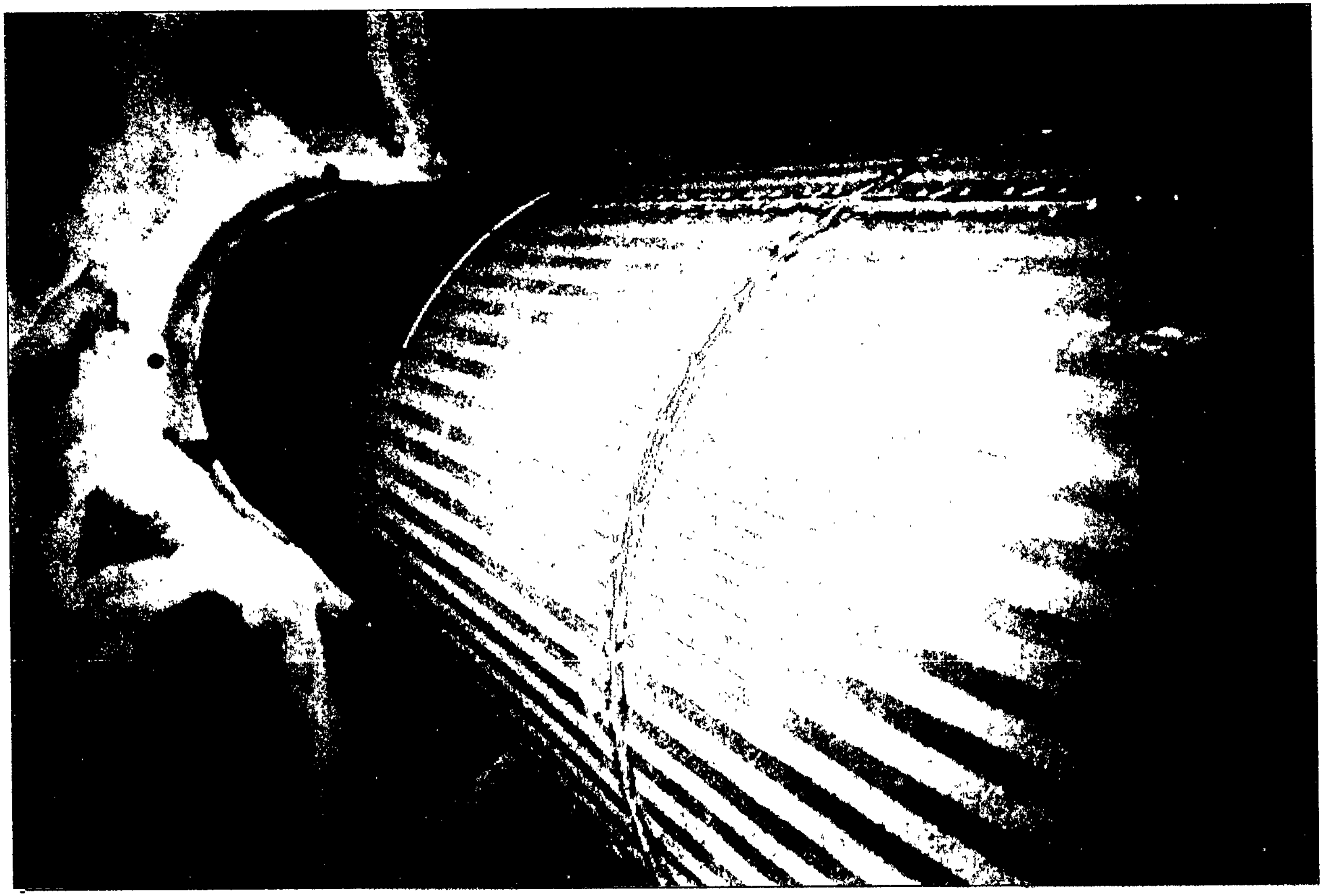

Figure 1-2. RSB Field Test for 62.5 MBtu/hr TEOR Boiler. Striped pattern of perforated and nonperforated metal mat is clearly visible.

- **Phase 2: Concept Validation at Pilot Scale**

  A pilot scale burner system was designed, fabricated, and tested in a single burner application which was a 100,000 lb/hr, Zurn "O" type boiler in San Francisco. Results of the Phase 2 testing are discussed in this report and will be incorporated into the design of the Phase 3 system. Additionally in Phase 2, two new materials were qualified for use with the RSB to further lower the cost to allow a better acceptance in the market.

- **Phase 3: Concept Demonstration**

  A full-scale burner system will be fabricated based on the tests performed in Phase 2. This system will be designed to operate continuously at the project targets of sub-9 ppm NO_x and sub-50 ppm CO (corrected to 3 percent stack oxygen). Certified emissions tests will be performed before and after the host site facility modification to assess the impact of the new technology. The results will be published in a final report and presented at a technical conference.

1.2 NO_x REDUCTION TECHNIQUES

To achieve sub-9 ppm NO_x emissions with the RSB, dramatic reductions in both NO_x emissions and excess air requirements were needed. After reviewing the available literature on NO_x reduction techniques, Alzeta selected the most promising techniques to evaluate both experimentally and analytically and applied them to the existing RSB. The techniques included:

1. High excess air operation to reduce flame temperatures and corresponding thermal NO_x formation rates
2. Improved internal FGR using an optimized selectively perforated pattern on the surface of the metal fiber matrix burner
3. External FGR to reduce flame temperatures and corresponding NO_x formation rates
4. Fuel staging, or the addition of raw fuel downstream of the lean premixed main burner.

5. Combined FGR and fuel staging techniques

The relative advantages and disadvantages of each technique are discussed below.

1.2.1 High Excess Air

Earlier work with the RSB (Reference 1) demonstrated that NO_x emissions below 9 ppm (corrected to 3 percent O_2) are possible at 50 percent excess air. In fact, any desired NO_x emissions level can be achieved by a simple excess air adjustment to provide a low NO_x burner (less than 30 ppm) or a very low NO_x burner (less than 9 ppm). The advantage of this NO_x reduction technique is its simplicity in controls and its high reliability and low maintenance requirements. However, for many industrial processes, the additional excess air needed to reduce the NO_x emissions results in an unacceptable loss in thermal efficiency that has greatly limited its acceptance in the marketplace.

1,2.2 Internal FGR

Internal FGR techniques rely on recirculation of the furnace gases within the radiant section of the furnace into the reaction zone of the burner to reduce the peak flame temperature and corresponding thermal NO_x formation rate. High burner throat velocities are used to induce the recirculation zones.

In contrast, the RSB uses a selectively perforated metal burner surface to induce its own unique internal FGR. However, because the flame is distributed over a large burner surface, less furnace gas is recirculated into each blue-flame zone relative to a diffusion burner which has far greater momentum. Further NO_x reductions may be possible by further optimizing the selectively perforated pattern on the burner surface. This could be achieved by increasing the blue-flame jet velocities to induce more furnace gases. However, the momentum of the blue-flame jet is limited by the low pressure of the premixed reactants available in the burner plenum and the large surface area of the burner. A higher pressure combustion air blower could be used to increase the available premix pressure, but a significant operating cost penalty is incurred.

1.2.3 External FGR

The addition of external flue gas to the main flame is an effective and common technique to reduce peak flame temperatures and corresponding thermal NO_x emissions. In external FGR, a portion of the flue gas downstream of the convection section is pumped to the burner using an existing or auxiliary blower and mixed with the combustion air.

In conventional low NO_x burners, NO_x emissions decrease as the level of FGR increases until the stability limit of the burner is reached. The amount of flue gas recirculated is often limited by burner stability and is usually limited to a maximum of about 20%. Above this level, burner stability is compromised and excessive CO emissions can result. For conventional low NO_x burners, the stability limit is reached well before 9 ppm NO_x emissions are achieved.

The major benefit of using FGR as a NO_x reduction technique on the RSB is that FGR is well understood and accepted, and its effectiveness with the RSB has already been demonstrated in Alzeta's laboratory (See Figure 1-3). Because the RSB is a fully premixed surface combustion burner it can operate at higher levels of FGR without excess CO emissions or stability problems. Thus, external FGR was investigated as a NO_x reduction technique for Phase I.

There are efficiency penalties associated with external FGR. First, the additional flow through the boiler reduces the heat transfer and raises the stack temperature slightly resulting in a lower thermal efficiency. Second, the additional brake horsepower needed to pump the flue gas through a larger primary fan (or a separate smaller fan) increases electrical energy costs to operate the boiler.

While both high excess air operation and external FGR lower thermal efficiency and increase operating costs, external FGR is preferred over additional excess air because some of the energy lost in the stack can be recovered by reintroducing it into the burner as preheated (but vitiated) combustion air.

FGR can be particularly difficult to apply to package boilers because of the relatively large pressure drop built into package boilers to keep the foot print small. Reference 3 discusses the costs associated with FGR in more detail. Because of the operating penalty associated with an FGR solution, a problem that is most pronounced with package boilers, an external FGR solution was pursued as a contingency option at

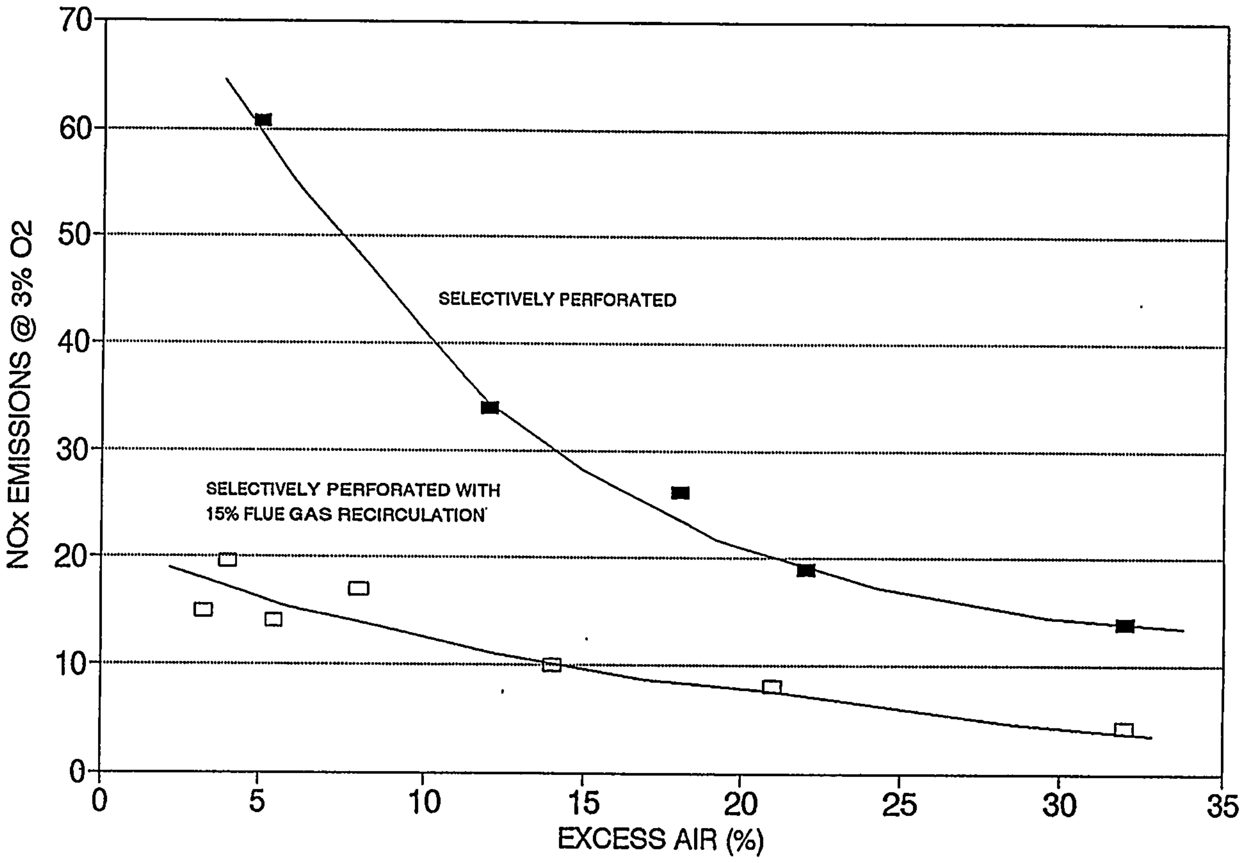

Figure 1-3. Experimental Data Demonstrating the Significant Reduction in NO_x Achieved Simultaneously with Low CO Emissions Using the RSB Concept. Fired Duty -- 1 MMBtu/hr-ft^2

the beginning of Phase 2. Full-scale tests completed at two field sites during Phase 2 have now made external FGR the preferred low-NOx approach with the RSB.

1.2.4 Fuel Staging

Fuel staging is a technique where fuel is introduced into two separate combustion regions, one very lean and the other fuel-rich. This is a common NO_x reduction technique for diffusion burners and can be combined with FGR to further lower NO_x emissions.

In the first stage, the burner is operated very lean (high excess air) to reduce thermal NO_x formation. Once the first stage has radiated a portion of its energy to reduce its flame temperature by a few hundred degrees, the second, fuel-rich stage is introduced. The secondary fuel is introduced downstream of the first stage to consume the unreacted oxygen and is introduced in such a way to induce furnace gases to cool the reaction while not forming excessive CO levels. This type of staging is referred to as fuel staging, because fuel is added in the second stage.

Although fuel staging techniques had not been tried on surface combustion burners at an industrial scale prior to the start of the DOE project, the RSB appeared to be well suited to fuel staging. The RSB had already demonstrated stable, low NO_x operation (less than 10 ppm NO_x) under very lean stoichiometric operation. A secondary, fuel-rich combustion zone could easily be introduced over the surface of the primary burner by using carefully placed fuel nozzles.

The advantage of this technique with the RSB is that the primary burner is a proven ultra-low NO_x burner and is much more stable than conventional burners under very lean conditions. There is no thermal efficiency penalty associated with fuel staging as there is with external FGR. The advantages of fuel staging as a NO_x reduction technique were attractive enough that the technique was investigated as the primary NO_x reduction approach at the start of Phase 2.

1.2.5 Combined FGR and Fuel Staging

To achieve ultra-low NO_x emissions, both FGR and fuel staging can be combined. The recirculated flue gas can be introduced into the primary burner to reduce NO_x emissions in the first stage, or it can be introduced into the second stage to dilute the raw fuel gas. The claimed advantage of adding the recirculated flue gases into the fuel stream rather than the air stream is that a far smaller volume is needed to achieve the same NO_x reduction relative to conventional FGR (References 4 and 5). Also the fuel pressure available at industrial boiler sites is often high enough to induce sufficient amounts of flue gas to achieve very low NO_x emissions. This technique does not increase operating costs from pumping flue gas such as external FGR does. A combination of FGR and staging could be applied to the RSB if fuel staging alone is not sufficient to achieve sub-9 ppm NO_x emissions.

1.2.6 Conclusions

After evaluating these NO_x reduction strategies and reviewing the available low NO_x products on the market, Alzeta selected the fuel staging option as the most likely to achieve the stated project technical goals and achieve market acceptance. However, recognizing that fuel staging alone may not be sufficient in all applications to achieve sub-9 ppm NO_x emissions, alternate NO_x reduction strategies were also investigated. In order of preference, the strategies investigated were:

1. Fuel staging
2. Fuel staging combined with FGR
3. External FGR

Each of these techniques was applied to the RSB and evaluated by Alzeta in Phase 1 of this project. A Zurn package boiler was chosen in San Francisco as a pilot scale commercial site for Phase 2 tests. Fuel staging was selected as the most likely option to achieve Phase 2 goals. After reviewing the initial results of the pilot scale start-up, it was decided to test both fuel staging and FGR in Bakersfield in the same boiler used for testing in Phase 1. The next section discusses the results of these tests in detail.

SECTION 2

LABORATORY AND FIELD TEST RESULTS

This section discusses the results of the tests performed under Phase 2 of this project. As described in the previous sections, during Phase 2 Alzeta tested both fuel staging and FGR in a pilot scale RSB installation to simultaneously lower NO_x emissions and excess air requirements. These tests were conducted as described below.

2.1 TEST FACILITIES

Alzeta used two facilities for the Phase 2 activities. For the initial pilot scale test of the fuel staging concept, we installed a burner in a 125 MMBtu/hr Zurn watertube boiler located in the San Francisco Thermal facility in San Francisco, California. This boiler was retrofitted with a CSB-36-5SO-30FS burner capable of fuel staging. Once it was decided that more tests were needed, and because the San Francisco site is a commercial facility with continuous operating needs, we returned to the Chevron owned facility in Bakersfield which was used in Phase 1 of this project. This was a steam generator originally retrofitted in 1994 with a CSB30-4SO-30 burner. This burner was modified once for the tests in Phase 1 and again for the tests conducted in Phase 2. The following sections briefly describe each facility.

2.1.1 100,000 lb/hr Watertube Boiler

Alzeta sold a Pyromat CSB36-5SO-30FS burner for retrofit into a Zurn "O" type Keystone package boiler to S.F. Thermal in San Francisco, California. S.F. Thermal is a company that sells steam to downtown buildings for general heating and process steam. Information on San Francisco Thermal is presented in Appendix A. The boiler has 7926 ft^2 of heating surface and is capable of producing 100,000 lb/hr of steam at 200 psig. The internal dimensions of the radiant section are 267 inches long by 105 inches wide by 77 inches tall. This provides a heat release rate of about 100,000 Btu/ft^3, which is comparable to the 3 MMBtu/hr laboratory watertube boiler used in Phase 1 of this project. A multi-pass convective section sits on either side of the radiant section. Figure 2-1 illustrates the tube configuration for the Keystone boiler.

The boiler was equipped with two round viewports in the back wall. It was also equipped with pressure gages on the windbox, in the burner, and inside the furnace to assist in tuning the burner and to understand the flow dynamics. A thermocouple was located in the stack for determining efficiency and a pollutant emissions analyzer was inserted into the stack to verify O_2 measurements and to record real-time NO_x and CO measurements.

2.1.2 50,000 lb/hr Oil Field Steam Generator

Alzeta returned to the 50,000 lb/hr oil field steam generator used in Phase 1 of this project for further tests. The steam generator, shown in Figure 2-2, has a radiant section 9.5 feet in diameter by 37 feet long. The watertubes make one pass through the radiant section and are 3 inches in diameter and are arranged parallel to the centerline on 6-inch centers. The units operate at a steam pressure of 1100 psig corresponding to a steam temperature of 550°F.

The steam generator was equipped with a Pyromat CSB30-4SO-30 burner element. The burner was cylindrical and 30 inches in diameter by 120 inches long. This burner was installed originally in 1994, then modified with fuel staging rings on the end in 1995 for Phase 1. For Phase 2 tests, the active burner length was not changed, however staging rings were added between segments and an FGR line was added to connect the exit of the convective section to the inlet of the blower. The staging rings placed between each segment allowed for three independent rows of air or gas to be injected between each segment. This allowed for various staging combinations to be tried to achieve clean mixing and low emissions. No casing gasses were used during this test.

The steam generator was equipped with viewports in the front side and rear walls. Temperature measurements were made from thermocouples located to measure the gas temperature along the radiant section, the exposed and insulated tube wall temperatures and the tube temperature before the convective section. Heat flux was measured using a heat flux probe.

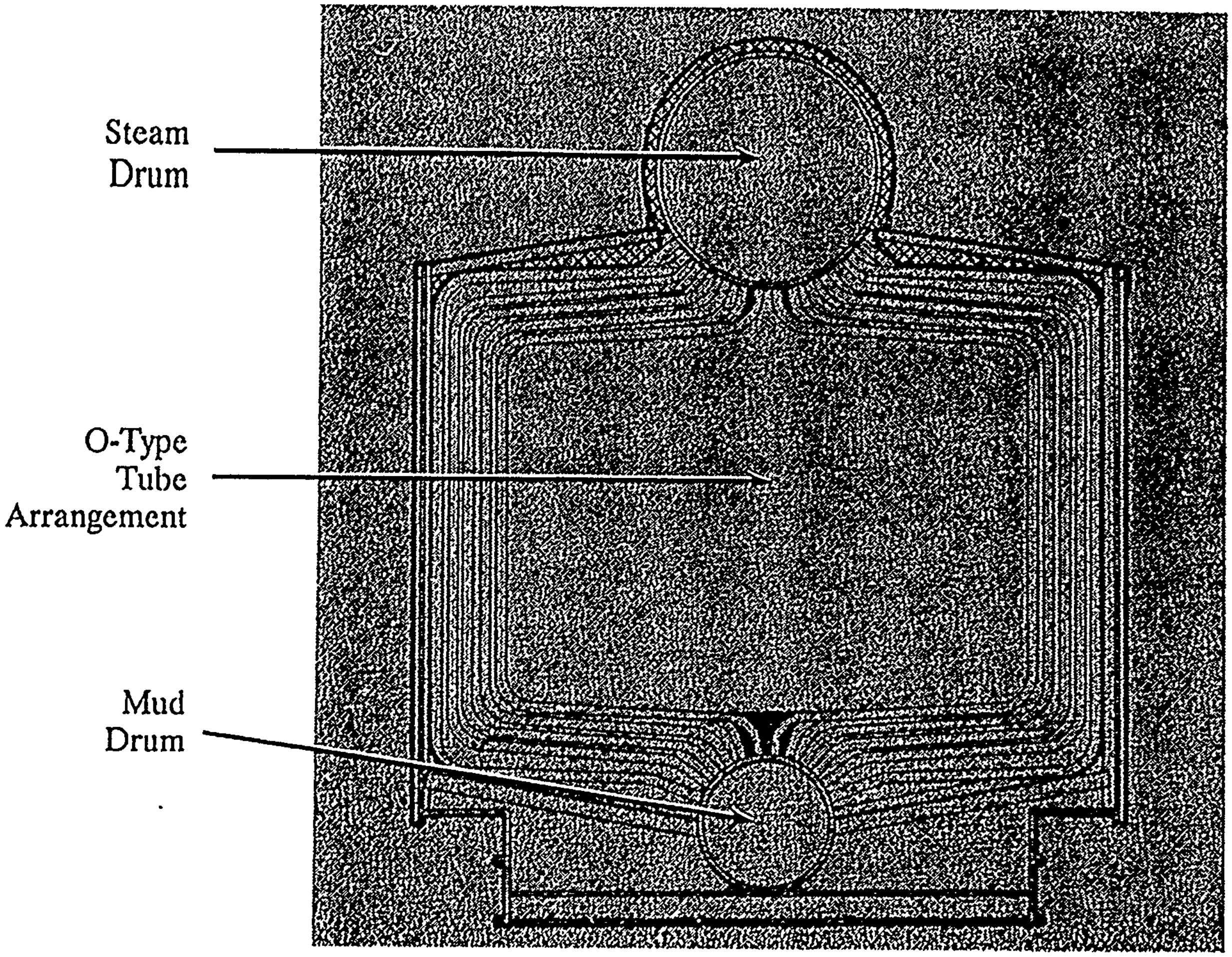

Figure 2-1. Internal Geometry of "O" Type Boiler

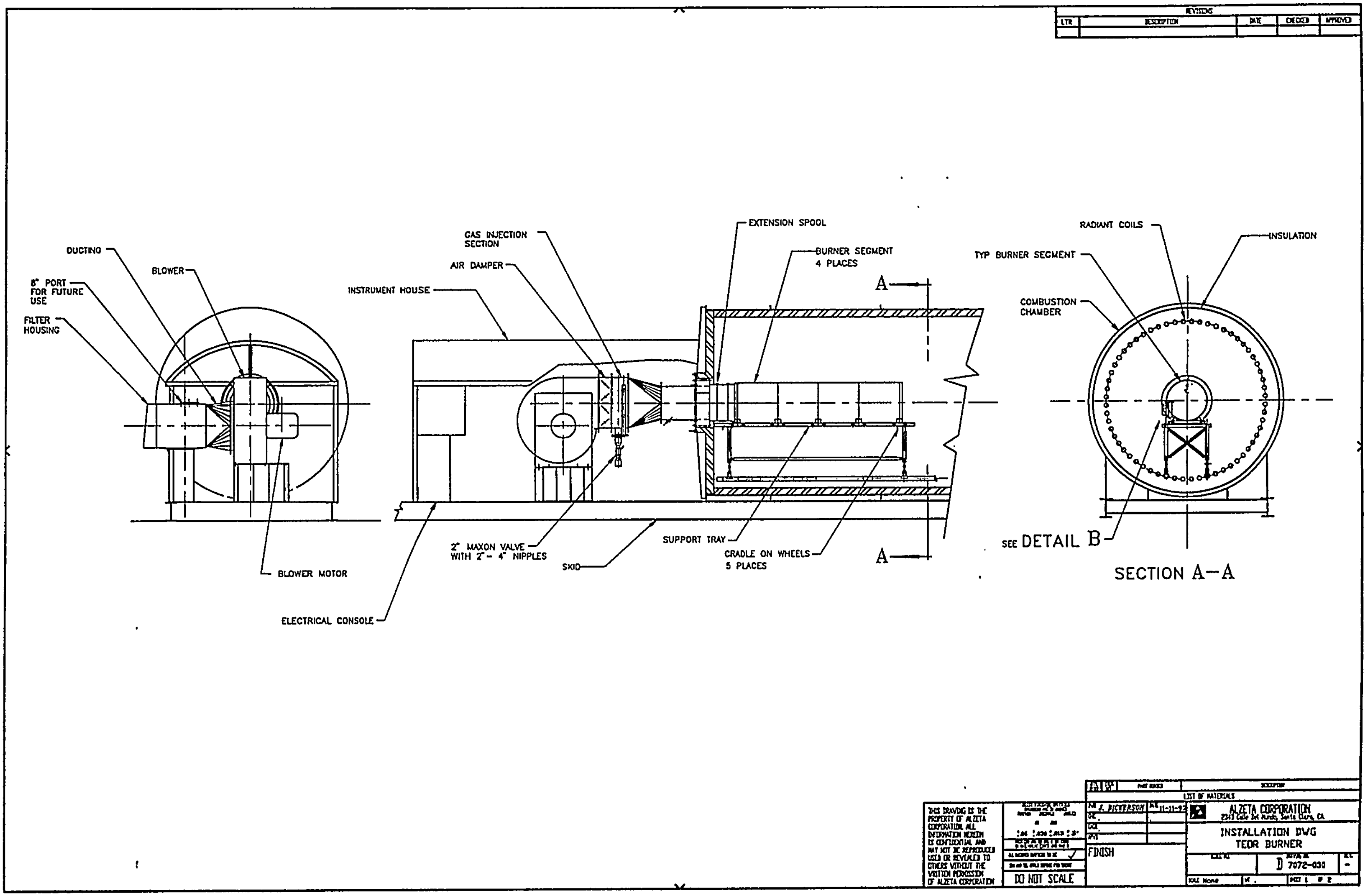

Figure 2-2. Test Configuration of Cymric Field TEOR Steamer

2.2 100,000 LB/HR FUEL STAGING TESTS

The boiler at SF Thermal was equipped with a cylindrical Pyromat CSB36-5SO-30FS burner element. The burner consisted of two parts: the primary RSB type burner and the secondary fuel staging injector. The burner was installed in late September of 1996, with the first tests occurring in the first part of October. A Pyromat CSB36-5SO-30 burner was designed to accommodate the existing furnace and windbox. The dimensions of the primary burner were 30 inches in diameter by 150 inches long. The primary burner was fully modulating and capable of firing to 90 MMBtu/hr at 60 percent excess air. If necessary the primary burner could be over-fired to achieve full nameplate rating of 125 MMBtu/hr without using the secondary fuel injection.

The secondary injector was located on the end of the primary and was capable of delivering the remaining 35 MMBtu/hr of gas that was needed to reach boiler capacity. It was important to properly distribute the staged or secondary fuel into a combustion zone that was hot enough to oxidize all the fuel, but not so hot as to form large amounts of thermal NO_x in the secondary combustion zone. The design of the end mounted secondary injector was derived from the results of the Phase 1 Thermally Enhanced Oil Recovery (TEOR) steam generator tests.

Due to a short testing window given to us by the customer, the injector was designed so that a minimum amount of effort was required to change the injection nozzle configuration if necessary. The initial test points were set for a 30 percent secondary gas staging with contingencies of 25 percent secondary staging, 15 percent secondary staging and then running the primary burner only on excess air. Figure 2-3 illustrates the burner's configuration inside the boiler.

The primary objective of this test was to prove the staging concept in an industrial pilot site. This meant demonstrating that secondary fuel staging could obtain, as a minimum, less than 30 ppm NO_x and less than 200 ppm CO at an excess air level of 15-20 percent. A second objective was to optimize the secondary gas distribution into the secondary flame zone and further define the variables needed to achieve the lowest possible NO_x, with sub-9 ppm NO_x emissions being the target of parametric tests prior to final system tuning. A third objective was to demonstrate the Pyromat RSB burner as a cost effective solution when compared to other low NO_x burners on the

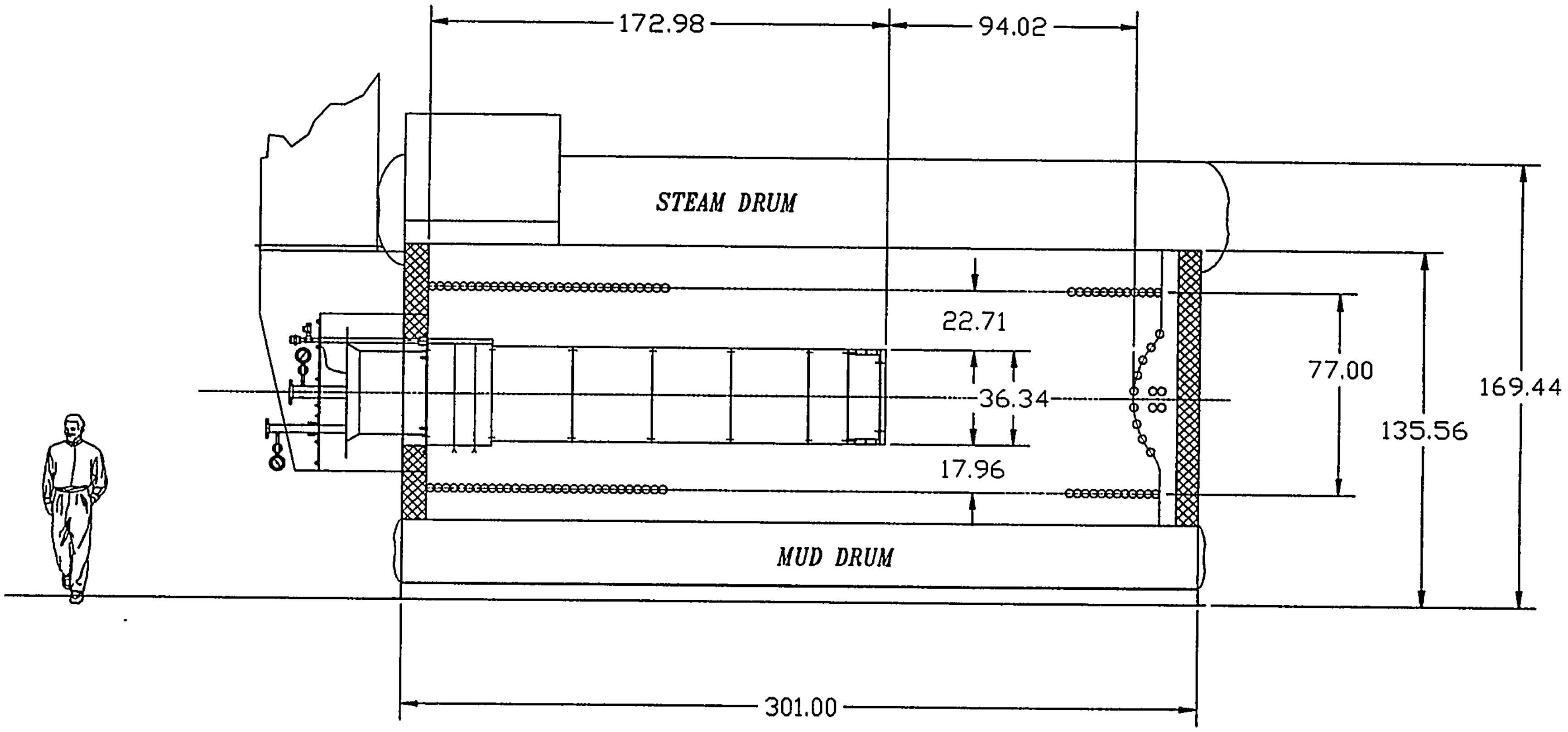

Figure 2-3. Burner Configuration Inside SF Thermal Boiler

market. While the actual price may be somewhat higher, it was important to demonstrate that operating costs would be lower.

In order to test burner performance, the surface combustion burner was first operated at a reduced load under very lean conditions where very little NO_x is formed. (We had previously demonstrated NO_x emissions less than 10 ppm at 8 percent stack oxygen.) Then enough raw gas was to be distributed around the end of the burner element to make up the additional capacity and complete the reaction so that the boiler was operating at a more desirable 3-4 percent stack oxygen.

When the primary burner was lit, one side of the burner had some pulsations, which is an indicator of poor mixing. This was largely due to the use of a windbox on this boiler and is a common sight on package boilers of this type, but something Alzeta had little design experience with. Tests were completed taking into consideration the mixing problem, and plans were made to modify the windbox entrance for better mixing of the gas and air.

Figure 2-4 compares the results of the "primary only" tests with the results of the 1994 TEOR steamer data. In Figure 2-4, NO_x emissions are plotted as a function of stack oxygen. At the low end of the firing rate, the excess air was adjusted to maintain the emissions under 30 ppm NO_x. This is the reason that the curve for the unstaged data flattens out. It can be seen from the two sets of data that the unstaged performance is very similar to that found at the 1994 site. The curve is shifted slightly toward higher excess air due to the different thermal conditions. This difference is very noticeable for the staged data. Achieving the low NO_x numbers at SF Thermal was not possible in the 3-4 percent range of stack oxygen.

Another factor that probably contributed to the higher NO_x values at SF Thermal was the higher volumetric heat release rate in this boiler. Figure 2-5 shows the NO_x trends as firing rate is varied on a plot of NO_x versus percent stack oxygen (dry). The trend shows that as the firing rate was increased the amount of NO_x generated also increased. Previous Alzeta data had shown that while NO_x emissions increased with firing rate when using the RSB, the increase was usually not significant. However, Figure 2-5 shows that the trend increases enough to warrant attention.

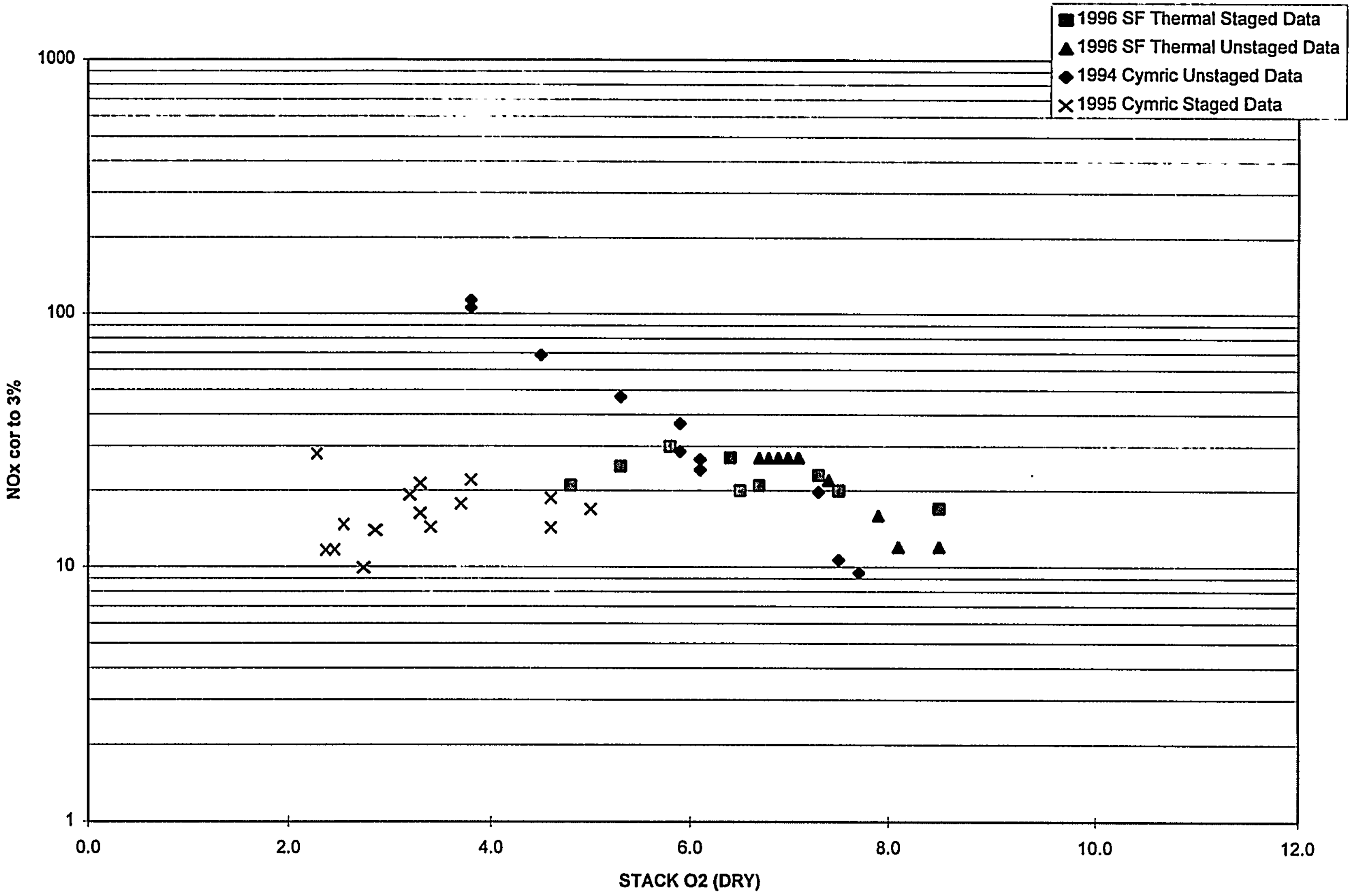

Figure 2-4. Plot of NOx Versus Percent Stack Oxygen (Dry)

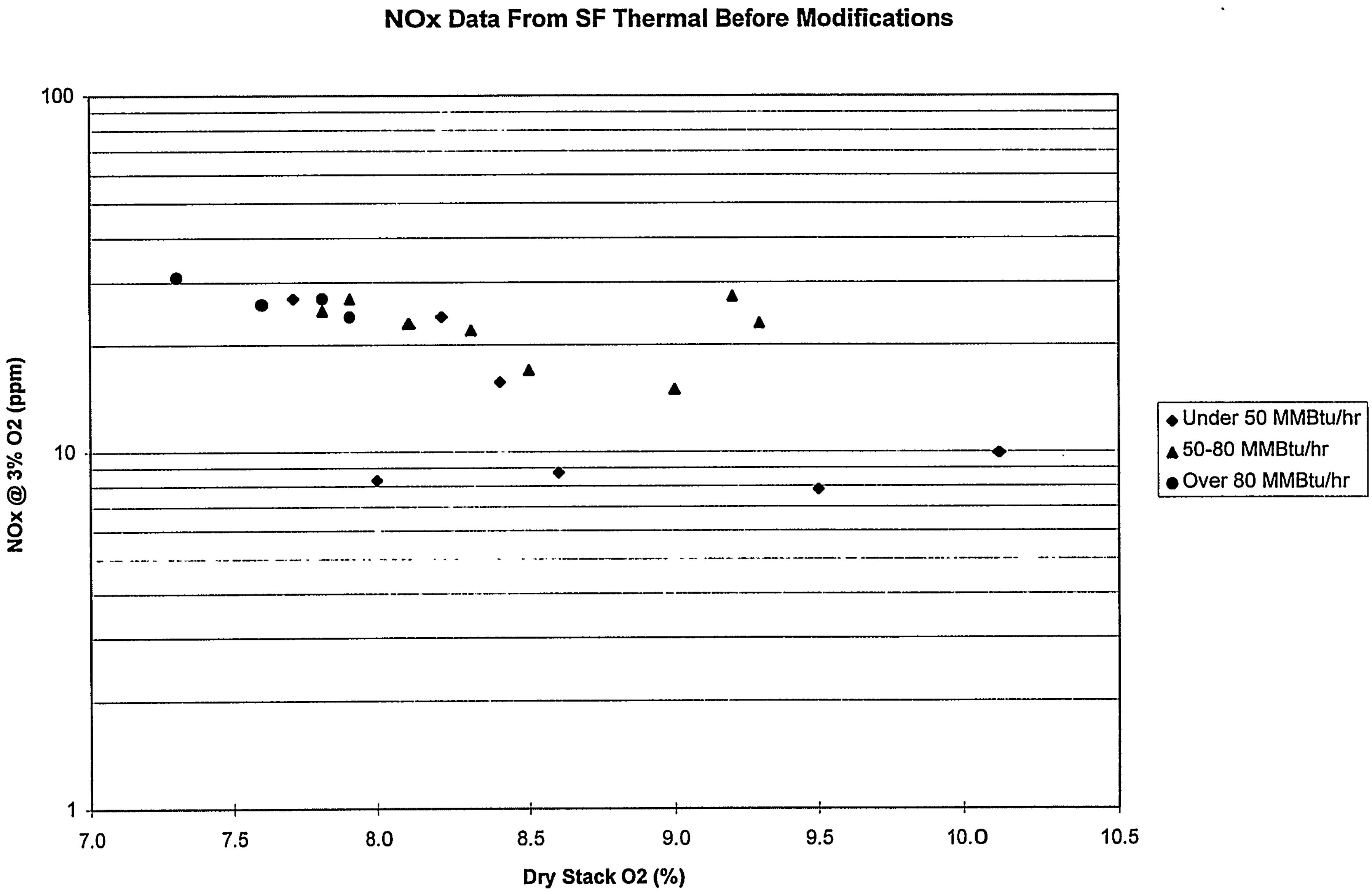

Figure 2-5. Trend of Firing Rate on NOx as Plotted Against Percent Stack Oxygen (Dry)

While the staging data showed trends similar to the 1994 staged data, the staging at SF Thermal came at the cost of creating a great deal of soot. Enough soot was created that the operators would not let the staging tests continue for more than a minute or two at a time. The soot was generated due to the hot compact burner environment and the short burnout region after the burner. Figure 2-6 compares CO generated to stack oxygen. Since the flame length went up with the percent staged gas, large amounts of CO were created as the percent staged gas was increased. The largest percent of gas that could be staged was around 10 percent. This did not meet Alzeta's minimum objectives for this customer.

During the modifications to resolve the primary burner mixing problems, the secondary staging hardware was removed from the burner. This was done so that there was not a need for continuous cooling of the metal work while the burner was operating during the winter months. S.F. Thermal was willing to let us wait until the summer of 1997 to improve their efficiency. They have only short downtimes during the winter months since they provide the steam to heat many downtown San Francisco offices. Figure 2-6 shows how improving the mixing also reduced the CO generation. While reducing CO generation of the primary stage would lower the primary and secondary combined numbers, it would not reduce the CO emissions enough to stage significantly larger percentages of secondary fuel.

Our work showed that thermal environment and the secondary fuel distribution are critical to the emissions performance of the burner. Proper distribution results in low NO_x and CO emissions and a tight flame envelope with little chance of flame impingement. Improper distribution can result in flame impingement, excessive CO formation or even sooting. The operational envelope for fuel staging is defined on the low end by turndown and distribution, and on the high end by the thermal and geometrical conditions. More work is needed in this area to define the temperature operating parameters available for secondary staging.

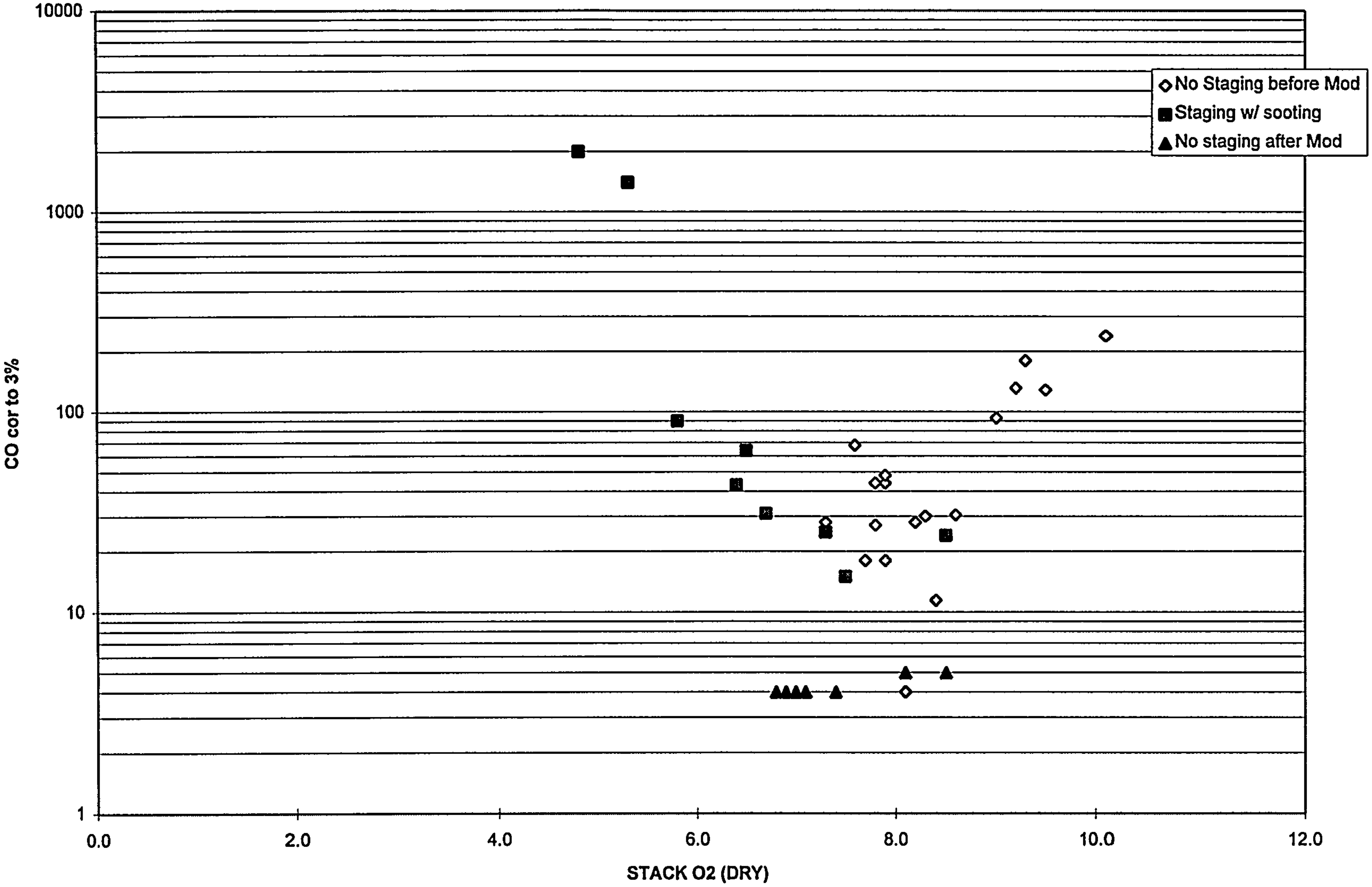

Figure 2-6. Plot Of CO Versus Percent Stack Oxygen (Dry)

2.3 50,000 LB/HR STEAMER FUEL STAGING/FGR TESTS

The Chevron steam generator was equipped with the CSB Pyromat burner, fuel staging rings and Flue Gas Recirculation (FGR) piping. The burner was a Pyromat CSB30-4SO-30 that had been used in earlier tests, but which was modified for the Phase 2 work. The end plate on this burner was replaced with an end-cone which reduced the unfired area on the downstream end of the burner. The burner was only capable of firing to 35 MMBtu/hr due to fan limitations and a higher pressure drop across the burner. Nameplate rating for the steamer is 62.5MMBtu/hr. In order to improve mixing and distribution, the staging rings were moved from the end plate to between each of the segments. Each staging location contained three compact rings of nozzles capable of staging air or natural gas. This would allow for firing one ring of fuel and one or two rings of air, or any other combination, to improve the mixing and emissions. The FGR line was run from just above the convection section to the inlet of the blower. The addition of the FGR line allowed for testing FGR and combinations of staging and FGR.

The tests were originally scheduled to start in the month of February, 1997, but were delayed until July due to other construction taking place at the Chevron facility. During the period between planned and actual testing, Alzeta conducted some small scale staging and FGR tests in conjunction with the California Energy Commission (CEC). The results of these smaller scale tests are relevant to the RSB project and are summarized here. A CSB-8SO-15 burner with a diameter of 8 inches and a length of 15 inches was modified with a fuel/air staging end plate. The endplate was originally designed to stage off the end plate on the downstream end of the burner, similar to the original Cymric Fields tests in 1995. This burner was placed inside a PVI firetube boiler with a radiant section diameter of 24 inches. Initial tests were performed using the gas and air rings to stage fuel. Tests were also performed using FGR.

Figure 2-7 presents results from the tests with the 8 inch diameter burner, previous tests, and latter Cymric Field staging data in terms of NO_x versus excess air. The data show that when the NO_x emissions are lowest, then soot is being generated. This sooting is attributed to poor mixing. When the mixing is improved and the flame is clean, then the NO_x emissions are above 30 ppm (corrected to 3% O_2). This tradeoff illustrates the difficulties that have been encountered in our

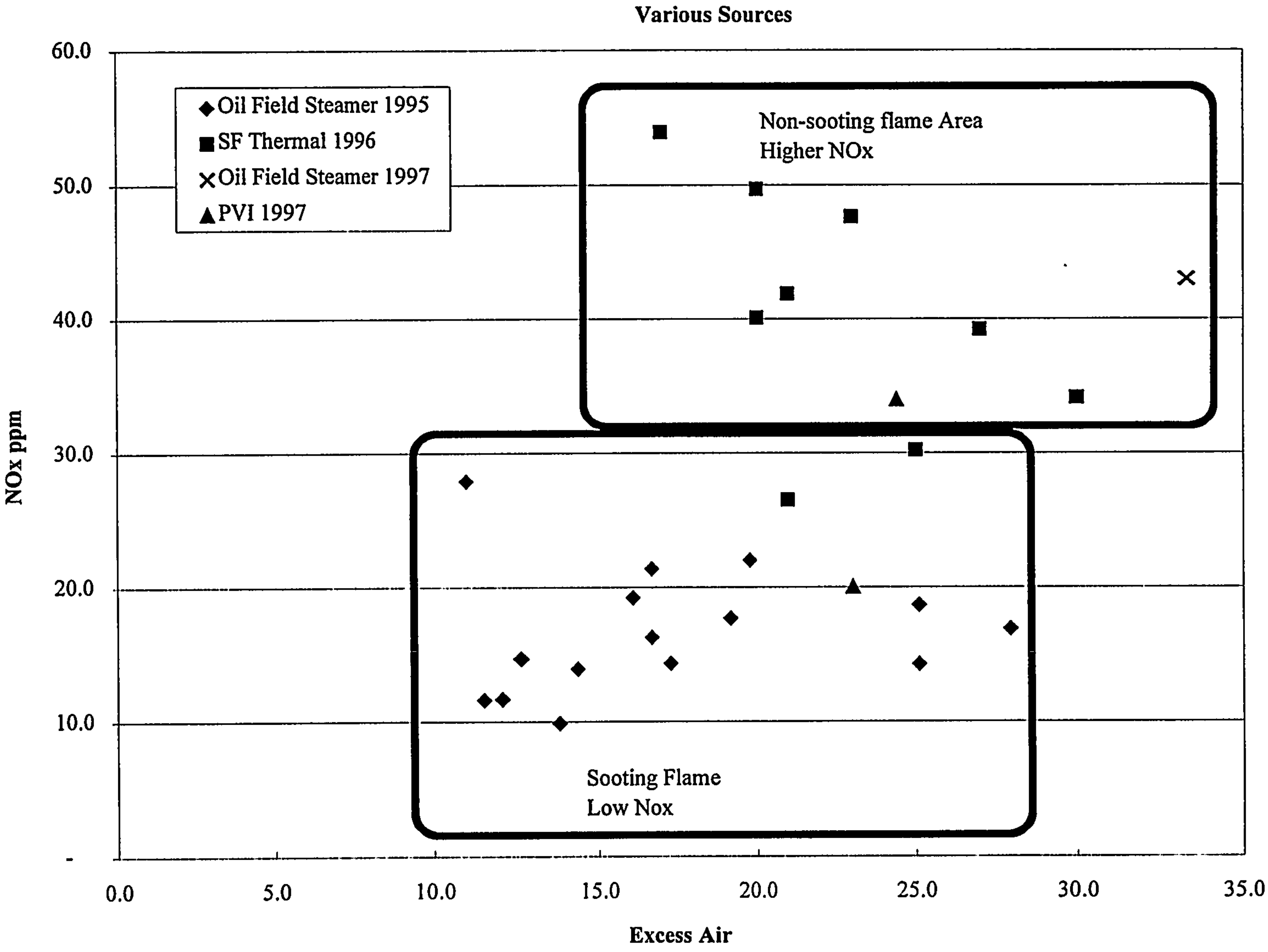

Figure 2-7. Staging Data

tests of fuel staging as a sub-9 ppm NO_x technology. This, and control problems associated with modulating a fuel-staged system, led us to believe that a system utilizing some external FGR would be the more cost effective solution for industrial boilers.

When Chevron completed their construction in June and we were allowed to test in early July, it was decided that the FGR tests should be run first. This decision was made because we had less RSB data with FGR, and also because these tests were the most involved from a control standpoint.

The results of the Cymric FGR tests are shown in Figure 2-8. The FGR data points illustrate the same trend line slope as the excess air data points, due to NO_x formation with the RSB burner being a function of dilution gas, regardless of whether it is air or flue gas. This is true, to some extent, with most burners, however the RSB burner is a surface burner with the added advantage of a broader stability range.

There is a slight shift between the excess air data for Cymric and for the commercial RSB applications because the TEOR steamer radiant section is much larger and therefore cooler than a commercial package boiler. Since NO_x formation is a function of total dilution and the thermal environment of the boiler, the same shift would be present for the FGR trend line. This shift would increase the total dilution (with combined air and FGR) required to meet specific NO_x emissions objectives, but would not be significant enough to change our project objectives.

Figure 2-9 shows the NO_x emissions for specific values of excess air. In Figure 2-9, the region where excess air is below 15% is labeled "high efficiency," and the region where NO_x levels are below 9 ppm is labeled "low emissions." The intersection of these two regions, shaded in gray, is the high efficiency, low emissions operating region. Thus the use of FGR, combined with the other properties of the Alzeta burner, give a boiler burner that is high-efficiency, low emissions and stable over a wide operating range.

Staging tests were conducted after the FGR tests. With the staging rings we were able to test various combinations of air and gas staging. The results of the staging tests are included in Figure 2-7 along with the small scale tests mentioned earlier. The results show, for the various configurations tested to date, low NO_x emissions with sooty flames and clean flames with high NO_x emissions. The sooty

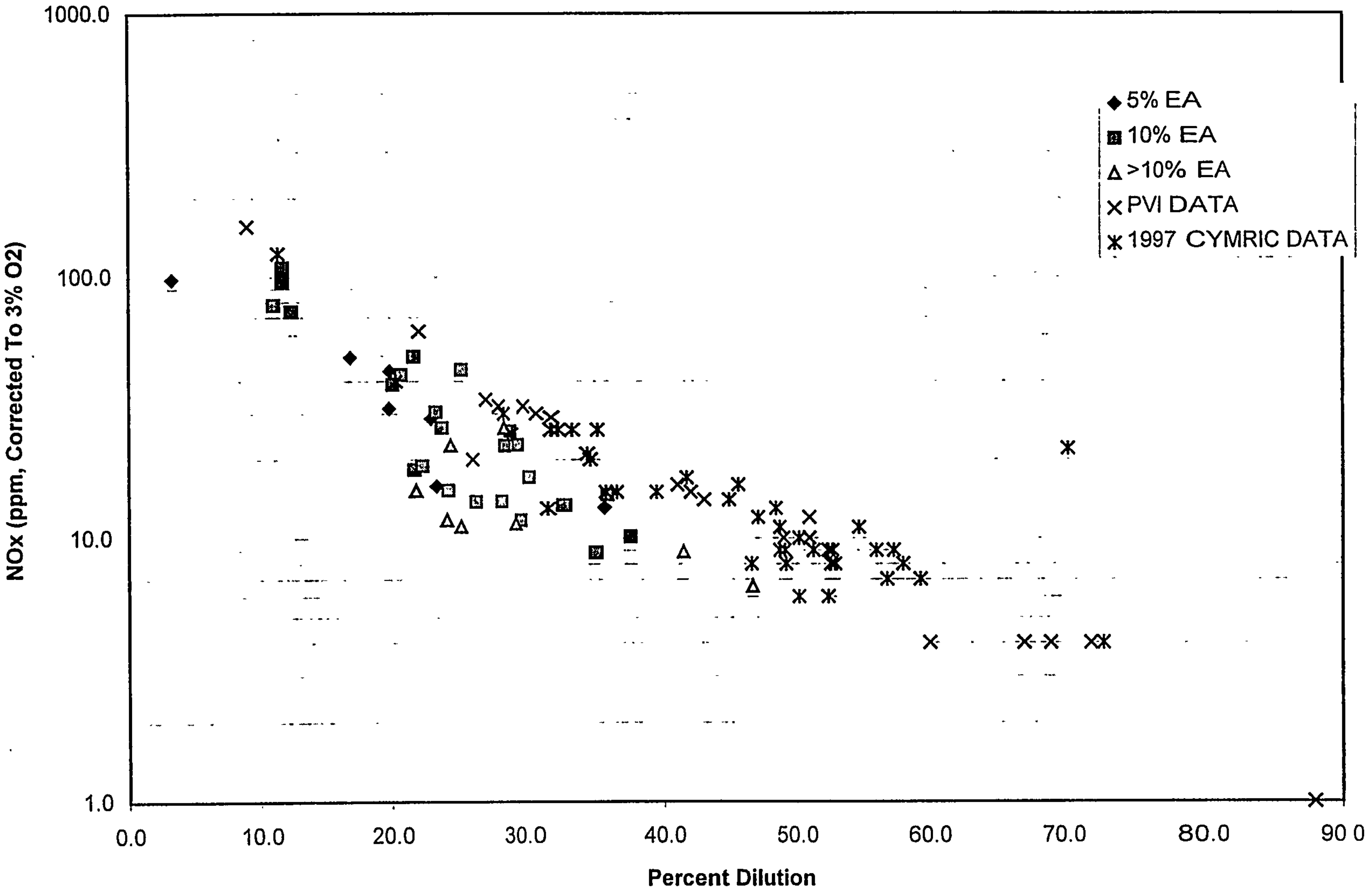

Figure 2-8. NO_x Emissions with Flue Gas and Air Dilution

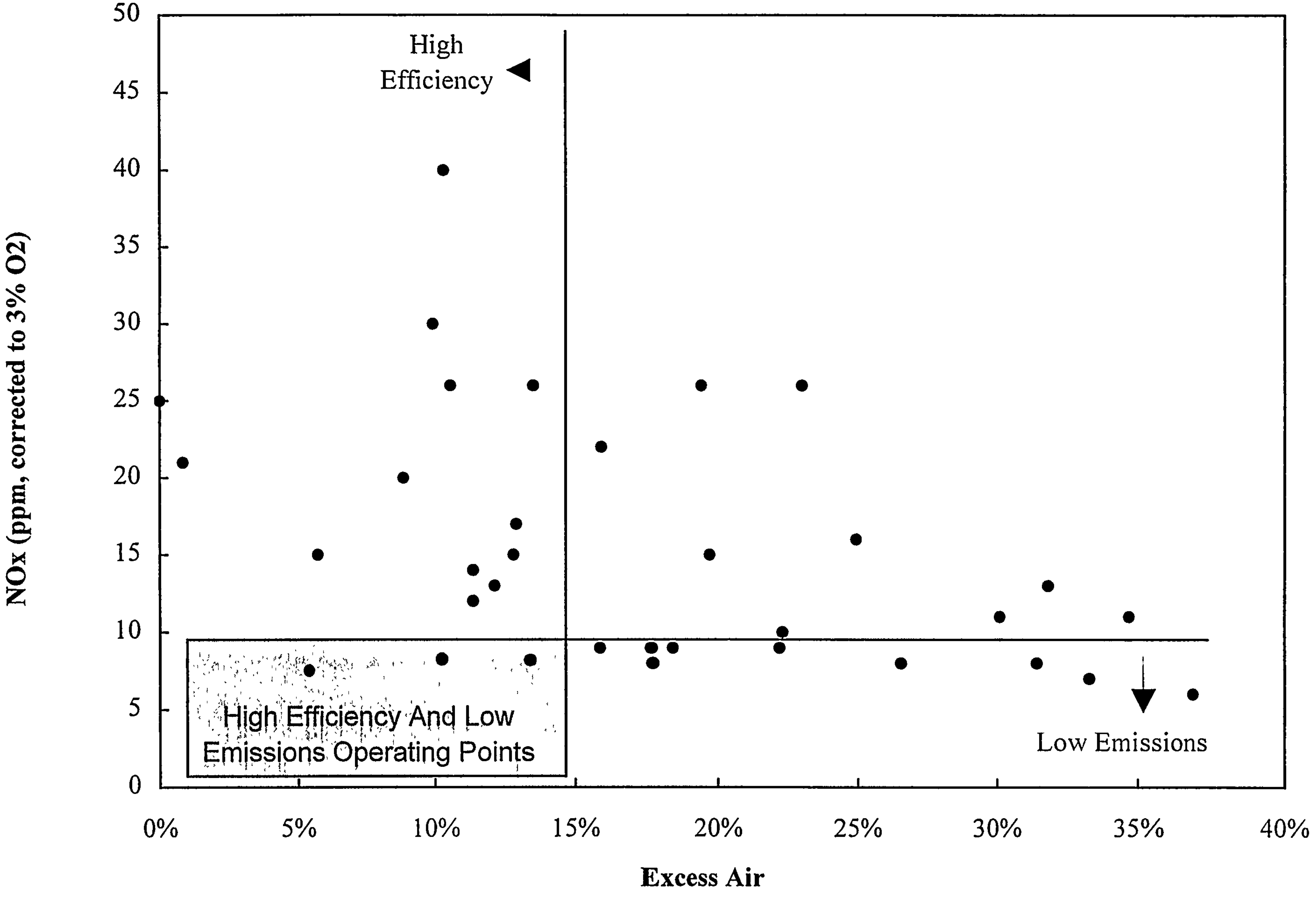

Figure 2-9. NO$_x$ vs. Excess Air

flame is unacceptable because soot gathers on the tubes, lowering the efficiency of the boiler. These results showed that the difficulty in getting low emissions simultaneously with complete burnout, along with the difficulty in mixing with full burner modulation, meant that fuel staging with the RSB was not currently a viable option. A test report summarizing the Alzeta tests at Cymric is presented as Appendix B.

Temperature data and heat flux data collected during the Cymric tests were supplied to the B&W Power Generation Group in Barberton, Ohio for analysis. The purpose of supplying B&W with data was to allow them to evaluate the impact of an extended surface burner on boiler performance. Their intent was to analyze the benefits of using the RSB in a boiler configuration that has reduced firebox dimensions and additional tube surface in the boiler firebox.

By using Computational Fluid Dynamics (CFD) codes, B&W was able to correlate their model to heat flux and temperature data from Cymric, and also to predictions from Alzeta plug flow and gas phase emissivity models. The B&W modeling was useful in verifying our models, and did provide some insight into the effects of changing boiler firebox dimensions and adding additional heat transfer surface to a boiler. The two part B&W report is included in this report as Appendix C.

2.4 CONCLUSIONS

In Phase 2 of this project, we attempted to prove the performance of the staged fuel technology in pilot scale installations located in San Francisco, California and Bakersfield, California. The goal of these tests was to prove that the staging concept would be a viable new RSB technology offering sub-9 ppm NO_x emissions. We were unsuccessful with the staging technology due in part to unusual thermal conditions in the package boiler chosen. The boiler chosen had a firebox that was more compact then most package boilers in its size range. From this demonstration, it was learned that compact and high temperature environments have an effect on the amount of staging that can be introduced. For some package boilers it may be necessary to use FGR or a combination of staging and FGR. Additional tests at the Bakersfield site confirmed these findings.

We were able to prove that the RSB could be used commercially to attain sub-30 NO_x emissions and even sub-9 NO_x using solely high excess air or FGR. We were able to prove that the use of FGR, combined with the other properties of the Alzeta burner, provides a boiler burner that has high-efficiency, low emissions, and is stable over a wide operating range with simple controls. Because there are already a large number of burners that use FGR and the limitations of FGR are well documented, other benefits of the RSB (such as more compact firebox design) must be exploited in order to achieve commercial success. We are presently working with B&W to incorporate these boiler changes for the Phase 3 demonstration.

SECTION 3

DESIGN IMPROVEMENTS

During Phase 2 of this project many design improvements were made to improve performance or reduce costs. While design changes are part of the design of any new product, there were a few improvements that are worthwhile noting. Section 3.1 covers the changes made in the burner pad fastening technique and discusses new burner pad options. Section 3.2 discusses the improvements to the air/fuel mixer discussed in Section 2 of this report. Section 3.3 covers the design of the conical end cap and Section 3.4 covers some miscellaneous yet significant control changes.

3.1 FASTENING IMPROVEMENTS

The fastening technique that is used to hold the burner pad to the metal frame of the RSB is a simple clip and rivet technique. Figure 3-1 shows the basic components of the first design for pad fastening. The first configuration had few problems, but due to the cost of the pad and a labor intensive mounting method, a configuration was desired which reduced the number of clips and inactive surface. Figure 3-2 shows the second generation mounting technique. The pad was overlapped at the axial seams to cut down on the inactive area of the pad and the number of clips and rivets being used. This configuration also involved an easier manufacturing process. After the installation at S.F. Thermal it was noticed that the axial seams appeared to be hotter than the circumferential clips.

The third and final configuration is shown in Figure 3-3. After some investigation it was decided that the flange which hung directly into the cross-flow premix stream (in the original design configuration) was contributing significantly to the convection cooling of the axial seams. In the third configuration, a flange extends through the support screen into the cross-flow premix stream. As a final precaution, the metal used to make the clip under the rivet was upgraded from a standard stainless steel to a more resistant alloy. This alloy was only available in certain sizes so the thickness was increased slightly. This required that new rivets be selected for the connection along the axial seams. Finally, there was a need to find a means of manufacturing the support structure more cost effectively. This was also accomplished with the design shown. The edges of all three pieces making up the seam of the support structure are configured so that the seam can be spot welded in a one step process. There is less setup time involved with the spot welded seam and the row of spot welds is cheaper to produce than having the seam hand welded using a Tungsten Inert Gas (TIG) type welding process.

One of the most costly, and proprietary, components of the Alzeta burner is the porous metal burner surface. Alzeta identified promising methods of reducing burner costs in Phase 1, and was able to evaluate these new methods at small scale during the past year. During Phase 2 Alzeta began testing 2 new burner materials at burner sizes ranging from 2 MMBtu/hr to 6 MMBtu/hr. The results of these tests have been successful enough to warrant further testing at larger scale, with the ultimate objective being to reduce burner costs for all burner sizes.

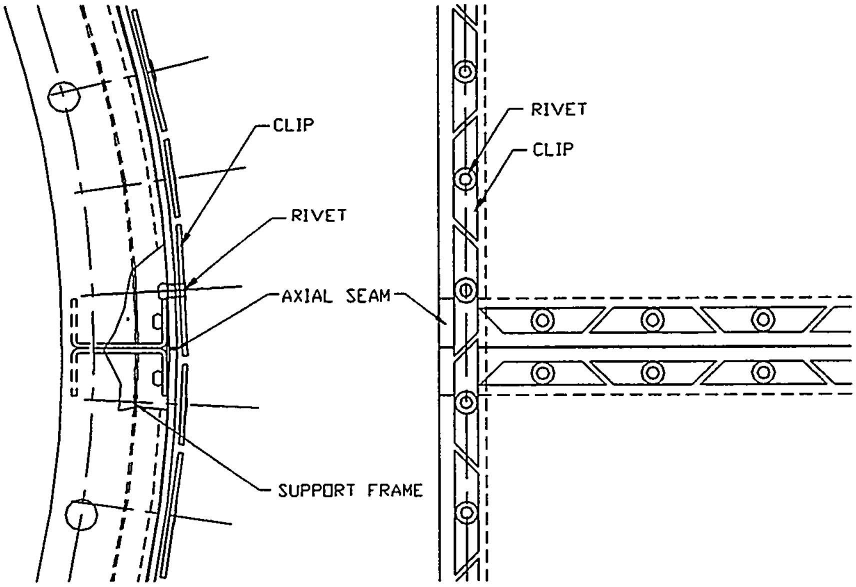

Figure 3-1: Original Design Configuration of Axial Seams of RSB Burner

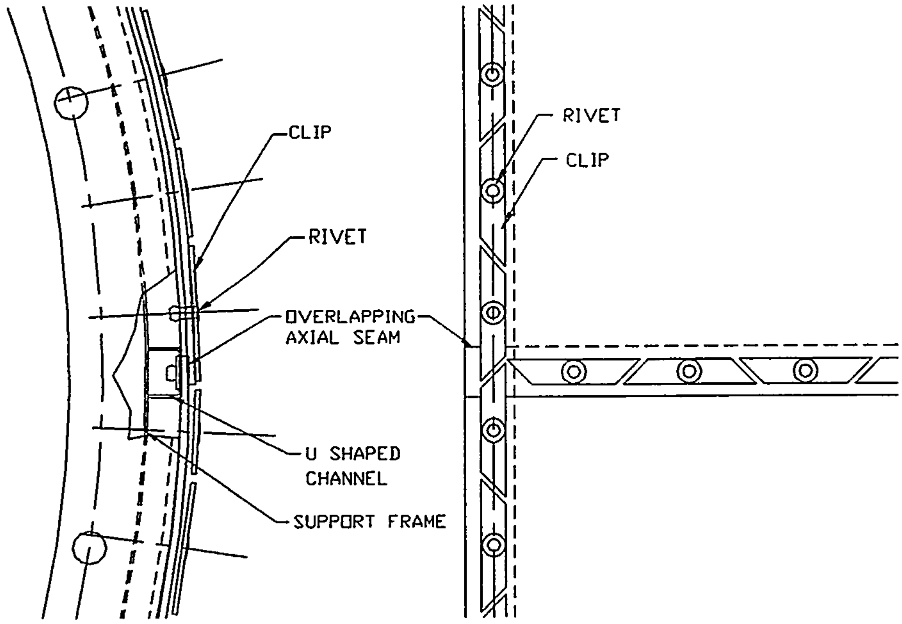

Figure 3-2: Second Design Configuration of Axial Seams of RSB Burner.

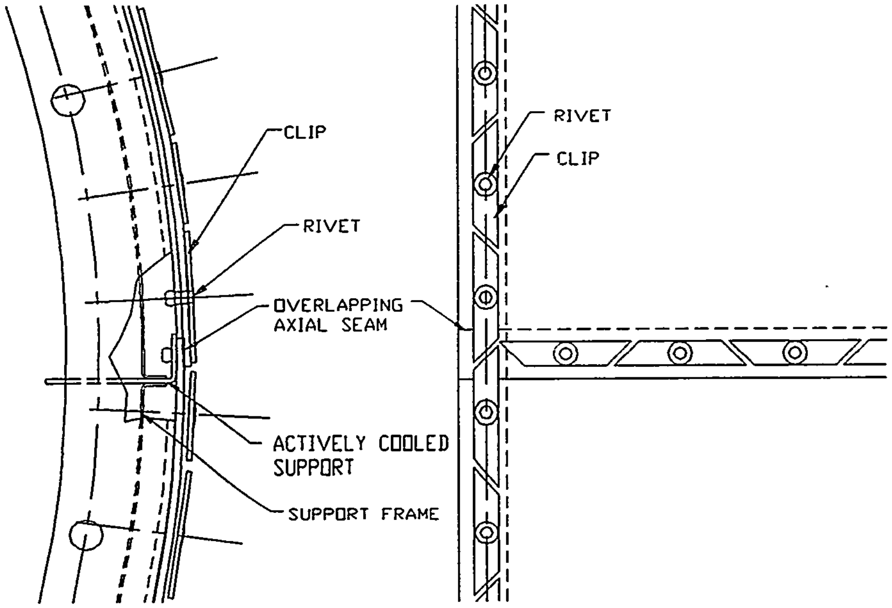

Figure 3-3: Final Design Configuration of Axial Seams of RSB Burner.

3.2 FUEL AIR MIXER

The fuel/air mixer is located just downstream of the gas injection spool. It mixes the gas with air using the turn, length and some mixing tabs. The original mixer is shown in Figure 3-4. Its gas injection spool was simply a pipe in the center of the mixer that injected the gas outward and relied on a short length and tabs to mix the gas and air. As mentioned in Section 2, this mixer design, which was originally used at S.F. Thermal, had to be redesigned because the flame was oscillating due to poor mixing.

The new mixer is shown in Figure 3-5. While there are other means of mixing the gas in short distances, the main objective of this design was to mix the gas thoroughly without suffering more pressure loss. If too much pressure was lost in mixing the gas, then the burner could not reach capacity. The new design involved redesigning the gas air mixer so that the gas was introduced into the annular part of the mixing spool before it takes the turn. This allows for the gas to be injected uniformly while the air is spread across a larger area. The air fuel mixture then takes the turn into the center of the mixer, down the length of the mixer and across the tabs before it hits the burner. This new design assures that the air and fuel mix very well before combustion.

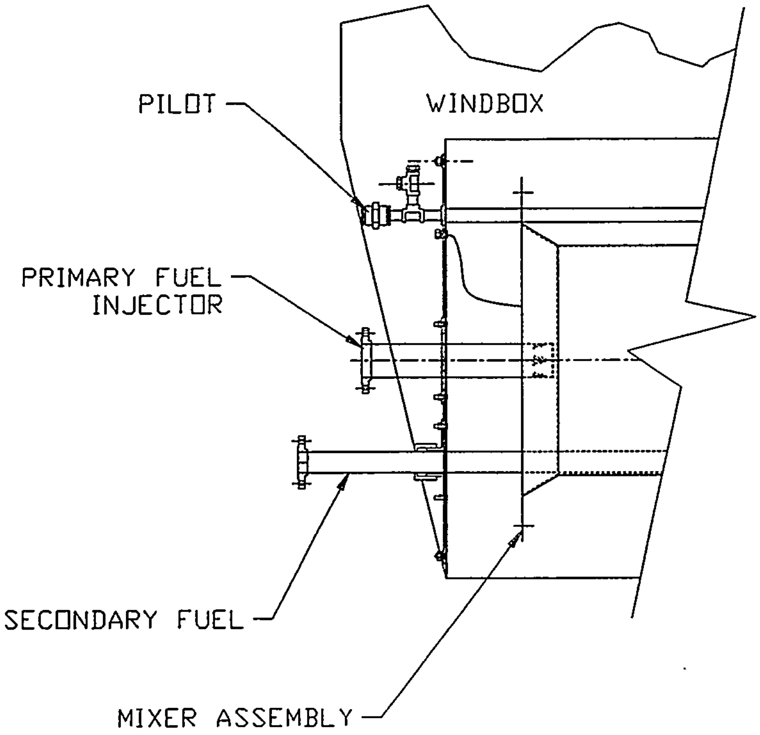

Figure 3-4: Old Air/Fuel Mixer Design

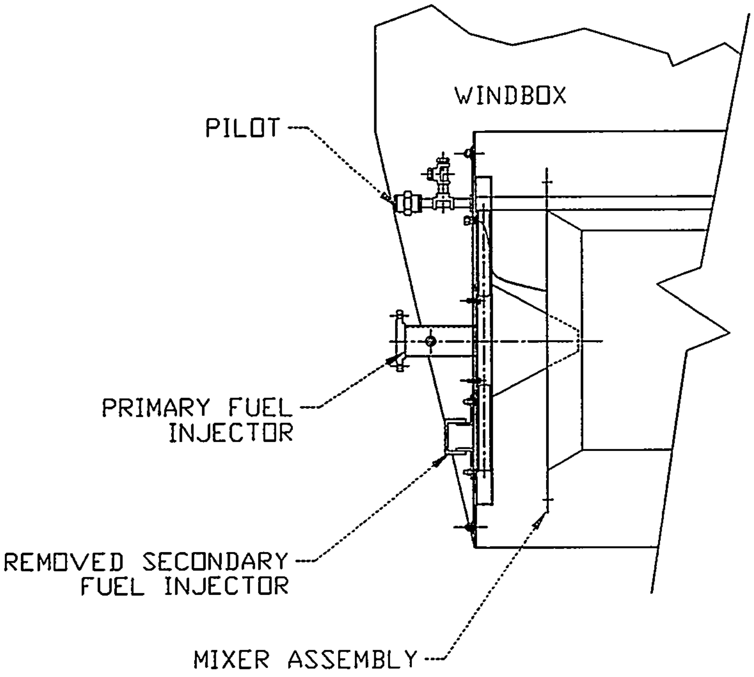

Figure 3-5: New Fuel/Air Mixer Design

3.3 CONICAL END ENCLOSURE

The conical end enclosure was designed to accomplish two purposes. The primary purpose of the end cone is to reduce the size of the inactive end enclosure. The cap which seals the end of the burner is basically an insulated plate which caps the end of the burner. If the cap is too large then it becomes difficult to insulate properly. It is impractical to make the flat plate an active part of the burner due to the flow dynamics of the cylindrical burner. The design that was adopted is shown in Figure 3-6. The conical end adds to the active surface area and reduces the end diameter of the burner. This allows a smaller end cap to be installed. The smaller end cap means less inactive material inside the furnace. Active surface of the burner is cooled by the gases flowing through the active surface. Inactive surfaces rely on insulation and internal cooling. The end cap is the place where the internal flow nears zero velocity, which means there is little internal cooling.

The second purpose of the conical end enclosure is to soften the flow dynamics of the cylindrical burner. The flow down the center of the burner comes to zero velocity at the end of the burner and is forced out the sides of the burner. The effect is that the gases are “slammed” into the end cap of the burner. This changes the flow at the end of the burner when compared to the front of the burner. This effect is more noticeable in larger diameter burners. By reducing the diameter through a conical section the “slamming” effect is reduced.

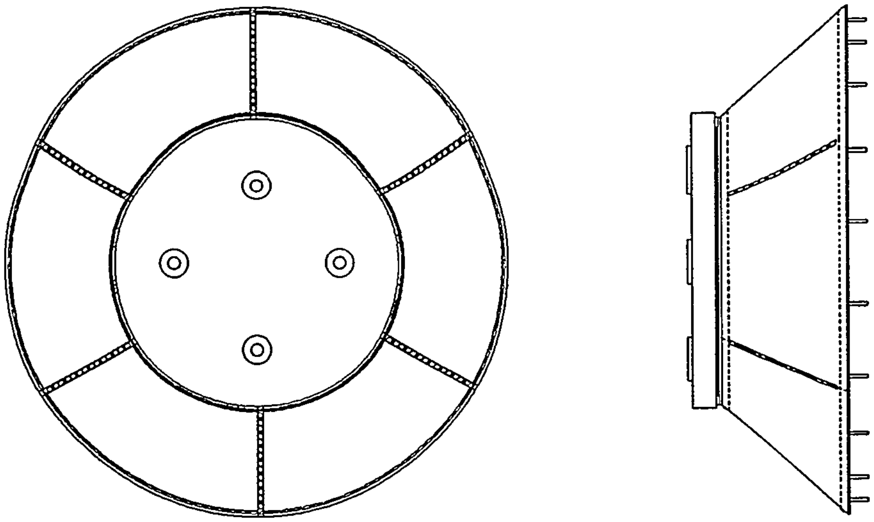

Figure 3-6: Conical End Enclosure

3.4 SYSTEM REQUIREMENTS

Some changes were made in the burner control system during Phase 2 to improve both the safety and reliability of the burner and burner/boiler package.

- A differential pressure switch was added to monitor the differential pressure between the burner plenum and boiler firebox during the pre-ignition purge sequence. During high purge air flow conditions, a low differential pressure would indicate a breach in the burner surface and the ignition sequence would be aborted. This modification will prevent a plant operator from restarting the burner following any system shutdown that has resulted in damage to the burner.
- The internal temperature of the premix plenum is continuously monitored during operation. At the start of Phase II this monitoring was done with thermocouples mounted on the inside of the burner. This method had several shortcomings. The thermocouples proved to have reliability problems, with several failing during operation. In addition, these faulty thermocouples could only be replaced by disassembling the burner which would lead to unacceptable down time. The thermocouples were replaced with a single infrared (IR) thermocouple mounted on the front of the windbox. This positioning allows the IR thermocouple to view burner internal conditions, and also allows the scanner to be replaced from outside of the boiler.
- For a flue gas recirculation system a damper operated by a single control shaft off the gas valve control shaft is all that would have to be added. This would allow the flue gas to be modulated with the burner.

SECTION 4

PHASE 3 PROJECT PLAN

To expand the applications of this burner into larger package or field-erected watertube boilers, installations using larger burners or multiple burners will be required. The goal of Phase 3 remains unchanged from our original proposal: to demonstrate sub-9 ppm NO_x and sub-50 ppm CO emissions using the RSB (with secondary flame envelope and/or FGR) in a full scale industrial boiler application.

Phase 3 is scheduled for 12 months duration and is divided into five subtasks as outlined below.

Task 3.1 Host Site Preparation

The host site must be verified and a schedule to obtain the permits for installation established. B&W will provide the boiler design based on the test information gathered from the last set of tests performed at Chevron's Cymric Oil Field.

Task 3.2 System Design and Fabrication

The information gathered in Phase 2 of this project will be used to design and fabricate the burner(s) for the new boiler design.

Task 3.3 Field Installation

The burner will be included in the new or retrofit boiler designed by B&W and installed at an industrial site. Then several months of operational data, including emissions performance as a function of boiler load, stack oxygen, and thermal efficiency, will be collected and analyzed by a third party testing service.

Task 3.4 Performance Tests and Data Analysis

The reduced test data collected in the field will be used to produce the final report for this project. Detailed design drawings and an economic analysis based on the test data will be prepared.

Task 3.5 Management and Reporting

Quarterly progress reports will be submitted to DOE. When appropriate, more detailed information on project performance, schedule, and budget will be submitted.

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3. Wilhelm, D.J., Johnson, H.E., and Karp, A.D., "The Potential Cost and Environmental Benefits of Very low Emissions Burners for NO_x Control," Final Report prepared by SFA Pacific, Inc. Mountain View, CA for U.S. Department of Energy, Contract DE-AC01-94FE63260, July 1995.

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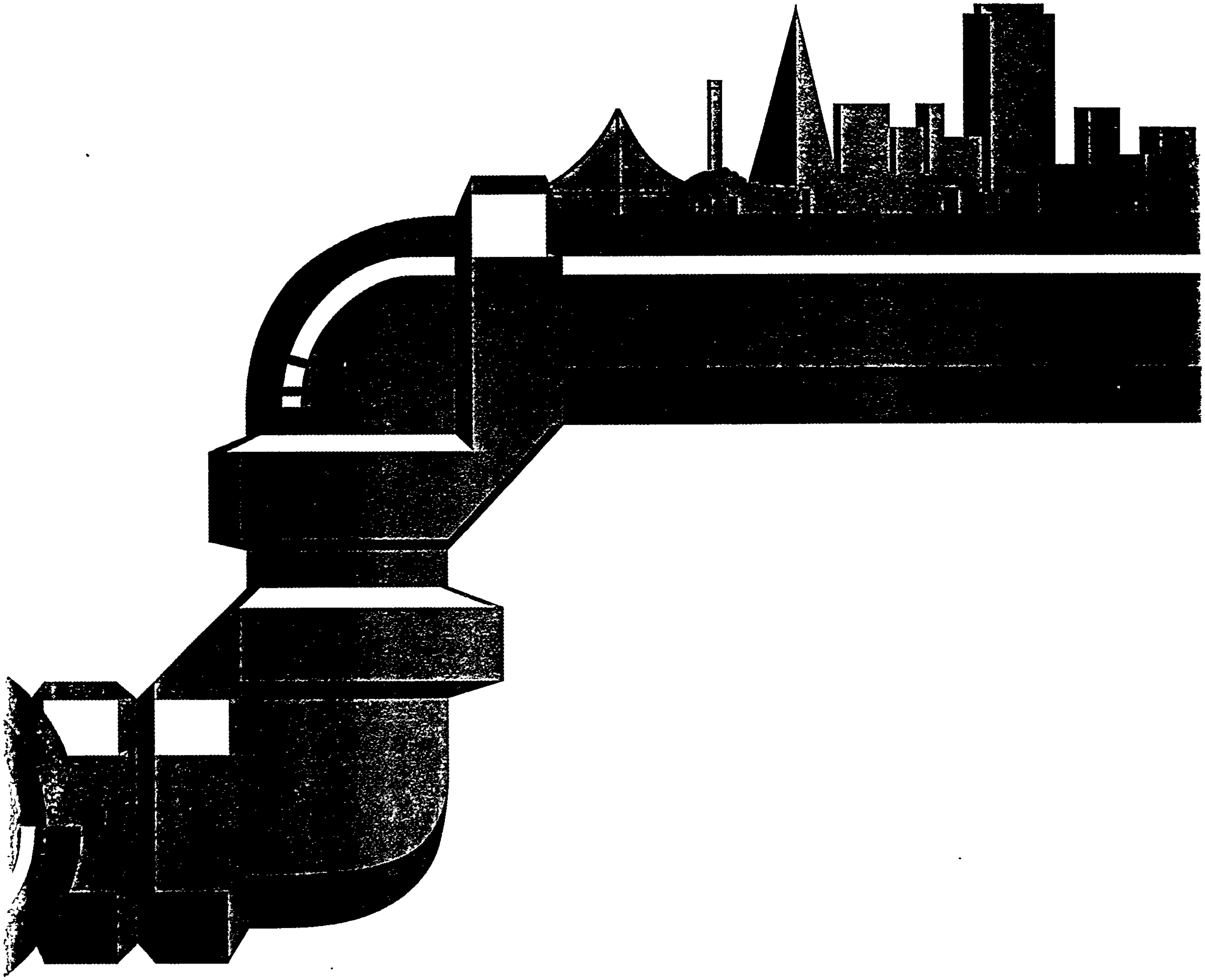
APPENDIX A

SF THERMAL FACILITY INFORMATION

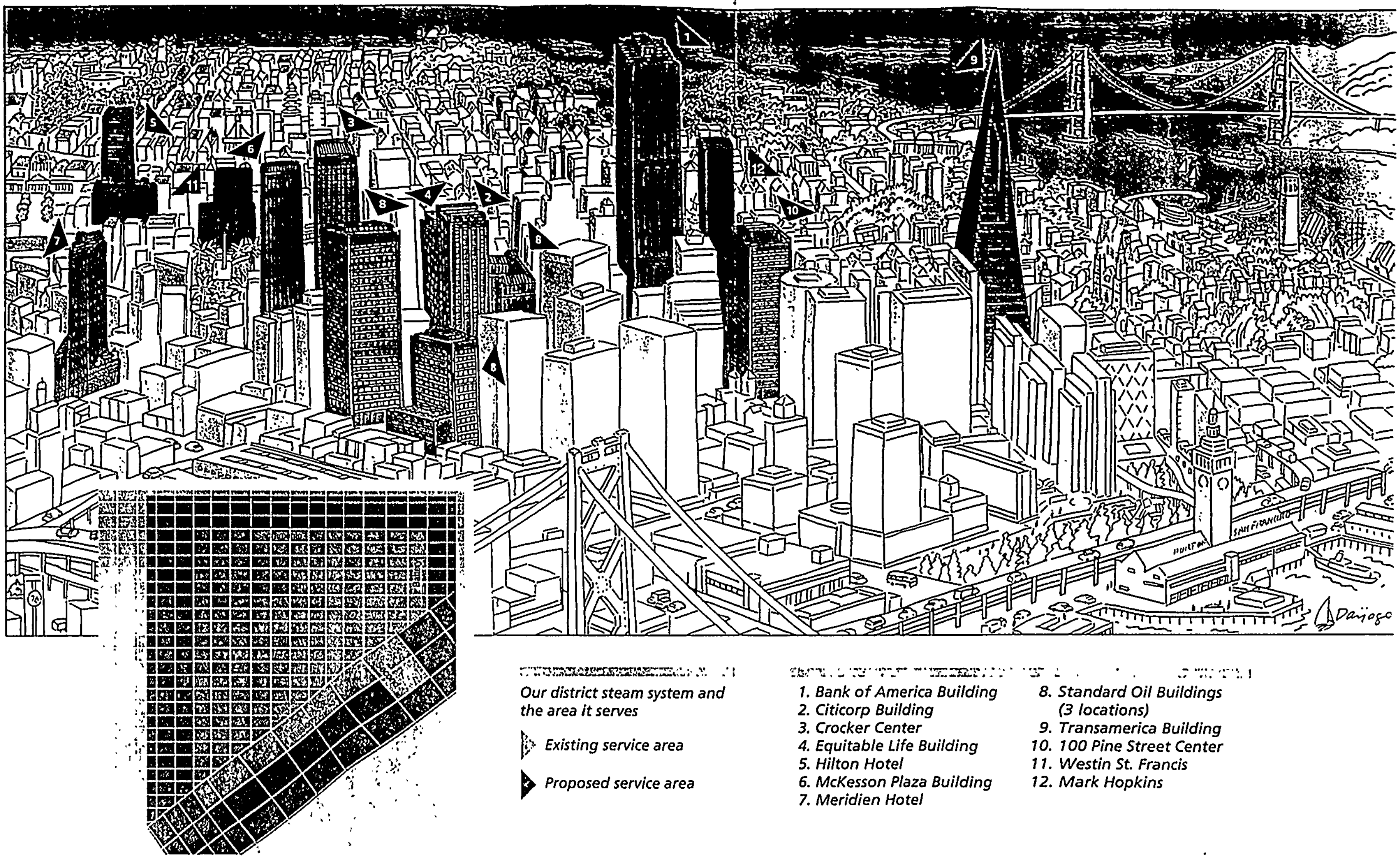
DISTRICT HEATING



SAN FRANCISCO THERMAL LIMITED PARTNERSHIP

A look at some of our customers

Thermal's current steam customers include more than 200 buildings in the heart of San Francisco's financial district and its adjoining areas. Many of these buildings use modern heating, ventilating, and air conditioning technologies for building climate control and hot water. Some of our customers include:



Our district steam system and the area it serves

▷ *Existing service area*

▶ *Proposed service area*

1. *Bank of America Building*
2. *Citicorp Building*
3. *Crocker Center*
4. *Equitable Life Building*
5. *Hilton Hotel*
6. *McKesson Plaza Building*
7. *Meridien Hotel*
8. *Standard Oil Buildings (3 locations)*
9. *Transamerica Building*
10. *100 Pine Street Center*
11. *Westin St. Francis*
12. *Mark Hopkins*

What are the uses for steam?

District steam is available to Thermal customers at consistent conditions of temperature and pressure 24 hours a day. This steam is ready for instantaneous conversion to suit the customer's various energy needs.

Space heating. Surveys of communities that use district steam have shown that overall ownership and operating costs associated with building heating are reduced where district steam is available and used.

Domestic hot water heating. District steam offers rapid recovery rates and an unlimited source of hot water.

Absorption air-conditioning. Some customers incorporate absorption air conditioning into their building HVAC system to meet all or a portion of their space cooling needs. This allows them to reduce the on-peak requirements and demand charges for electricity when air-conditioning is required. Absorption air conditioning does not use freon, a global-warming gas.

Commercial processes. Many processes require the direct application of steam. Examples include various uses by restaurants, hospitals, hotels, laundries, and dry cleaners. District steam enables these needs to be met flexibly and reliably. District steam also offers immediate adjustment of delivered steam volume without costly changes in installed boiler capacity.

High pressure steam (without expense of full-time boiler operators). Many commercial processes require high pressure boilers, necessitating a full-time boiler operator. The Thermal steam system supplies high pressure steam *without* the need for a full-time boiler operator at the customer's site. ⊗

Our current customers are familiar with these advantages. We would be pleased to introduce you to some of our customers if you would like to talk to them directly about our system and our services. ⊗

We invite you to look into our district steam service. We hope that you will call us to learn more about how Thermal's district steam can be beneficial to you.

San Francisco Thermal
460 Jessie Street
San Francisco, CA 94103

Telephone (415) 777 3415
Fax (415) 777 378
Contact Richard Mayer, Pre

APPENDIX B

CYMRIC TEST REPORT

Emissions and Installation Report for the Use of Flue Gas Dilution with Large Diameter CSB's

Alzeta Project 7097:

Development and Demonstration of the Radiation Stabilized Distributed Flux Burner

Final Report for Cymric Test Results

Prepared by

Scott Smith, Steve Greenberg, and Andy Webb
Alzeta Corporation
2343 Calle Del Mundo
Santa Clara, CA 95054-1008

Emissions and Installation Report for the Use of Flue Gas Dilution with Large Diameter CSB's

Operating and emissions tests of flue gas recirculation (FGR) were conducted using Alzeta's 30" diameter CSB low NO_x burner installed in a Struthers Steamer at Chevron's Cymric Oil Field. Installation of the Alzeta surface burner was performed by J.E. Construction and T.J Cross Engineering provided design work. Test results demonstrated flame stability over a wide range of firing rates and excess air, and low emissions when operated with dilution (by excess air or flue gas recirculation) of 50% or more (low emissions means under 9 ppm NO_x and less than 50 ppm CO corrected to 3% O_2). These tests confirm that burner performance depends upon total dilution, and not whether the dilution is a result of excess air or flue gas. Therefore, when operated with flue gas recirculation (FGR), the Alzeta burner is a stable, low NO_x, high efficiency burner. Additional comments are made on the fully tabulated data, and the possibility of fuel staging.

Installation

The test burner installation went as smoothly as any commercial site with the help of J.E. Construction. The single difficulty resulted from an older segment connection design. The segments connected from the end cap toward the burner wall, necessitating the use of a support tray during installation. The extra handling on the support tray resulted in a torn pad segment, which had to be replaced. Drawing 1 is an assembly drawing of the burner placed in the 37-ft-long Struthers Steamer, and Drawing 2 is an assembly drawing of the burner segment.

Burner Test Results

Burner Stability

Figure 1 shows the operating envelope for the 60 MMBtu/hr Alzeta CSB inside the Struthers Steamer. The figure shows that the burner is stable over a broad operating envelope of firing rate and total dilution. This operating envelope is bordered by high dilution (65%) above which lean flame-out can occur, and minimum dilution (10%) below which high CO levels may result. Maximum firing rates are determined by total surface area (60 ft^2) and maximum surface firing rates (1.2 $MMBtu/hr/ft^2$), and minimum firing rates are turndown dependent, set at 6:1.

The borders of the stability curve shown in Figure 1 are derived from previous Alzeta burner tests. The confidence in these limits is high enough that test time at the Cymric site was not used to reconfirm them experimentally.

Burner Emissions

Figure 2 illustrates the expected emissions levels inside the overall stability curve. Shaded bands show expected emissions in three regions, 15-30 ppm NO_x, 9-15 ppm NO_x, and below 9 ppm NO_x. NO_x levels that are independent of firing rate are a characteristic of Alzeta's smaller CSB products (less than 5MMBtu/hr, less than 8" diameter), while the large CSB line shows some emissions increase with increasing firing rate. CO levels in this well-mixed system are consistently below 9 ppm, which is far enough below the 50 ppm DOE project target that no plot is shown.

The six data points shown on Figure 2 are all derived from high efficiency cases, where excess air levels are near 15%, with the remaining dilution the result of flue gas recirculation.

Burner Efficiency

The results from Figures 3, 4 and 5 show that when flue gas recirculation is used in the correct proportions, the low excess air and low stack O_2 give a high efficiency boiler. Figure 3 shows the NO_x emissions as they drop with increasing volumetric dilution. NO_x levels near 30 ppm occur when total dilution reaches 30%, levels near 15 ppm occur with 40% dilution, and levels near 9 ppm occur with 50% dilution. Dilution levels of 60% will guarantee NO_x levels below 9 ppm, corrected to 3% stack O_2. Figure 4 is a compilation of data from Alzeta surface burners of different applications, geometries, and excess air levels. This plot shows the emissions levels perform similarly for similar values of total dilution. Figure 5 shows the NO_x emissions for specific values of excess air. In Figure 5, the region where excess air is below 15% is labeled high efficiency, and the region where NO_x levels are below 9 ppm is labeled low emissions. The intersection of these two regions, shaded in gray, is the high efficiency, low emissions operating region. Thus, the use of flue gas recirculation, combined with the other properties of the Alzeta burner, give a boiler burner that is high-efficiency, low emissions and stable over a wide operating range.

Tabulated Data

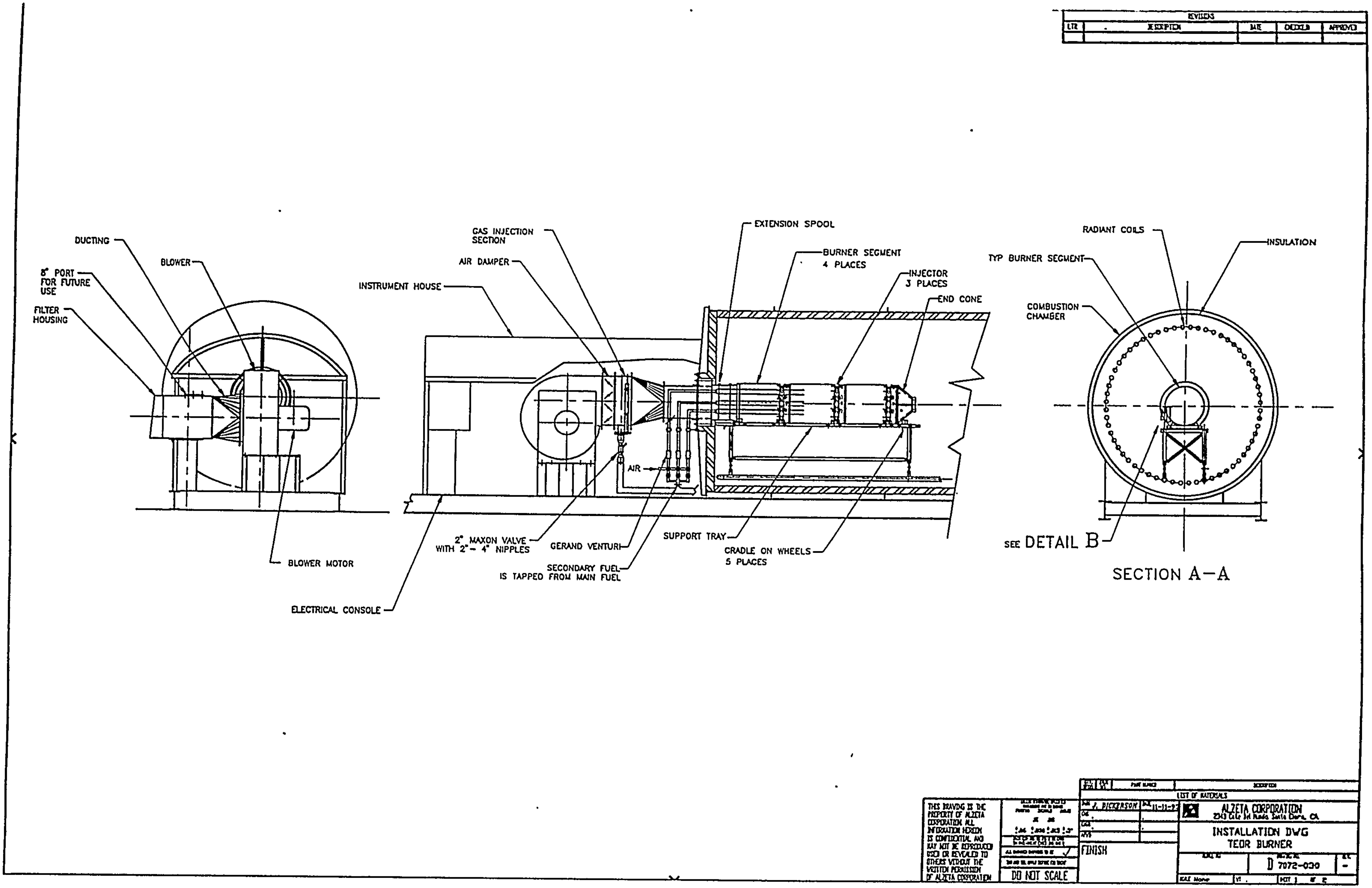
Table 1 and Table 2 contain the full tabulated data for the Cymric tests. The data is broken into excess air data points, where all dilution resulted from air, and FGR points where partial dilution with flue gas was used. Scratch points were recorded for flow rate and emissions data only. Note that the date and point columns provide a unique reference to each data point.

Information on specific columns follows: Total firing rate is given as Tot. Gas in MMBtu/hr. Stack O_2 (dry) is read by an Ecom-AC from the stack of the Struthers Steamer. Mix O_2 is the percent oxygen in the combined flue gas/air stream before gas is mixed. Excess air (EA) is given as the additional percentage of stoichiometric air added to the combustion premix. Flue gas dilution (FGD) is also given as a percentage of stoichiometric air, except this is flue gas that is added to the premix. FGR is the traditional definition of Flue Gas Recirculation, the percentage of the total air and flue gas that is flue gas. Total dilution is the addition of EA and FGD. Stack levels of CO_2, CO, NO, and NO_2 are given. Fuel flow and stoichiometric airflow is given in scfm. A small amount of cooling air is always present through the nozzles (used for different fuel staging tests); thus excess air through the burner, and cooling air flow rates are given.

An overview of temperature and heat flux data follows: T1 through T6 are uncorrected thermocouple readings from inside the steamer. (Locations are given as distance from the steamer front wall, and the clockwise angle when viewed from the fan side of the steamer, 0° corresponding to straight up.) T1 (4ft, 90°) and T3 (8ft, 315°) are measure flue temperatures using ceramic coated thermocouples, hanging 2ft radially into the steamer. T2 (8ft, 45°) and T4 (4ft, 270°) measure outer tube wall temperatures, and are covered by generous amounts of refractory coating. T5 (14ft, 0°) and T6 (16ft, 0°) are uncovered thermocouples hanging from the top of the boiler, 3 ft down. The single heat flux gauge (4.5 ft, 90°) is measured at two positions for each data point before its failure. The first position corresponds to 20 inches from the burner surface, the second 40 inches from the surface. Note that the second position is flush with the tube walls. Stack temperature is read by the Ecom-AC at the exhaust. The FGR temperature is the flue gas temperature just before mixing with the air. The burner throat temperature is the premix temperature before combustion. Steam and Tube temperatures are recorded just before the convective section begins. Exhaust temperature is in the stack. St. out, Conv, Coil, and Water in are recorded pressures. All data from 'L Steam' to 'H2O in' is recorded from the steamer's controls.

Fuel Staging Results

Fuel staging results from four tests at three different sites are shown in Figure 6. Changes in site, configuration, and fuel flows result in two broad performance categories, shown in two boxes in Figure 6. Translucent flames that are cleaner burning all have NO_x levels above 30 ppm. Orange flames gave lower NO_x levels due to lower flame temperatures as soot radiates heat energy from the combustion. These lower emission flames are not a low-emission, high-efficiency burner solution because of the soot residue they would leave on the boiler tube walls. In short, fuel staging is not ready for installation at a commercial site.


REVISIONS
LTR
DESCRIPTION
DATE
CHECKED
APPROVED
DUCTING
8" PORT FOR FUTURE USE
FILTER HOUSING
BLOWER
BLOWER MOTOR
ELECTRICAL CONSOLE
GAS INJECTION SECTION
AIR DAMPER
INSTRUMENT HOUSE
2" MAXON VALVE WITH 2" - 4" NIPPLES
GERAND VENTURI
SECONDARY FUEL IS TAPPED FROM MAIN FUEL
AIR
EXTENSION SPOOL
BURNER SEGMENT 4 PLACES
INJECTOR 3 PLACES
END CONE
SUPPORT TRAY
CRADLE ON WHEELS 5 PLACES
RADIANT COILS
INSULATION
TYP BURNER SEGMENT
COMBUSTION CHAMBER
SEE DETAIL B
SECTION A-A
LIST OF MATERIALS
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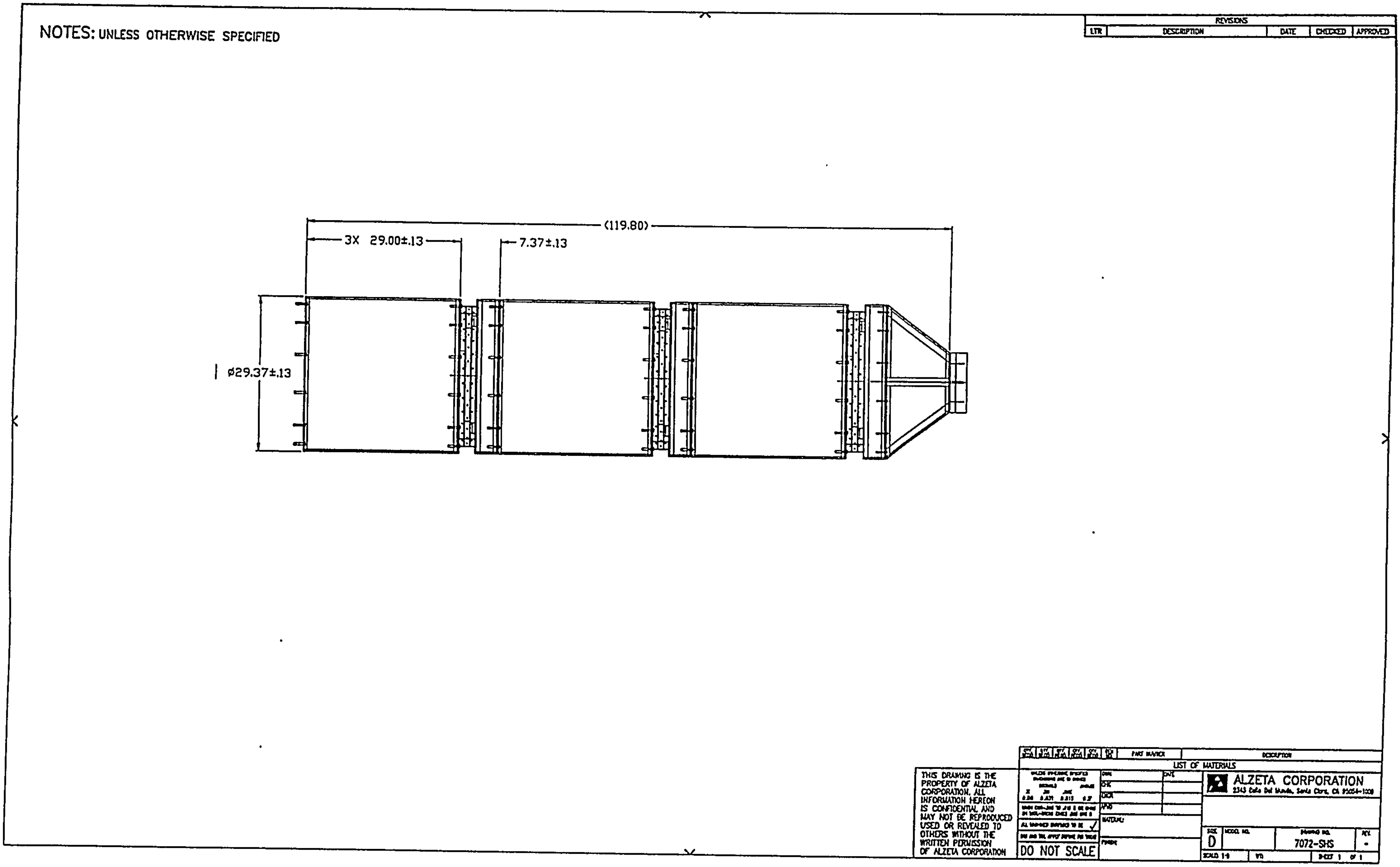
DO NOT SCALE
J. DICKERSON
11-11-97
FINISH
ALZETA CORPORATION
2343 Calle del Mundo Santa Clara, CA
INSTALLATION DWG
TEOR BURNER
D 7072-030
-
SCALE None
SHEET 1 OF 2

Drawing 1


NOTES: UNLESS OTHERWISE SPECIFIED
REVISIONS
LTR
DESCRIPTION
DATE
CHECKED
APPROVED
(119.80)
3X 29.00±.13
7.37±.13
ø29.37±.13
PART NUMBER
DESCRIPTION
LIST OF MATERIALS
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DO NOT SCALE
DATE
MATERIAL
FINISH
ALZETA CORPORATION
2343 Calle Del Mundo, Santa Clara, CA 95054-1008
SIZE
D
DRAWING NO.
7072-SHS
REV
-
SCALE 1:8
SHEET 1 OF 1

Drawing 2

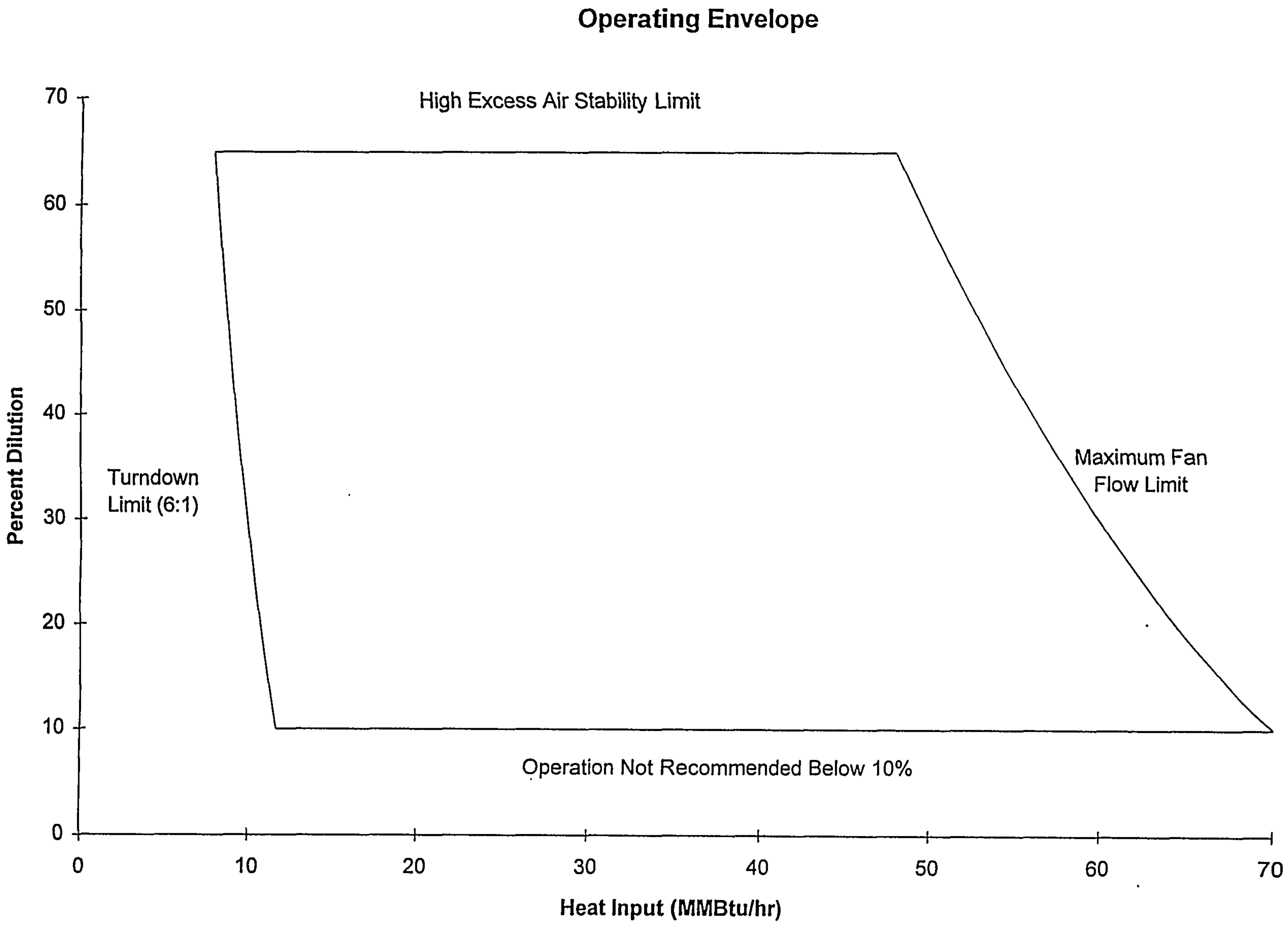

Operating Envelope
High Excess Air Stability Limit
Turndown
Limit (6:1)
Maximum Fan
Flow Limit
Operation Not Recommended Below 10%
Percent Dilution
0
10
20
30
40
50
60
70
0
10
20
30
40
50
60
70
Heat Input (MMBtu/hr)

Figure 1

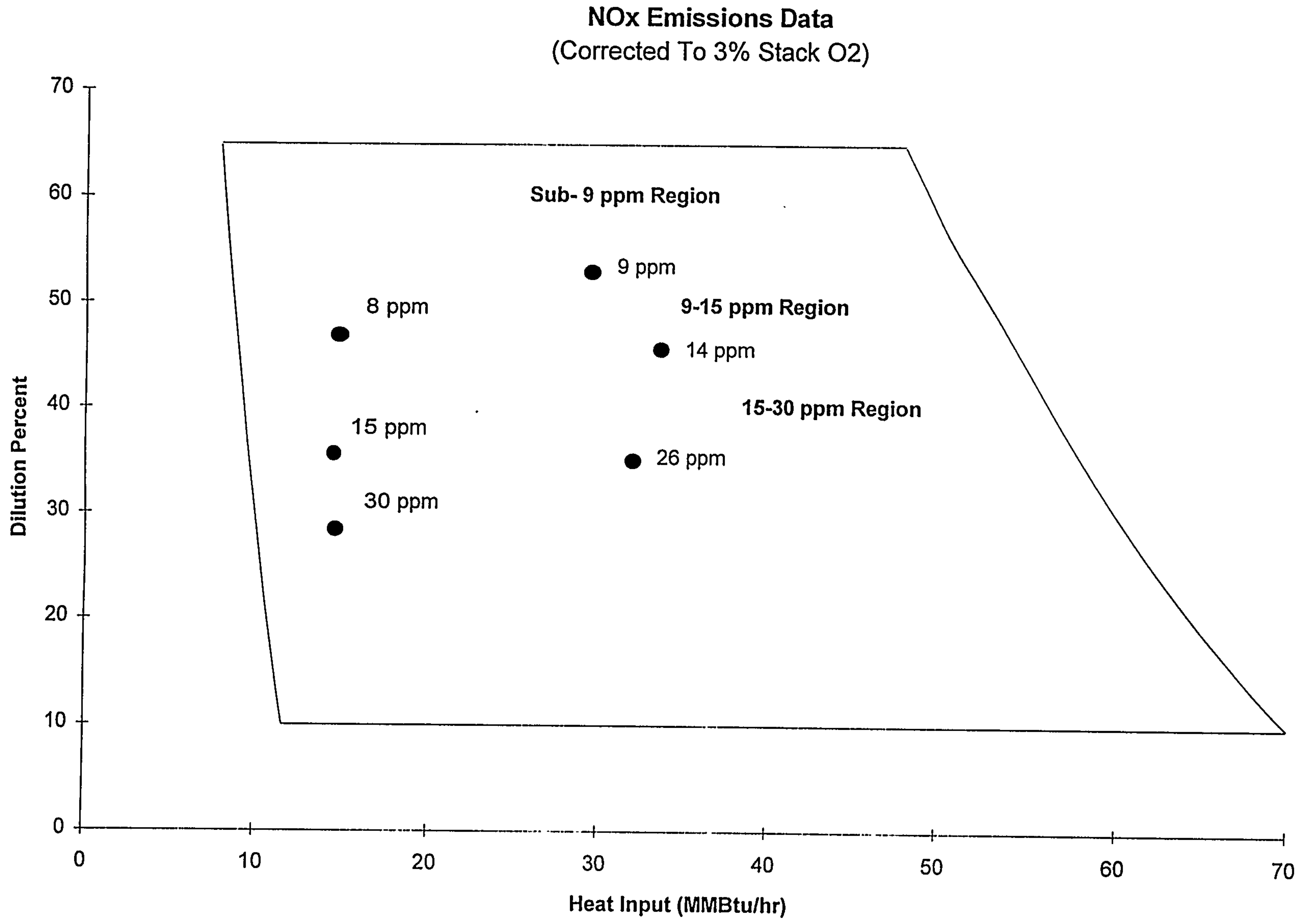

NOx Emissions Data
(Corrected To 3% Stack O2)
Sub- 9 ppm Region
9 ppm
9-15 ppm Region
14 ppm
15-30 ppm Region
26 ppm
8 ppm
15 ppm
30 ppm
Dilution Percent
0
10
20
30
40
50
60
70
Heat Input (MMBtu/hr)
0
10
20
30
40
50
60
70

Figure 2

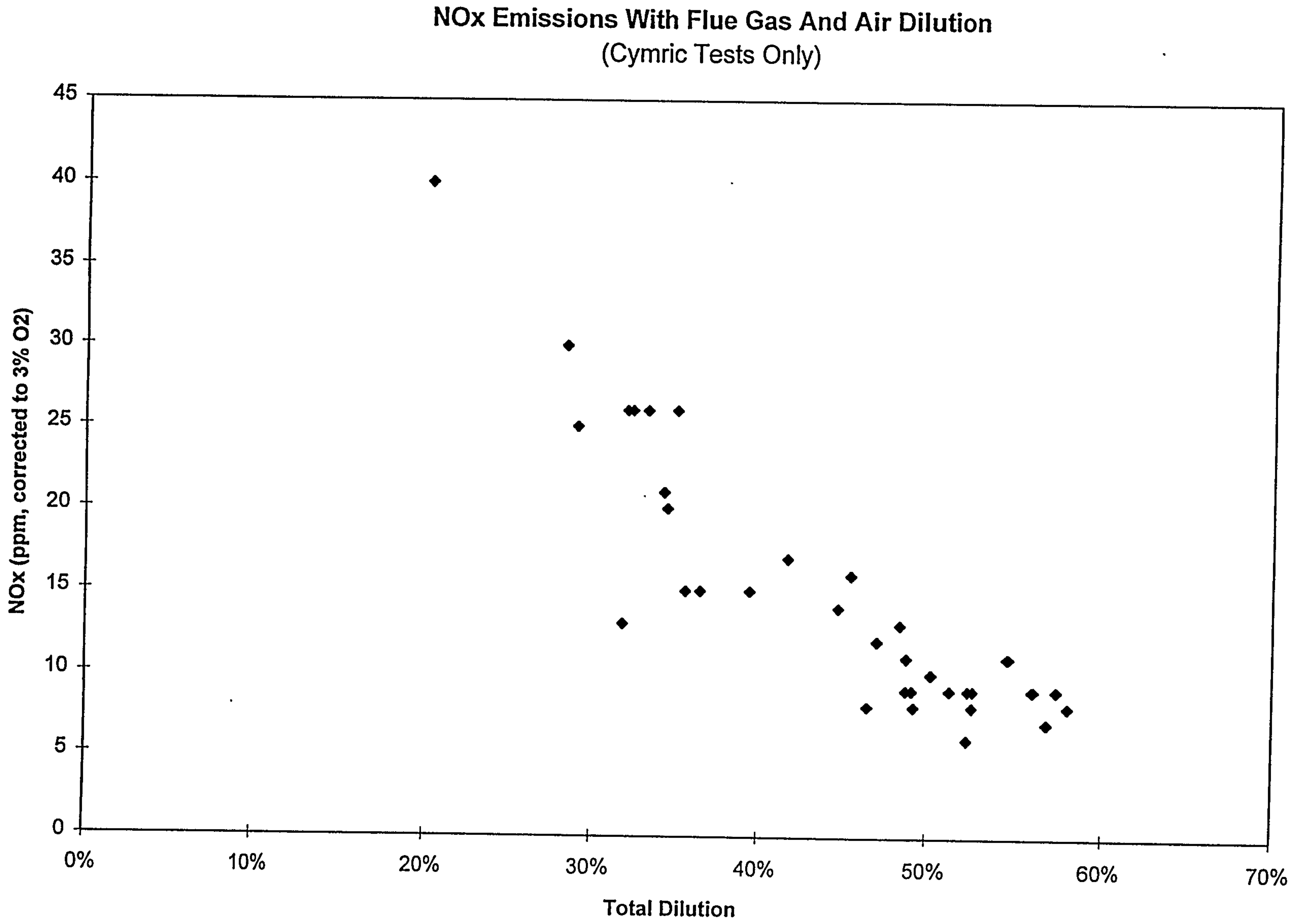

NOx Emissions With Flue Gas And Air Dilution
(Cymric Tests Only)
NOx (ppm, corrected to 3% O2)
45
40
35
30
25
20
15
10
5
0
0%
10%
20%
30%
40%
50%
60%
70%
Total Dilution

Figure 3

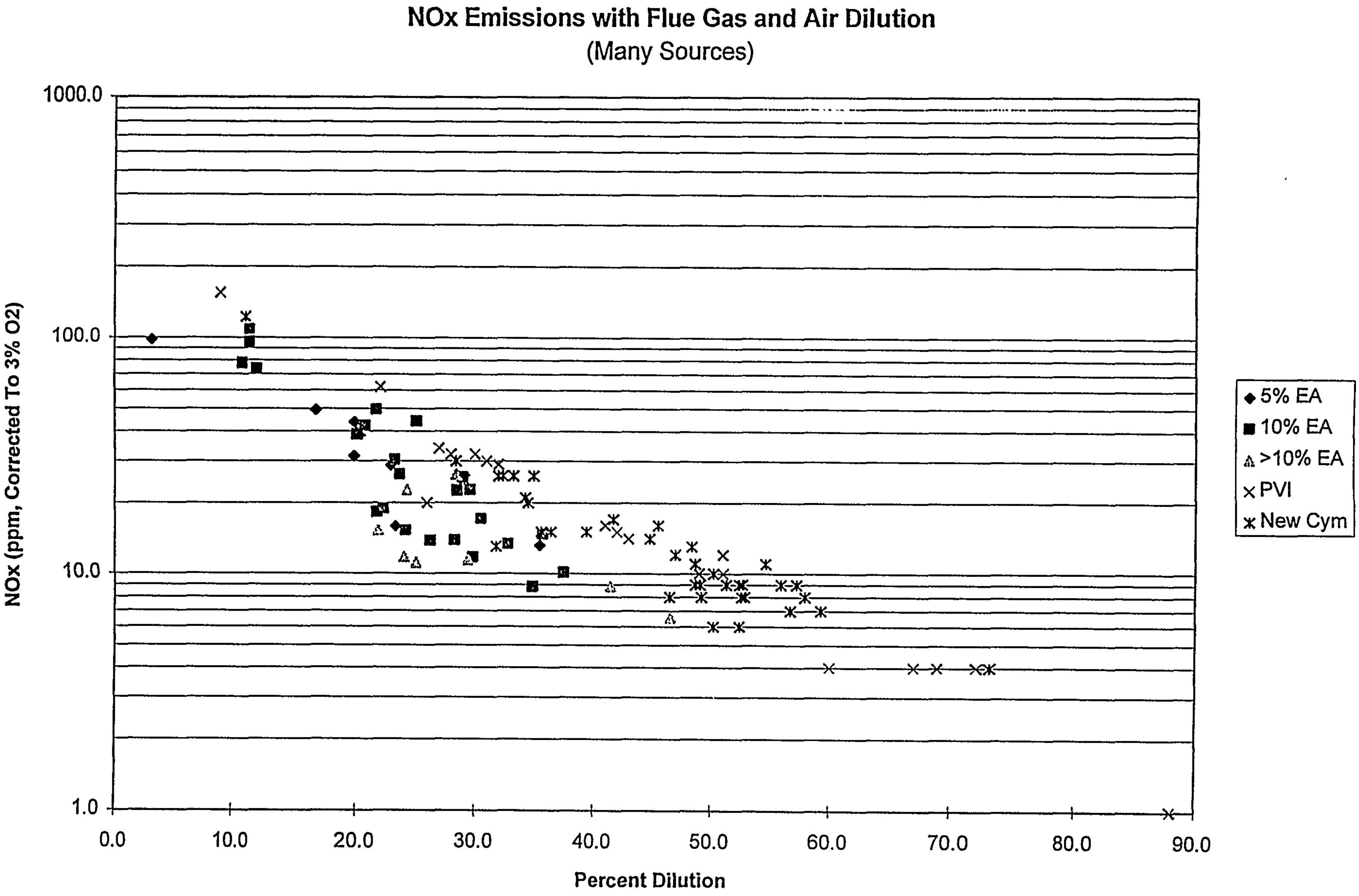

NOx Emissions with Flue Gas and Air Dilution
(Many Sources)
NOx (ppm, Corrected To 3% O2)
1000.0
100.0
10.0
1.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
Percent Dilution
◆ 5% EA
■ 10% EA
△ >10% EA
× PVI
✳ New Cym

Figure 4

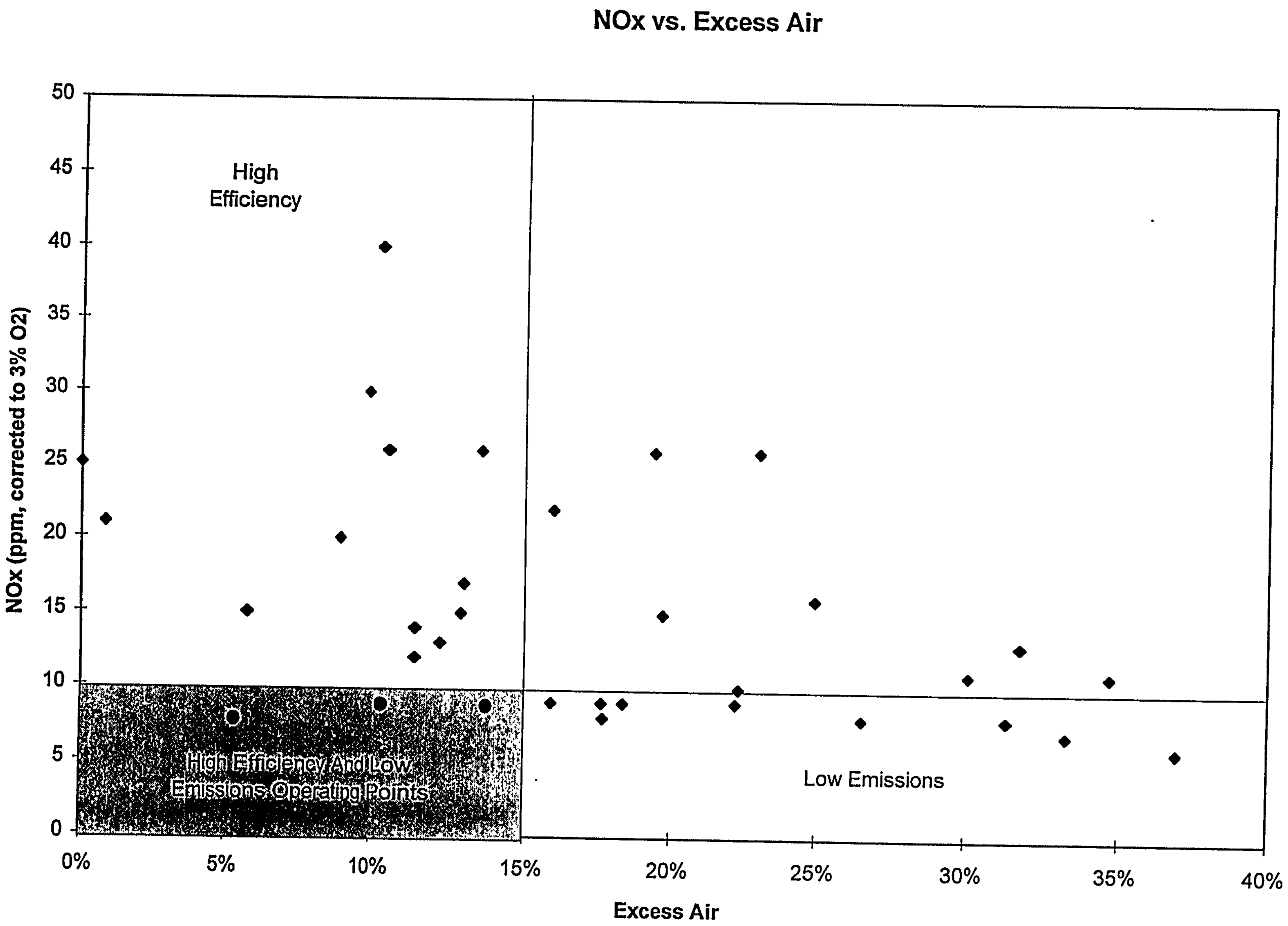

NOx vs. Excess Air
NOx (ppm, corrected to 3% O2)
50
45
40
35
30
25
20
15
10
5
0
0%
5%
10%
15%
20%
25%
30%
35%
40%
Excess Air
High
Efficiency
High Efficiency And Low
Emissions Operating Points
Low Emissions

Figure 5

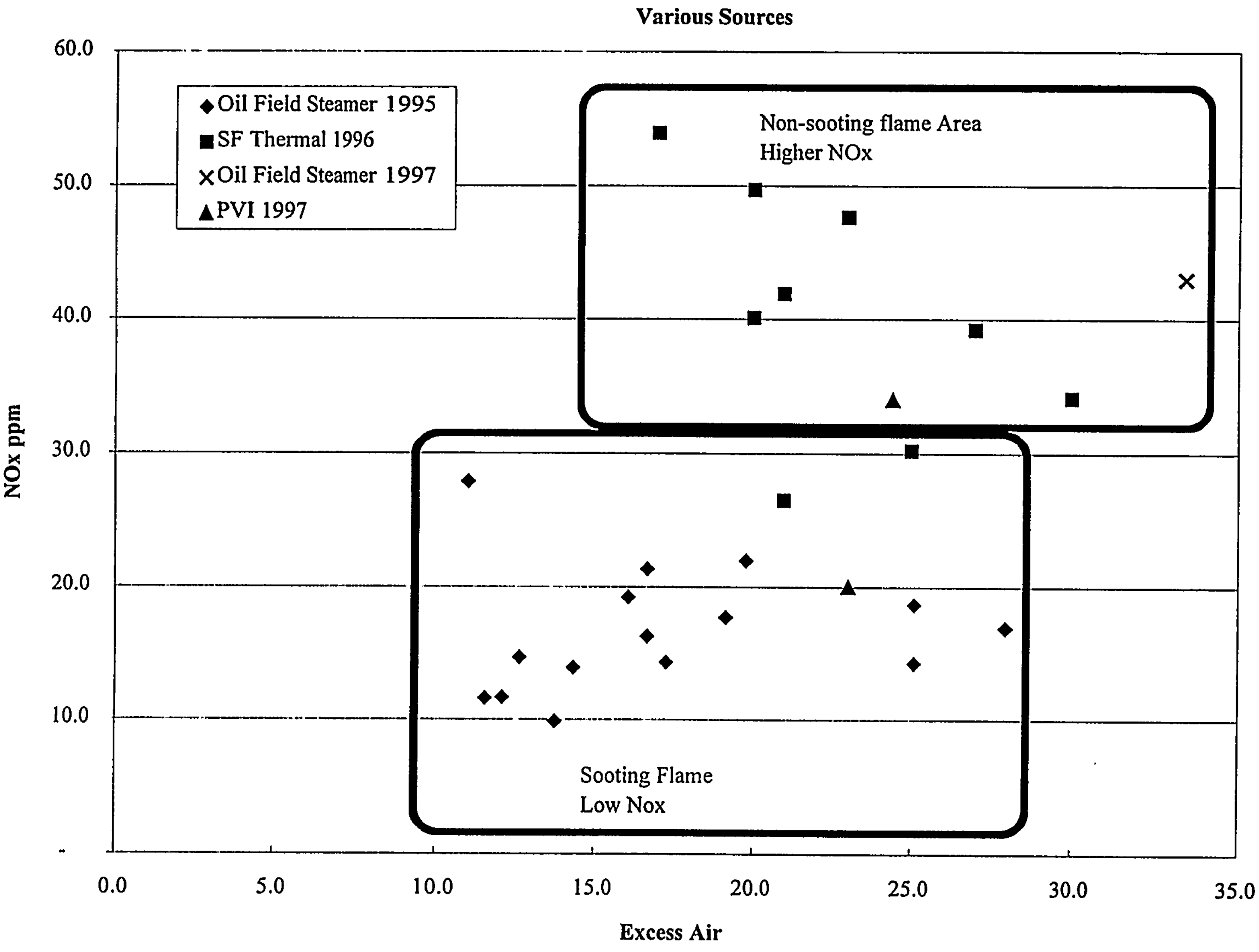


Figure 6. Staging Data

Emissions And Flow Characteristics

Date	Time	Point	Tot. Gas	Stack O2	Mix O2	EA	FGD	FGR	Total Dil	CO2	CO	NO	NO2	Fuel	Sto. Air	EA Burn	Cool Air
			MMBtu/hr	Dry	Dry				Dry	%	ppm	ppm	ppm	scfm	scfm	scfm	scfm
Excess Air Points																	
6/24/97	?	2	11.9	8.6%	21.0%	50.2%	0.0%	0.0%	50.2%	7.1%	66	6	1	194	1842	925	221
6/24/97	?	3	33.7	9.8%	21.0%	73.0%	0.0%	0.0%	73.0%	6.2%	11	4	0	548	5219	3812	285
6/24/97	14:05	4	33.7	8.8%	21.2%	59.3%	0.0%	0.0%	59.3%	6.8%	1	7	0	548	5219	3094	283
6/25/97	9:10	A	42.3	8.2%	21.0%	52.9%	0.0%	0.0%	52.9%	7.1%	2	8	0	688	6550	3466	287
FGR Points																	
6/25/97	13:10	B	33.7	6.5%	19.3%	34.7%	20.0%	12.9%	54.7%	8.0%	0	11	0	548	5219	1810	283
6/25/97	13:30	C	33.7	5.3%	19.0%	24.9%	20.6%	14.1%	45.5%	8.6%	0	16	0	548	5219	1301	275
6/25/97	13:50	D	32.0	3.2%	18.1%	10.6%	24.5%	18.1%	35.0%	9.9%	0	26	----	521	4958	523	275
7/7/97	10:15	A	29.3	4.5%	17.6%	18.3%	34.3%	22.5%	52.7%	9.2%	0	9	0	476	4529	830	279
7/7/97	11:30	B	29.9	3.4%	17.1%	11.4%	35.7%	24.3%	47.0%	9.8%	0	12	0	486	4629	526	275
7/7/97	13:20	C	31.2	3.7%	18.7%	13.5%	19.8%	14.8%	33.3%	9.5%	0	26	0	507	4830	652	275
7/7/97	13:45	D	31.2	3.6%	17.8%	12.9%	28.8%	20.3%	41.7%	9.7%	0	17	0	507	4830	623	275
7/7/97	14:10	E	31.2	5.0%	18.3%	22.3%	27.9%	18.6%	50.2%	8.9%	0	10	0	507	4830	1078	275
7/7/97	14:30	F	33.8	1.1%	17.0%	0.0%	29.1%	22.5%	29.1%	11.0%	0	25	0	550	5233	0	275
7/7/97	14:40	G	29.9	3.4%	17.3%	11.4%	33.4%	23.1%	44.8%	9.8%	0	14	0	486	4629	526	275
7/7/97	14:55	H	26.0	4.5%	17.1%	17.7%	40.3%	25.5%	58.0%	9.2%	0	8	0	423	4025	711	275
7/7/97	15:10	I	26.0	3.9%	16.7%	13.7%	42.3%	27.1%	56.0%	9.5%	0	9	0	423	4025	550	275
7/7/97	15:25	J	26.0	3.9%	16.6%	13.7%	43.6%	27.7%	57.3%	9.5%	0	9	0	423	4025	550	275
7/8/97	9:25	A	15.0	3.4%	17.3%	5.7%	29.8%	22.0%	35.6%	9.8%	3	15	0	243	2315	132	268
7/8/97	9:55	B	15.0	4.1%	18.7%	9.9%	18.5%	14.4%	28.4%	9.5%	0	30	0	243	2315	230	275
7/8/97	10:10	C	15.0	3.4%	16.2%	5.3%	41.2%	28.1%	46.5%	9.8%	59	8	0	243	2315	123	277
Scratch Points																	
7/7/97		1	31.2	7.6%	21.1%	31.8%	0.0%	0.0%	31.8%	----	0	13	----	507	4830	1536	280
7/7/97		2	29.3	6.2%	19.4%	31.4%	17.8%	11.9%	49.2%	----	0	8	----	476	4529	1423	280
7/7/97		3	29.3	4.4%	17.8%	17.6%	31.5%	21.1%	49.1%	----	0	9	----	476	4529	798	280
7/7/97		4	29.9	6.8%	19.7%	37.0%	15.4%	10.1%	52.4%	----	0	6	----	486	4629	1711	280
7/7/97		5	29.9	6.4%	19.0%	33.3%	23.5%	15.0%	56.8%	----	0	7	----	486	4629	1539	280
7/7/97		6	29.9	5.6%	18.6%	26.6%	26.1%	17.1%	52.6%	----	0	8	----	486	4629	1229	280
7/7/97		7	31.2	5.1%	20.0%	23.0%	9.4%	7.1%	32.4%	----	0	26	----	507	4830	1111	280
7/7/97		8	31.2	4.6%	19.6%	19.4%	12.6%	9.6%	32.0%	----	0	26	----	507	4830	937	280
7/7/97		9	31.2	6.0%	19.3%	30.1%	18.6%	12.5%	48.7%	----	0	11	----	507	4830	1454	280
7/7/97		10	31.2	3.6%	18.0%	12.8%	26.6%	19.1%	39.4%	----	0	15	----	507	4830	618	280
7/7/97		11	31.2	5.0%	18.2%	22.2%	29.1%	19.2%	51.3%	----	0	9	----	507	4830	1073	280
7/7/97		12	32.5	2.9%	17.9%	8.8%	25.6%	19.1%	34.5%	----	0	20	----	529	5032	445	280
7/7/97		13	28.0	3.6%	17.1%	12.1%	36.2%	24.4%	48.4%	----	0	13	----	455	4327	525	280
7/7/97		14	29.9	1.5%	16.6%	0.9%	33.4%	24.9%	34.3%	----	0	21	----	486	4629	39	280
7/7/97		15	29.9	0.5%	16.0%	16.0%	54.3%	31.9%	70.3%	----	1	22	----	486	4629	738	280
7/7/97		16	26.0	3.4%	16.5%	10.3%	42.0%	27.6%	52.4%	----	0	9	----	423	4025	416	280
7/8/97		1	24.7	3.6%	21.2%	11.3%	0.0%	0.0%	11.3%	----	----	123	----	402	3824	431	280
7/8/97		2	15.0	5.5%	19.2%	19.7%	16.7%	12.3%	36.4%	----	0	15	----	243	2315	456	280
7/8/97		3	15.0	4.2%	19.7%	10.3%	10.0%	8.3%	20.3%	----	0	40	----	243	2315	238	280
7/8/97		4	15.0	5.0%	17.6%	15.9%	32.8%	22.1%	48.7%	----	29	9	----	243	2315	368	280

Table 1

Temperature And Heat Flux Data

Date	Time	Point	T1	T2	T3	T4(7)	T5	T6	Flux 20	Flux 20	Flux 40	Flux 40	Stack T	FGR T	Mix T	L Steam	H Tube	H Exh	Burn Thr	St Out	Conv Coil	H2O In
			°F	°F	°F	°F	°F	°F	mV	Btu/ft²/hr	mV	Btu/ft²/hr	°F	°F	°F	°F	°F	°F	°F	psi	psi	psi
Excess Air Points																						
6/24/97	----	2	*1093*	*358*	*1445*	*276*	*1491*	*1416*	----	----	----	----	----	----	----	----	----	----	----	----	----	----
6/24/97	----	3	*1550*	*566*	*1663*	*449*	*1654*	*1600*	----	----	----	----	----	----	----	----	----	----	----	----	----	----
6/24/97	14:05	4	*1637*	*636*	*1655*	*526*	*1686*	*1624*	----	----	----	----	----	----	----	----	----	----	----	----	----	----
6/25/97	9:10	A	*1653*	*657*	*1817*	*569*	*1738*	*1681*	*5.4*	*643464*	*6.8*	*810288*	405	----	----	520	540	380	----	800	1050	1150
FGR Points																						
6/25/97	13:10	B	*1618*	*638*	*1629*	*516*	*1653*	*1573*	*5.3*	*631548*	*6.1*	*726876*	333	----	106	520	540	300	130	800	1000	1050
6/25/97	13:30	C	*1643*	*645*	*1686*	*523*	*1653*	*1574*	*5.6*	*667296*	*5.8*	*691128*	331	----	109	530	540	310	125	800	1050	1100
6/25/97	13:50	D	*1687*	*657*	*1723*	*527*	*1673*	*1584*	*6.2*	*738792*	*5.2*	*619632*	321	----	115	520	540	300	125	800	1050	1150
7/7/97	10:15	A	*1515*	*645*	*1642*	*506*	*1598*	*1527*	*4.8*	*571968*	*4.7*	*560052*	321	245	103	120	540	300	135	800	1000	1100
7/7/97	11:30	B	*1557*	*645*	*1680*	*521*	*1632*	*1557*	*5.0*	*595800*	*5.5*	*655380*	323	248	106	120	540	300	140	800	1000	1100
7/7/97	13:20	C	*1665*	*656*	*1707*	*514*	*1666*	*1581*	----	----	----	----	320	226	106	110	540	300	125	800	1000	1150
7/7/97	13:45	D	*1593*	*651*	*1696*	*530*	*1657*	*1576*	----	----	----	----	334	249	108	110	520	300	140	800	1000	1100
7/7/97	14:10	E	*1555*	*654*	*1678*	*529*	*1632*	*1560*	----	----	----	----	350	261	111	110	540	310	140	800	1050	1150
7/7/97	14:30	F	*1646*	*663*	*1778*	*556*	*1702*	*1619*	----	----	----	----	333	262	110	110	545	310	145	800	1100	1175
7/7/97	14:40	G	*1571*	*650*	*1681*	*532*	*1620*	*1539*	----	----	----	----	330	260	113	----	----	----	----	----	----	----
7/7/97	14:55	H	*1493*	*647*	*1604*	*503*	*1550*	*1470*	----	----	----	----	314	244	114	520	540	300	150	800	1000	1100
7/7/97	15:10	I	*1497*	*642*	*1604*	*485*	*1547*	*1465*	----	----	----	----	308	241	106	520	540	290	150	800	1000	1050
7/7/97	15:25	J	*1455*	*631*	*1570*	*464*	*1519*	*1437*	----	----	----	----	305	236	117	520	530	290	150	800	975	1075
7/8/97	9:25	A	*1267*	*461*	*1410*	*323*	*1337*	*1228*	----	----	----	----	203	156	109	520	420	200	120	800	900	1000
7/8/97	9:55	B	*1208*	*465*	*1421*	*322*	*1343*	*1238*	----	----	----	----	198	153	109	520	420	190	115	800	900	1000
7/8/97	10:10	C	*1273*	*460*	*1394*	*323*	*1321*	*1209*	----	----	----	----	210	165	111	----	----	----	----	----	----	----

Note: Italics indicates data that are averages of data collected with Rustrack.

Note: "Flux 20" indicates heat flow at the tube wall. "Flux 40" indicates the heat flux 1/2 way between the burner surface and the tube wall.

Table 2

APPENDIX C

BABCOCK & WILCOX REPORTS

Babcock & Wilcox
a McDermott company

Power Generation Group
20 S. Van Buren Avenue
P.O. Box 351
Barberton, OH 44203-0351
(330) 753-4511

December 2, 1997

John Sullivan
Vice President, Engineering
2343 Calle Del Mundo
Santa Clara, CA 95054

Ref: Evaluation of the RSB and In-Furnace
Cooling Surface Using Modeling Techniques
Proposal No. P57-0013

Dear John,

Enclosed herewith are complete sets of the following computer runs:

OPTION 4: Increased Furnace Absorption Utilizing Membrane Wall Construction

MOD. 5: Close Spaced Burner/Wall Arrangement with Constant Resident Time, Reduced Burner Input Rating (per sq-ft), Larger Diameter Furnace & Larger Diameter Burner.

MOD. 6: Close Spaced Burner/Wall Arrangement with Constant Resident Time, Base Burner Input Rating (per sq-ft), & Through a Base Arc Length.

MOD. 8: Close Spaced Burner/Wall Arrangement with Reduced Resident Time, Base Furnace Diameter, Base Burner Input Rating (per sq-ft), & Through a Base Arc Length.

Also attach is a commentary documenting the results of each arrangement and the logic used in selecting the subsequent computer mode.

The results of the modeling thus far indicates that the original hypothesis is not supported. The original concept was that if heat could be absorbed from the combustion process at a higher rate, then the flue gases would be cooler and less thermal NOx would be formed. This is true to a minor extent, but the variations in absorption tested by 1) modeling a membrane wall verses a spaced wall with 50% exposed refractory, or 2) placing the burner heat release surface closer to the water cooled wall, had but a minor effect on furnace temperature. Neither case appreciably lowered the furnace gas temperature, and the effects on thermal NOx was slight. In fact, in the latter case, the NOx production actually went up.

It is estimated that approximately 80 % of the heat released from combustion supports the increase in the flue gas mass temperature, and only approximately 20 % is absorbed by the furnace. By increasing the furnace effectiveness by 12 to 14 % (the shift from OPTION 3 vs. OPTION 4), the shift in heat transfer is but approximately 2 to 3 % of the total. It is estimated that improving the effectiveness of the furnace wall still further with extended surface we could achieve up to 40 % improved heat transfer, resulting in an 8 percent shift of the total. This may result in a furnace temperature drop of an estimated 200 F. If we are close to the thresh hold of thermal NOx this could result in a more significant drop in NOx formation.

We took a closer look at the radiation heat transfer as compared to the convective heat transfer in OPTION 4. This is shown in the 2 plots labeled FURNACE HEAT FLUX; Ratiative & Convective. This incicates that 95 % of the furnace heat transfer is ratidative, and only 5 % is convective.

In the case of the closer spacing of the burner to the furnace wall (MOD. 5), it is concluded that the closer proximity of the burner to the wall didn't really change the overall radiation component, but did improve convection heat transfer slightly due to increased velocities adjacent to the wall. However, changes in the furnace internal recirculation patterns overshadowed this improvement. A far greater effect is seen in the amount of furnace gases entrained in the gas jets. It appears that it may be possible to use this characteristic to a greater extent by using stronger jets (higher pressure drop across the jets), and by arranging their location such that the furnace gases will realize less resistance to reach the root of the jet. Instead of having 1 inch perforation strips on 2 inch centers, perhaps it would work more effectively by doubling the clear space between every other perforation strip. This would result in increasing the clear space by approximately 50%, and increasing the jet velocity by about 50 %.

It is recommended that we extend the modeling program to investigate the above suggested possibilities. I would recommend the following:

1) Reconstructing the burner model to modify the perforation strips. The above arrangement would be one possibility; you may have some other suggestions.

2) Re-run OPTION 4 and MOD. 8 configurations with this modified burner design.

3) Increase the furnace wall heat transfer by adding a large amount of extended surface to the extent that it is even exaggerated to see if this will have a significant effect on Thermal NOx.

4) Repeat test runs 1 and 2 to evaluate relative effectiveness.

The cost of these additional runs is estimated as follows: ITEM		
	1)-------------	$ 900.00
	2)-------------	$ 900.00
	3)-------------	$1,800.00
	4)-------------	$ 900.00
TOTAL		$4,500.00

Should you have any questions regarding the attached please give me a call.

Regards,

Richard Vetterick

Richard C. Vetterick

Enclosure
cc: D. C. Langley
M. W. Hopkins
M. J. Albrecht

ALZETA BURNER MODELING

SUBSEQUENT COMPARATIVE STUDIES

OPTION 4:

OPTION 4 is identical to OPTION 3 with the exception that the absorption factors for the water cooled wall were increased to represent a membrane wall, as compared to 1 inch tubes on 2 inch centers with kaowool backing. As compared to Option 3, the furnace gas temperatures dropped approximately 44 F at the 8 ft location, and the NOx decreased by an average of 0.2 ppm, or 2.8%.

MOD. 5: Modification 5 is a reconstruction of the model to bring the burner closer to the water cooled furnace walls. This posed somewhat of a problem in that as the burner diameter was increased to bring the fire closer to the wall, the cross sectional flow area decreased dramatically; reducing resident time. It was decided to maintain resident time by increasing the burner diameter and the furnace diameter to the extent that the burner would be half the distance from the wall, but the cross sectional flow area would be the same. This resulted in a 120 inch burner diameter, and a 160 inch furnace diameter, with 20 inch spacing from the burner surface to the water cooled wall. This then posed a second problem, how to set the burner heat release rate. A reduced burner surface heat release rate was chosen, keeping the perforation pattern the same as option 3. This cut the burner heat release rate to one quarter of the previous rate. The absorption characteristic of the furnace wall was kept at the membrane wall factors.

The calculated average furnace temperature at the 4ft. and 8 ft. locations went down slightly (56 F & 30 F respectively), but the NOx went up significantly, from 6.9 ppm to 7.4 (6.9%) and 7.7 (10.4%) respective to the location. This is just opposite from what we expected, and caused us to review our assumptions. Since the burner heat release rate was reduced to one quarter, it was decided to reestablish this to the original values, and to use only a portion of the burner arc for the high input zone, still using the same perforation pattern. This lead to MOD. 6.

MOD. 6: The burner high heat release rate arc in this case returned to 23.6 inches, and the heat release rate returned to that used in OPTION 4. The clearance from the burner surface to the furnace surface was kept at 20 inches. In this case the average calculated furnace temperature at the 4 & 8 ft location dropped down slightly, but the NOx dropped dramatically! The NOx levels dropped from the 6.9 ppm levels in OPTION 3 to 5.4 ppm, some 21.7%. As compared to mod. 5, the drop was 27 % and 30 % respectively at the 4 ft. and 8 ft. locations. Since the heat absorption rates of the furnace wall were not changed, and the clearance from the burner to the furnace wall was not changed, it is concluded that the major contributing factor is the ability, in this arrangement, for the furnace gases to find a flow path back to the root of the burner jets. The velocity vector pattern and relative magnitude (vector length) indicates that there is considerable recirculation within the furnace in this arrangement. The low heat release rate zones on either side of the high heat release rate zone (where the perforations are) provide a flow path for the furnace gases to more easily return to the root of the perforation jets.

MOD. 8: It was decided at this point to return to the original size furnace, to maintain the 20 inch clear space between the burner and the furnace wall, and to maintain the 23.6 inch high heat input burner pattern. This left approximately 31.4 inches on either side of the high heat input burner zone for free flow recirculation patterns (as compared to 35 1/3 in MOD. 6). This produced essentially the same results as MOD. 6.

END

RCV (12/2/97)

Case	Description	Average Furnace Gas Temperature (°F)				Average NO_x (ppm)				Average Heat Flux (kBTU/hr-ft^2) <21ft (<10ft)
		4 feet	8 feet	14 feet	16 feet	4 feet	8 feet	14 feet	16 feet	
Test	Test Point Data	1637	1655	1688	1624	--	--	--	7	?
Alzeta	Spreadsheet Ave Data	2009	2089	1993	1925	--	--	--	--	19.5 (19.8)
Option 3	Model Average Data	2159	2140	1923	1852	7.1	7.1	7.1	7.1	19.0 (19.7)
Option 4	Model Average Data	2120	2096	1857	1780	6.9	6.9	6.9	6.9	21.8 (22.2)
Mod 5	Model Average Data	2064	2069	1745	1646	7.4	7.6	7.7	7.7	12.2 (13.4)
Mod 6	Model Average Data	1931	1956	1672	1578	5.4	5.4	5.4	5.4	13.5 (15.2)
Mod 8	Model Average Data	2172	2188	1909	1807	5.3	5.2	5.2	5.2	18.0 (18.3)

Table: Stage Two Summary Results

ALZETA SUMMARY OF B&W MODELING RESULTS

Attached are the two B&W reports summarizing the modeling of the Alzeta RSB that was done with DOE funds. We view these results as being useful to our effort to develop the RSB for industrial boilers, but additional work is required. Comments on this work are provided on this page as our summary to this Appendix.

The second report, dated December 2, 1997 presents the results of modifications made to the boiler to more quickly cool the flue gas. These modifications were:

- Model the effect of membrane wall construction versus the exposed refractory between tubes as existed at Cymric. Membrane wall construction results in a continuous metal wall surface, with the "membrane" between tubes being welded to the watertubes. The result of this should be slightly higher heat removal in the firebox.

- Model the effect of closer burner-to-wall spacing. Reduced burner-to-wall spacing should result in reduced gas phase radiation (if no other parameters are changed), with the result that NO_x production will increase (as observed by B&W). Reduced burner-to-tube spacing increases heat removal via gas phase radiation only if you split a large gas volume into several small volumes and add heat transfer surface between the small volumes. Reduced burner-to-wall spacing can increase convective transfer, but convection is a small component of total firebox heat transfer.

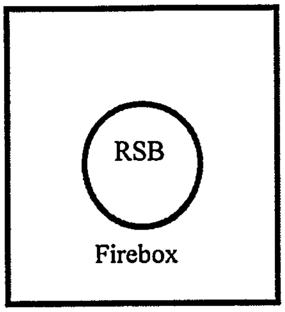
The B&W report concludes that "The results of the modeling thus far indicates that the original hypothesis is not supported." We disagree with this conclusion. **If** heat is absorbed from the combustion process at a higher rate, **then** the flue gases will be cooler and less thermal NO_x will be formed. The modifications modeled by B&W did not significantly increase heat removal, and therefore did not reduce NO_x. The B&W modeling did demonstrate that membrane wall construction and reduced burner-to-wall spacing, by themselves, are not sufficient to significantly increase heat transfer. This is valuable information, since additional modifications to remove heat from the firebox such as an intermediate tube wall in the firebox or extended tube surface will be more expensive to implement.

Other very useful information provided by B&W in the December 2 report is the split of heat absorption between the firebox and convective section, and between radiation and convection mechanisms, in the boiler. Understanding where, and by what mechanism, heat is removed is critical to the design of the sub-9 ppm boiler. In addition, the Alzeta plug flow model was shown to agree closely with the B&W CFD code. In the future we will use the Alzeta code to assess the impact of burner modifications on boiler performance with greater confidence.

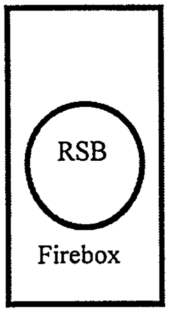
The Alzeta conclusions are as follows:

- Splitting a standard firebox into two burner compartments with an intermediate tube wall would have a significant effect on heat removal rate. Gas phase radiation is estimated to be increased by more than 25 percent in the firebox in a typical boiler configuration.

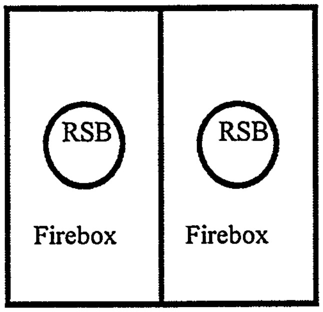
Adding extended tube surface to firebox boiler tubes will increase the heat removal rate, but the magnitude of this increase is still being evaluated. The increase due to increased convection is insignificant. The more significant impact will have to be the result from increased gas phase absorption.



1. End view of Standard Firebox with Alzeta burner



2. Configuration with Reduced Burner-to-Tube Spacing



3. Intermediate Tube Wall Configuration

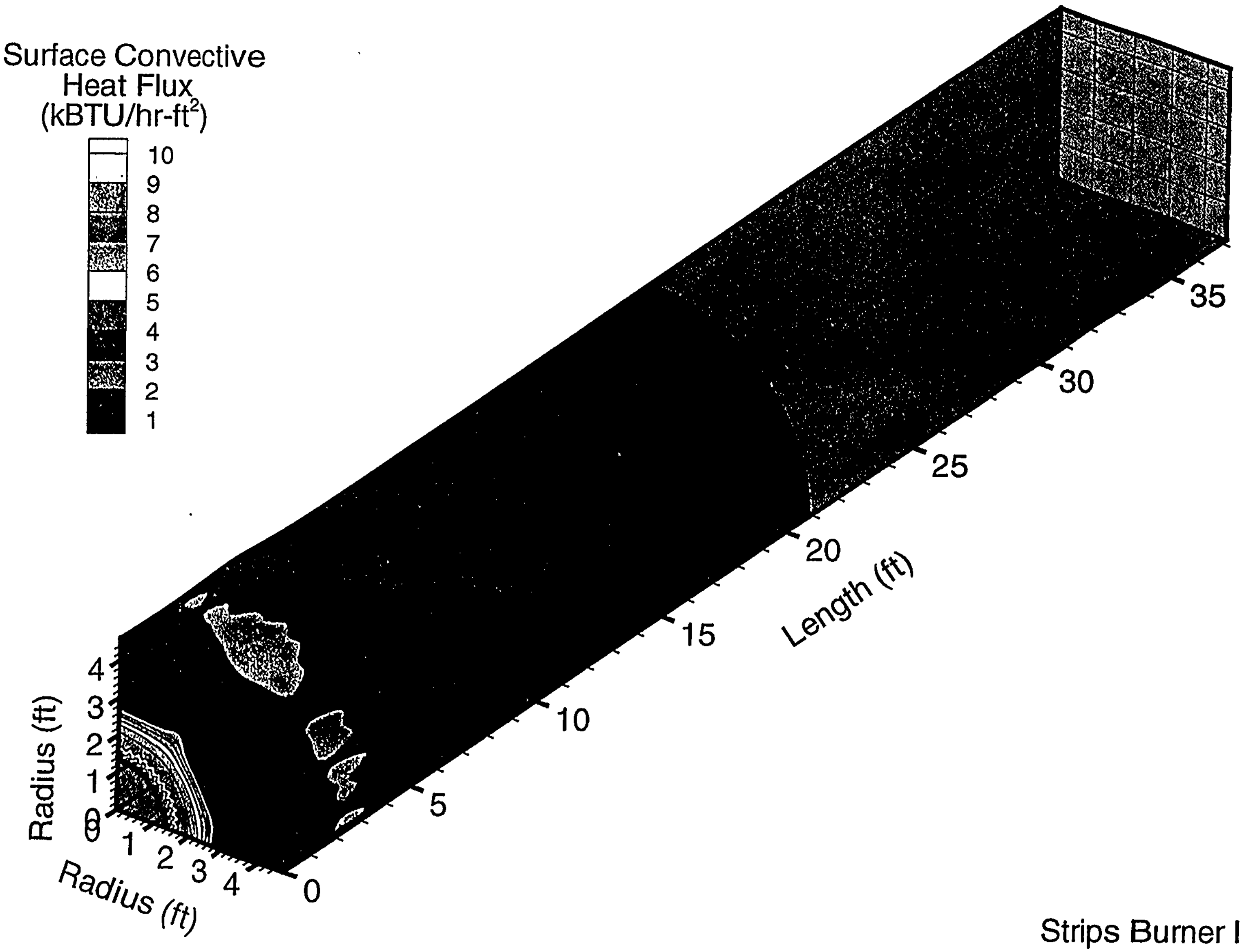
Configuration 1 shows the standard RSB configuration in a package boiler. Note that B&W modeled the cylindrical RSB inside of a cylindrical steam generator, but the same trends will be observed regardless of whether the firebox has a cylindrical or rectangular cross section.

In Configuration 2, the firebox volume is reduced. If the total fired duty of the burner is held constant between Configuration 1 and Configuration 2, then heat absorbed in the firebox is reduced. In the configuration presented, the residence time in the firebox is also reduced. The size of the box and the burner can both be increased to maintain both the Configuration 2 burner-to-tube spacing and the Configuration 1 residence time. In either case, heat absorbed in the firebox is reduced.

In Configuration 3, the firebox volume is equivalent to the Configuration 1 volume. An intermediate tube wall is added, with a burner in each cell. The total fired duty of the two Configuration 3 burners is equivalent to the fired duty of the Configuration 1 burner. Gas phase radiation to each tube wall is less in Configuration 3 relative to Configuration 1, but it is greater than 50 percent of the Configuration 1 flux. Therefore, when the additional tube wall is added to increase the firebox surface area, the result is an increase in total heat removal from the firebox.

Alzeta Burner Project, Cymric Model - Stage 2

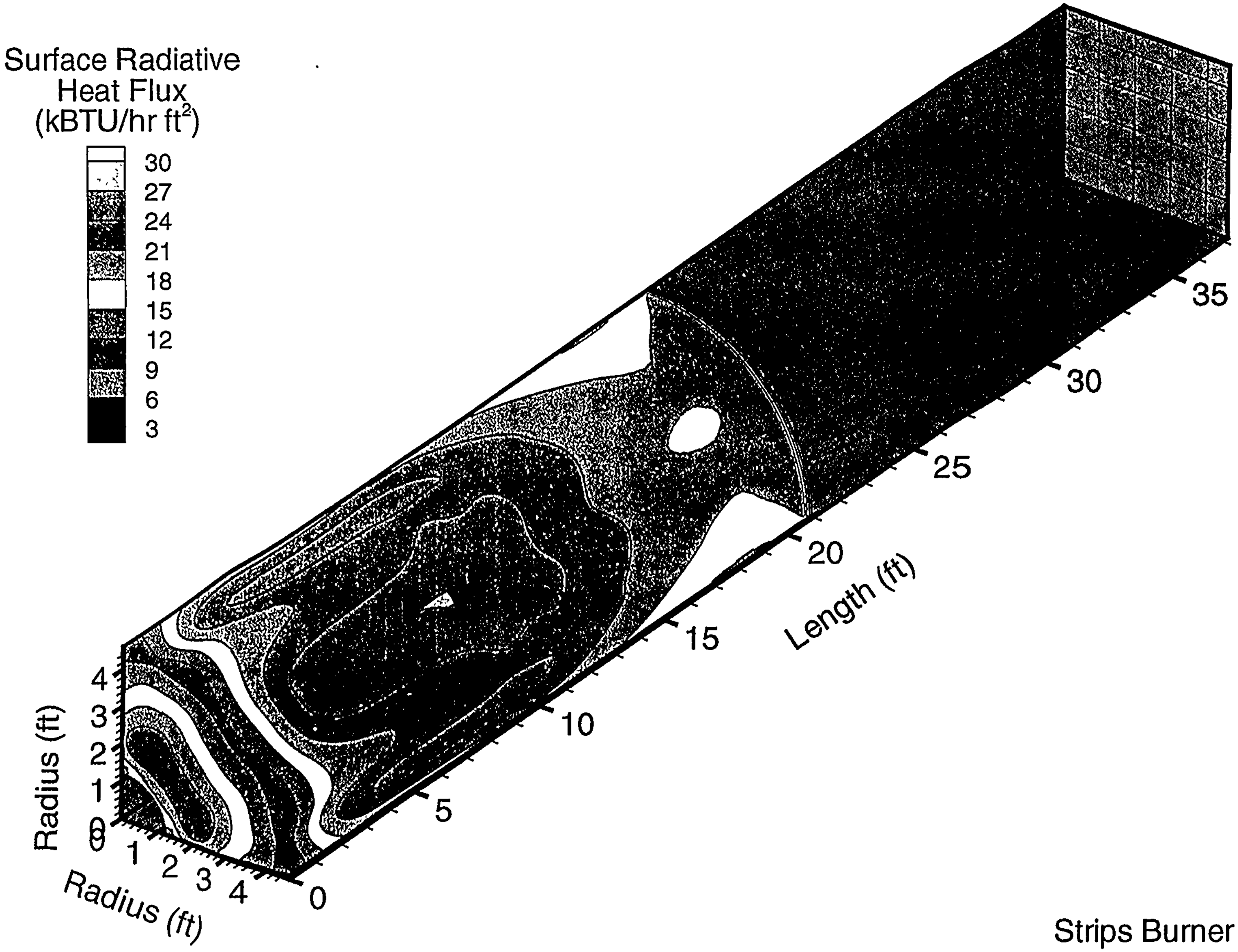
Option 4 - Furnace Heat Flux



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

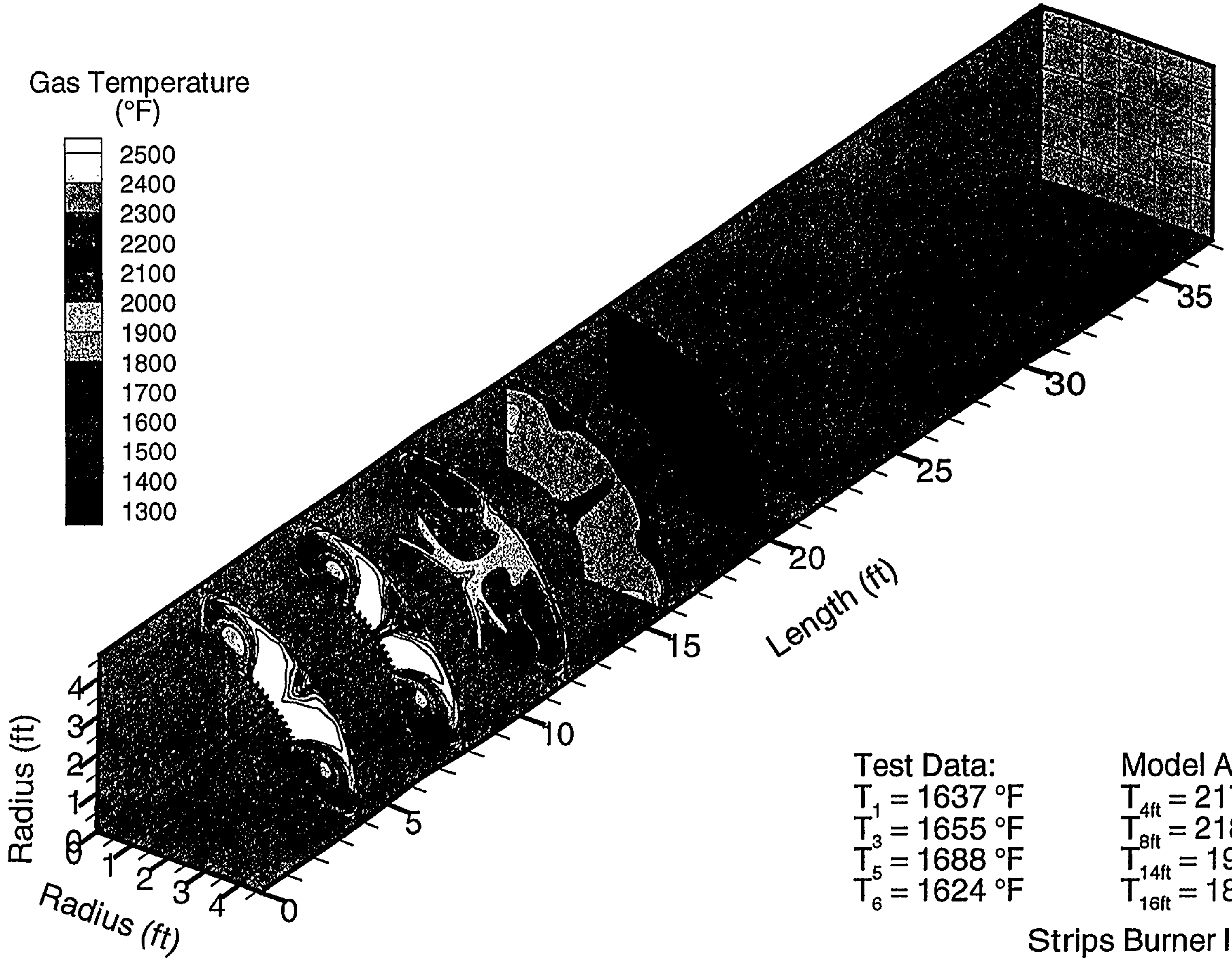
Option 4 - Furnace Heat Flux



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Modification 8 - Furnace Gas Temperatures



Test Data:
$T_1 = 1637$ °F
$T_3 = 1655$ °F
$T_5 = 1688$ °F
$T_6 = 1624$ °F

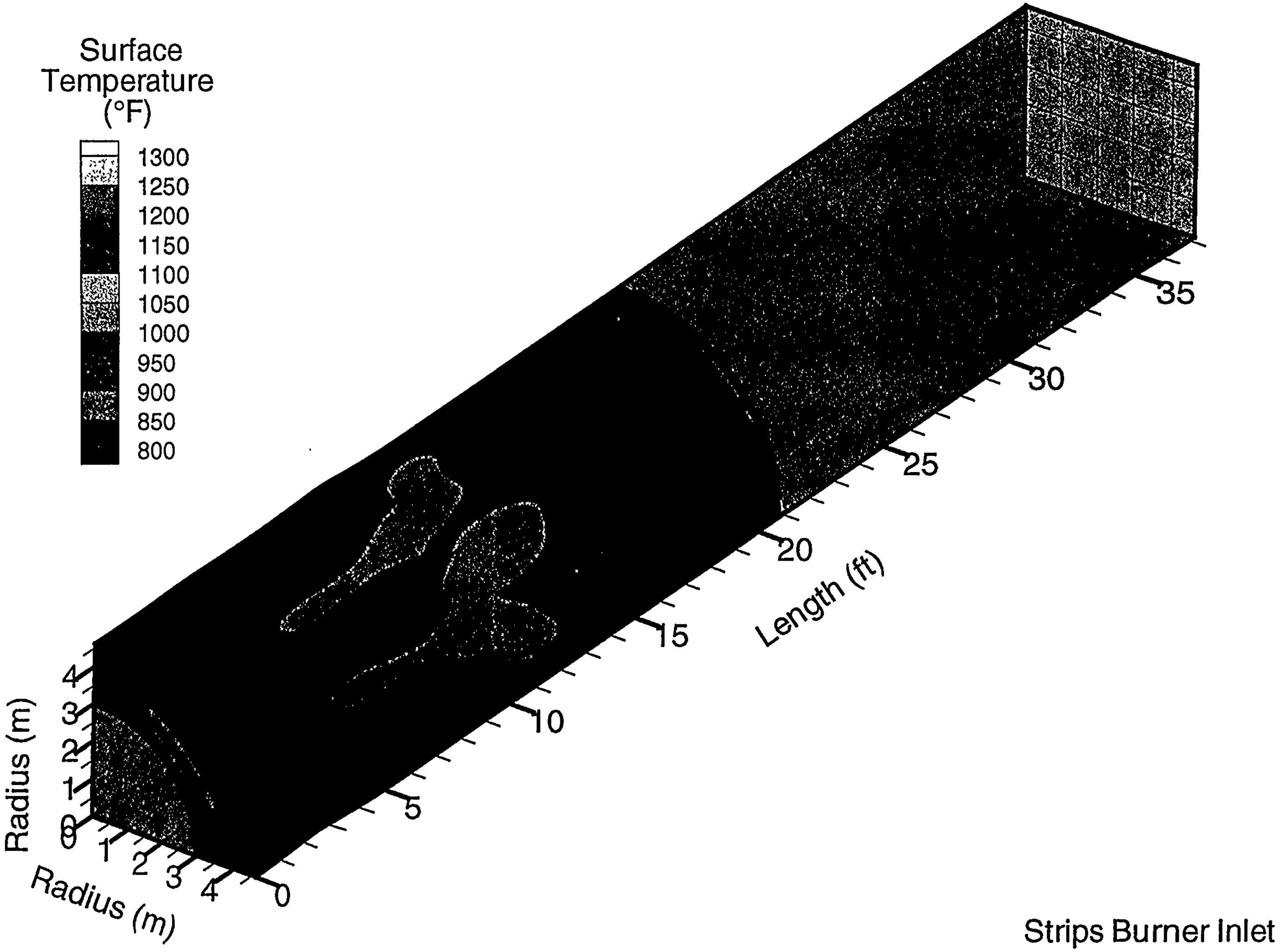
Model Ave:
$T_{4ft} = 2172$ °F
$T_{8ft} = 2188$ °F
$T_{14ft} = 1909$ °F
$T_{16ft} = 1807$ °F

Strips Burner Inlet

a

Alzeta Burner Project, Cymric Model - Stage 2

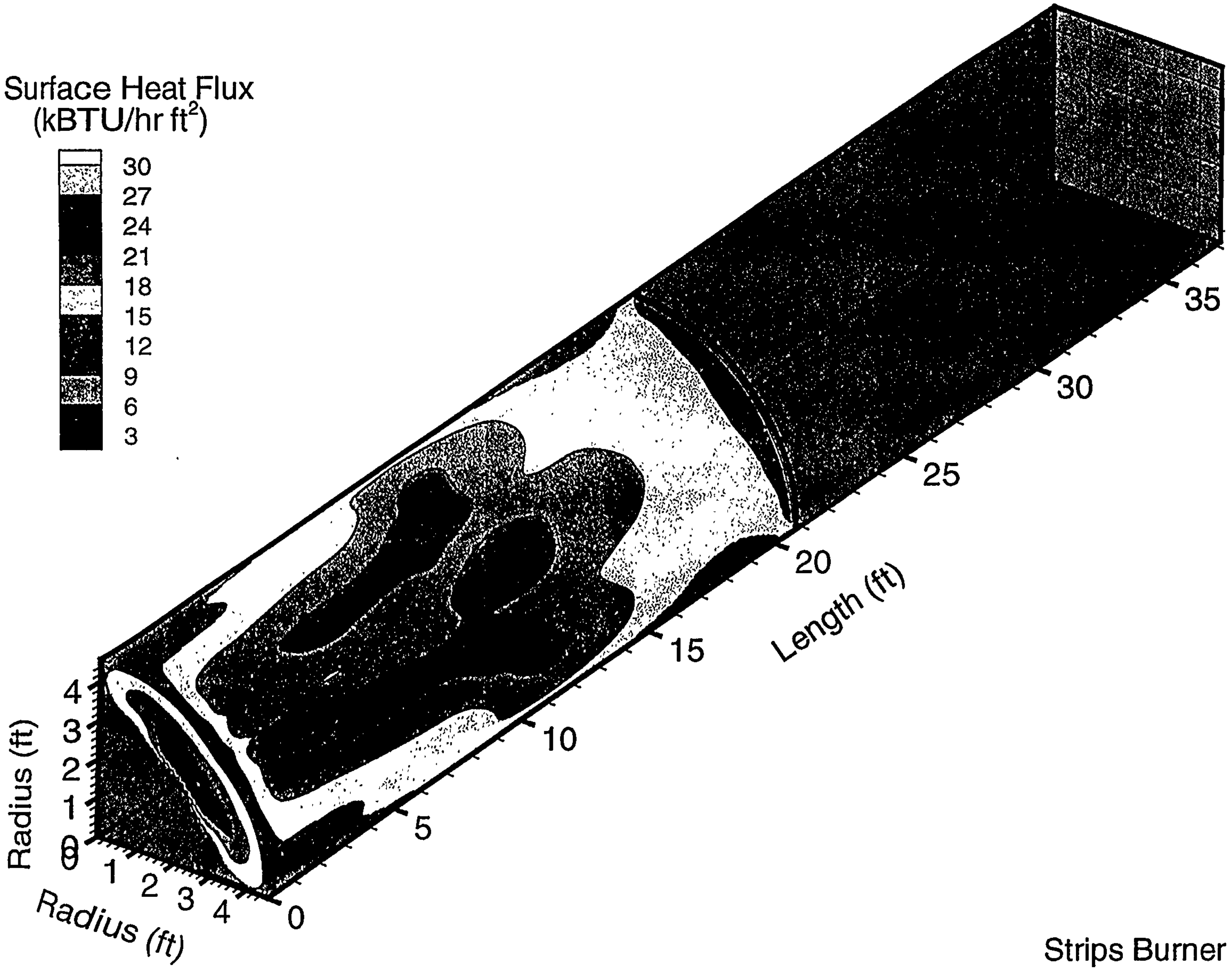
Modification 8 - Furnace Surface Temperatures



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

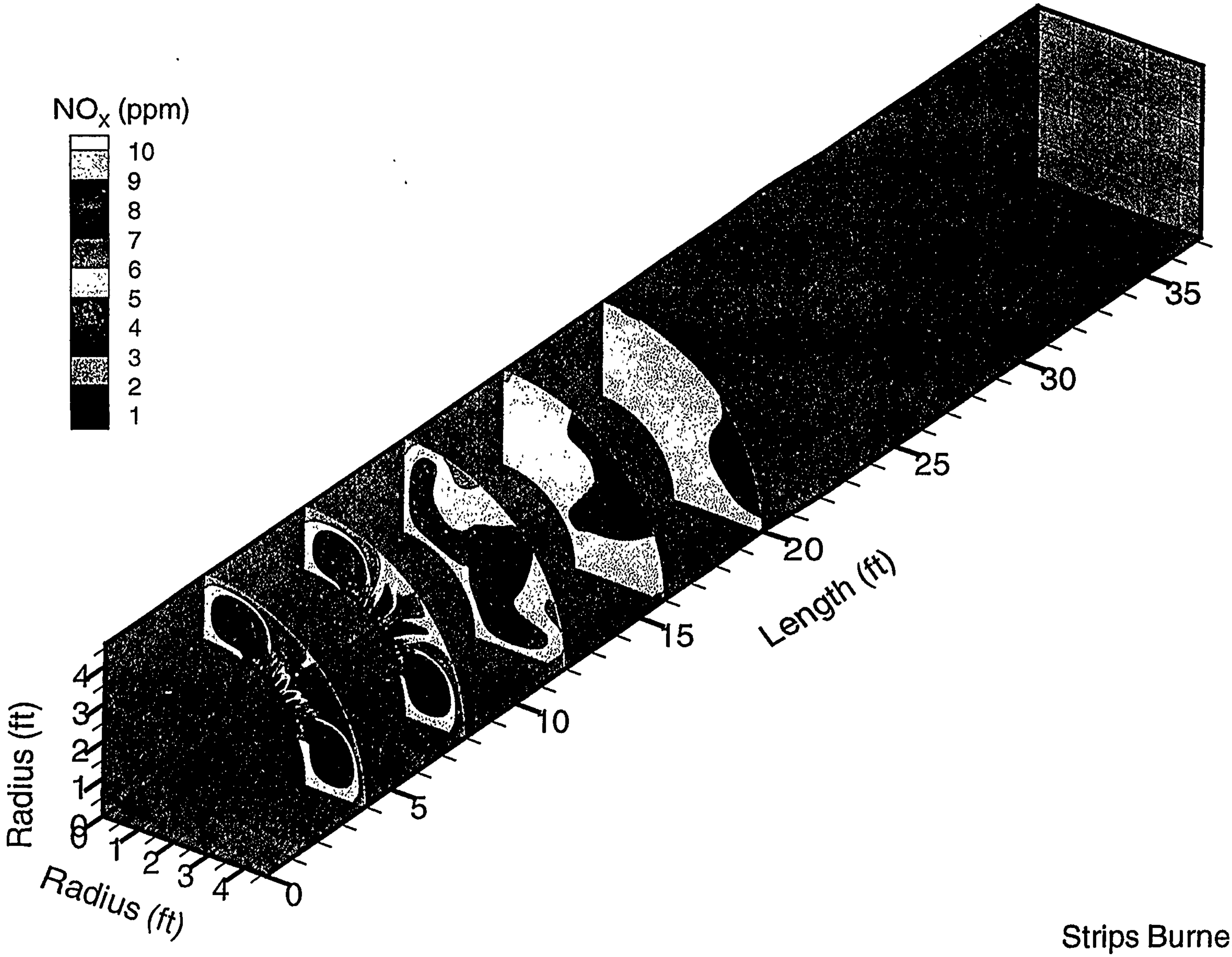
Modification 8 - Furnace Heat Flux



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Modification 8 - Furnace NO_x Levels

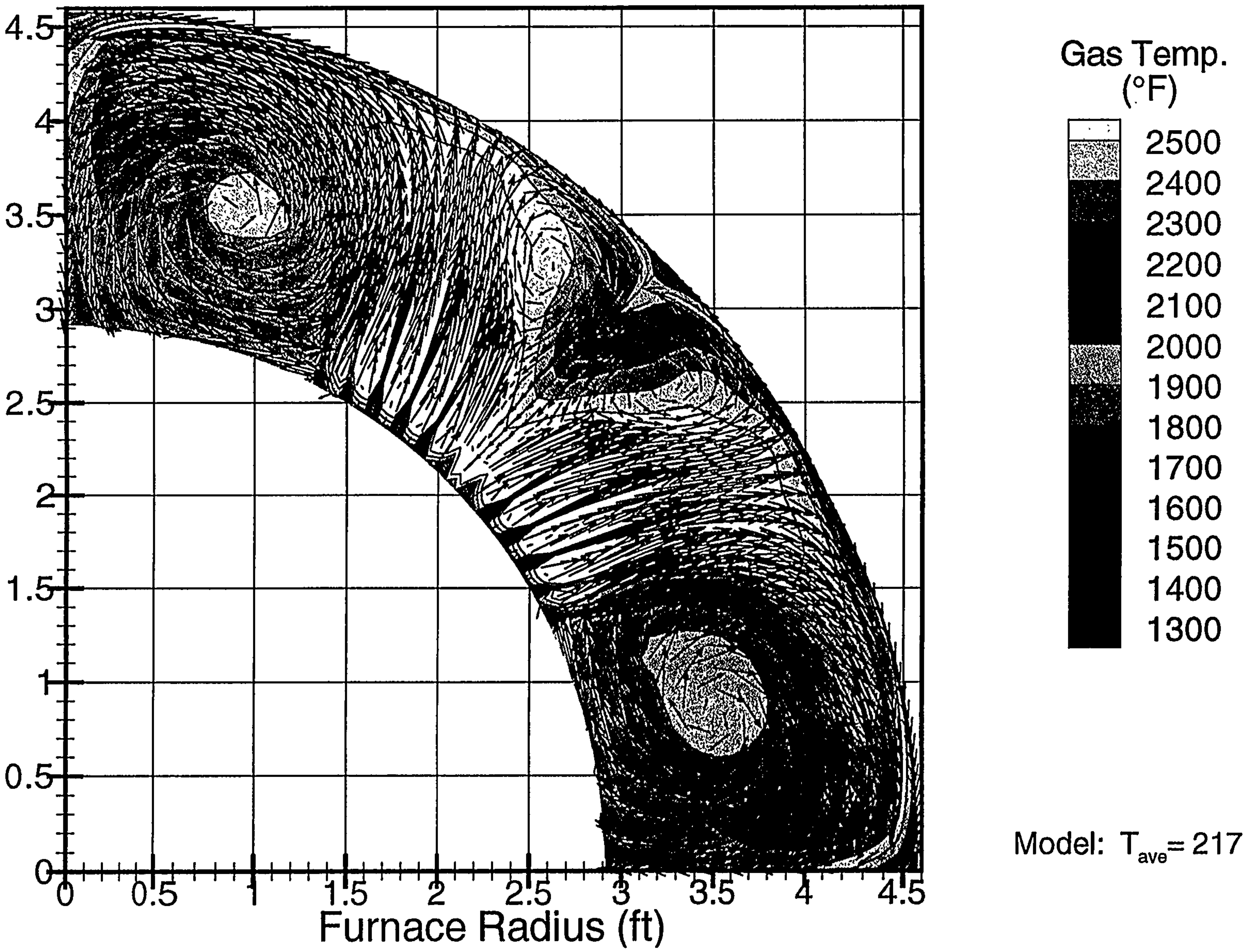


Strips Burner Inlet

d

Alzeta Burner Project, Cymric Model - Stage 2

Modification 8 - Furnace Location at 4 feet

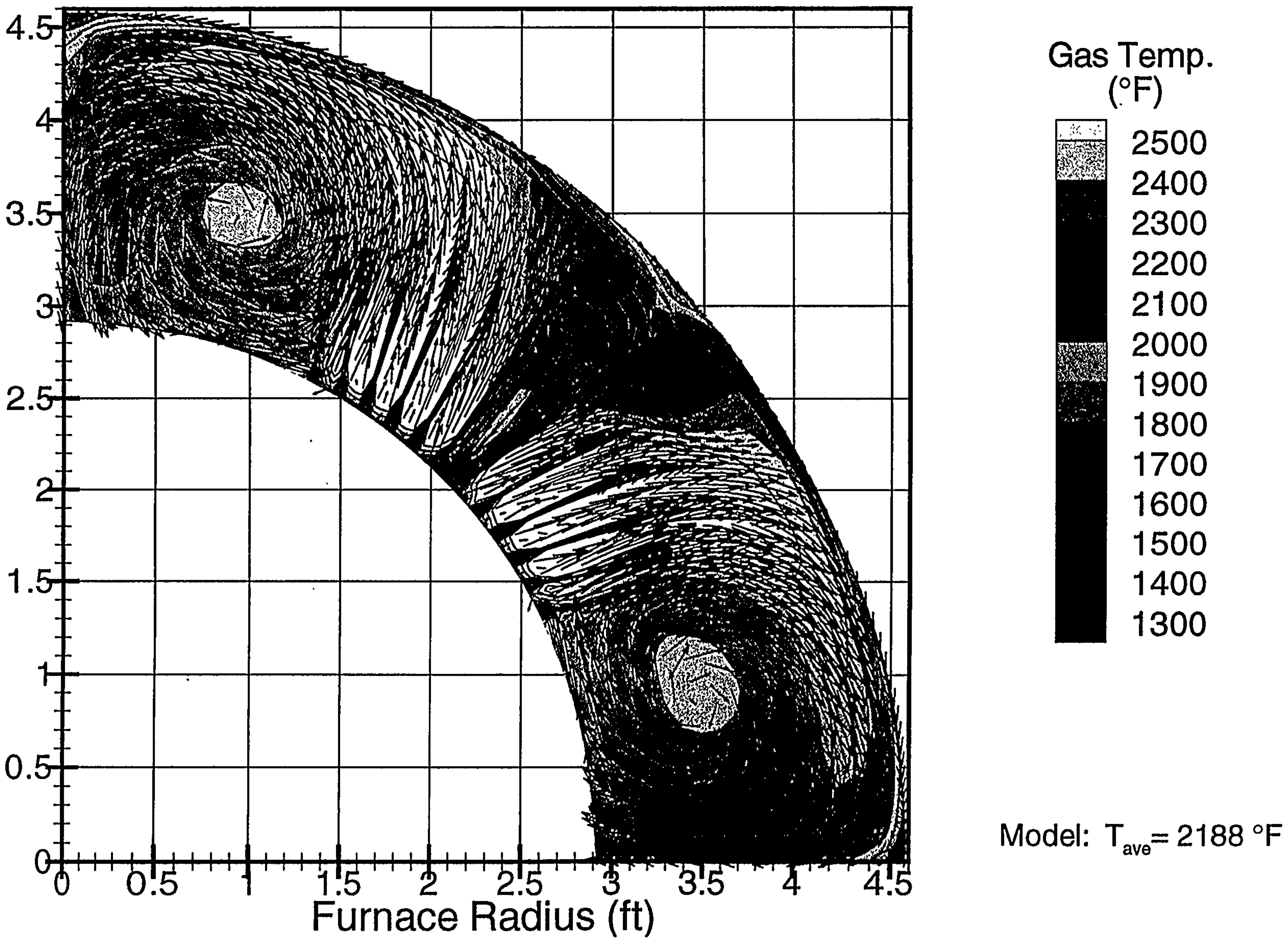


Model: T_{ave}= 2172 °F

e

Alzeta Burner Project, Cymric Model - Stage 2

Modification 8 - Furnace Location at 8 feet

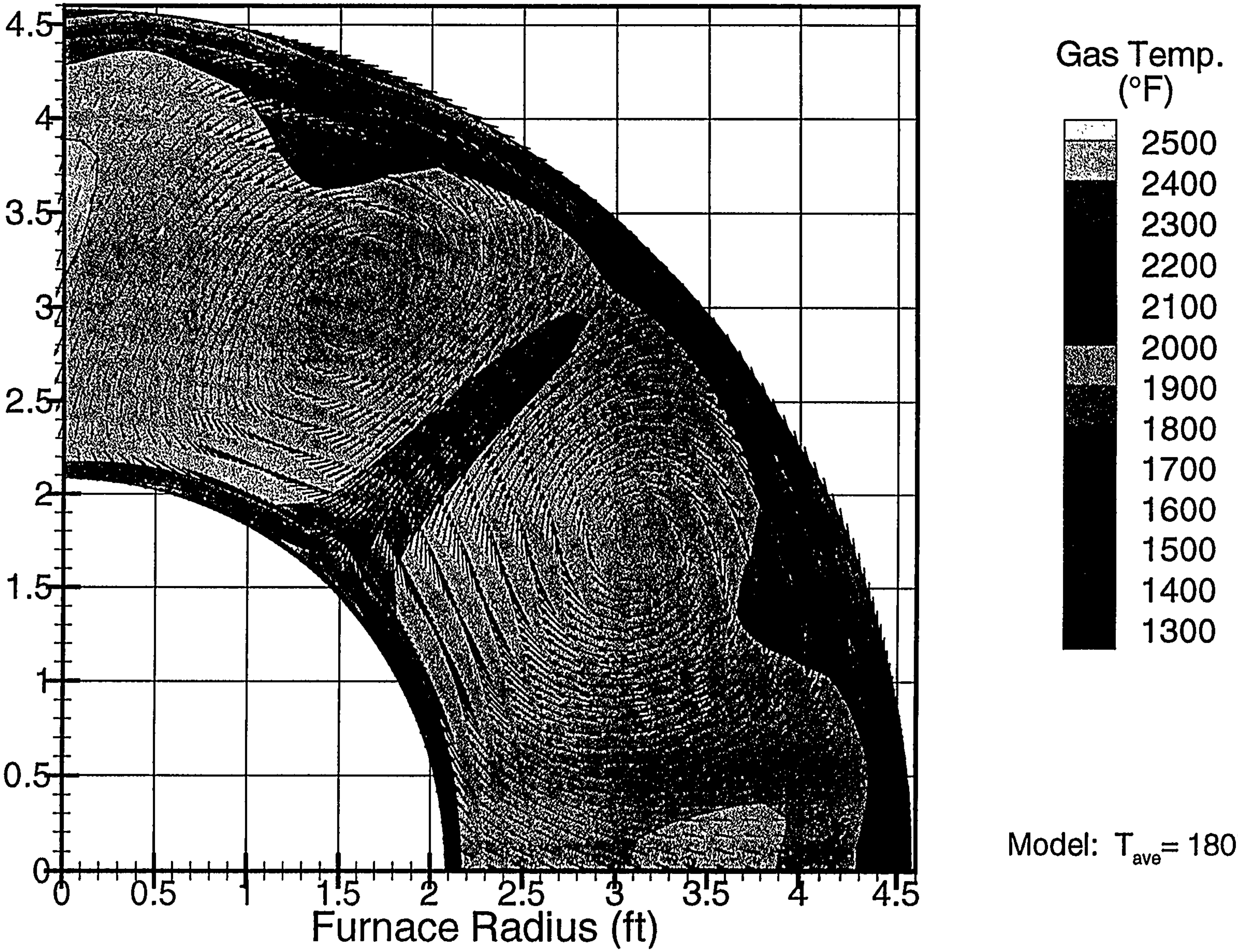


Model: T_{ave}= 2188 °F

f

Alzeta Burner Project, Cymric Model - Stage 2

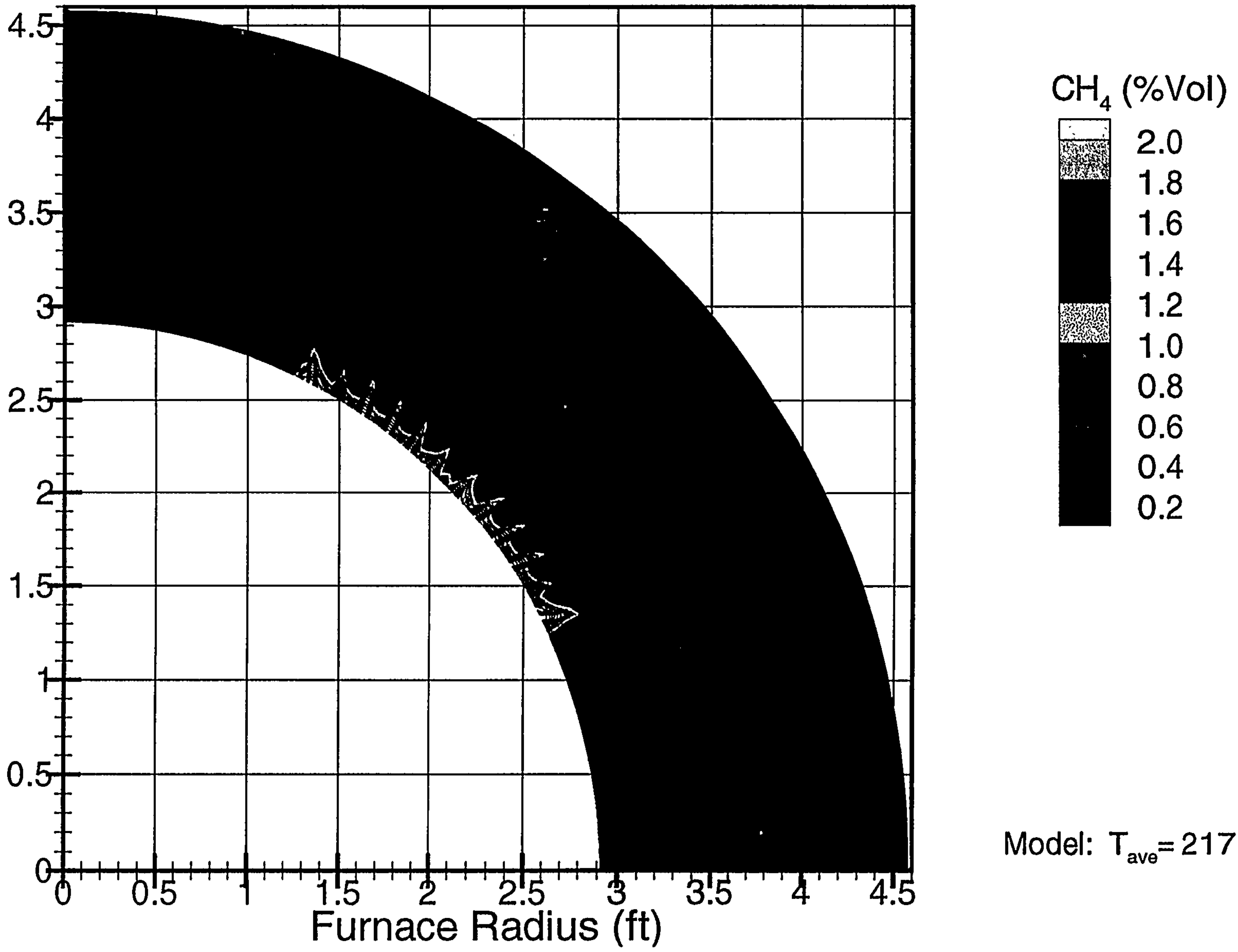
Modification 8 - Furnace Location at 16 feet



Model: T_{ave}= 1807 °F

Alzeta Burner Project, Cymric Model - Stage 2

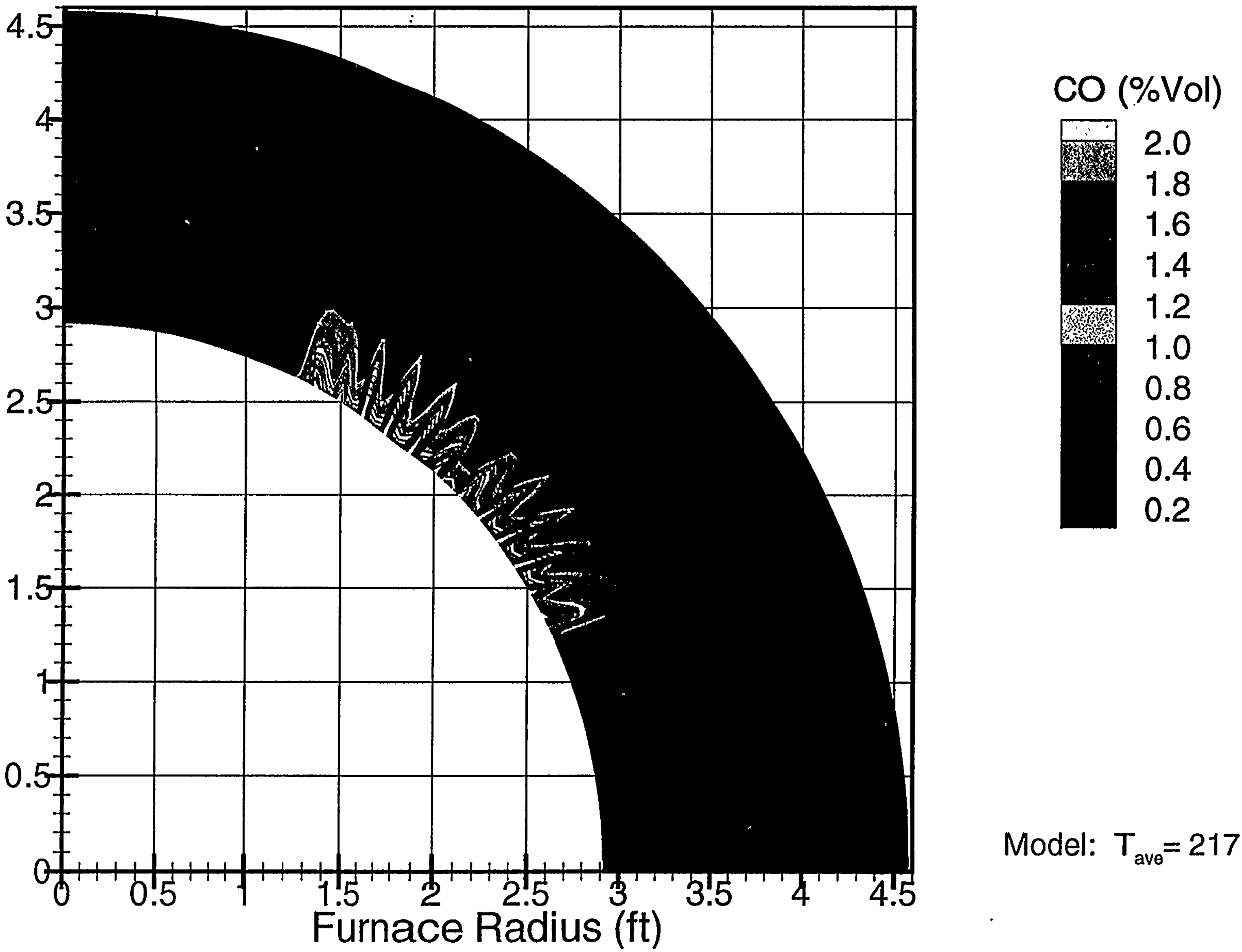
Modification 8 - Furnace Location at 4 feet



Model: T_{ave}= 2172 °F

Alzeta Burner Project, Cymric Model - Stage 2

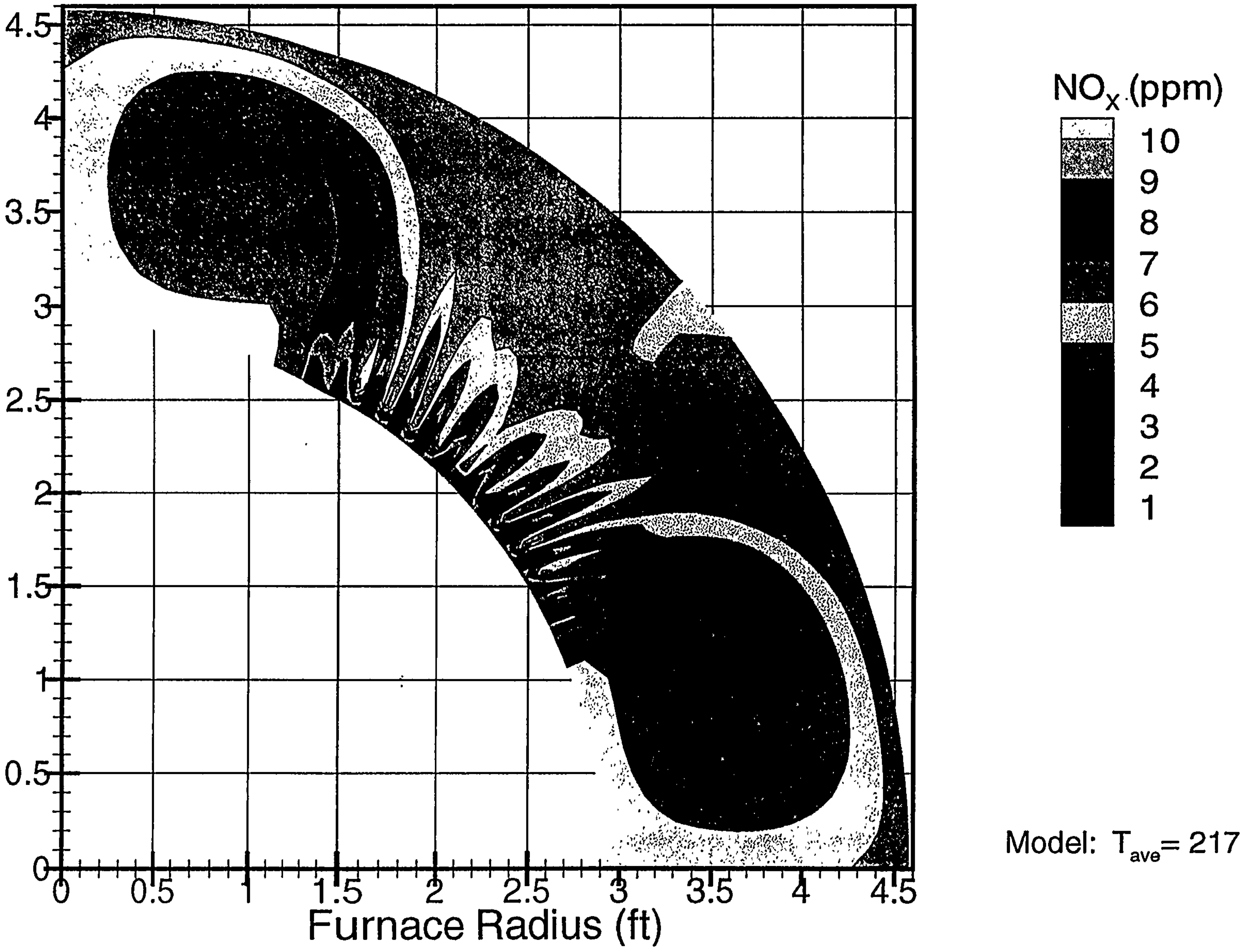
Modification 8 - Furnace Location at 4 feet



Model: T_{ave}= 2172 °F

Alzeta Burner Project, Cymric Model - Stage 2

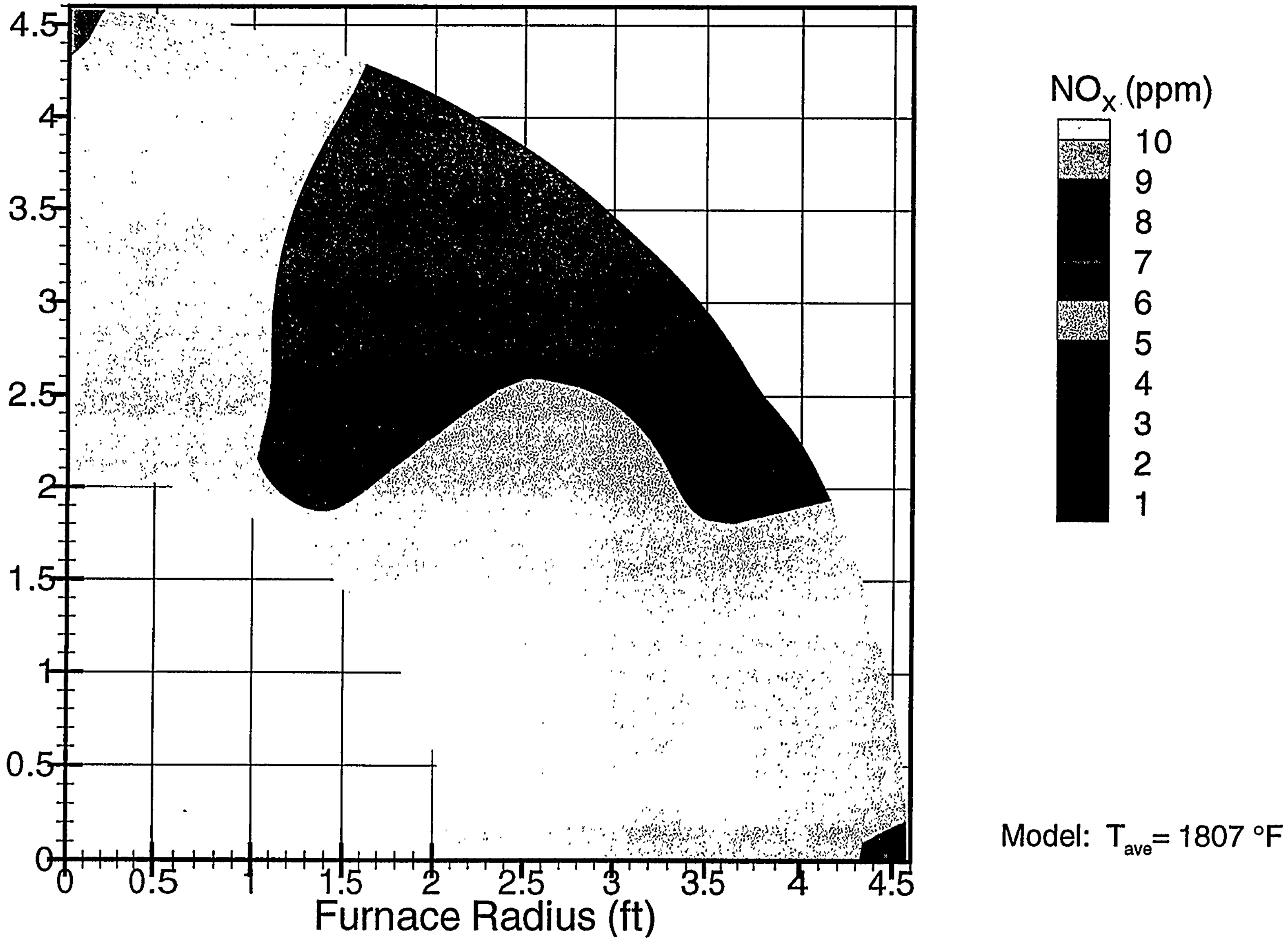
Modification 8 - Furnace Location at 4 feet



Model: $T_{ave} = 2172$ °F

Alzeta Burner Project, Cymric Model - Stage 2

Modification 8 - Furnace Location at 16 feet

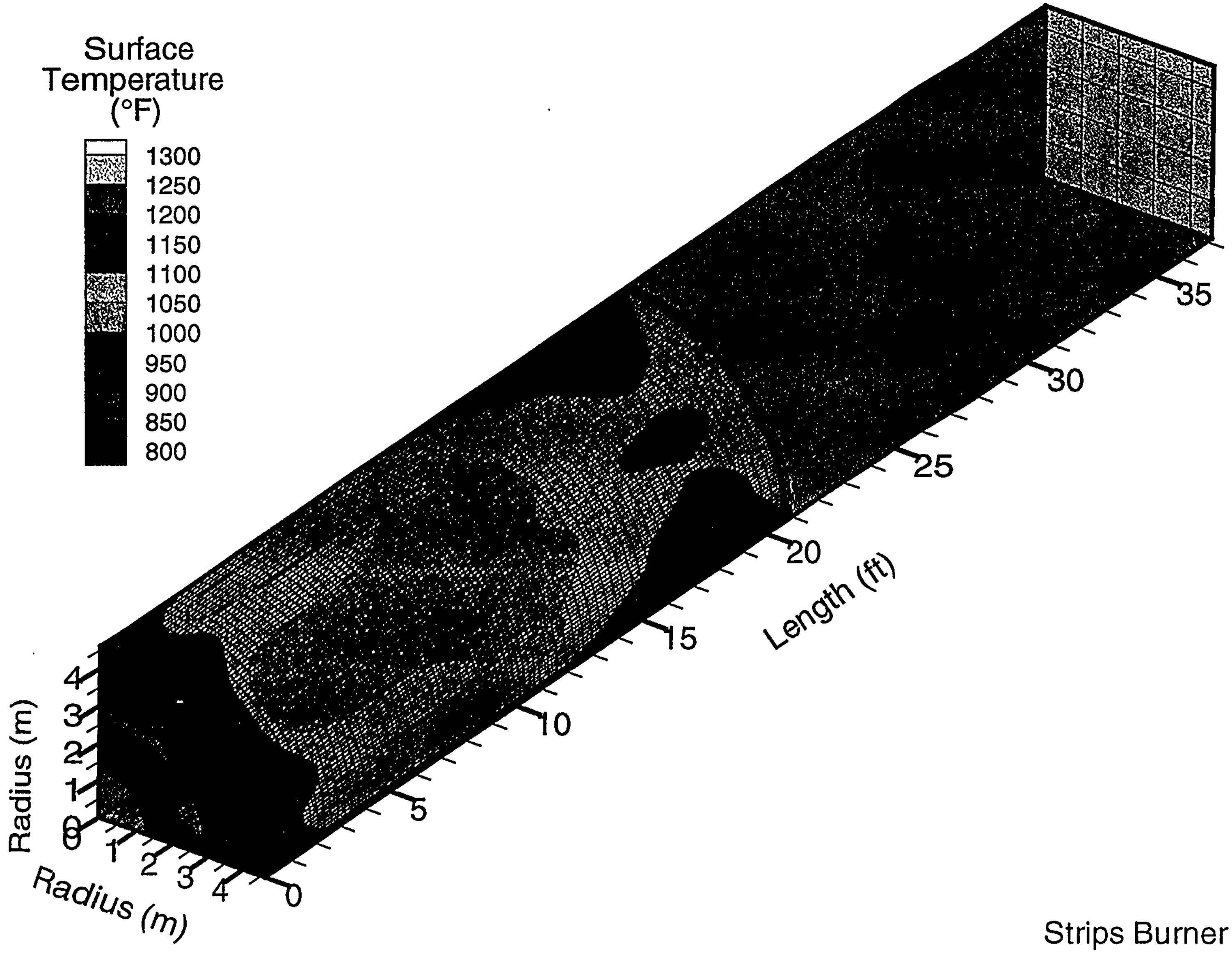


Model: T_{ave}= 1807 °F

l

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Surface Temperatures

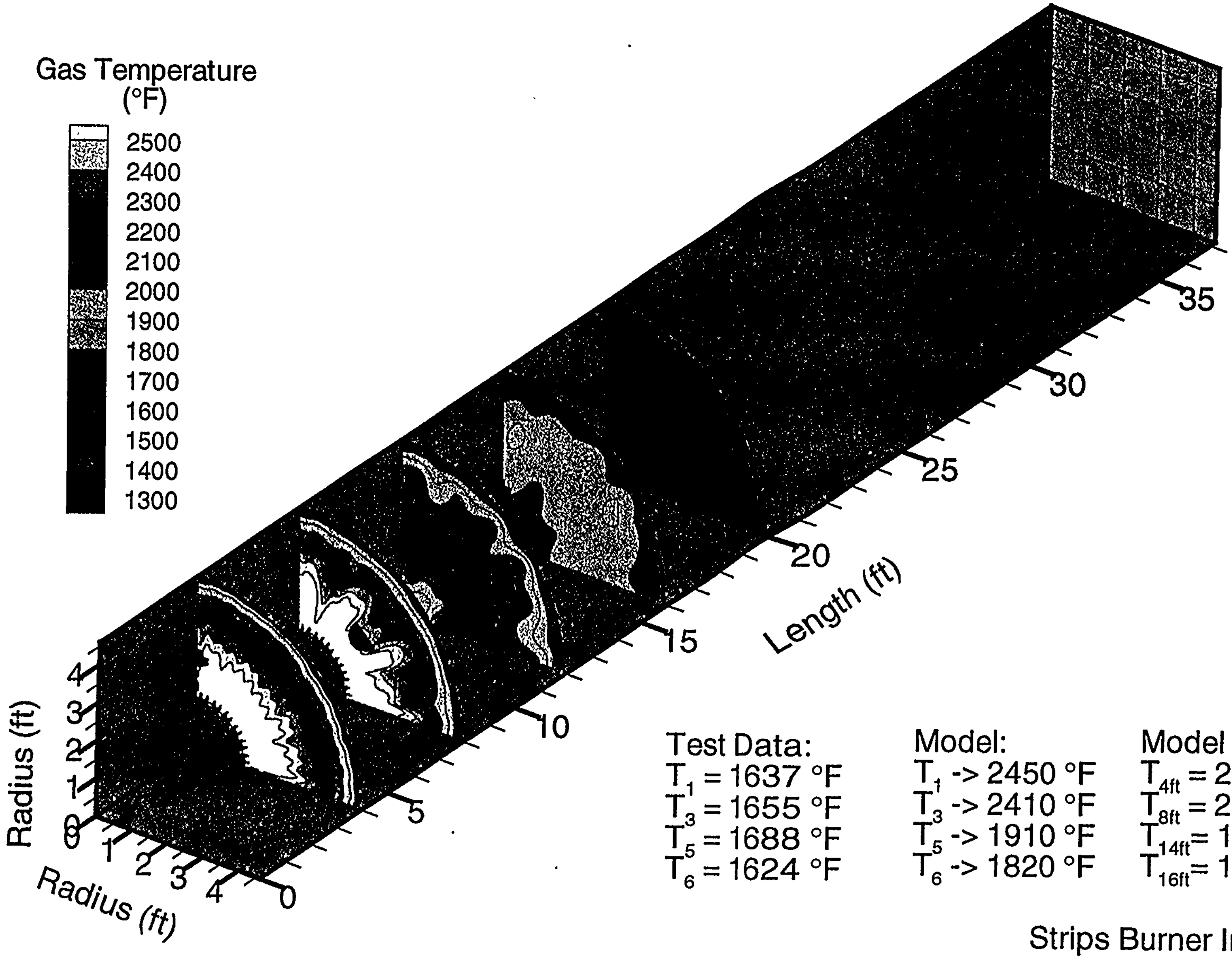


Strips Burner Inlet

a

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Gas Temperatures

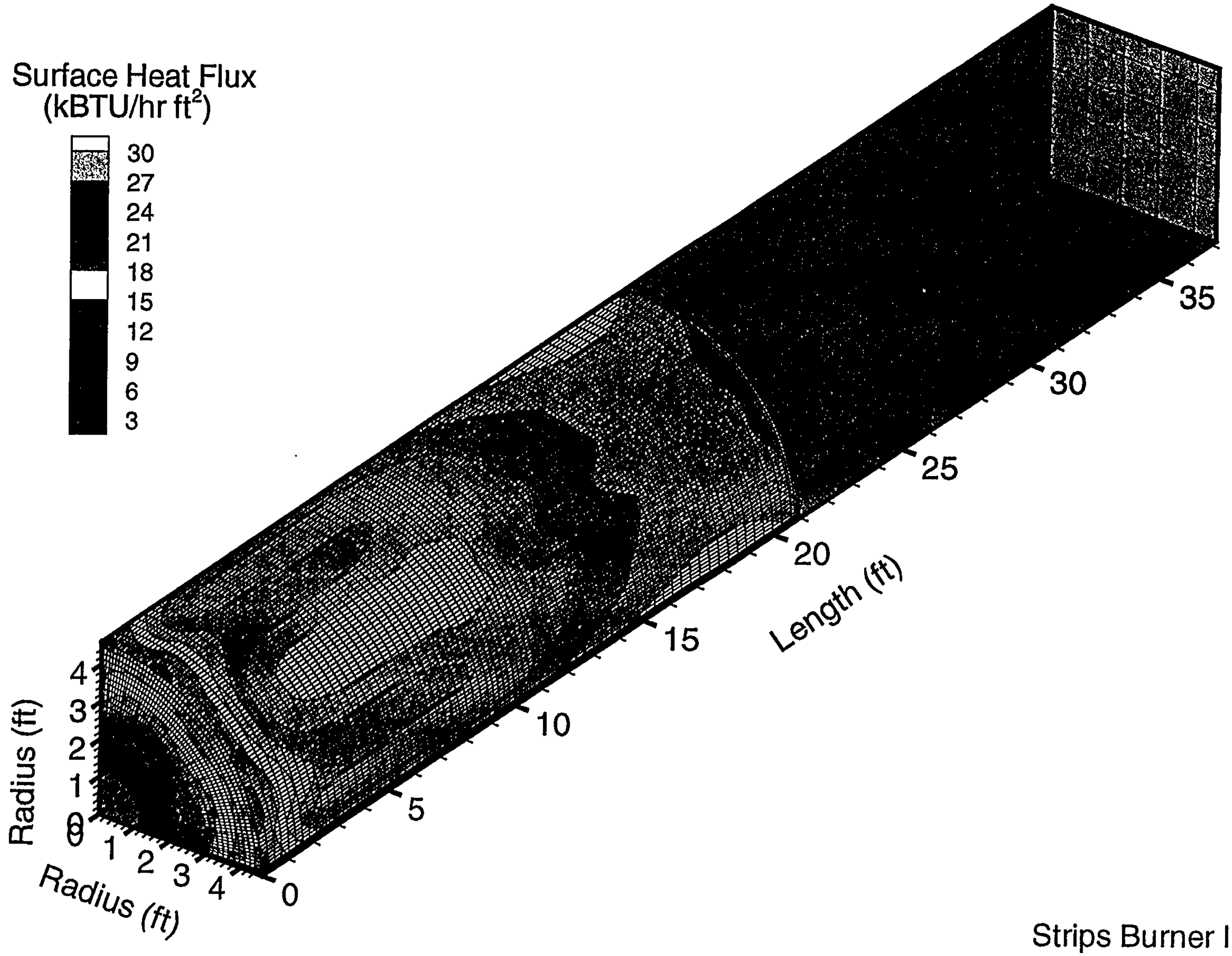


Test Data:	Model:	Model Ave:
$T_1 = 1637$ °F	T_1 -> 2450 °F	$T_{4ft} = 2120$ °F
$T_3 = 1655$ °F	T_3 -> 2410 °F	$T_{8ft} = 2096$ °F
$T_5 = 1688$ °F	T_5 -> 1910 °F	$T_{14ft} = 1857$ °F
$T_6 = 1624$ °F	T_6 -> 1820 °F	$T_{16ft} = 1780$ °F

Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Heat Flux

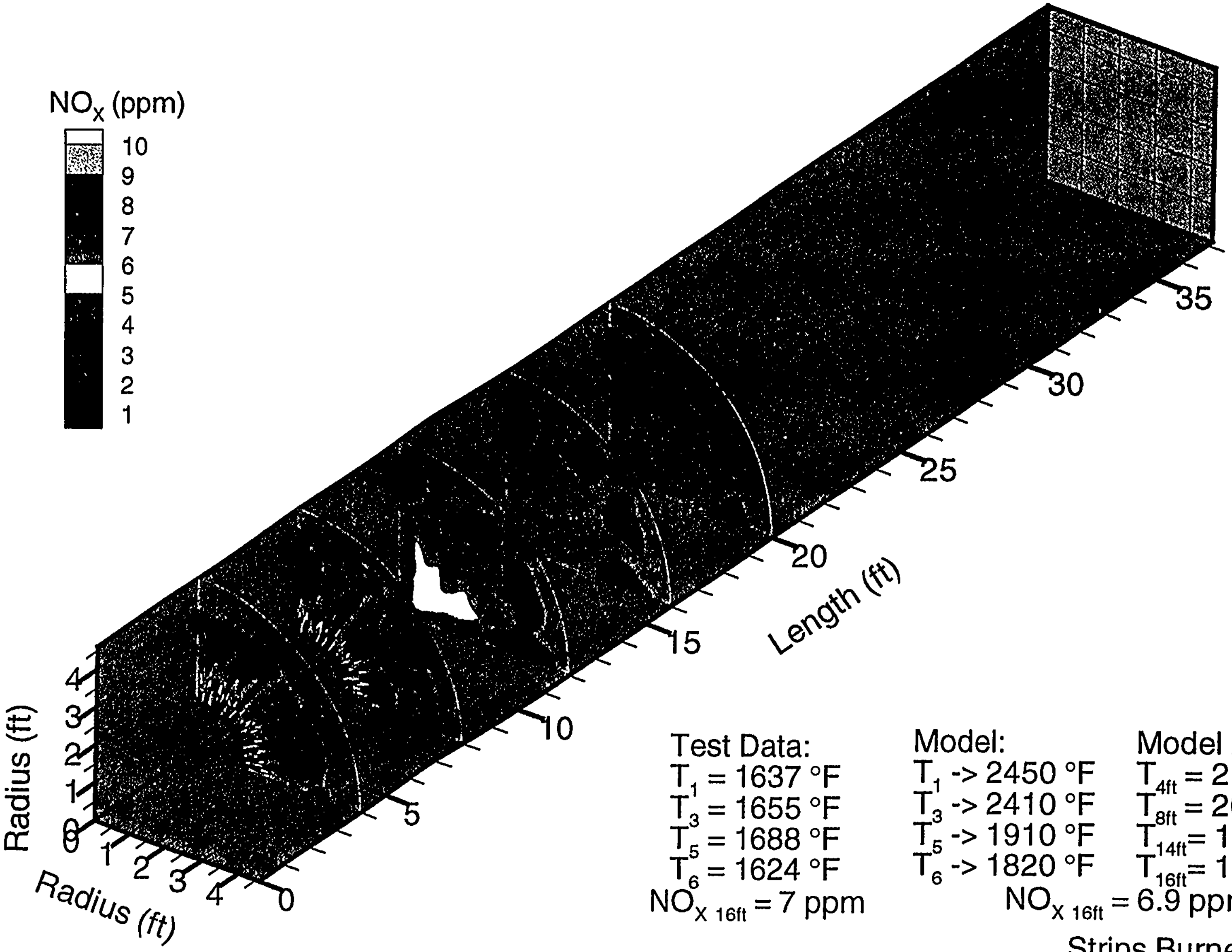


Strips Burner Inlet

C

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace NO_x Levels

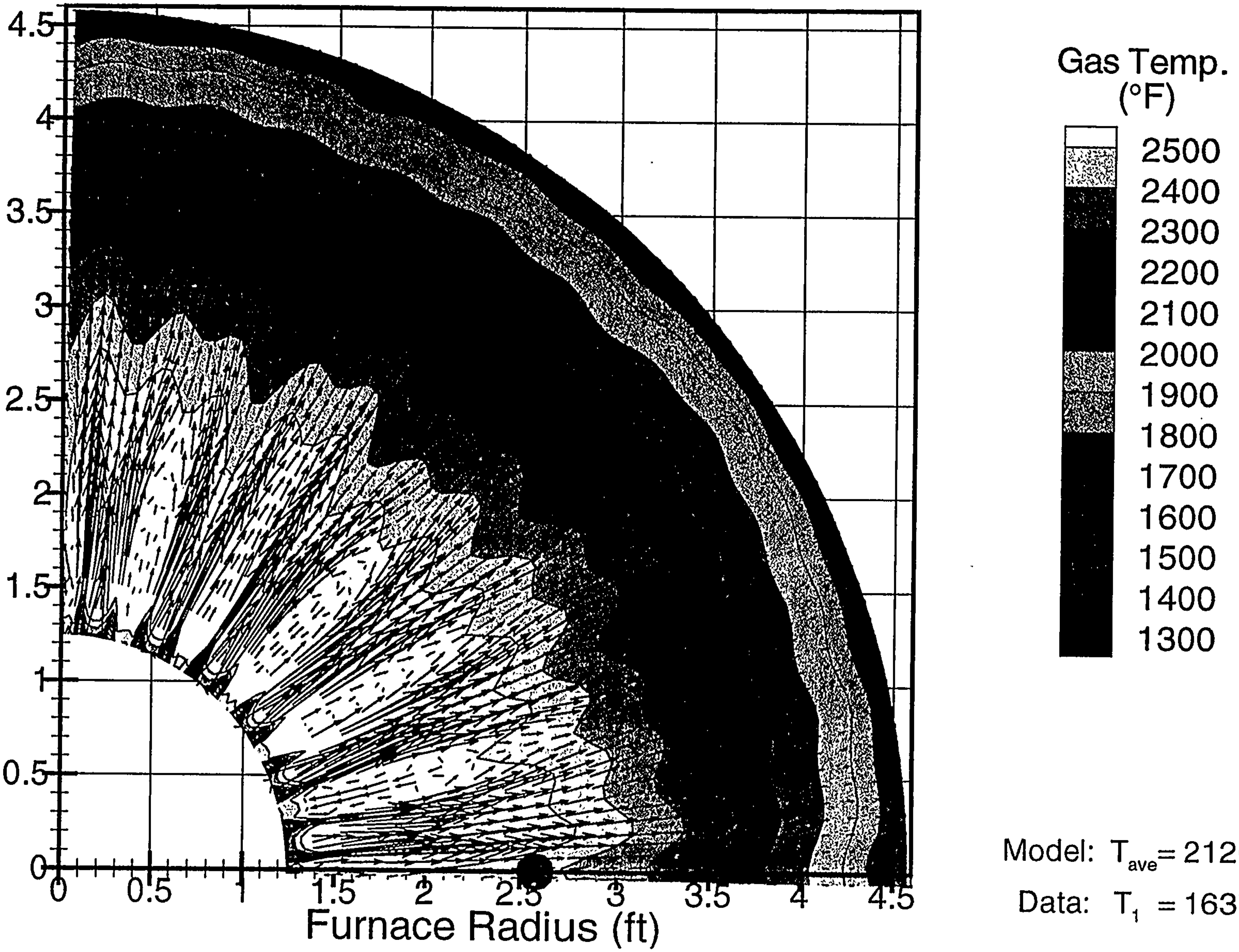


Test Data:	Model:	Model Ave:
T_1 = 1637 °F	T_1 -> 2450 °F	T_{4ft} = 2120 °F
T_3 = 1655 °F	T_3 -> 2410 °F	T_{8ft} = 2096 °F
T_5 = 1688 °F	T_5 -> 1910 °F	T_{14ft}= 1857 °F
T_6 = 1624 °F	T_6 -> 1820 °F	T_{16ft}= 1780 °F
$NO_{X\ 16ft}$ = 7 ppm	$NO_{X\ 16ft}$ = 6.9 ppm	

Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Location at 4 feet



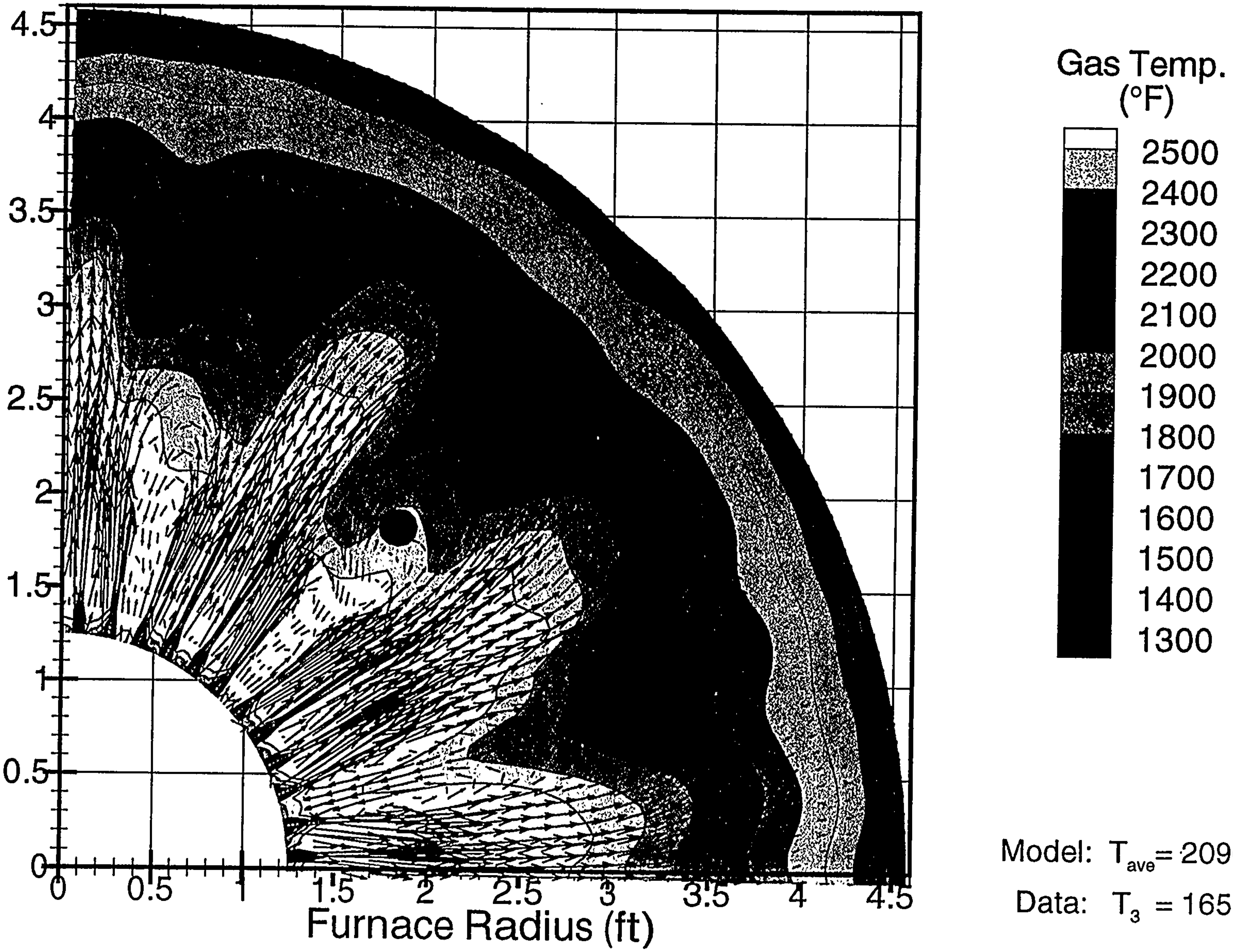
Model: T_{ave} = 2120 °F

Data: T_1 = 1637 °F

e

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Location at 8 feet

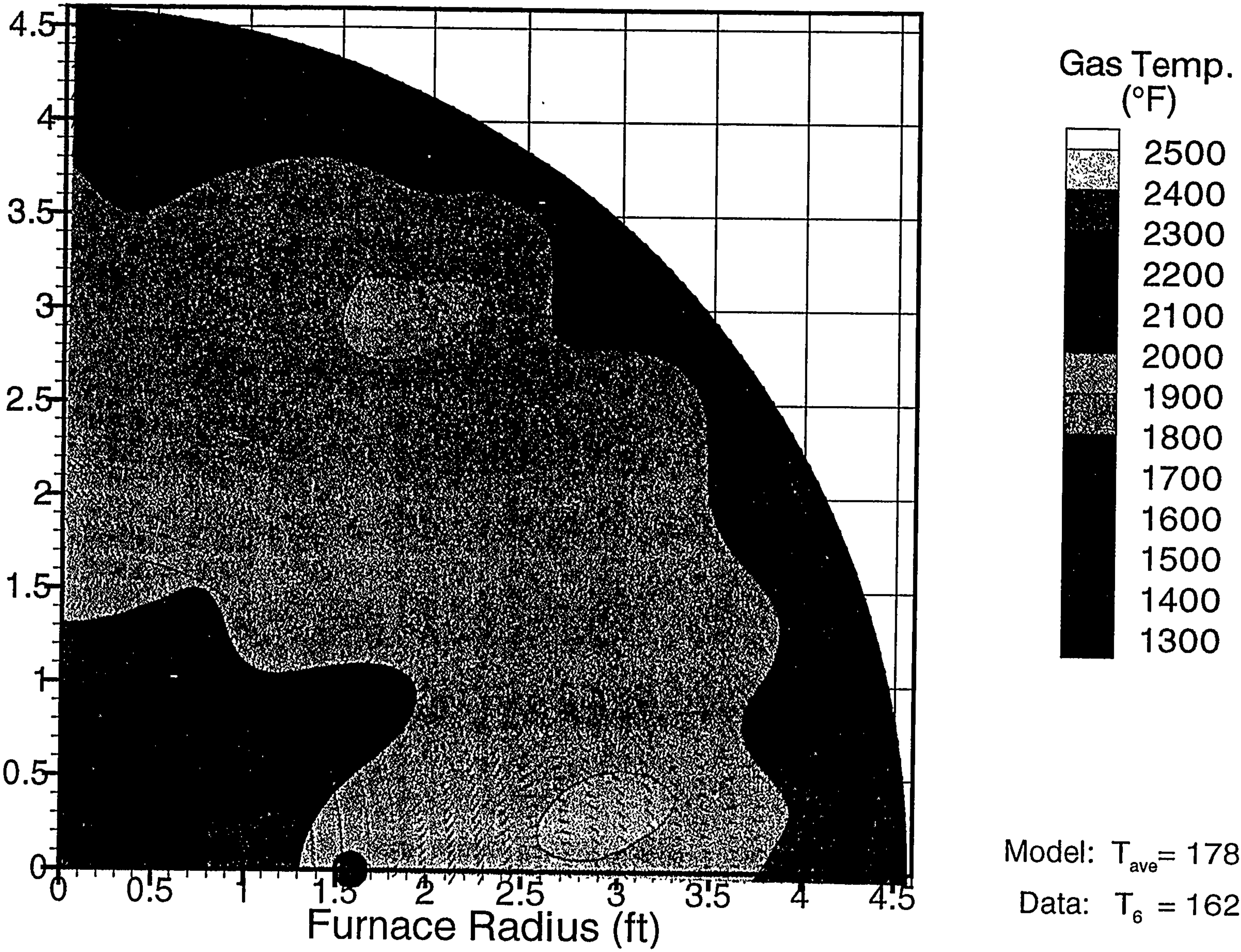


Model: $T_{ave} = 2096$ °F

Data: $T_3 = 1655$ °F

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Location at 16 feet

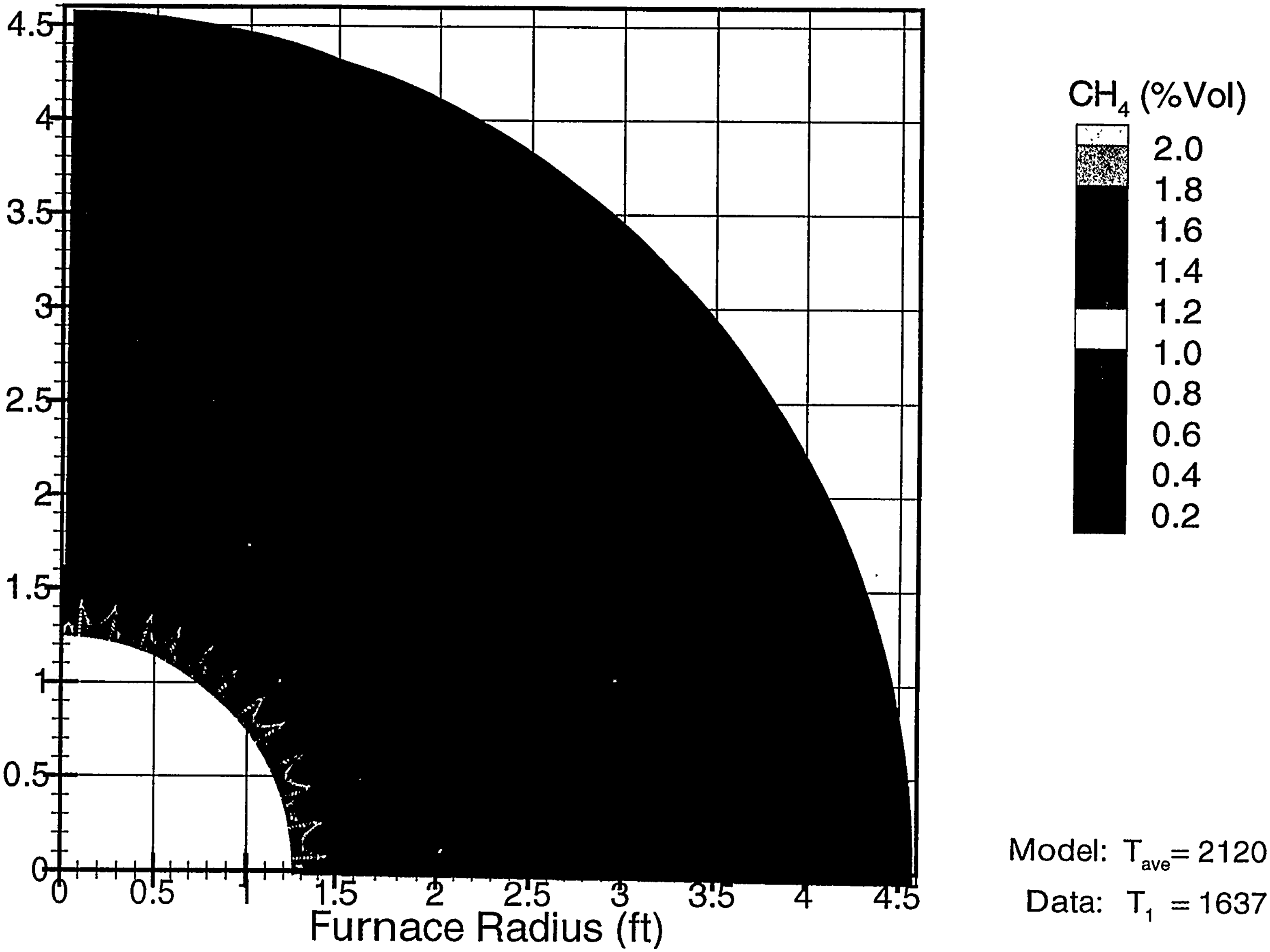


Model: T_{ave} = 1780 °F

Data: T_6 = 1624 °F

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Location at 4 feet



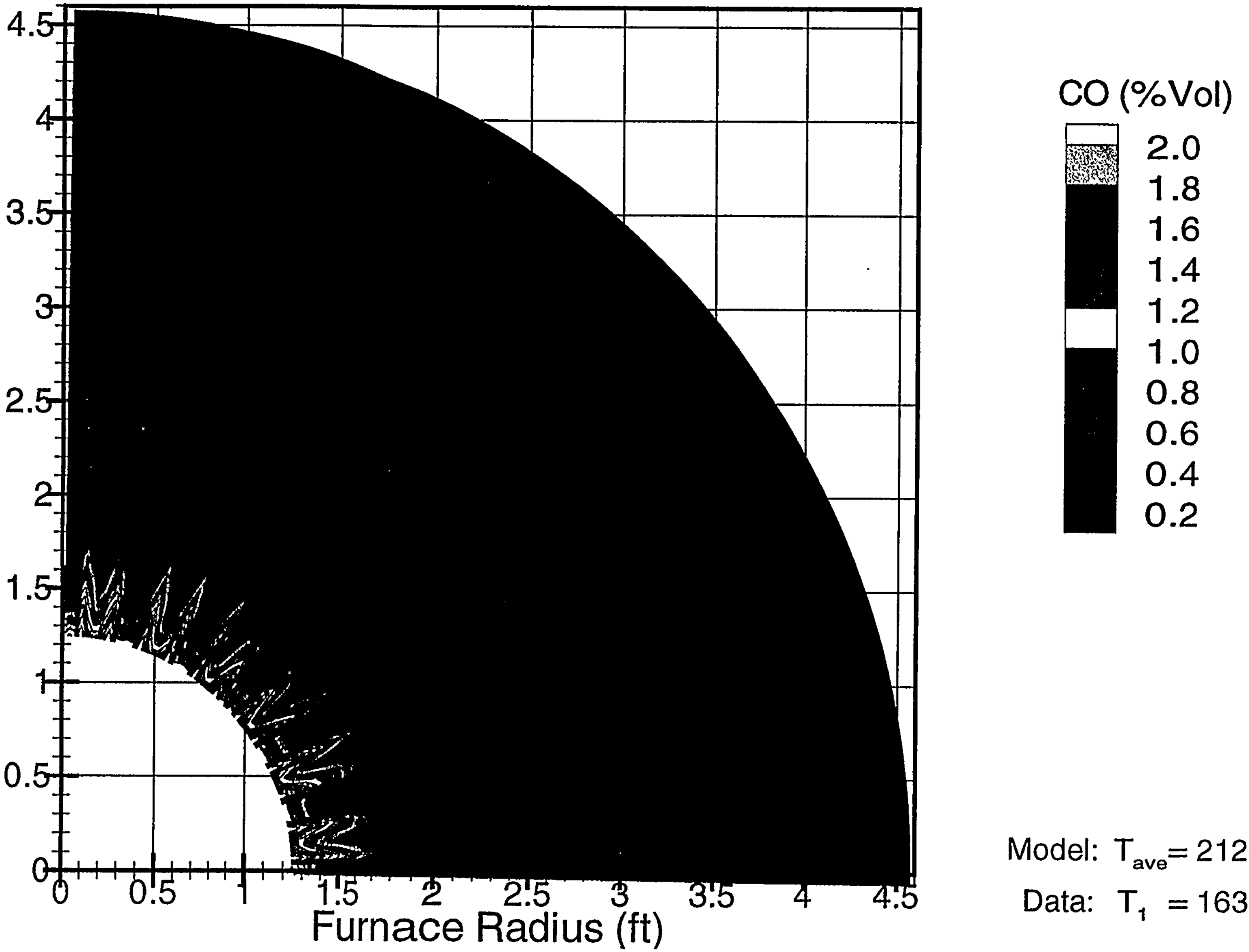
Model: $T_{ave} = 2120$ °F

Data: $T_1 = 1637$ °F

h

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Location at 4 feet

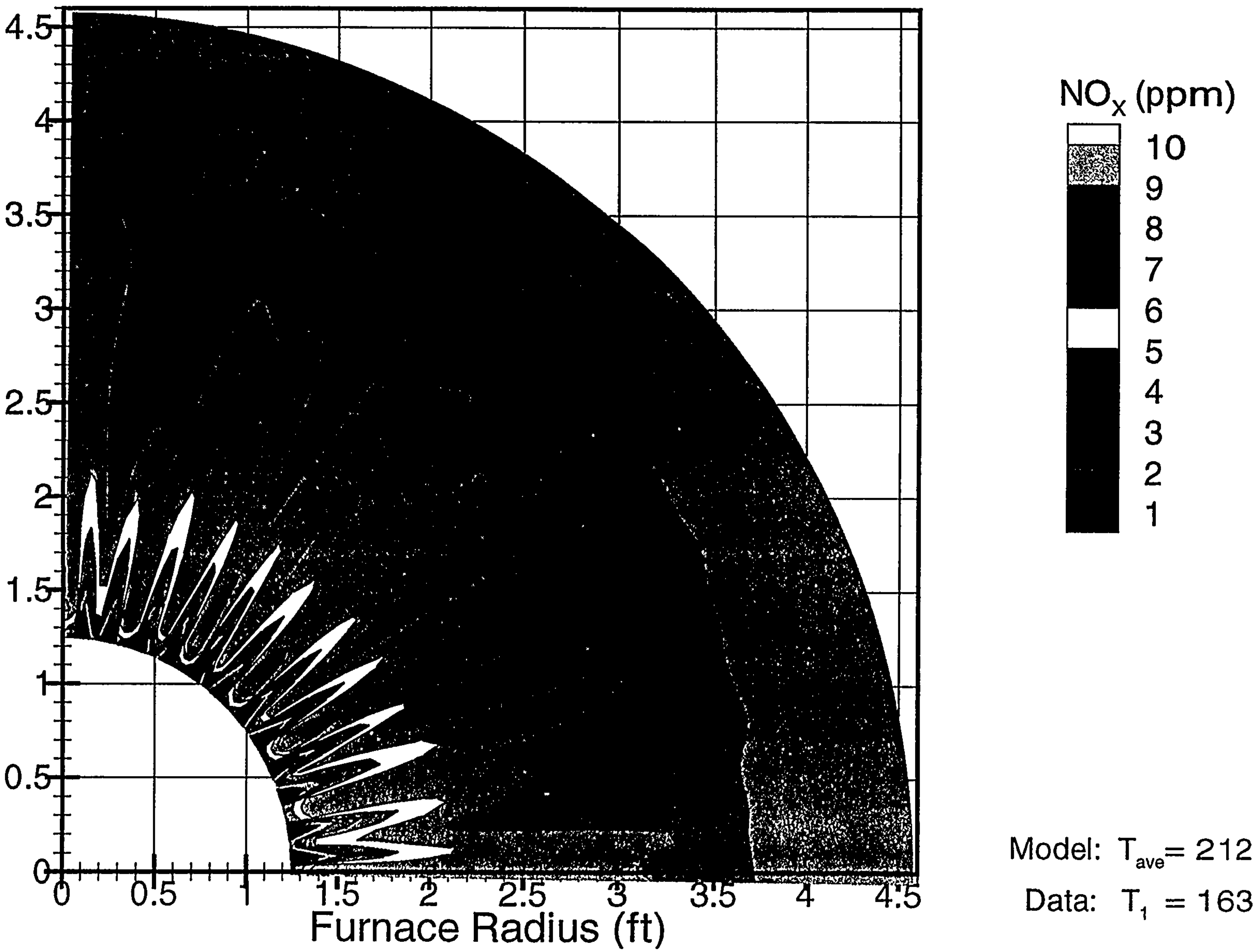


Model: T_{ave}= 2120 °F

Data: T_1 = 1637 °F

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Location at 4 feet



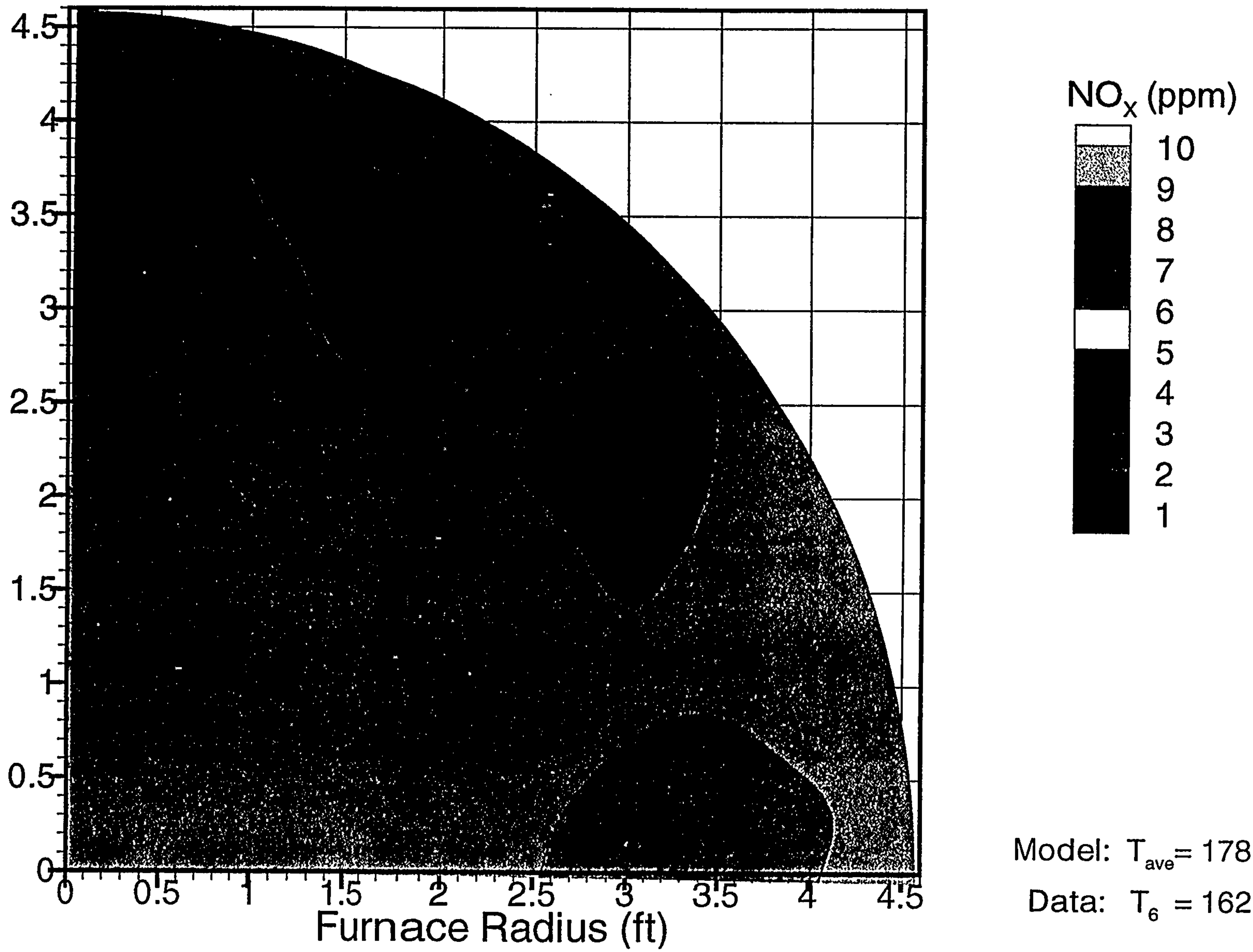
Model: T_{ave} = 2120 °F

Data: T_1 = 1637 °F

k

Alzeta Burner Project, Cymric Model - Stage 2

Option 4 - Furnace Location at 16 feet



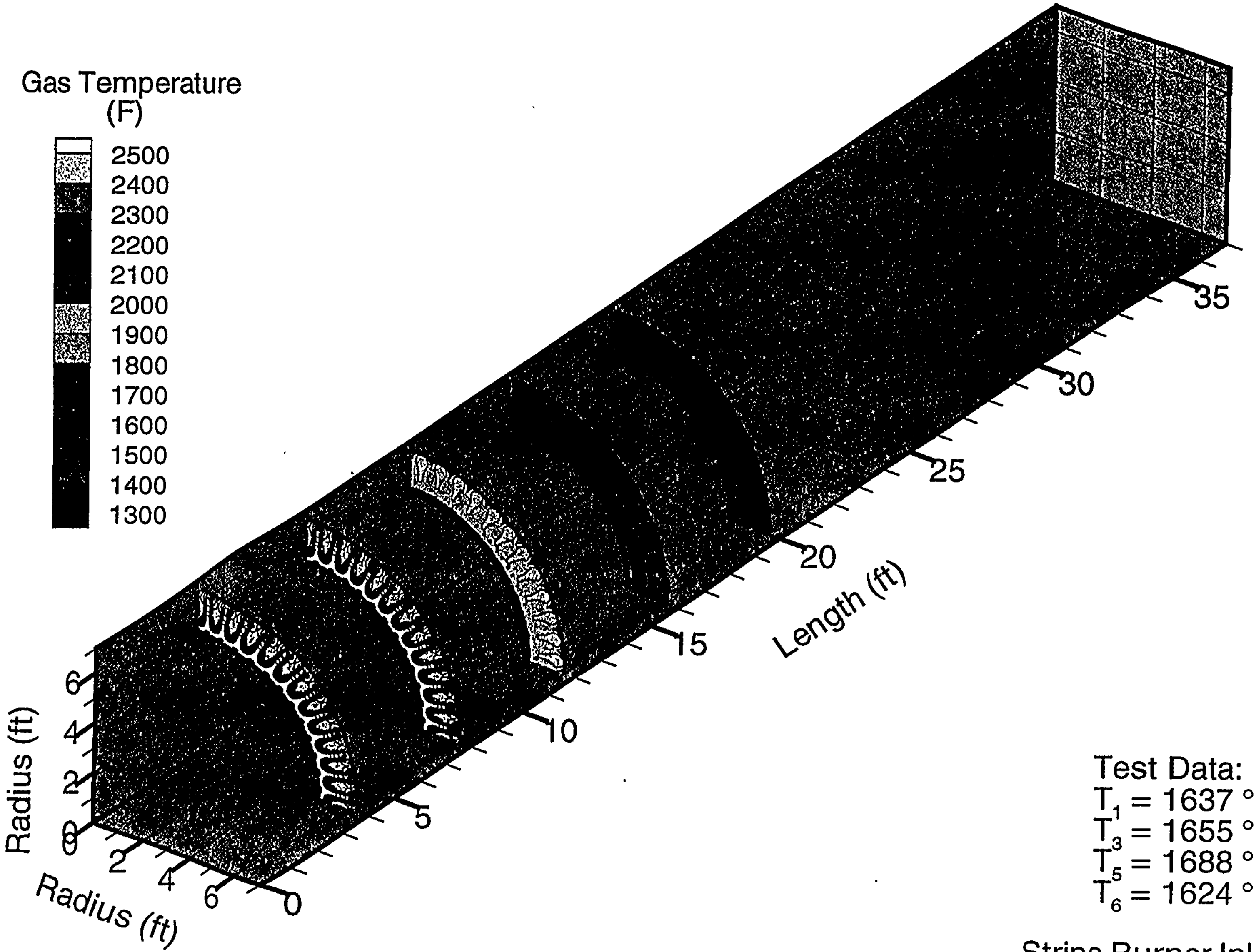
Model: T_{ave}= 1780 °F

Data: T_6 = 1624 °F

ℓ

Alzeta Burner Project, Cymric Model - Stage 2

Modification 5 - Furnace Gas Temperatures



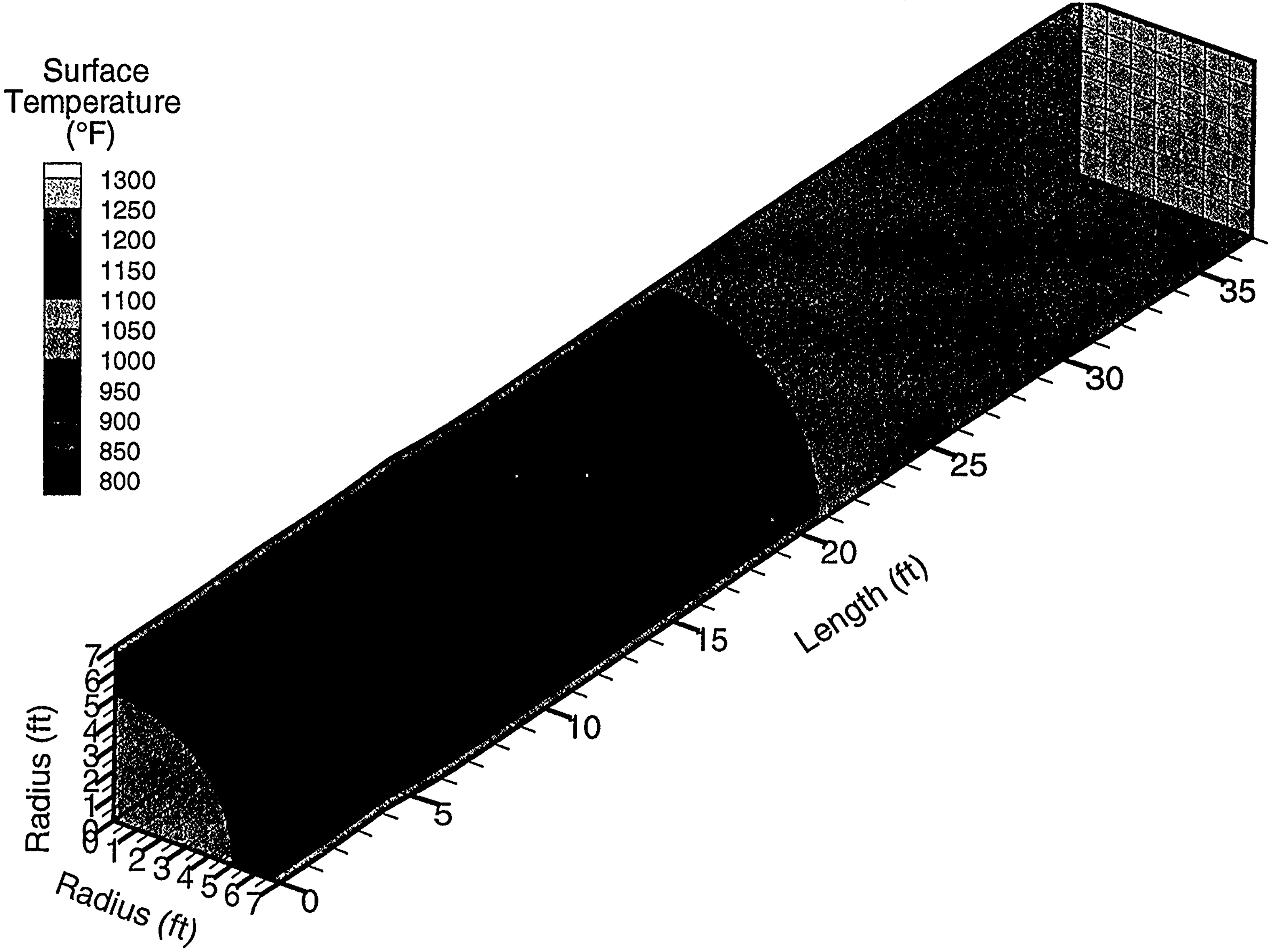
Test Data:
T_1 = 1637 °F
T_3 = 1655 °F
T_5 = 1688 °F
T_6 = 1624 °F

Strips Burner Inlet

a

Alzeta Burner Project, Cymric Model - Stage 2

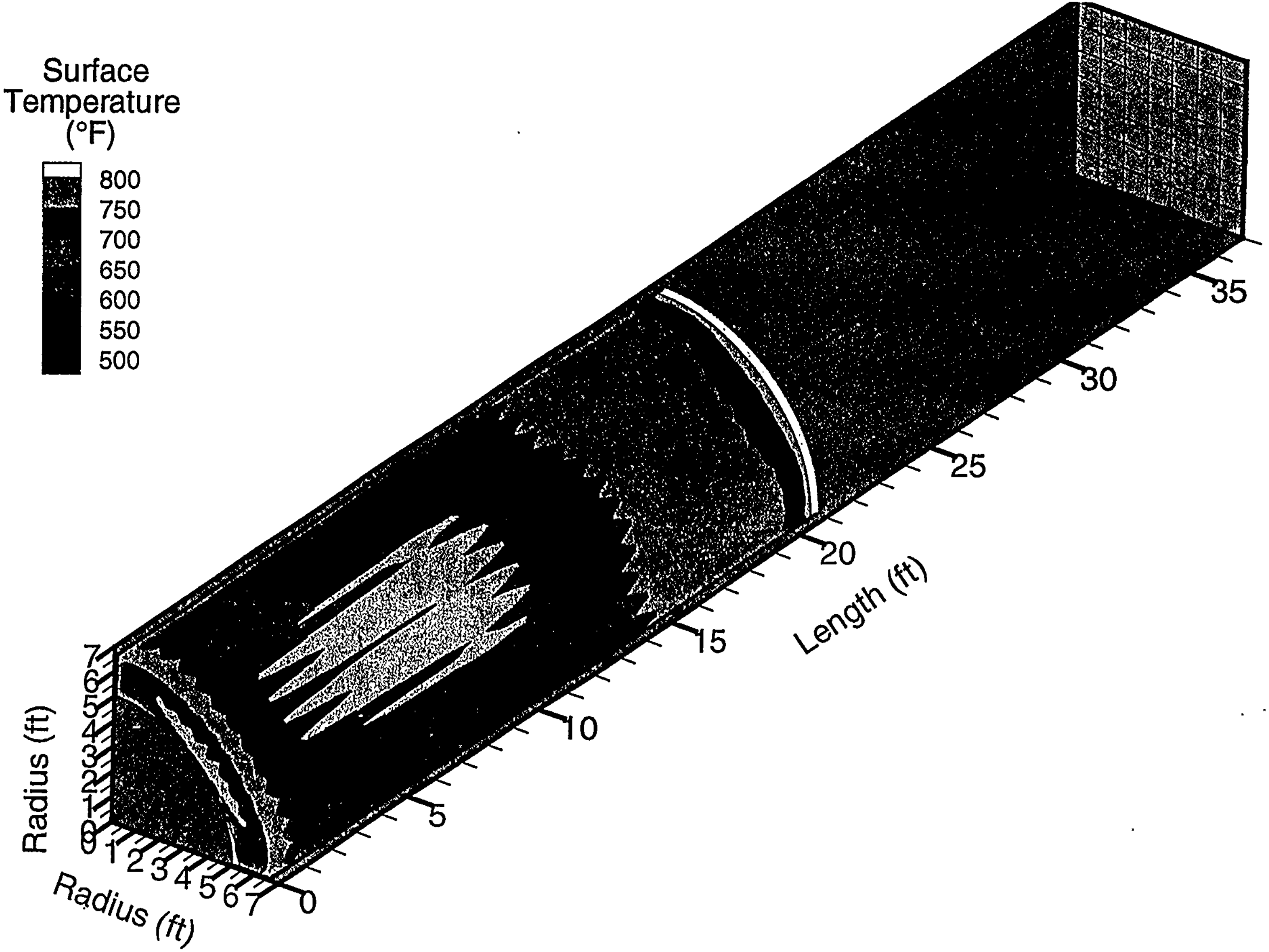
Modification 5 - Furnace Surface Temperatures



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

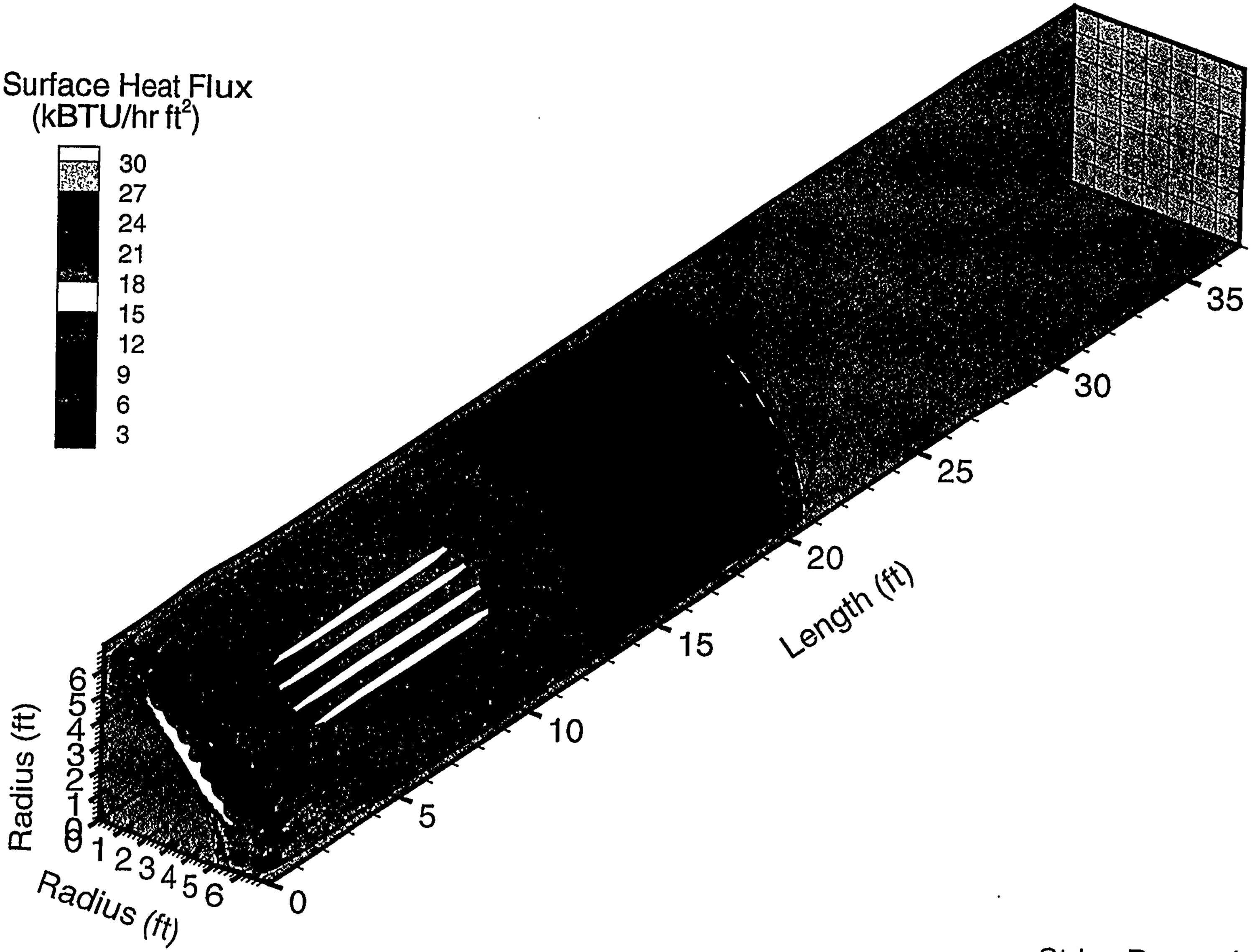
Modification 5 - Furnace Surface Temperatures



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

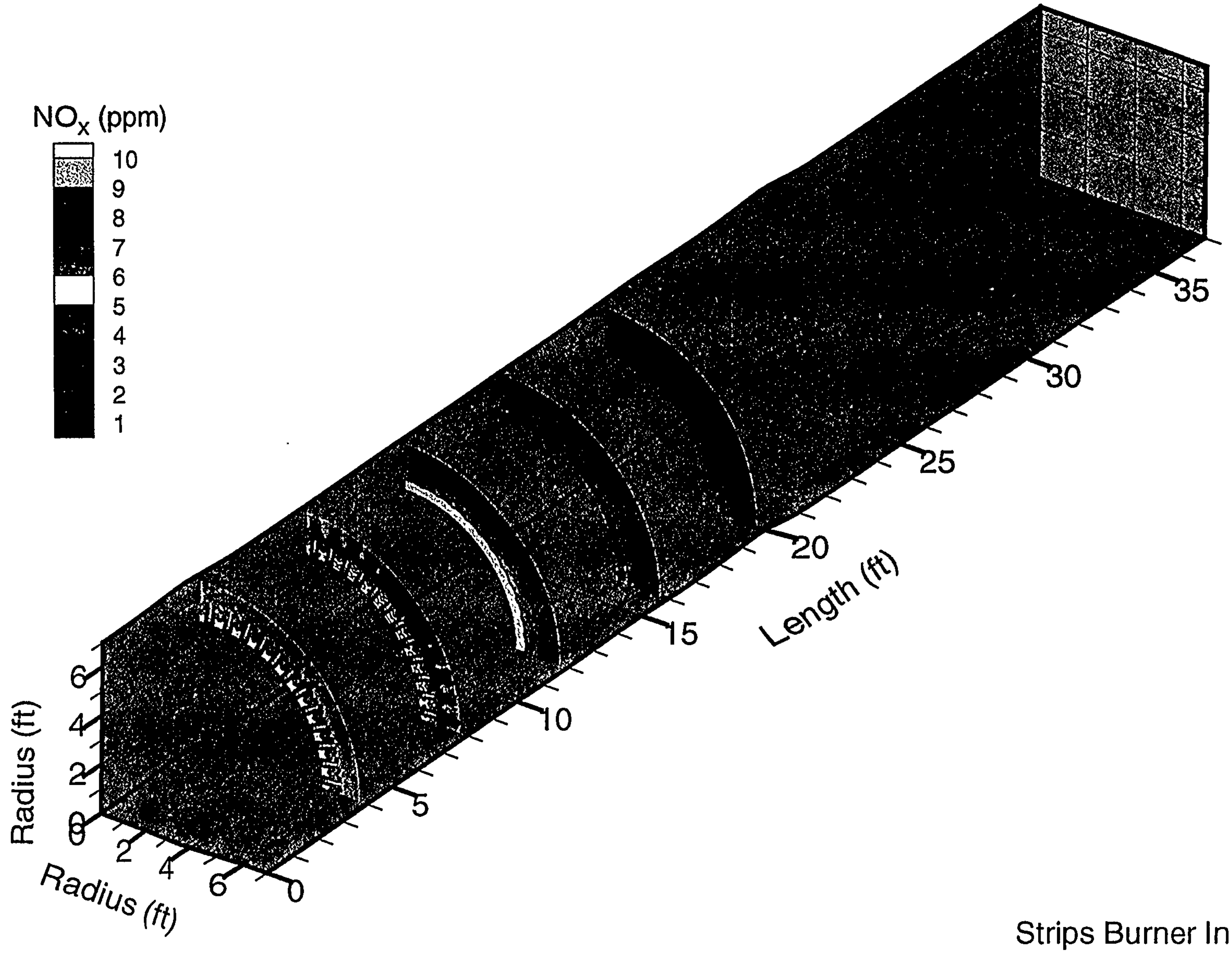
Modification 5 - Furnace Heat Flux



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Modification 5 - Furnace NO_x Levels

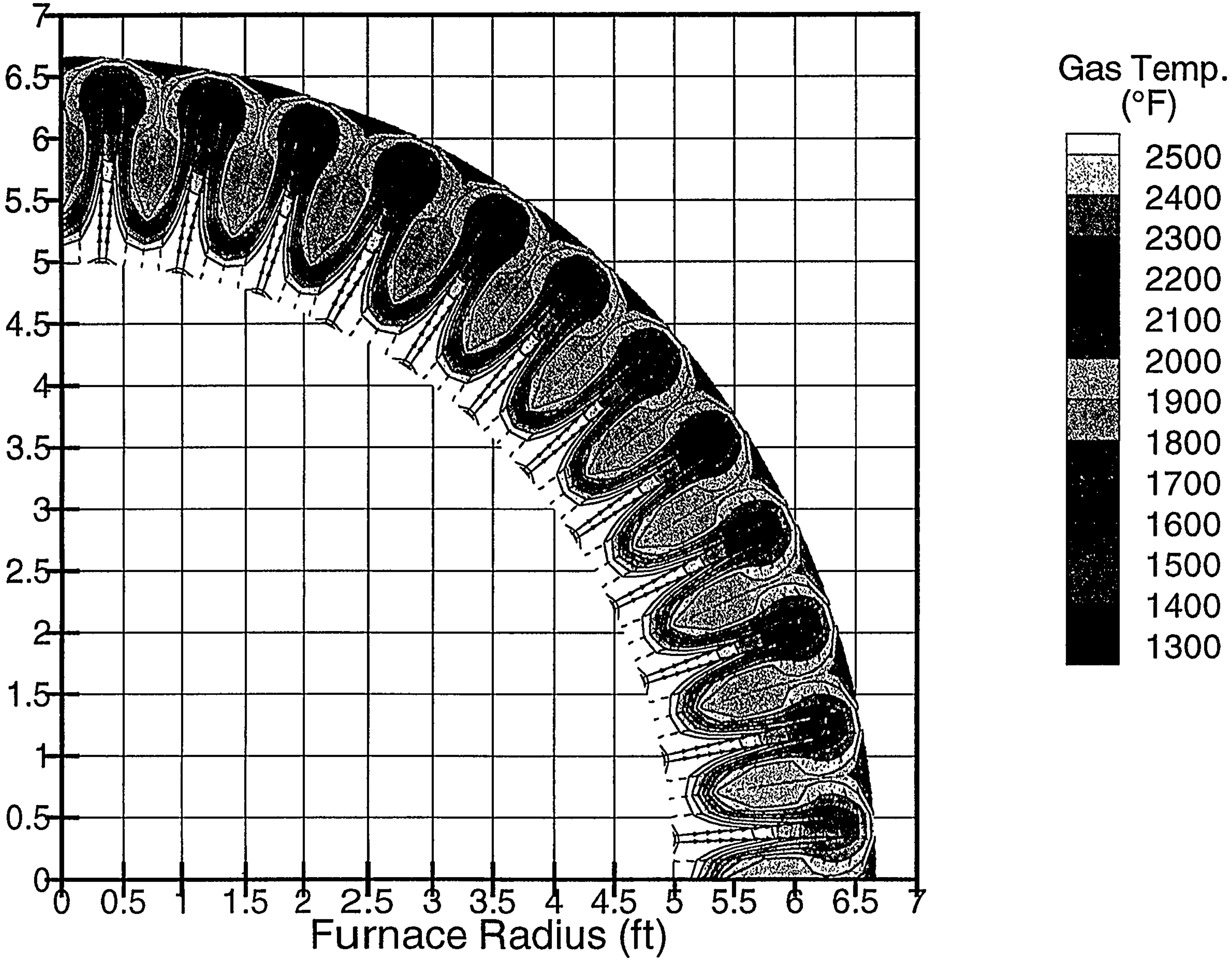


Strips Burner Inlet

d

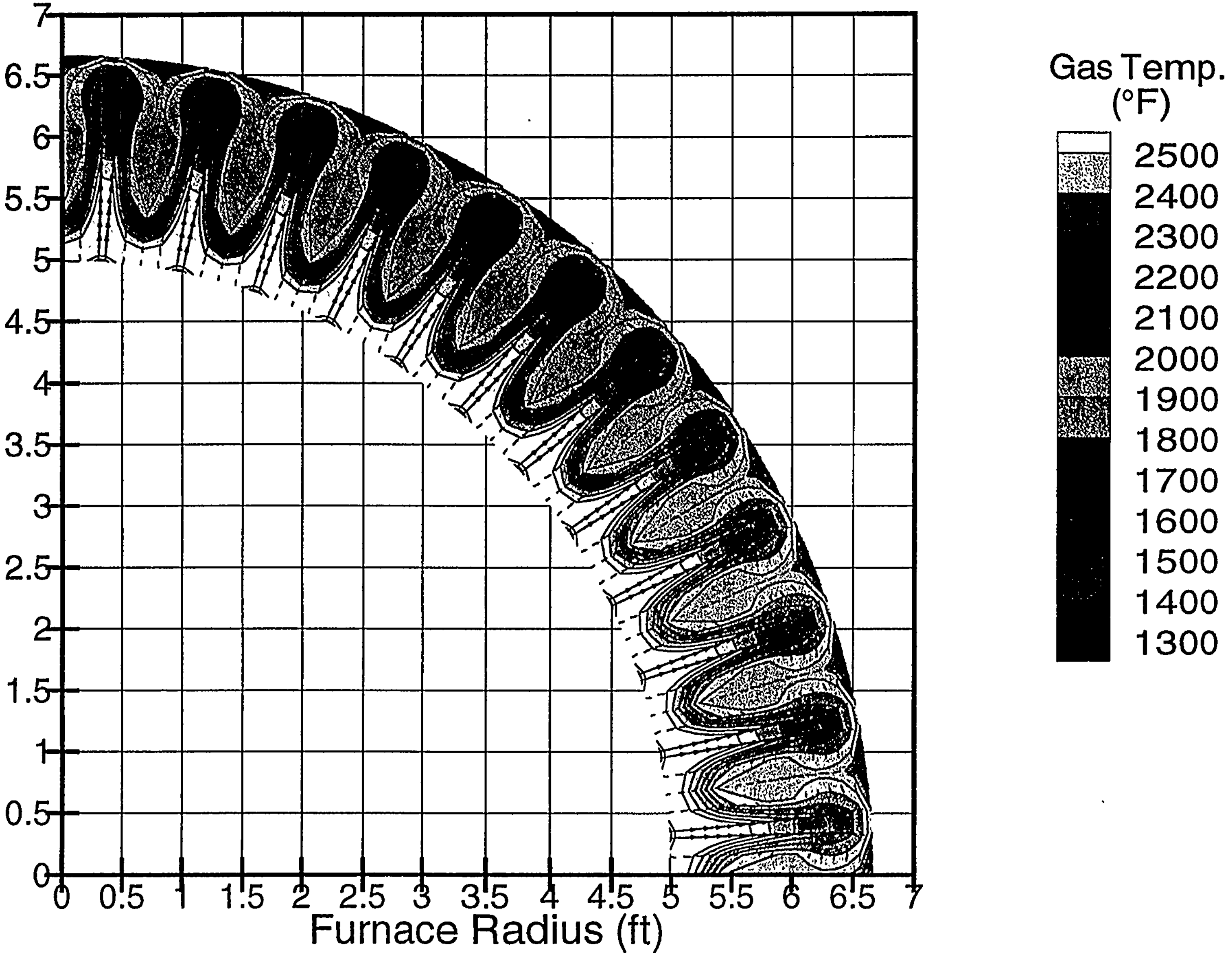
Alzeta Burner Project, Cymric Model - Stage 2

Modification 5 - Furnace Location at 4 feet



Alzeta Burner Project, Cymric Model - Stage 2

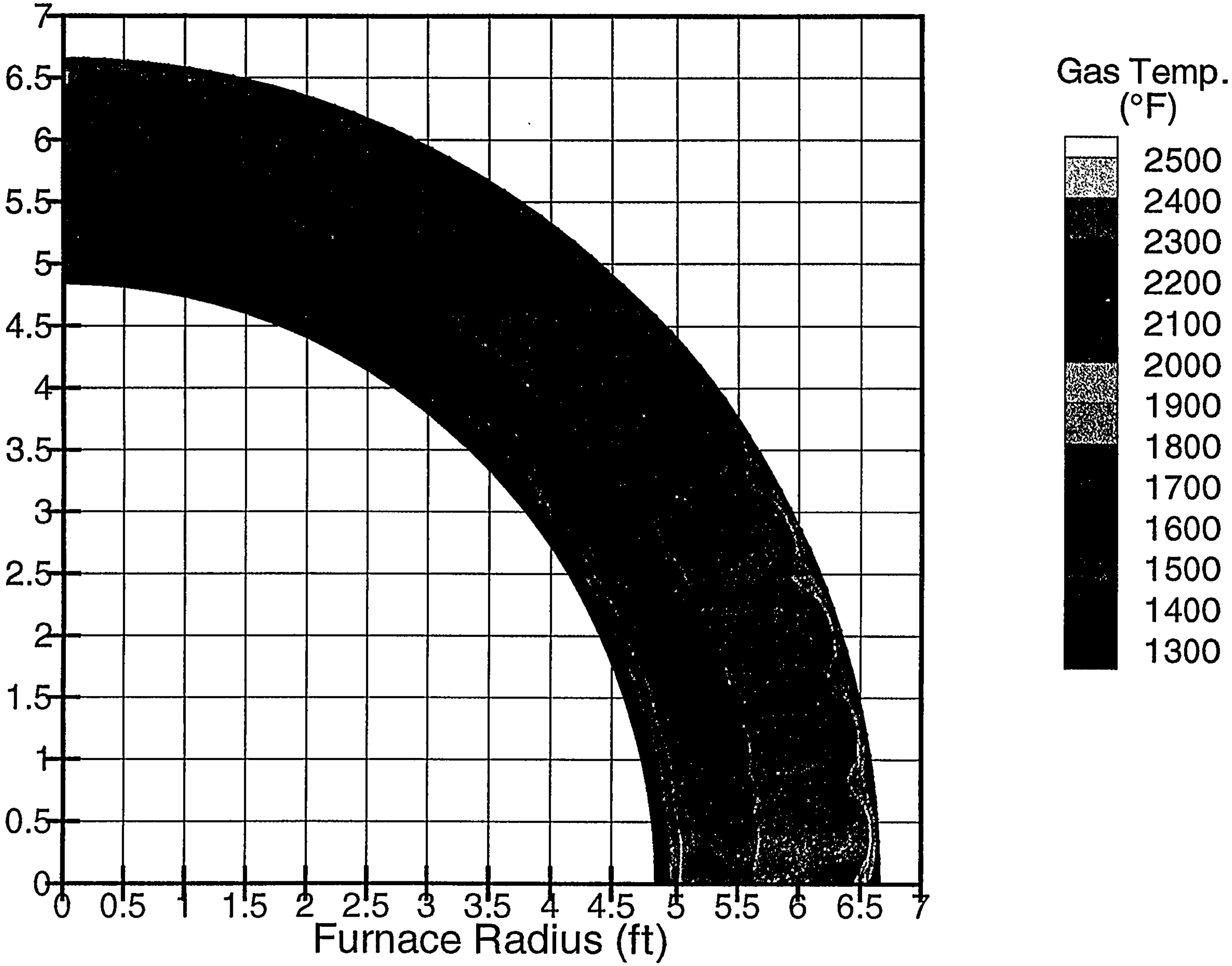
Modification 5 - Furnace Location at 8 feet



f

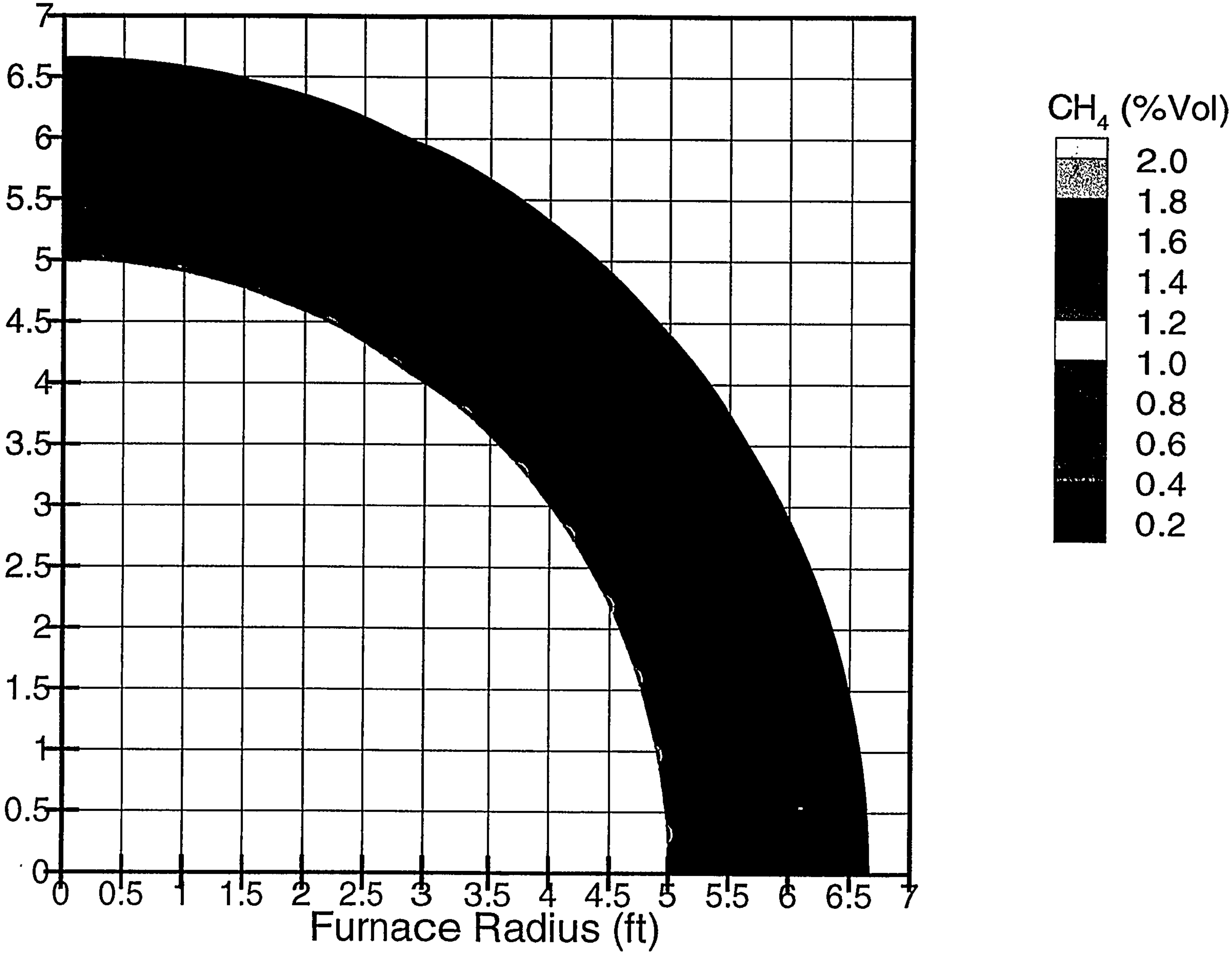
Alzeta Burner Project, Cymric Model - Stage 2

Modification 5 - Furnace Location at 16 feet



Alzeta Burner Project, Cymric Model - Stage 2

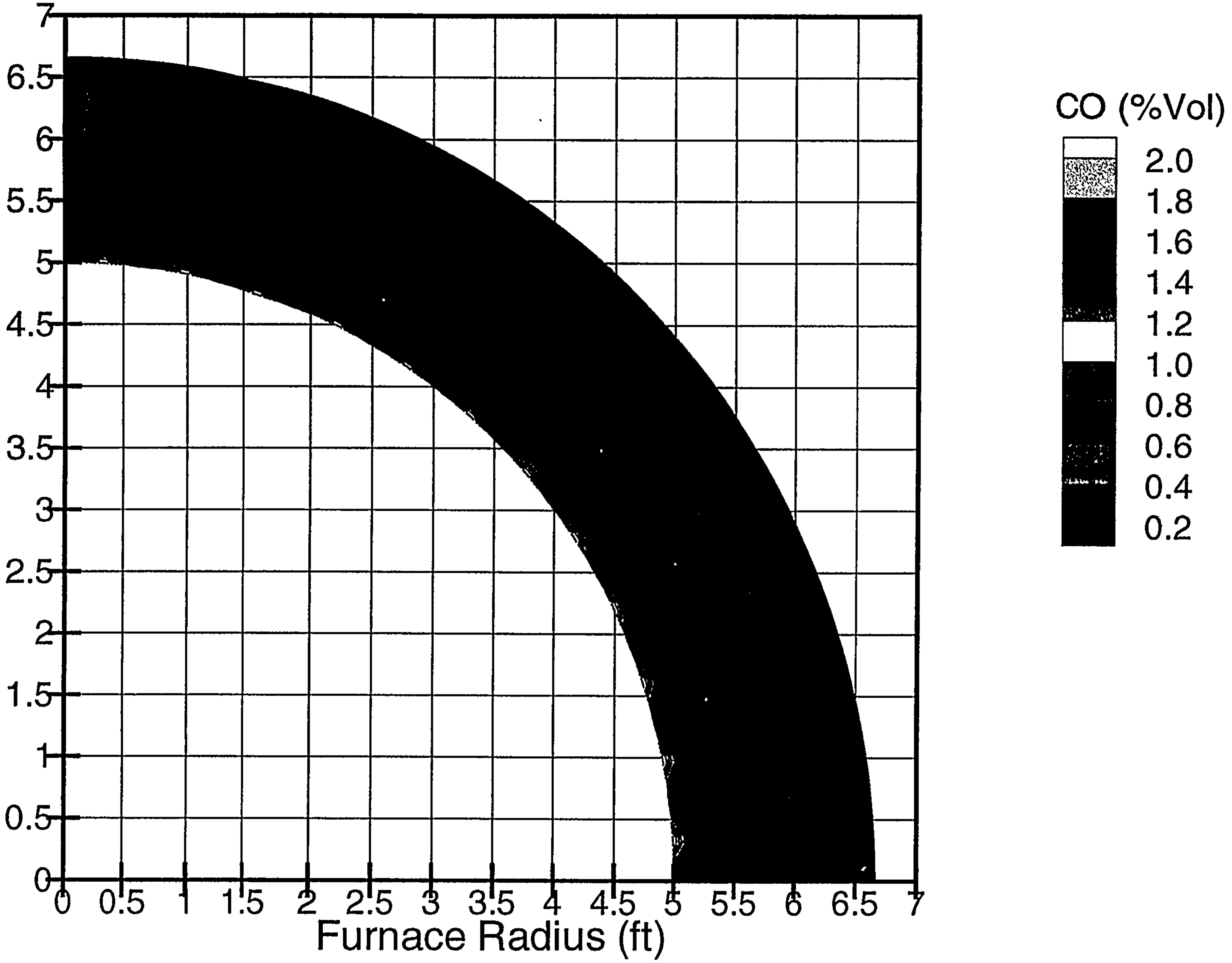
Modification 5 - Furnace Location at 4 feet



h

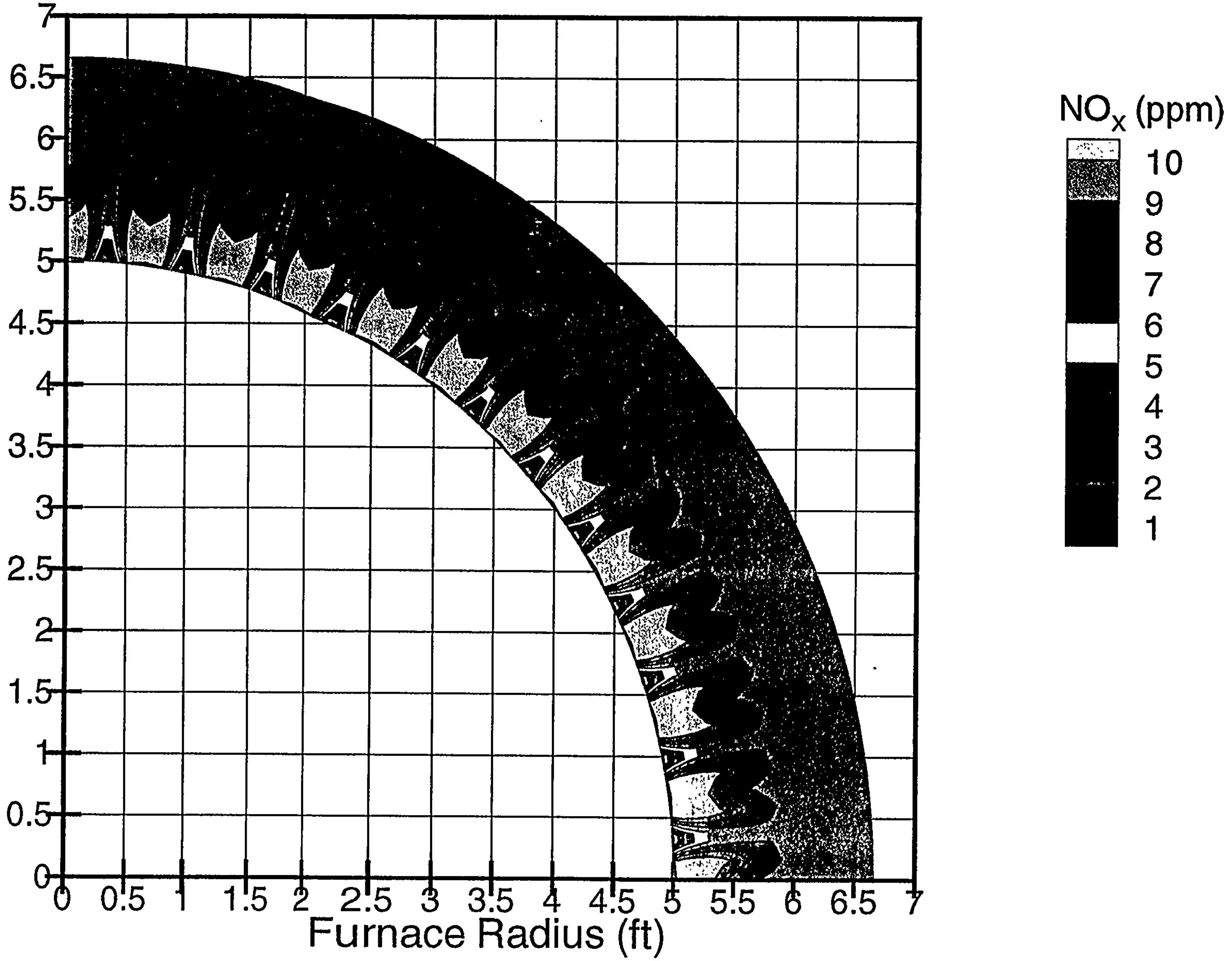
Alzeta Burner Project, Cymric Model - Stage 2

Modification 5 - Furnace Location at 4 feet



Alzeta Burner Project, Cymric Model - Stage 2

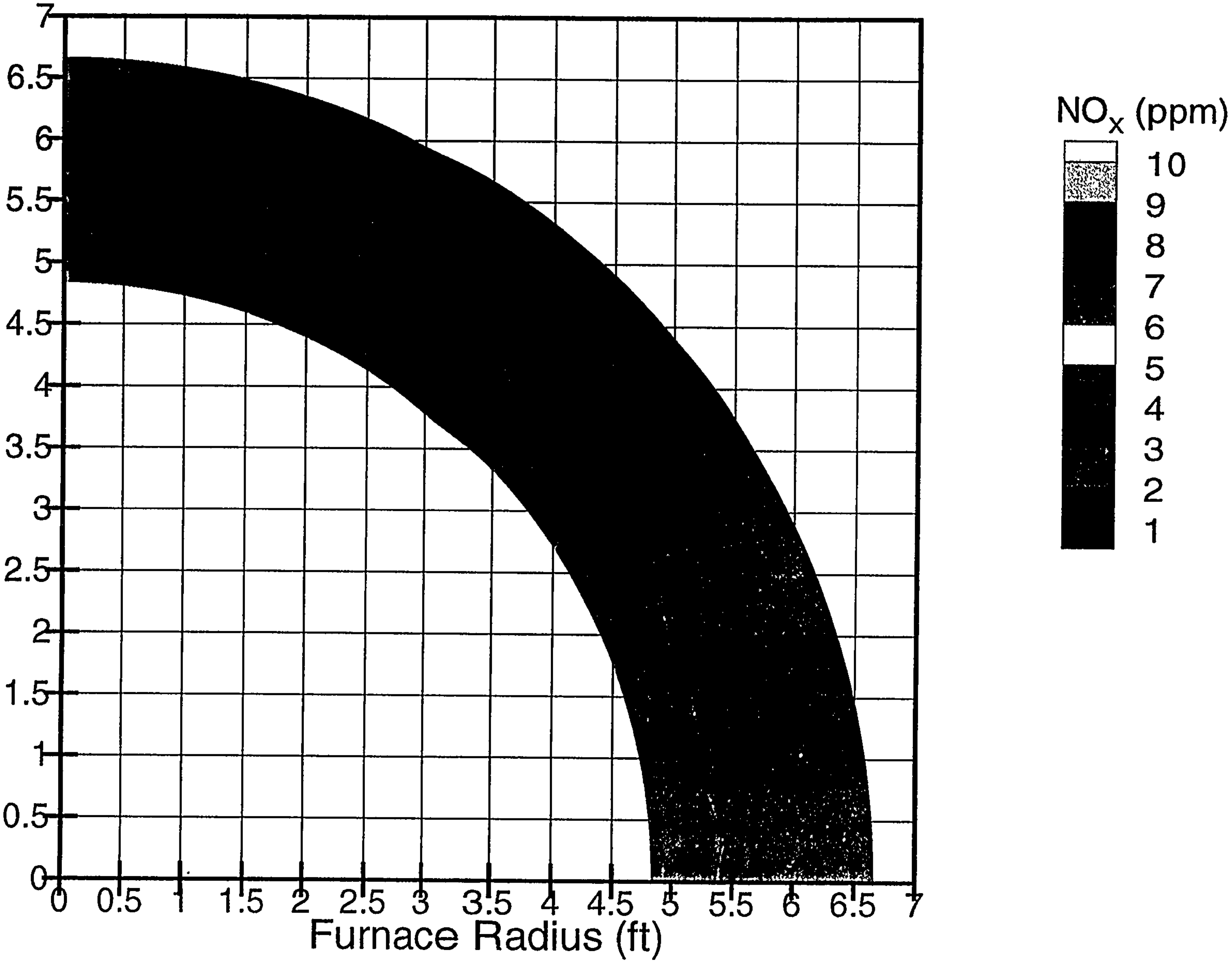
Modification 5 - Furnace Location at 4 feet



K

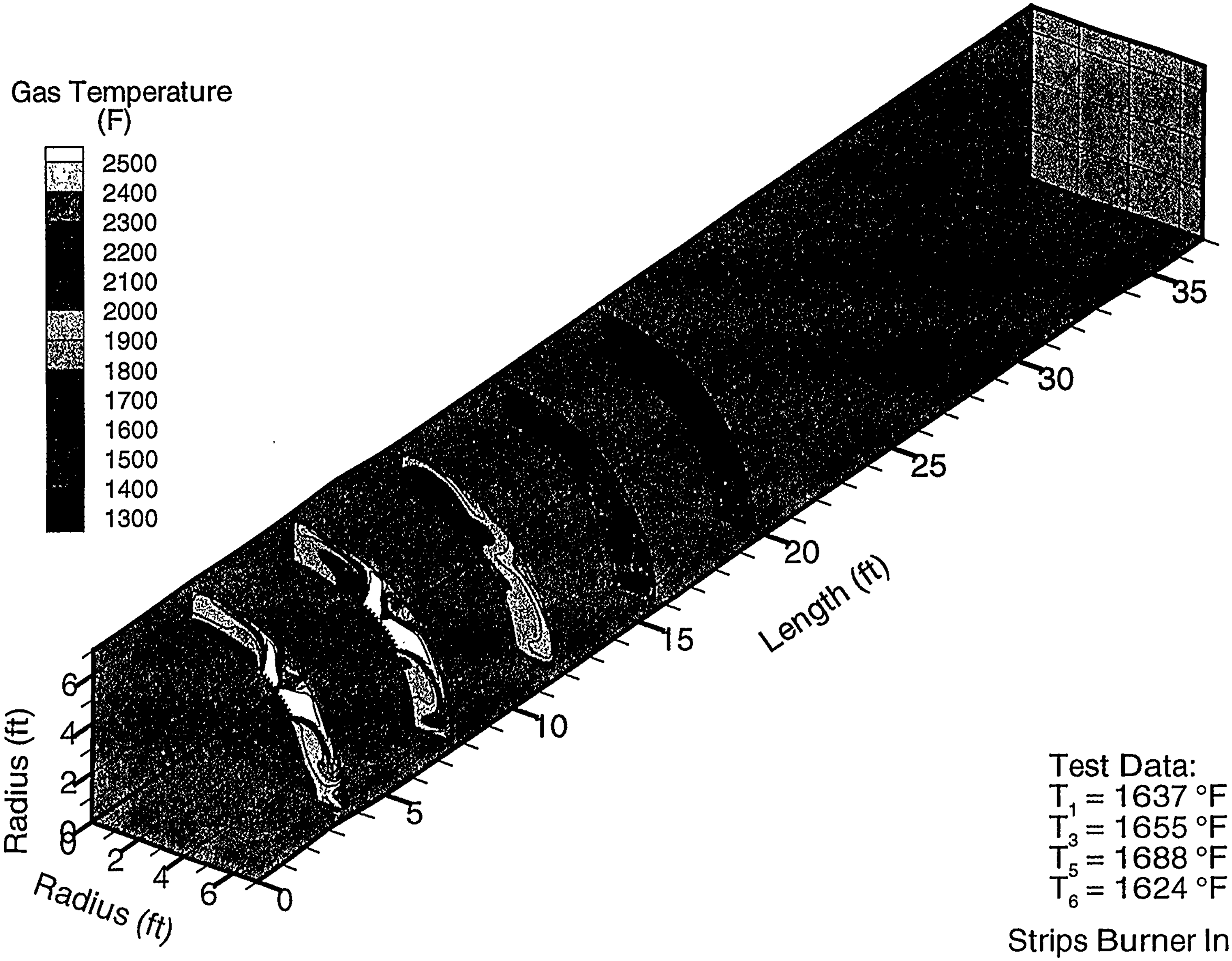
Alzeta Burner Project, Cymric Model - Stage 2

Modification 5 - Furnace Location at 16 feet



Alzeta Burner Project, Cymric Model - Stage 2

Modification 6 - Furnace Gas Temperatures



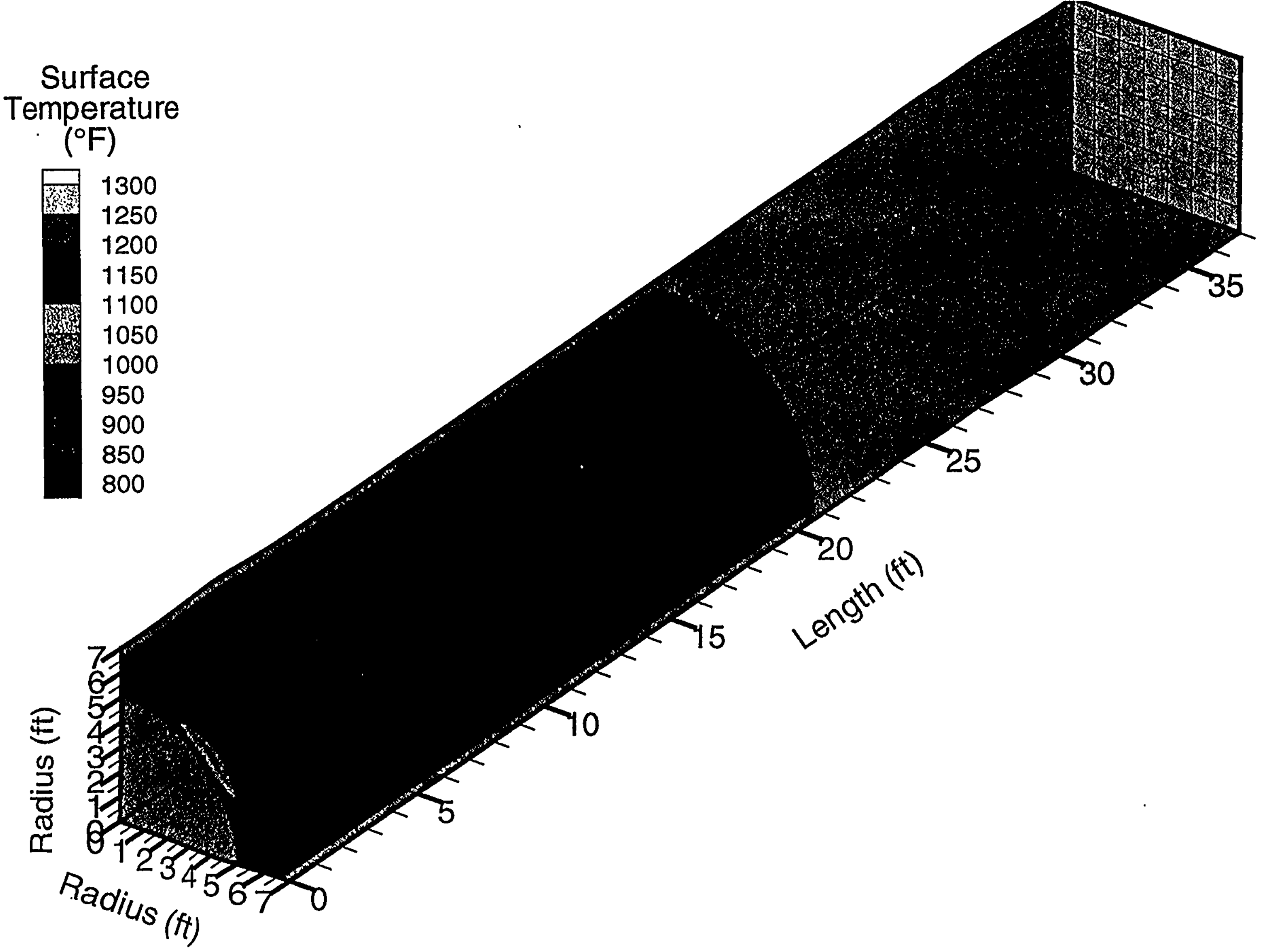
Test Data:
T_1 = 1637 °F
T_3 = 1655 °F
T_5 = 1688 °F
T_6 = 1624 °F

Strips Burner Inlet

a

Alzeta Burner Project, Cymric Model - Stage 2

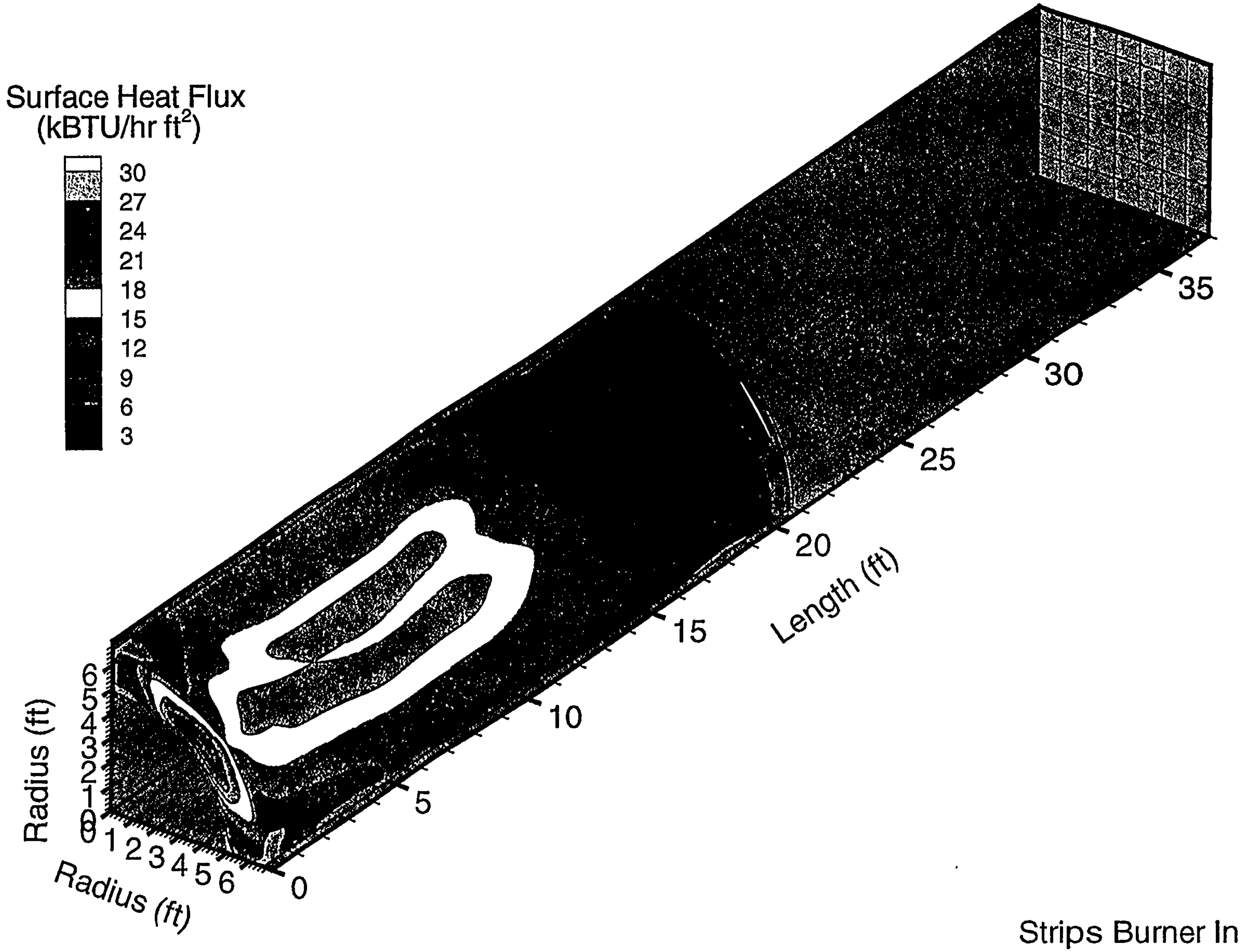
Modification 6 - Furnace Surface Temperatures



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

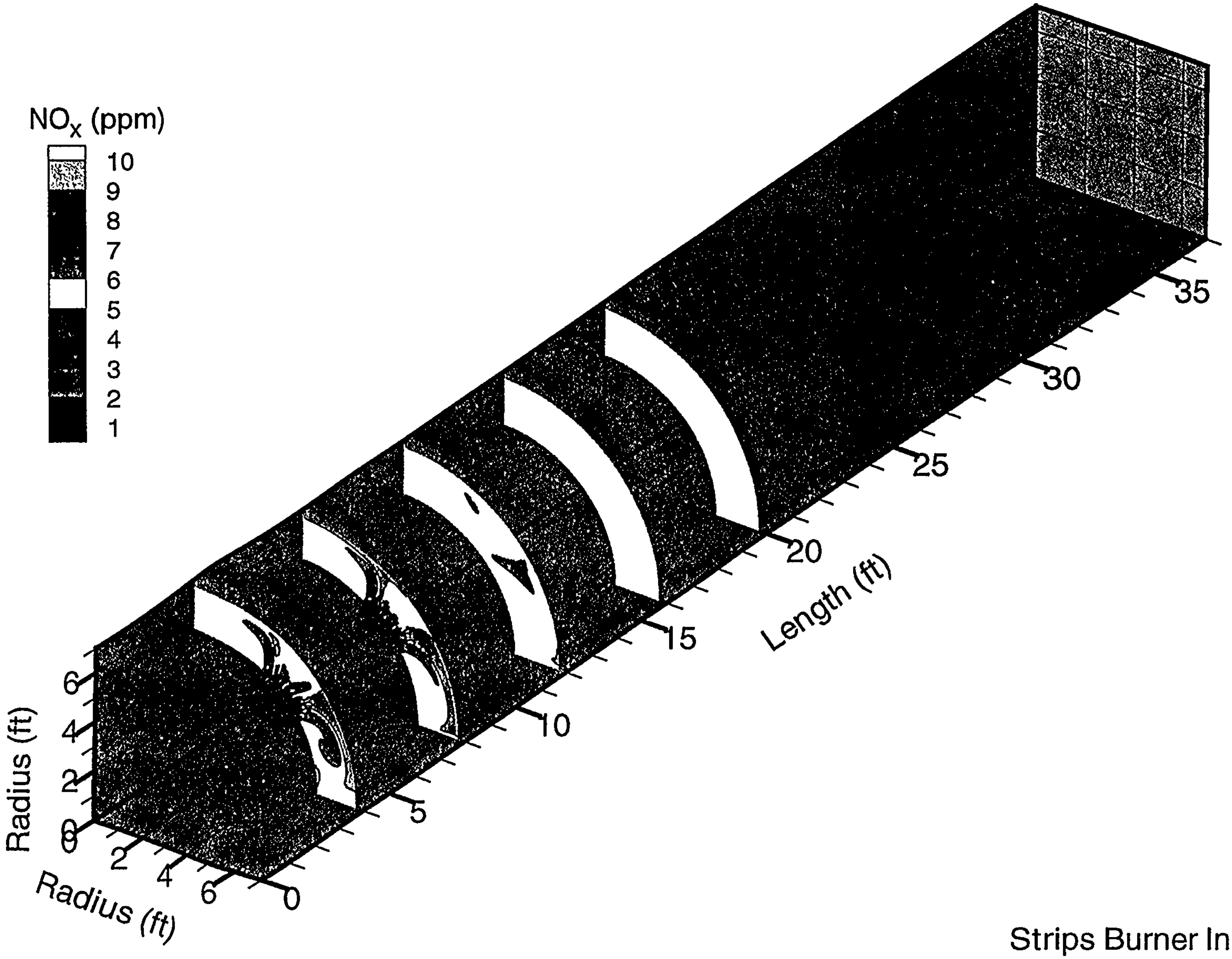
Modification 6 - Furnace Heat Flux



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

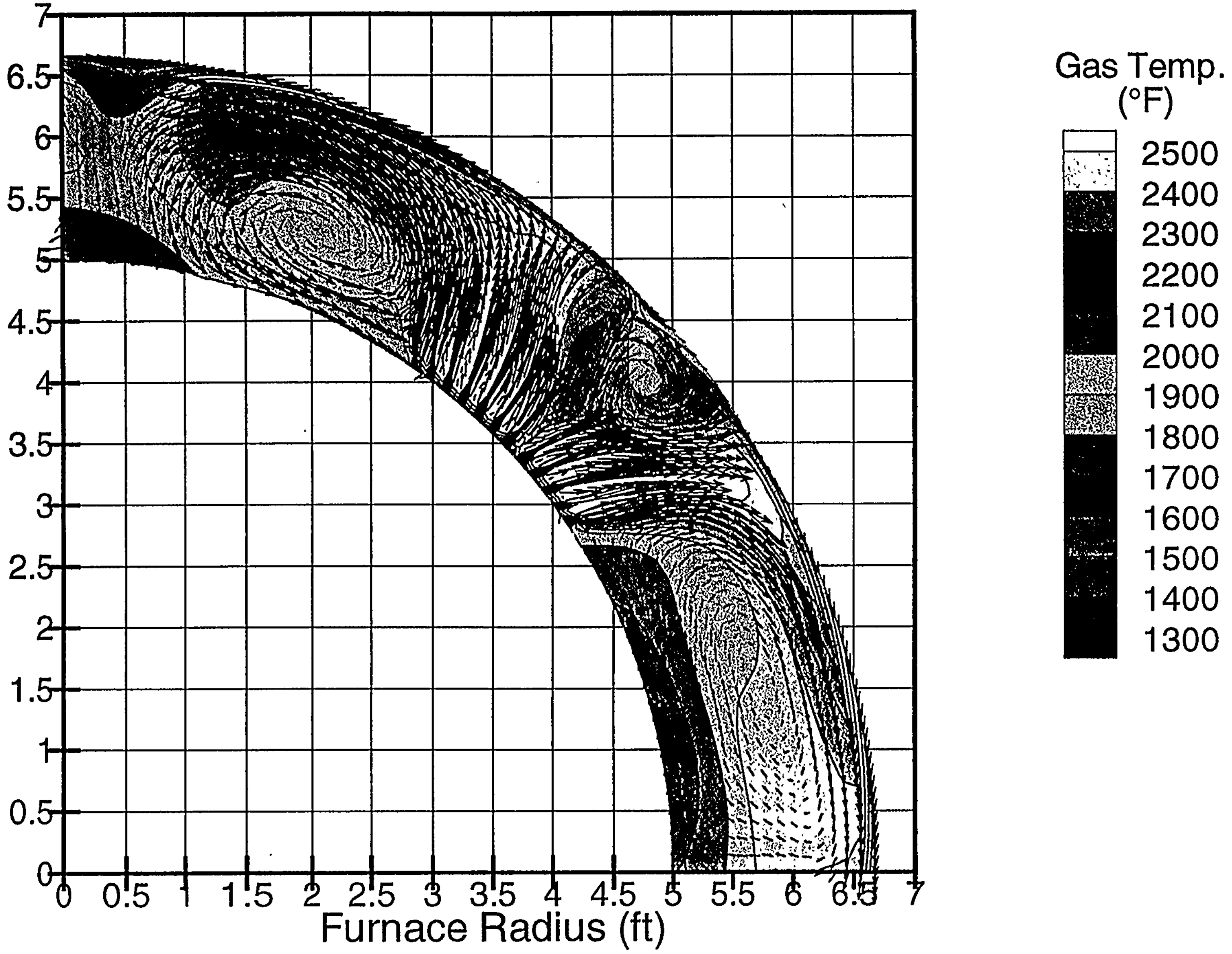
Modification 6 - Furnace NO_x Levels



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

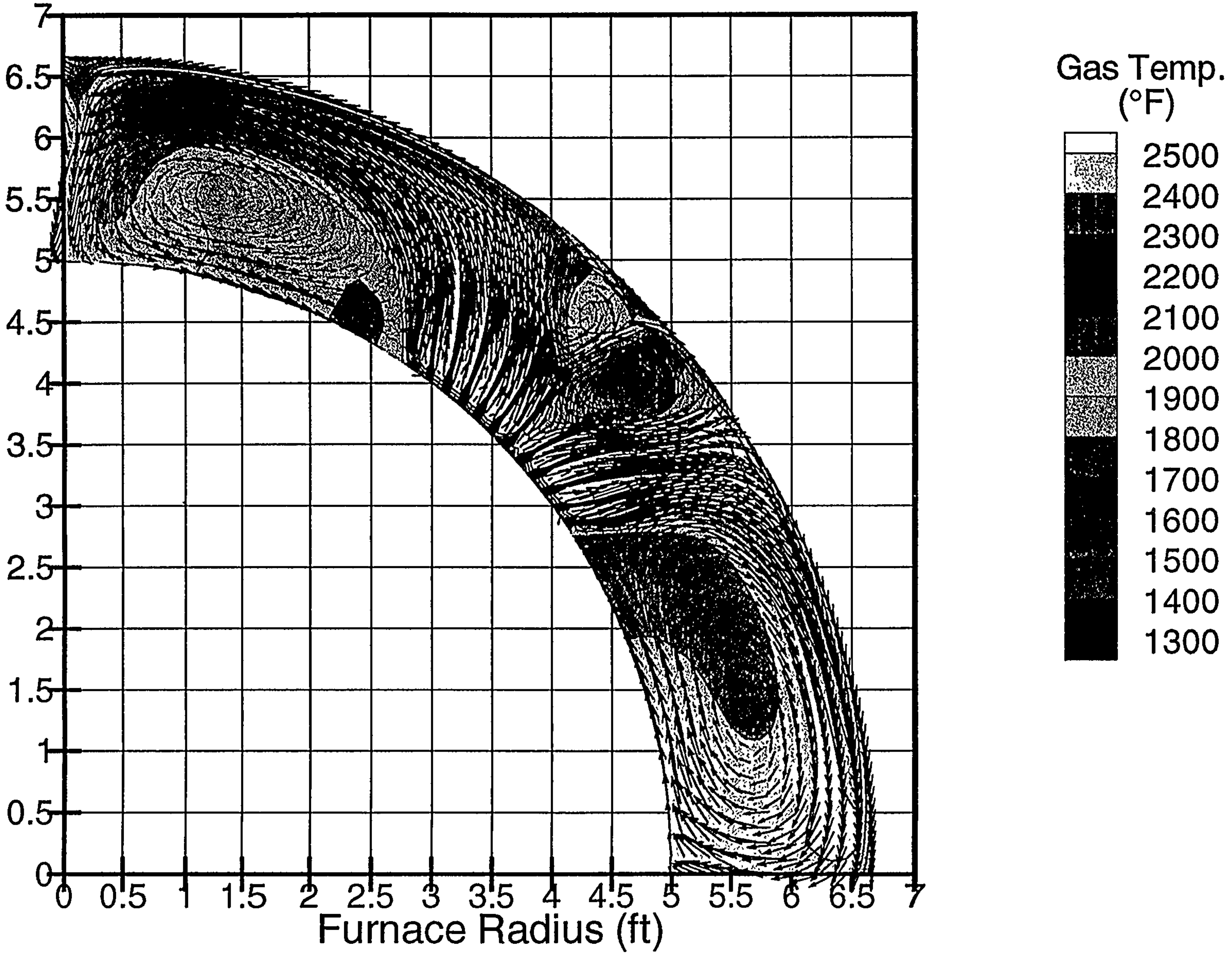
Modification 6 - Furnace Location at 4 feet



e

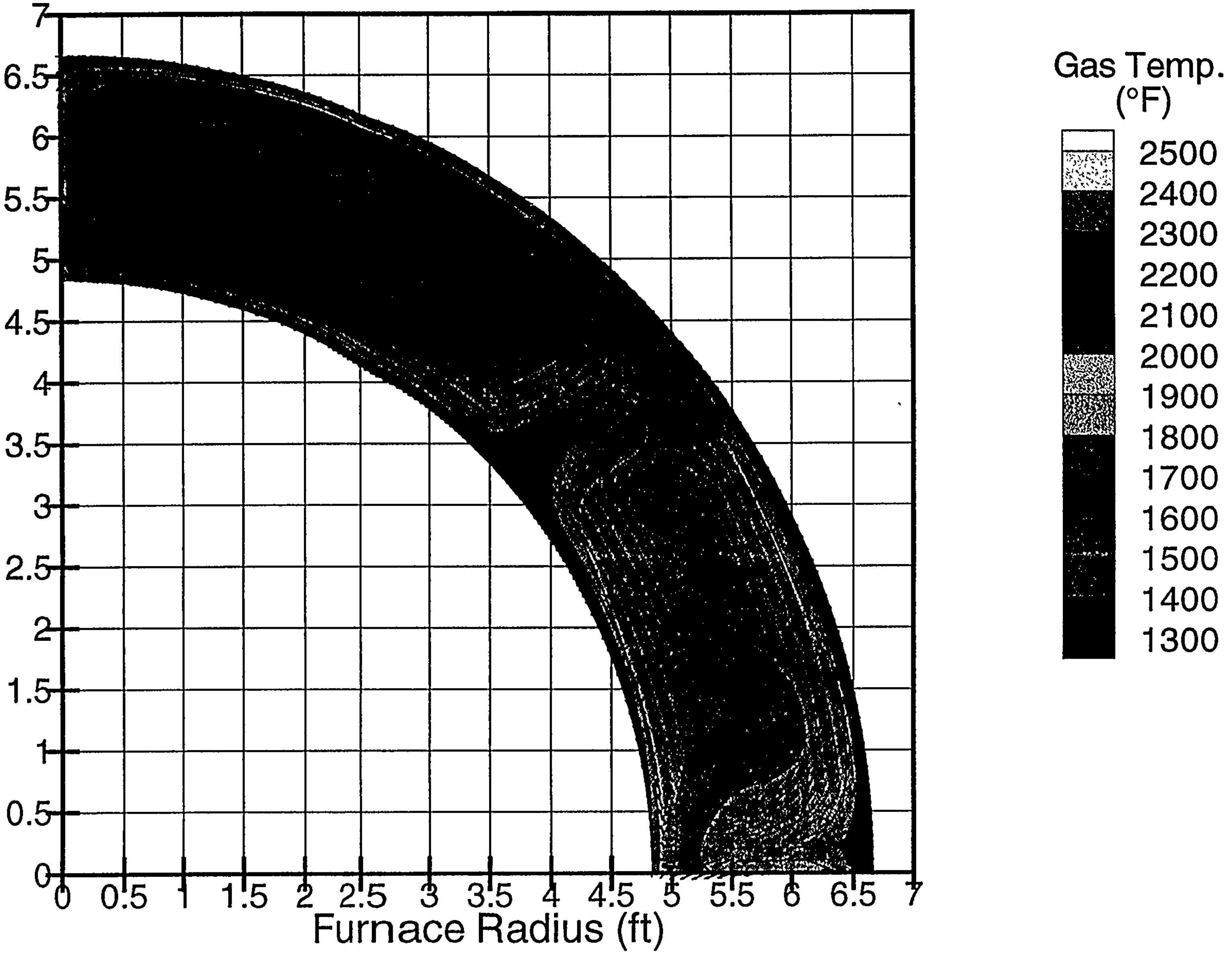
Alzeta Burner Project, Cymric Model - Stage 2

Modification 6 - Furnace Location at 8 feet



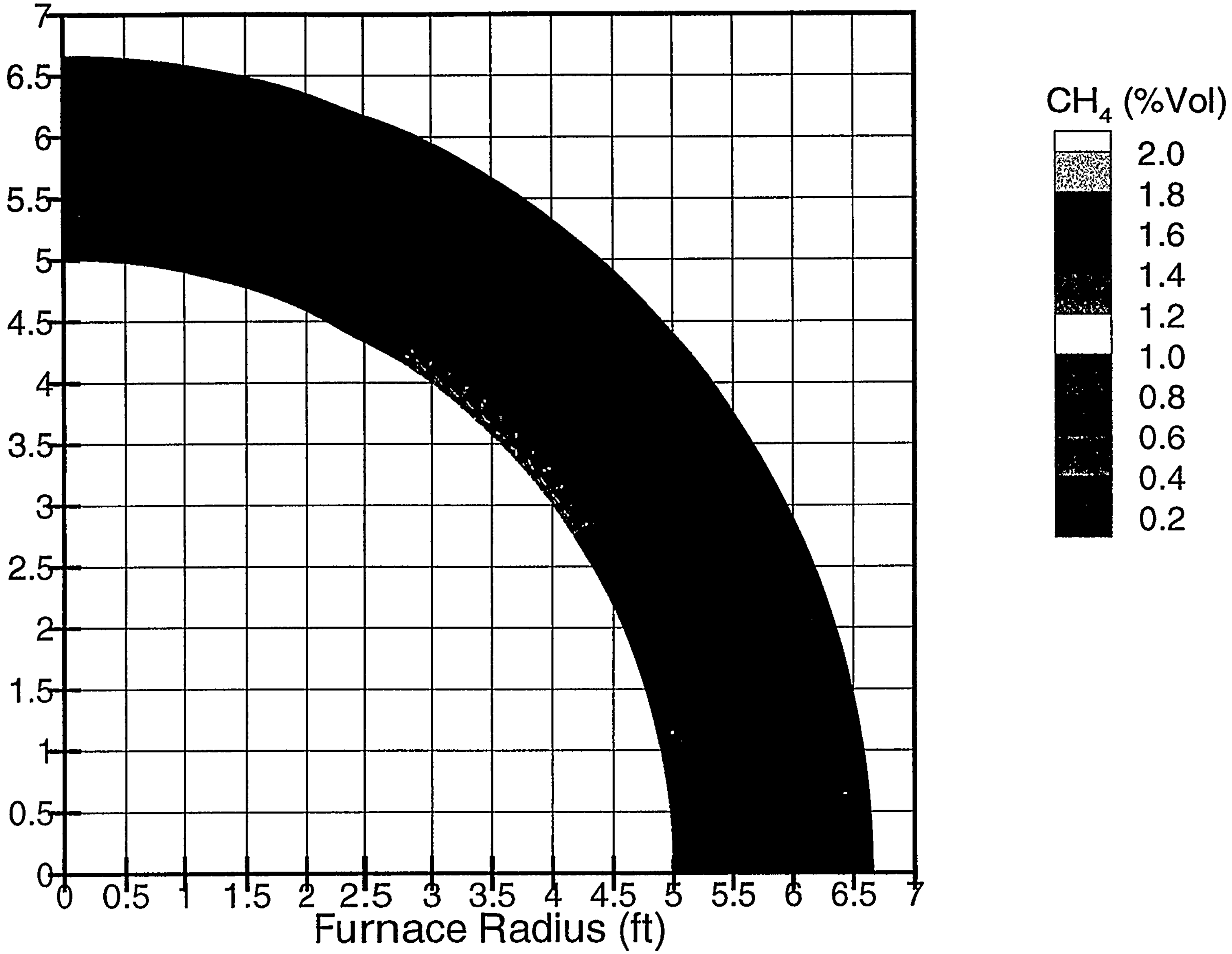
Alzeta Burner Project, Cymric Model - Stage 2

Modification 6 - Furnace Location at 16 feet



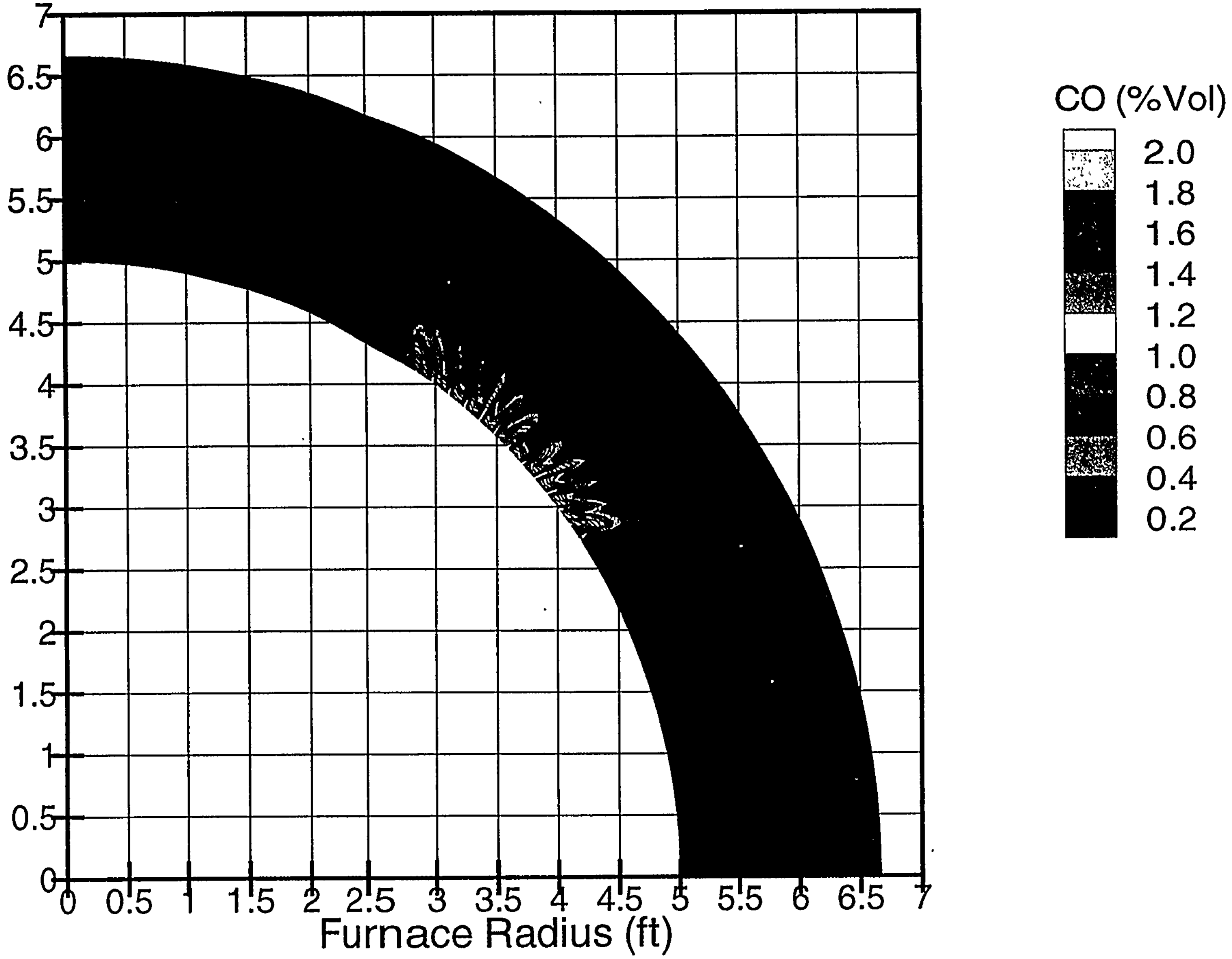
Alzeta Burner Project, Cymric Model - Stage 2

Modification 6 - Furnace Location at 4 feet



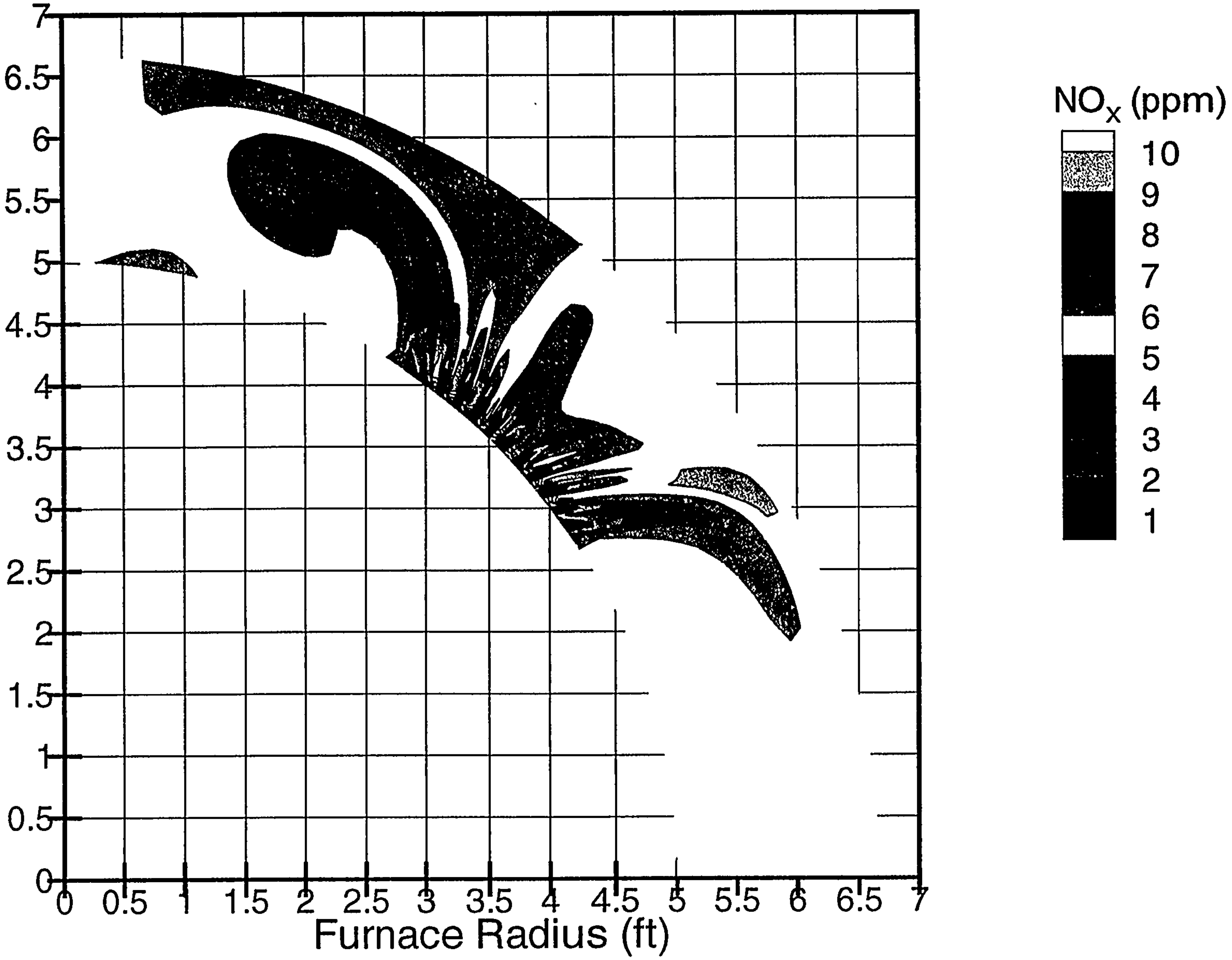
Alzeta Burner Project, Cymric Model - Stage 2

Modification 6 - Furnace Location at 4 feet



Alzeta Burner Project, Cymric Model - Stage 2

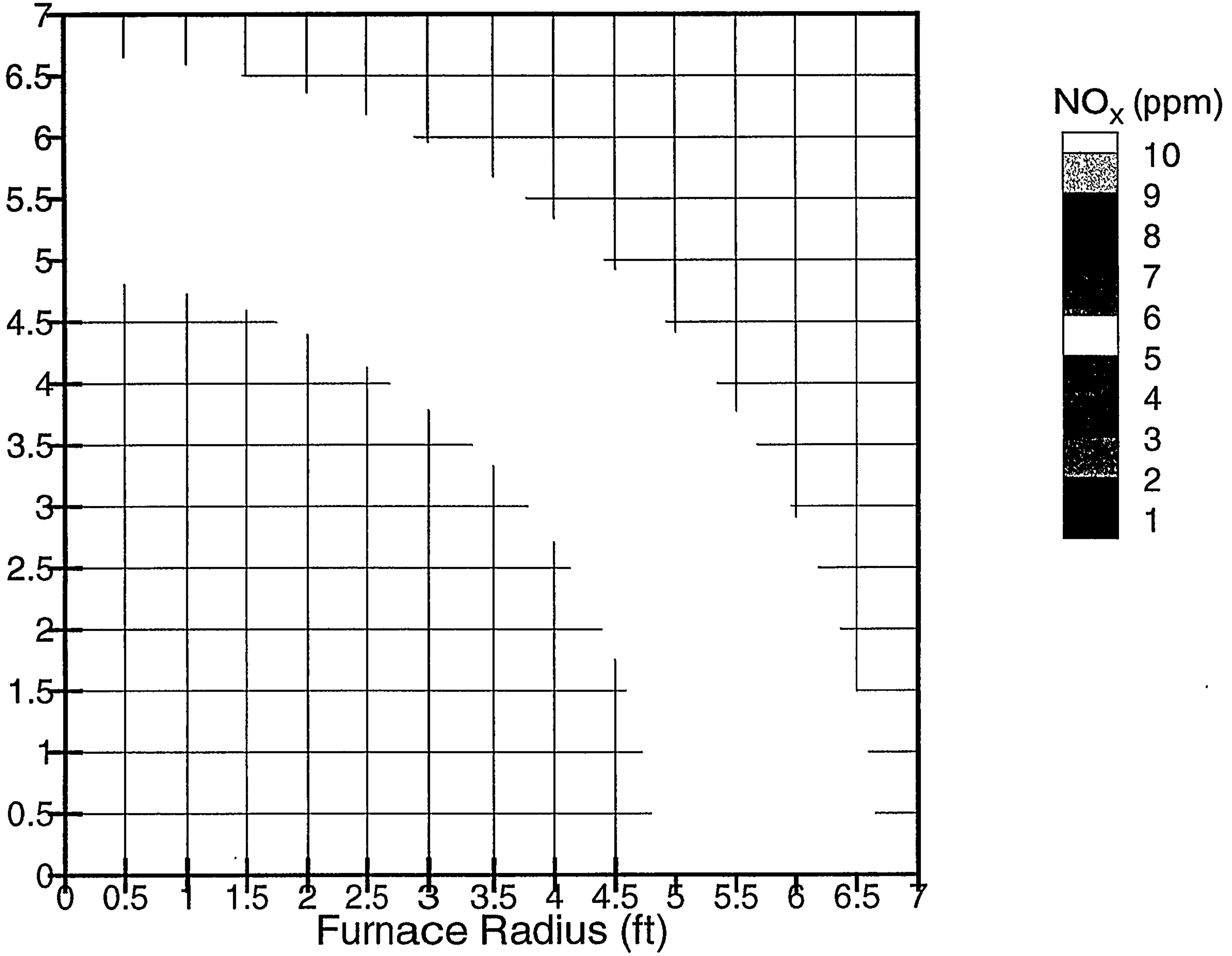
Modification 6 - Furnace Location at 4 feet



K

Alzeta Burner Project, Cymric Model - Stage 2

Modification 6 - Furnace Location at 16 feet



Babcock & Wilcox
a McDermott company

Power Generation Group
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P.O. Box 351
Barberton, OH 44203-0351
(330) 753-4511

November 17, 1997

John Sullivan
Vice President of Engineering
2343 Calle Del Mundo
Santa Clara, CA 95054

Ref: Evaluation of the RSB and In-Furnace
Cooling Surface Using Modeling
Proposal No. P57-0013

Dear John,

I am enclosing here with the results to the numerical computer modeling completed on the referenced project. Enclosures include:
1) Summary comments from the Computational Fluid Mechanics Department.
2) One set of "Base Case" plots consisting of a) a longitudinal cut away with 9 slices of temperature plots, b) a 3 dimensional tube surface temperature plot, c) a 3 dimensional furnace heat flux plot, d) a longitudinal cut away with 9 slices of NOx level plots, e) a cross sectional view at the 4 ft. point location plotting temperature and velocity vectors, f) a cross sectional view at the 8 ft. point location plotting temperature and velocity vectors, g) a cross sectional view at the 16 ft. point location plotting temperature and velocity vectors, h) a cross sectional view at the 4 ft. point location plotting Methane, i) a cross sectional view at the 4 ft. point showing CO, j) a cross sectional view at the 16 ft. point showing CO, k) a cross sectional view showing NO at the 4 ft. point, and a cross sectional view at the 16 ft. point plotting NO.
3) One cross sectional plot of gas temperature at the 4 ft. location using a more elaborate model structure featuring rows of individual jets, labeled "Option 1".
4) One cross sectional plot of gas temperature at the 4 ft. location using a still more refined model structure, labeled "Option 2",
5) One set of "Option 3 Case" plots consisting of the most elaborate model, consisting of the same list as under the "Base Case". However in the longitudinal cut away's, only 5 slices of plots were calculated because of the complexity of the model, and because the slices down stream of the 20 ft. location reveals fairly even conditions.

The base case results varied somewhat from the test data, and therefore it was decided to do a more detailed model in the burner area. This lead to the "Option 1" case. This didn't vary much from the "base case" so "Option 2" was developed, and finially "Option 3". The results didn't change much except for the levels of NOx. In the more elaborate models it appears that the NOx was more realistic.

The temperature results were compared to those developed by Scott Smith in an Excell program, and the two correlated quite well, but both differed significantly from the test thermocouples at test locations 4 & 8 feet. All three correlated well at the 16 ft. location. The attached table and bar chart show these comparative results.

We are recommending a change in the program at this point. Instead of reconfiguring the furnace envelope to represent a D-TYPE package boiler, it is suggested that we continue to work with the circular furnace layout that we have, and focus on bring the burner closer to the water cooled furnace tubes, 2) reconfiguring the furnace tube construction to a fully membraned water cooled arrangement similar to a package boiler, and 3) evaluate the impact of extended surface on the heat flux rate. One factor must be kept in mind; the gas side velocities. In a package boiler with 2 burners and one additional chill tube wall the furnace gas flow velocities would not change significantly. It is suggested that we change the burner to furnace spacing by enlarging both the burner and the furnace envelop diameter so that the gas flow crossectional area (and therefore the flue gas velocities) do not change significantly. At one time we were thinking that the spacing could be as small as 6 inches. After you have had a chance to review these plots I would like your conformation of this alternative program. At this point I believe we can keep the program within the specified budget.

Yours Truly,

Dick Vetterick

R. C. Vetterick

Enclosures
RCV:lw

SUMMARY

STAGE ONE:

1. When the temperature on the face of the burner was estimated based on its color (1340 °F), the heat flux out of the burner and into the furnace walls ranged from 8% to 3%. The values were hand calculated based on average temperature of the furnace wall obtained from the Patran analyses. The heat flux was varied from 40 to 80 kBTU/hr-ft^2 with an inner tube water temperature of 540 °F.

2. When the temperature on the face of the burner was estimated based on data from the customer (1000 °F), the heat flux out of the burner and into the furnace walls ranged from 1% to -1%. The values were hand calculated based on average temperature of the furnace wall obtained from the Patran analyses. Again, the heat flux was varied from 40 to 80 kBTU/hr-ft^2 with an inner tube water temperature of 540 °F.

STAGE TWO:

1. Two sperate models were investigated. The first (Base) was based on a uniform velocity and heat input from the face of the burner to the furnace. The second (Option) was based on strips of high and low velocity and heat inputs.

2. The several different 'base case' models were analyzed using various combustion rate constants. This was investigated due to the large mismatch between several test data point temperatures and the resulting model output. The default rates were determined to be the most accurate.

3. Since COMO requires that the inlet gas steam and the inlet surface temperature be identical, the temperature of both were set to 500 °F. This results in the burner face for the 'base case' models to absorb about 13% of the total heat absorbed in the furnace.

4. The base models showed that the temperature data points around the burner (4ft and 8ft) were about 900 °F higher than those read by the thermocouples . The two points downstream of the burner (14ft and 16ft) were within ±50 °F of each other.

5. Several different ideas on why the data points around the burners were so different were discussed. These ideas included the temperature probes had not been properly calibrated (~-200 °F), the type of probe did not account for radiation loss (~-200 °F), and the COMO program doesn't contain a soot model (~-100 °F). However, these ideas could not take into account all of the temperature difference.

6. The option models were increased in numerical size (same geometry, larger number of control volumes) to account for a more accurate approach into the burner geometry. It was hoped that this modification would reduce the troubling temperature difference. Several models were investigated with increase burner grid resolution.

7. Since COMO requires that the inlet gas steam and the inlet surface temperature be identical, the temperature of both were again set to 500 °F. This results in the burner face for the 'option case' models to absorb about 15% of the total heat absorbed in the furnace.

8. The increase in grid resolution did create regions of slightly lower temperature in certain sections around the burner circumference most notably between the rows of burner jets. This did not, however, reduce the temperatures in the locations of the test thermocouples significantly.

9. The results from the spreadsheet that was created by Alzeta using a bulk model approach with Excel seemed to match the data obtained from the numerical modeling. There were a couple of discrepancies in the actual geometry of the burner and furnace in question. The COMO data was slightly modified to account for this difference.

10. The bulk temperatures between the two models around the burner zones were about ±60 °F. The heat flux comparison between the two models were off by about ±10%. The heat absorptions values were also very close with about a ±11% difference.

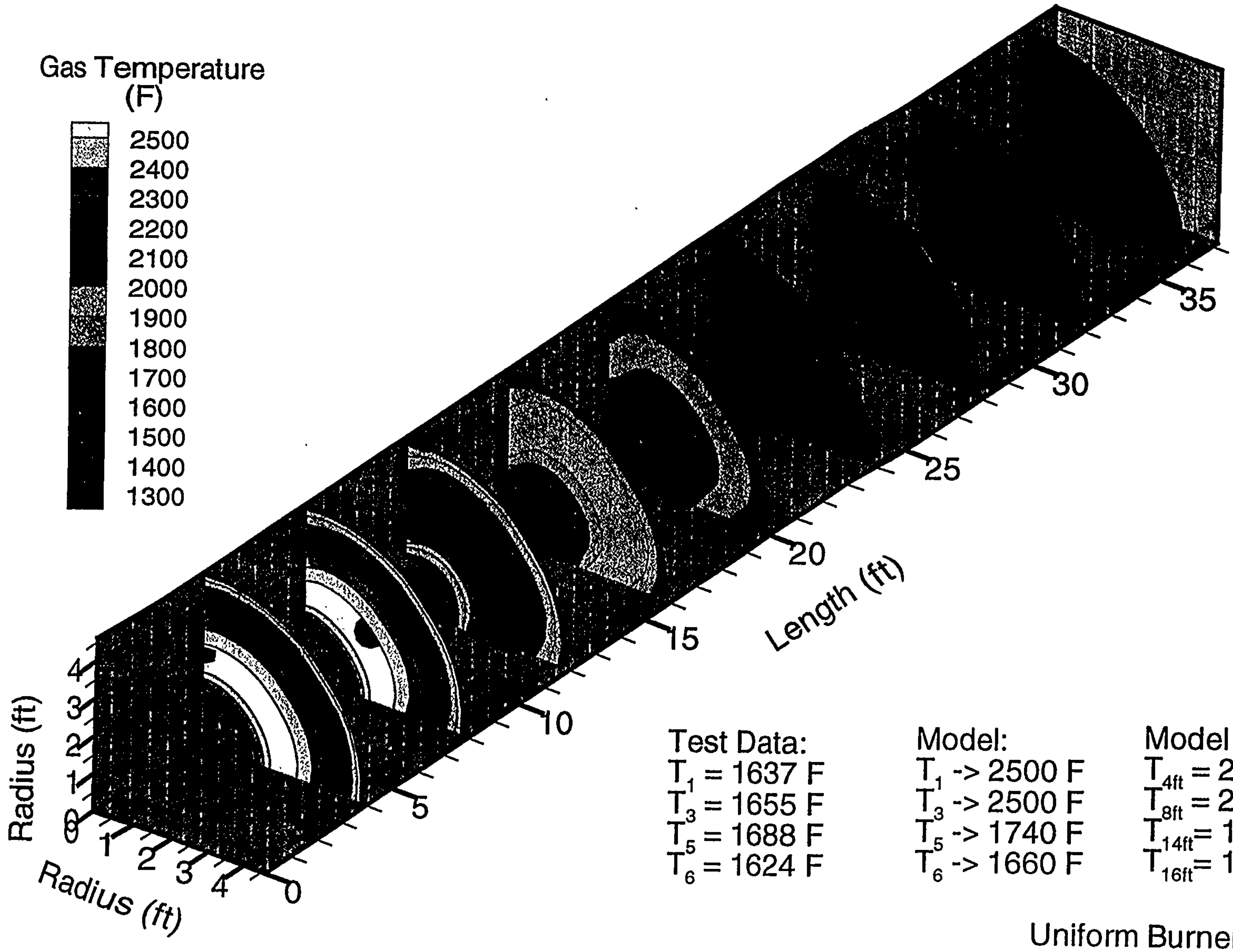
CONCLUSIONS

1. The similarities in the COMO model and the spreadsheet model seem to be in agreement. The data obtained from the numerical modeling and the test data for the data points not around the burner (14ft and 16ft) seem to match. It is my feeling that the two data points around the burner (4ft and 8ft) are not accurate enough for data correlation.

2. I think that COMO can to a good job of modeling the Alzeta Pyromat CSM^{TM} Low NO_X Burner. It should be used to model its installation into a B&W FM type boiler. If further field testing can be done, I believe that it should be done on the burner in the FM type boiler.

Alzeta Burner Project, Cymric Model - Stage 2

Furnace Gas Temperatures



Test Data:
$T_1 = 1637$ F
$T_3 = 1655$ F
$T_5 = 1688$ F
$T_6 = 1624$ F

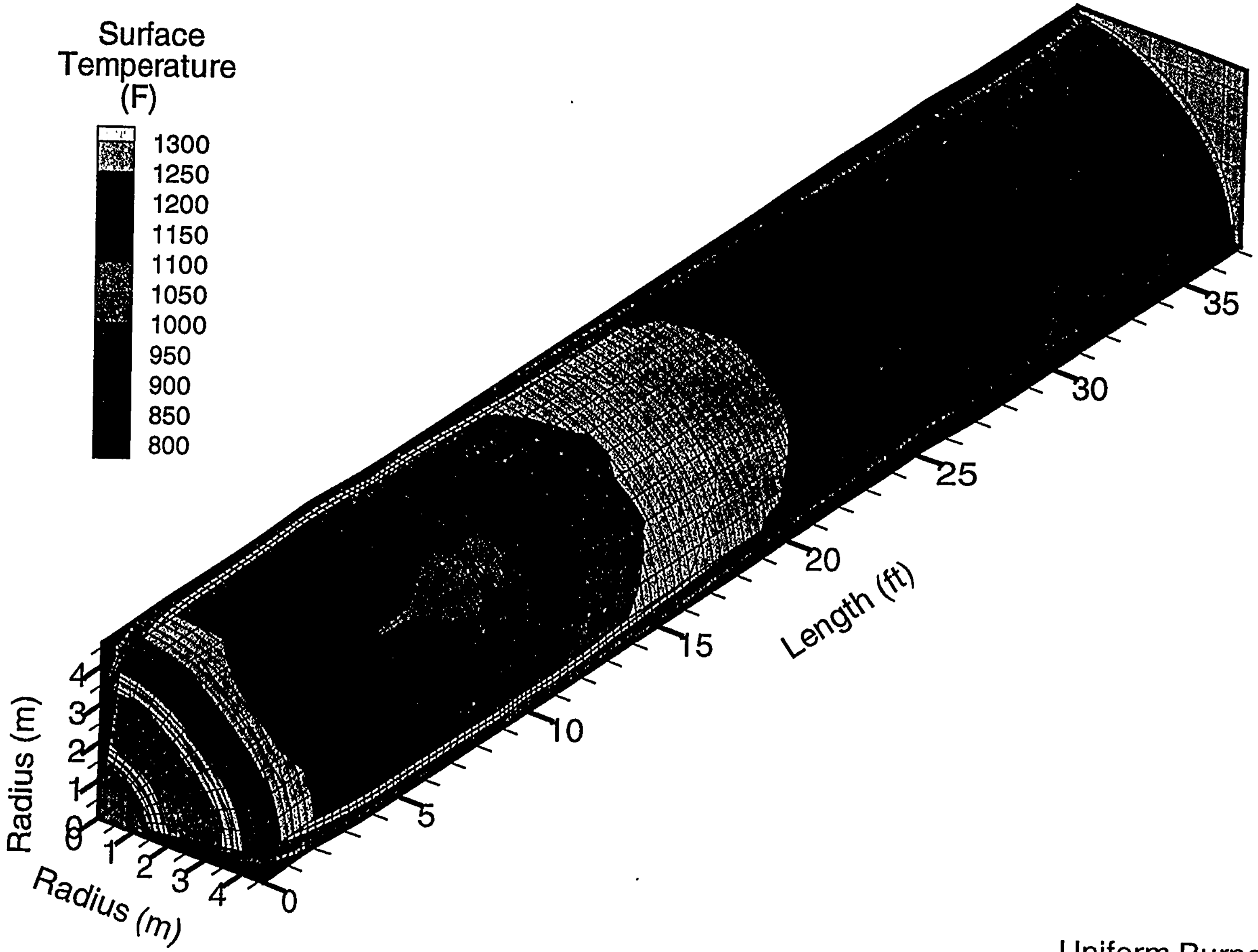
Model:
$T_1 \to 2500$ F
$T_3 \to 2500$ F
$T_5 \to 1740$ F
$T_6 \to 1660$ F

Model Ave:
$T_{4ft} = 2161$ F
$T_{8ft} = 2143$ F
$T_{14ft} = 1942$ F
$T_{16ft} = 1873$ F

Uniform Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

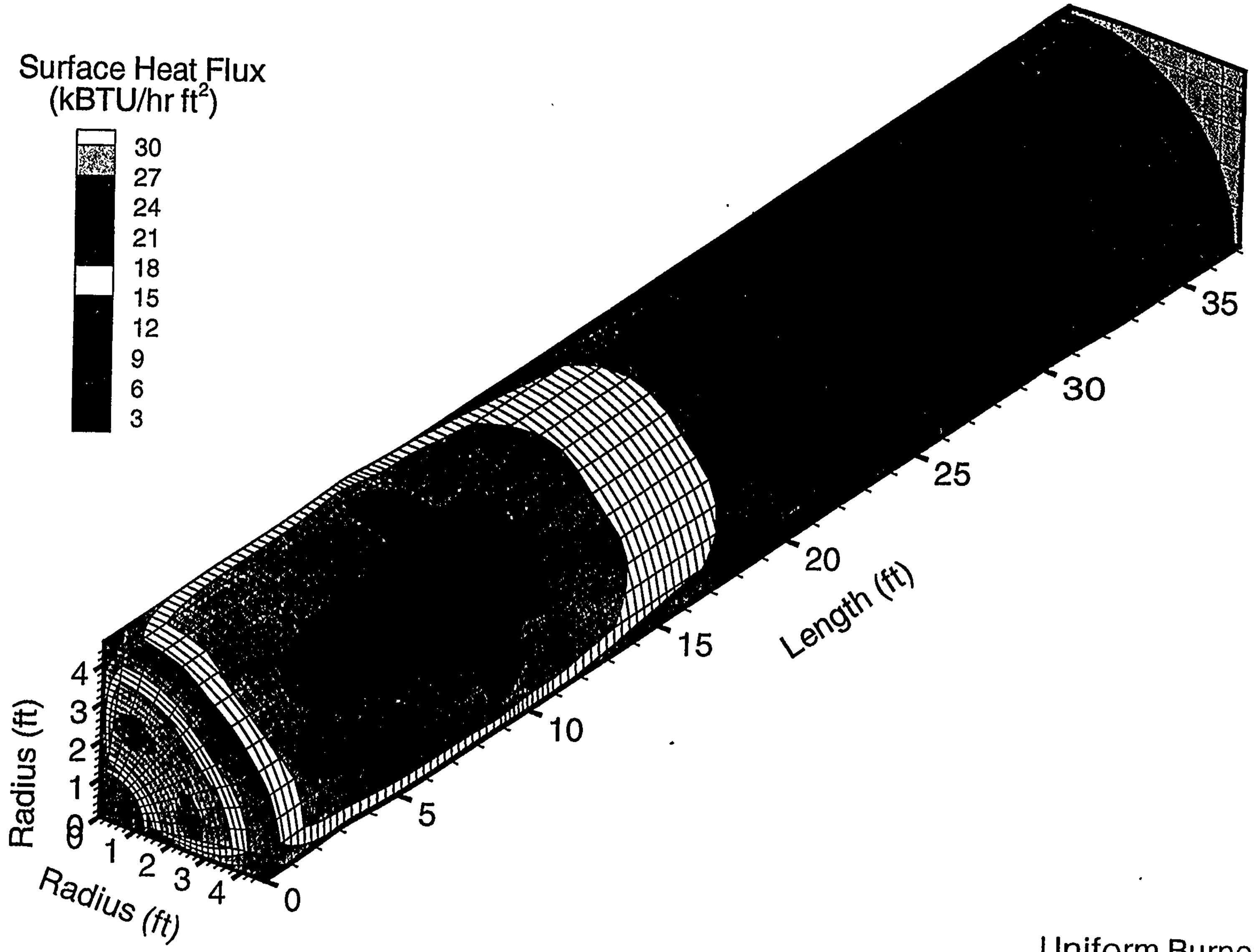
Furnace Surface Temperatures



Uniform Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

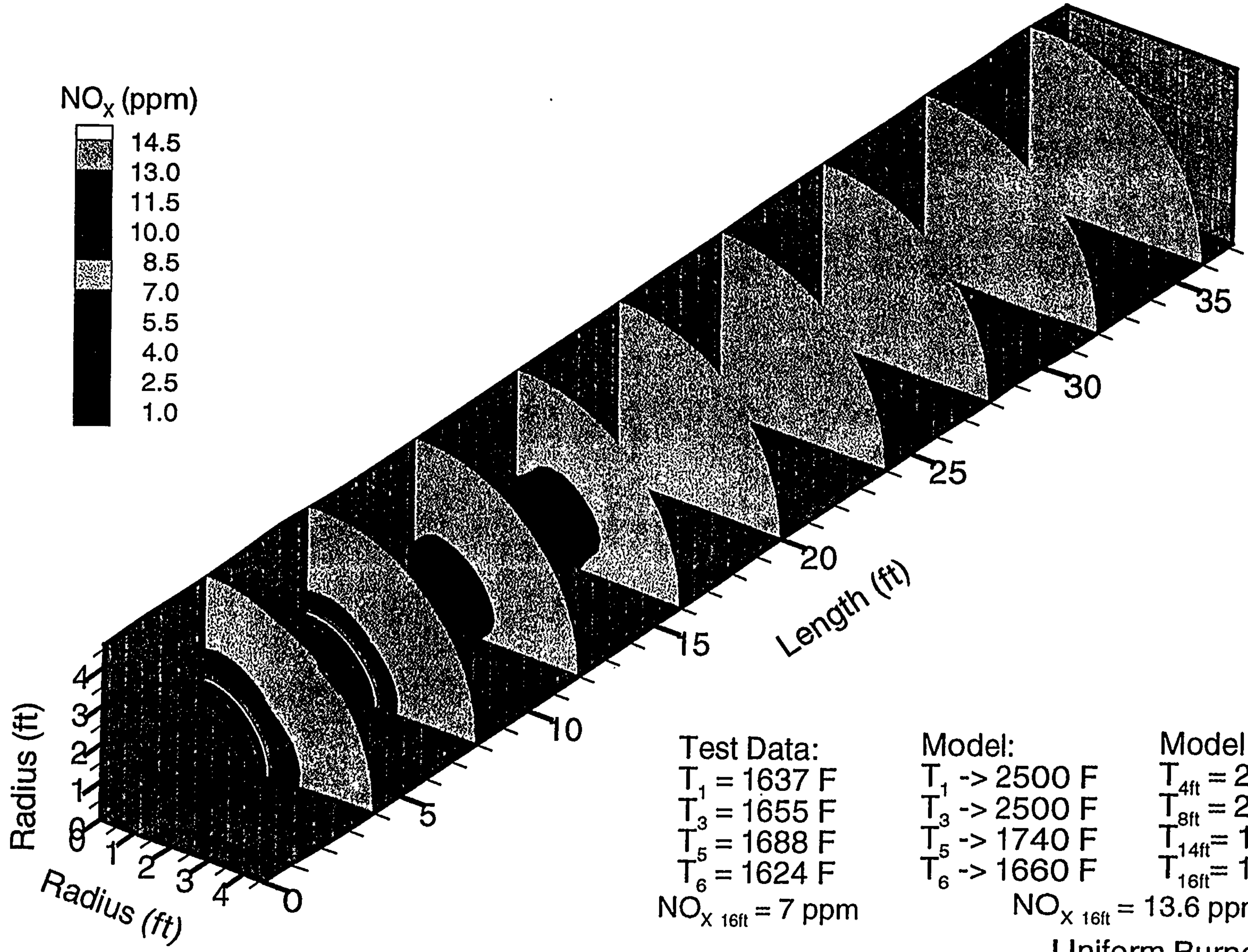
Furnace Heat Flux



Uniform Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Furnace NO_x Levels



Test Data:
$T_1 = 1637$ F
$T_3 = 1655$ F
$T_5 = 1688$ F
$T_6 = 1624$ F
$NO_{X\ 16ft} = 7$ ppm

Model:
$T_1 \rightarrow 2500$ F
$T_3 \rightarrow 2500$ F
$T_5 \rightarrow 1740$ F
$T_6 \rightarrow 1660$ F

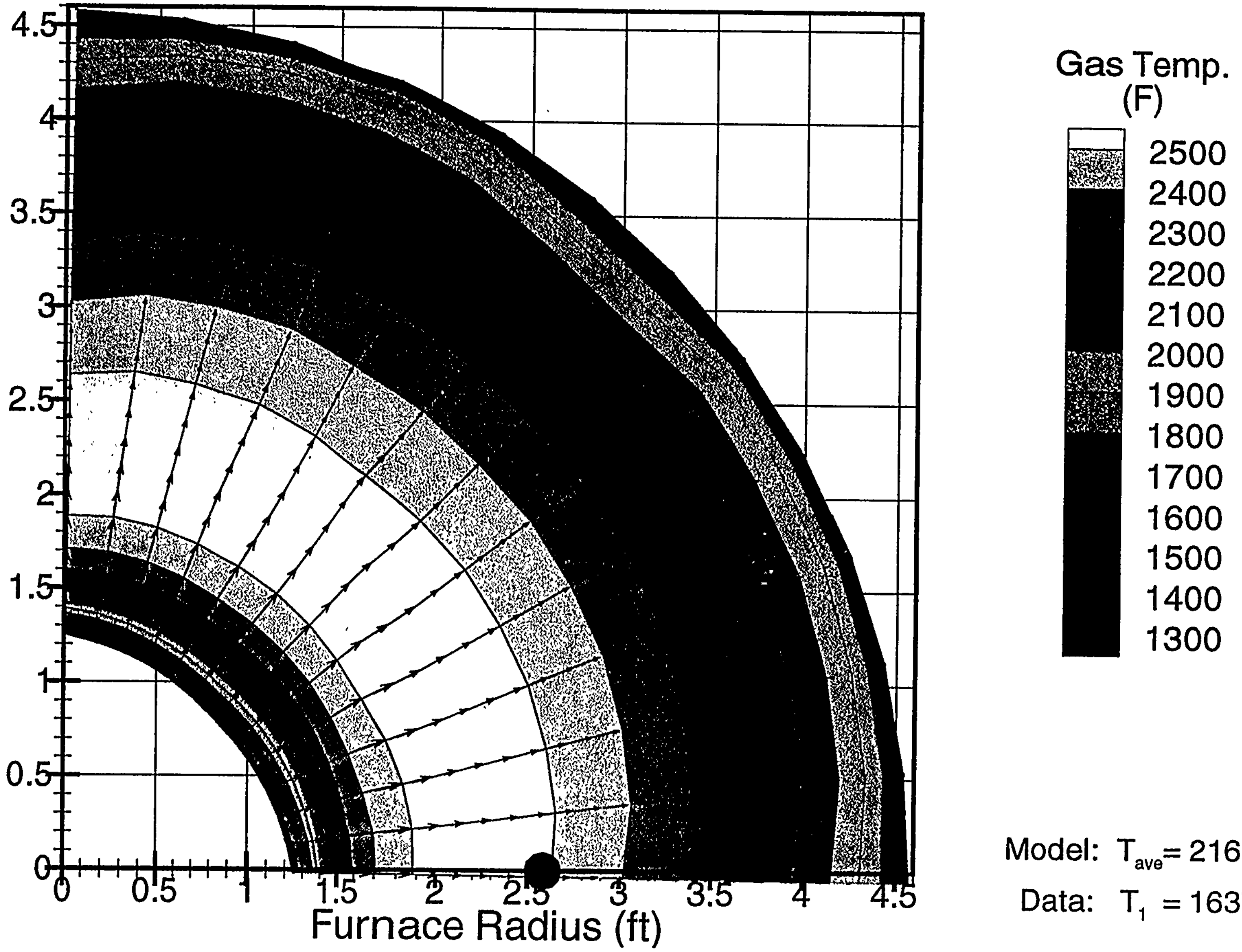
Model Ave:
$T_{4ft} = 2161$ F
$T_{8ft} = 2143$ F
$T_{14ft} = 1942$ F
$T_{16ft} = 1873$ F

$NO_{X\ 16ft} = 13.6$ ppm

Uniform Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Furnace Location at 4 feet

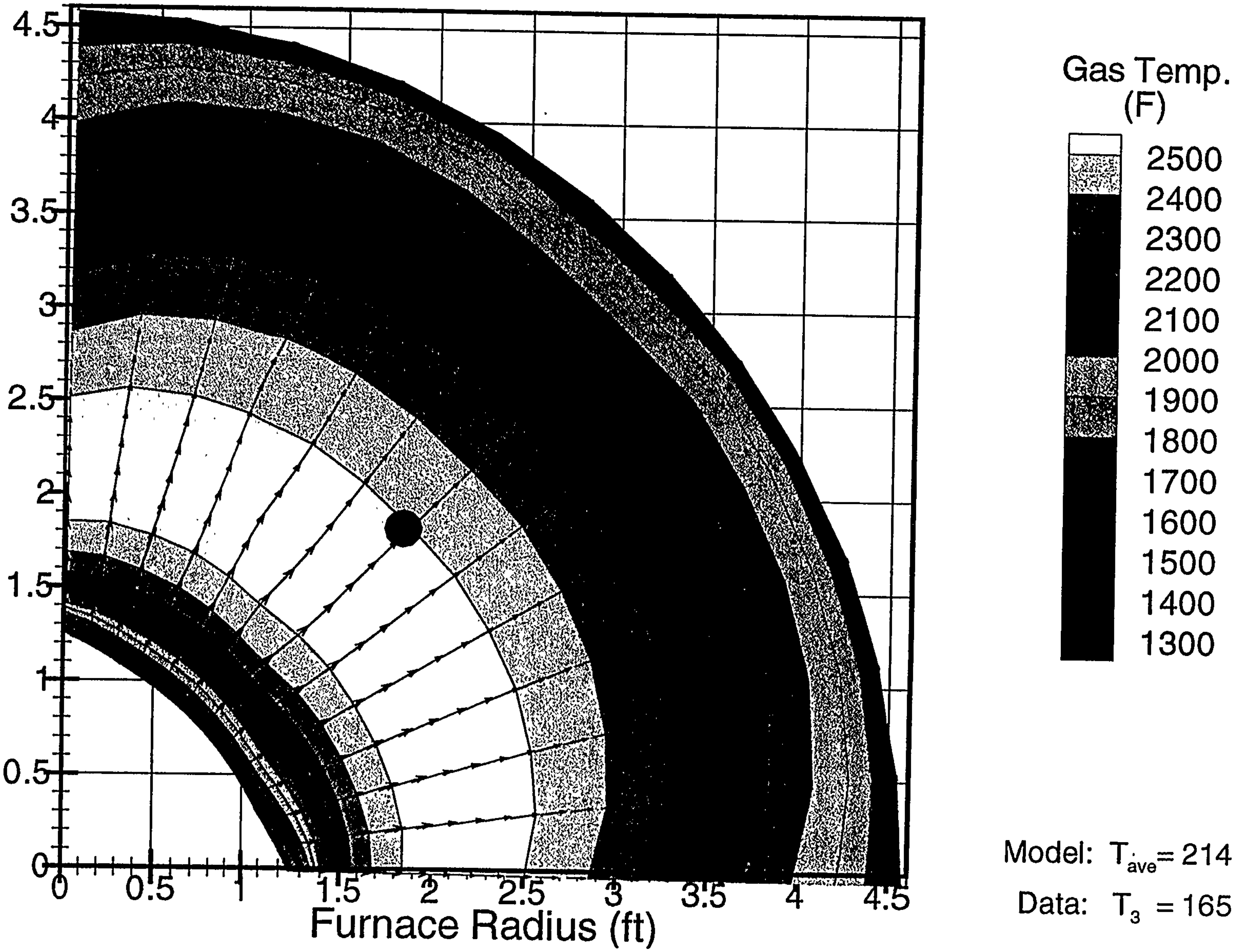


Model: T_{ave} = 2161 F

Data: T_1 = 1637 F

Alzeta Burner Project, Cymric Model - Stage 2

Furnace Location at 8 feet

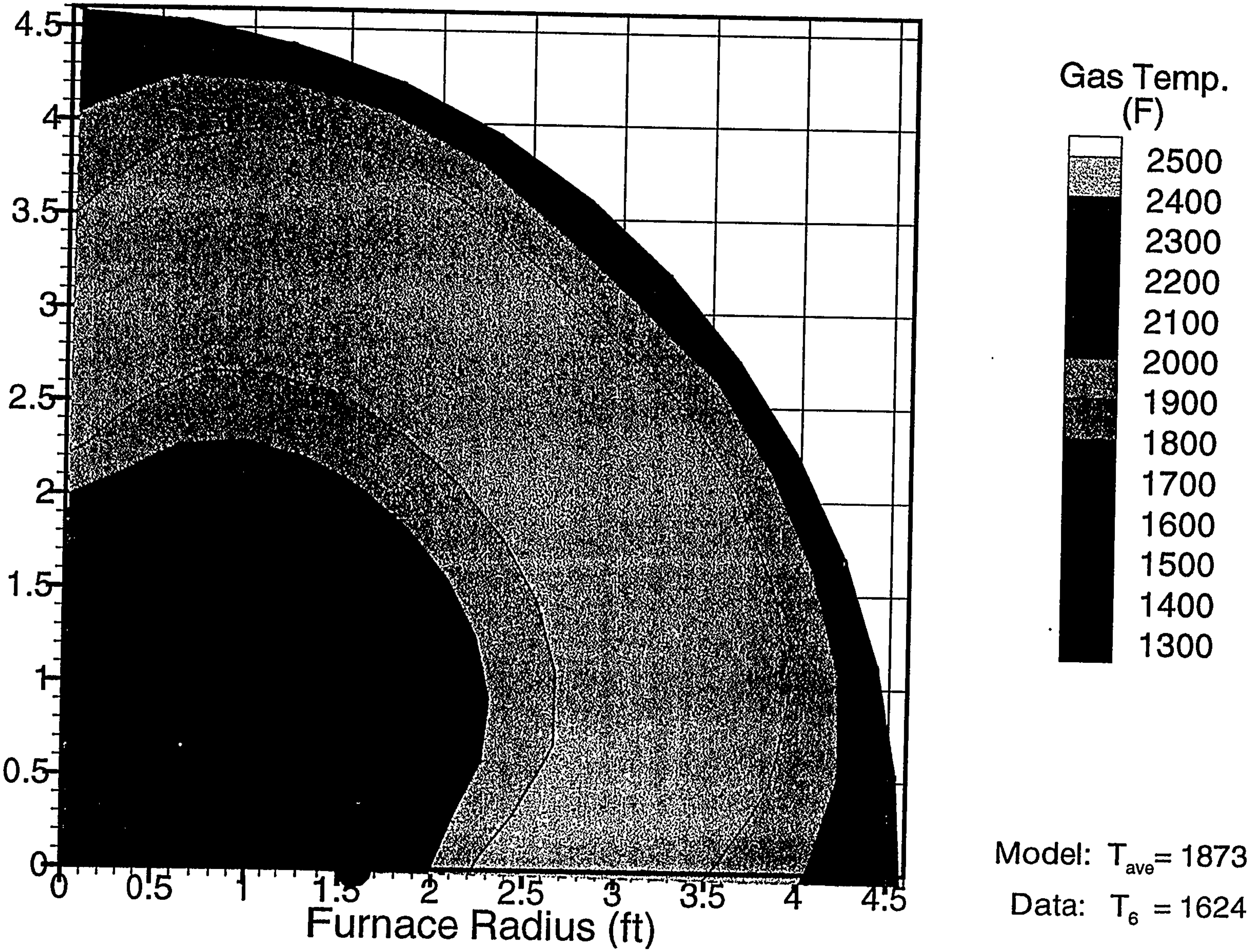


Model: $T_{ave} = 2143$ F

Data: $T_3 = 1655$ F

Alzeta Burner Project, Cymric Model - Stage 2

Furnace Location at 16 feet

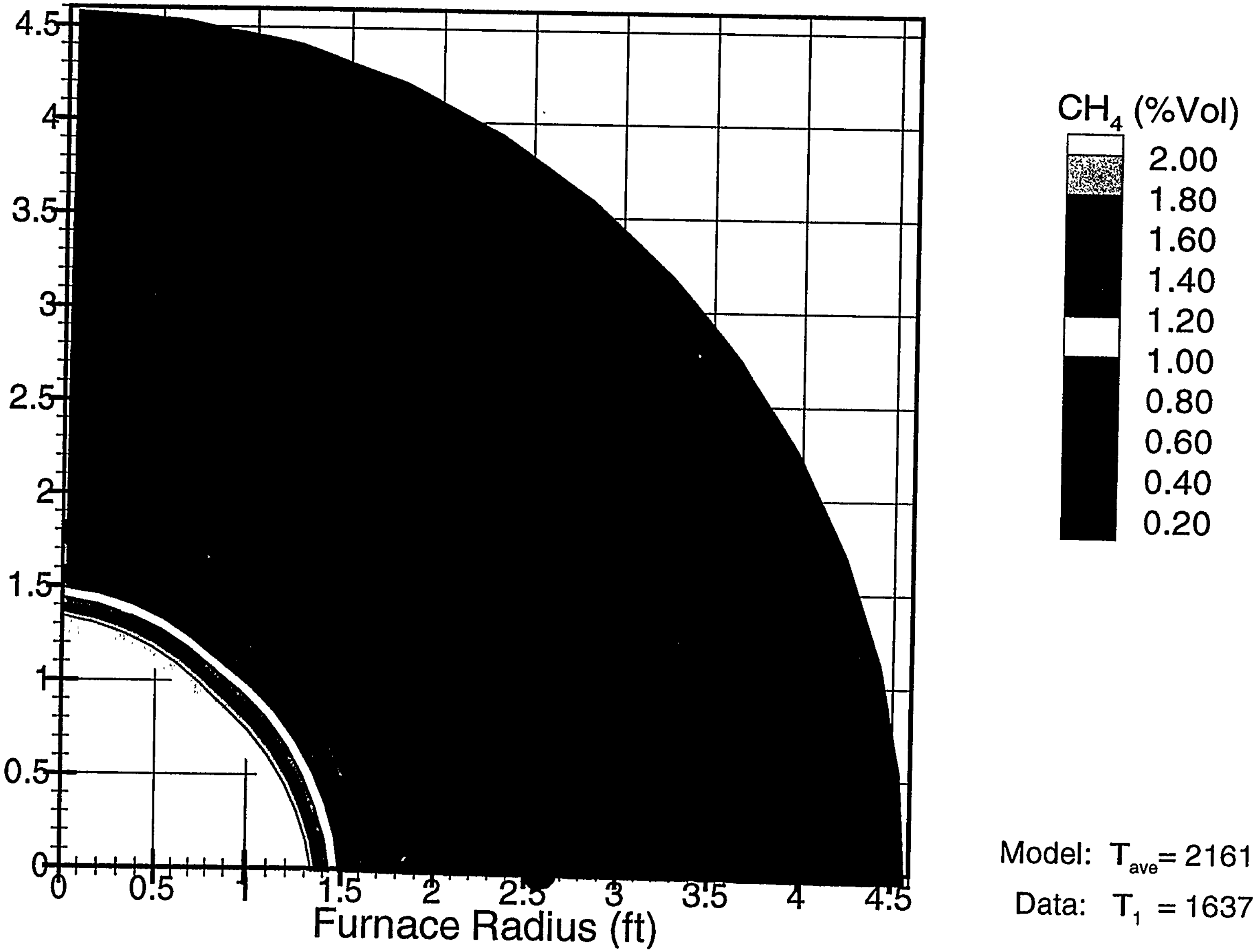


Model: T_{ave} = 1873 F

Data: T_6 = 1624 F

Alzeta Burner Project, Cymric Model - Stage 2

Furnace Location at 4 feet



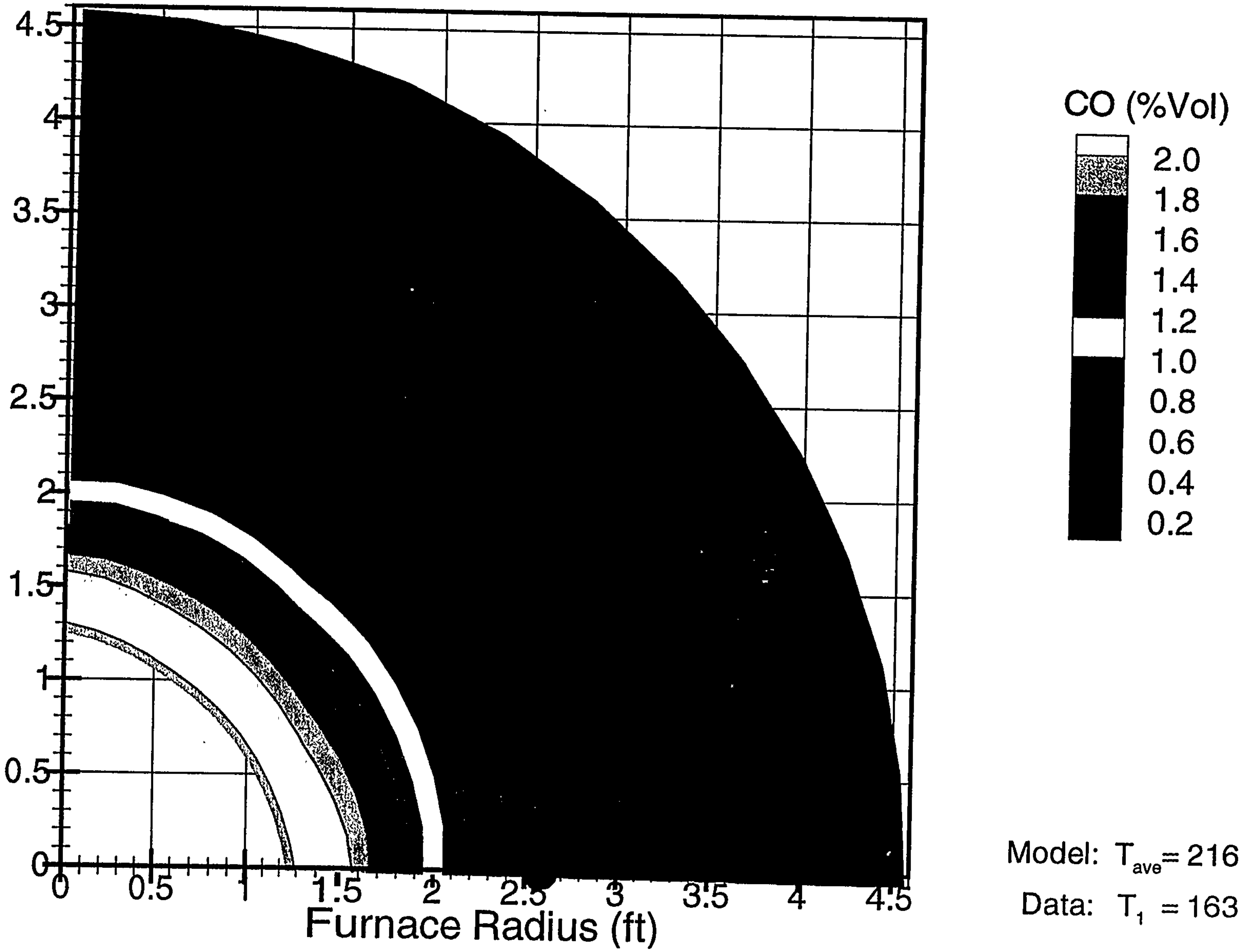
Model: $T_{ave} = 2161$ F

Data: $T_1 = 1637$ F

(h)

Alzeta Burner Project, Cymric Model - Stage 2

Furnace Location at 4 feet

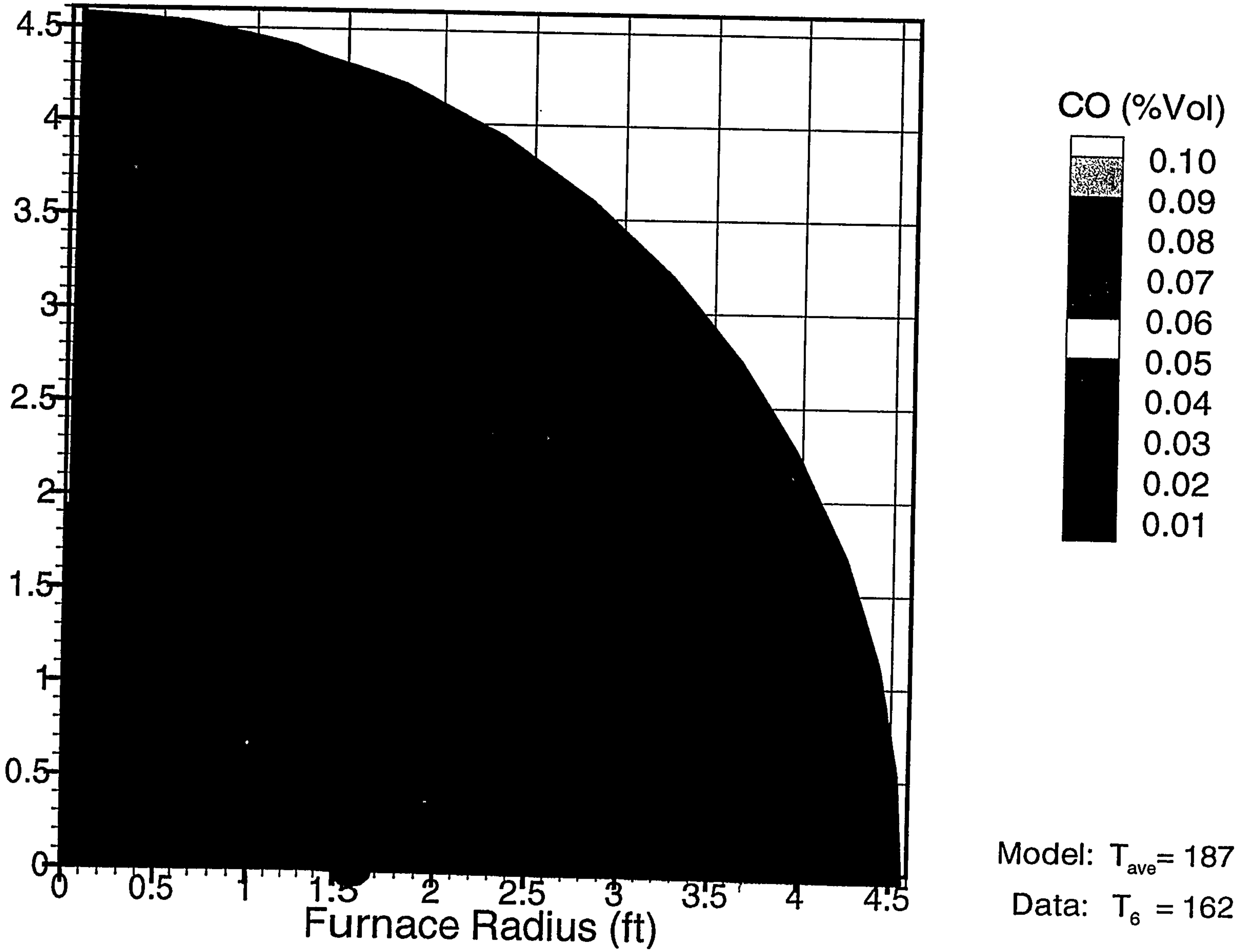


Model: $T_{ave} = 2161$ F

Data: $T_1 = 1637$ F

Alzeta Burner Project, Cymric Model - Stage 2

Furnace Location at 16 feet

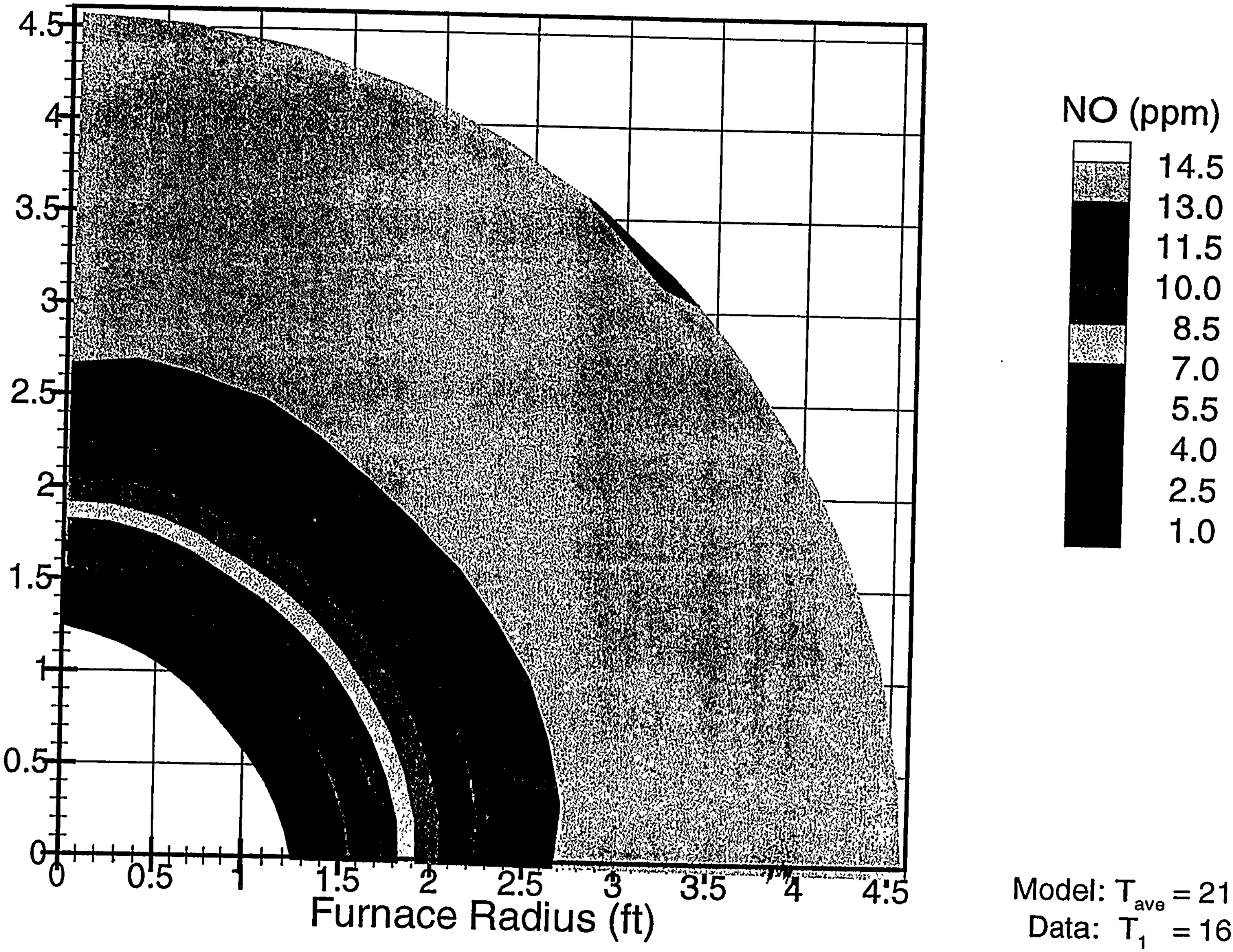


Model: T_{ave} = 1873 F

Data: T_6 = 1624 F

Alzeta Burner Project, Cymric Model - Stage 2

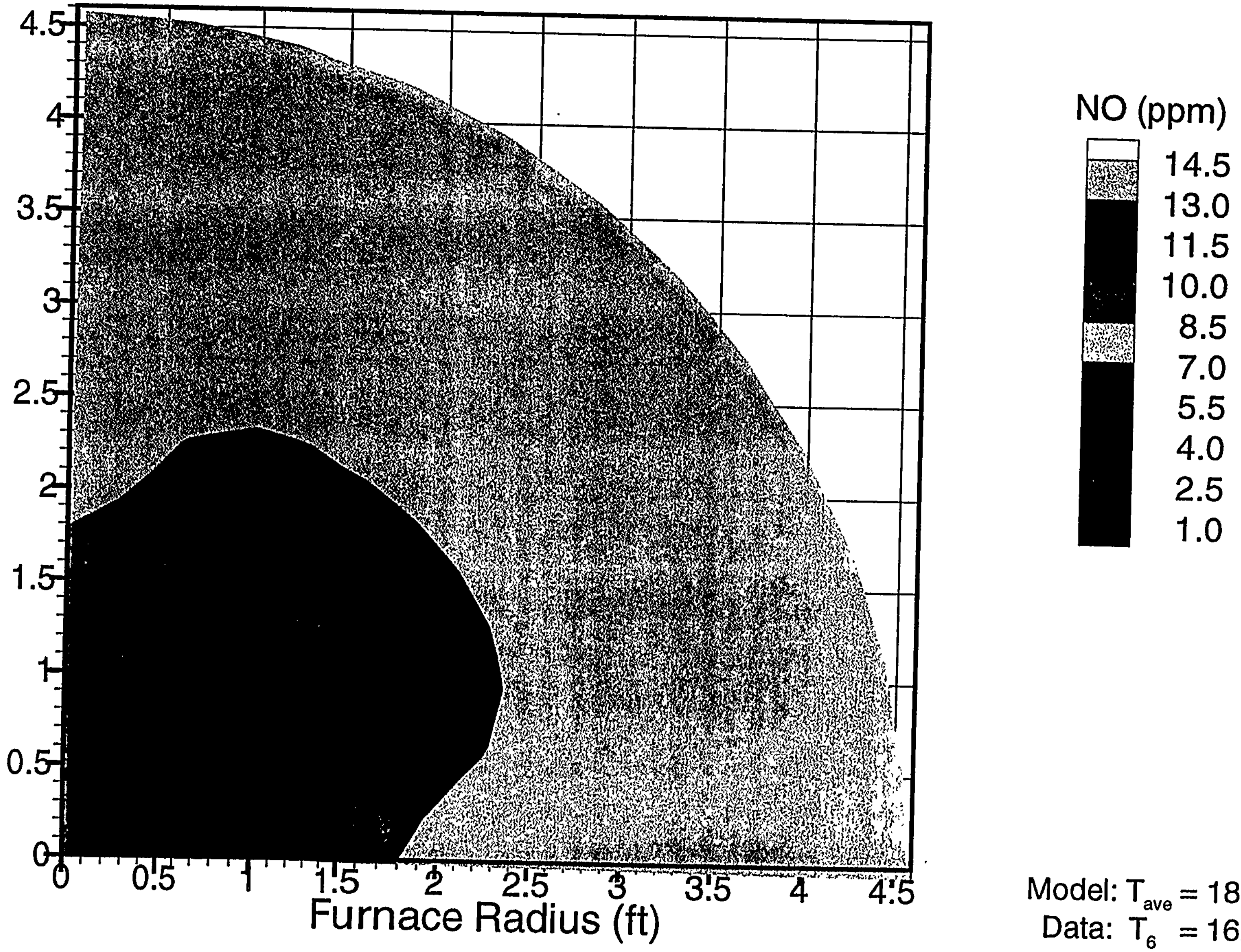
Furnace Location at 4 feet



Model: $T_{ave} = 2161$ F
Data: $T_1 = 1637$ F

Alzeta Burner Project, Cymric Model - Stage 2

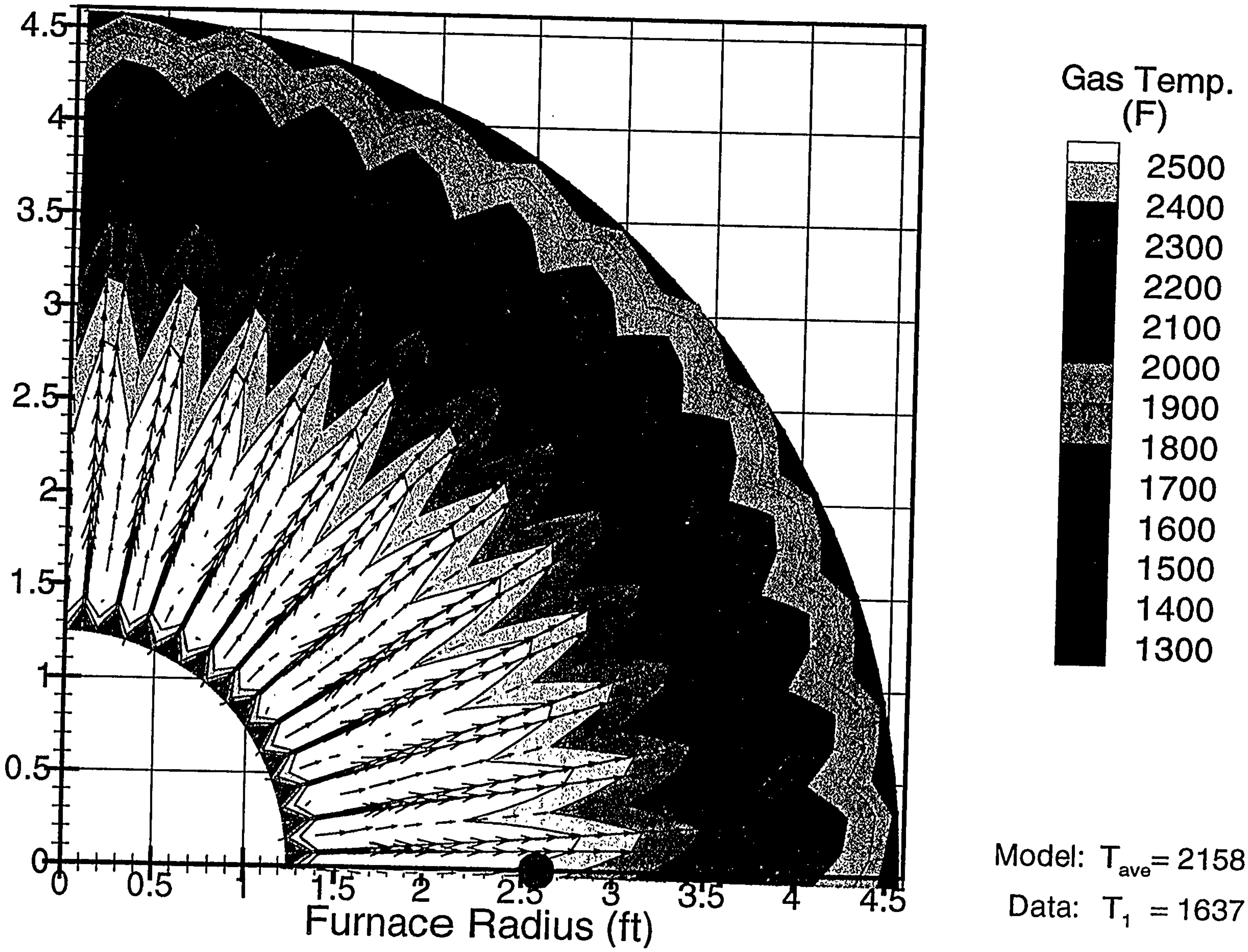
Furnace Location at 16 feet



Model: T_{ave} = 1873 F
Data: T_6 = 1624 F

Alzeta Burner Project, Cymric Model - Stage 2

Option 1 - Furnace Location at 4 feet

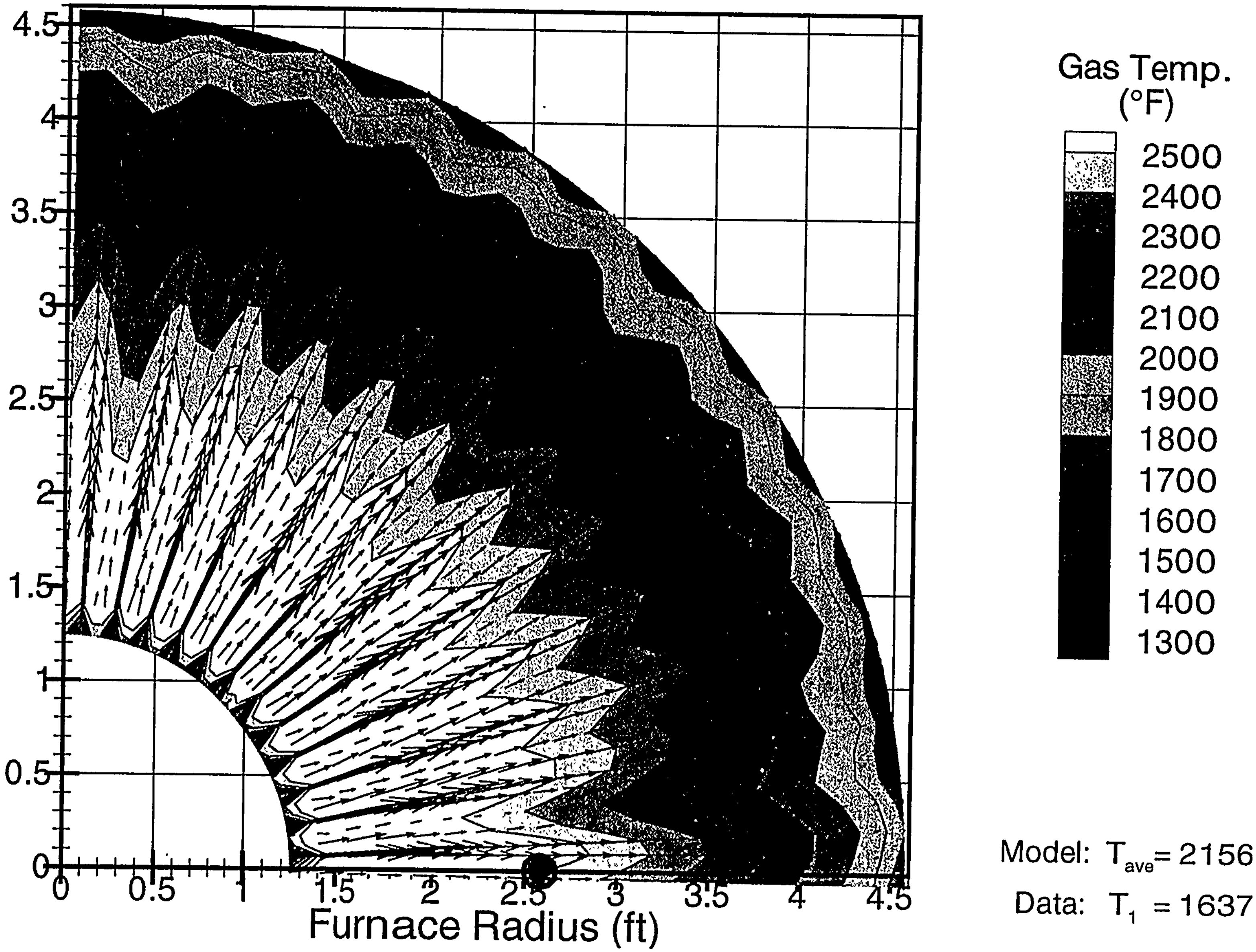


Model: T_{ave} = 2158 F

Data: T_1 = 1637 F

Alzeta Burner Project, Cymric Model - Stage 2

Option 2 - Furnace Location at 4 feet

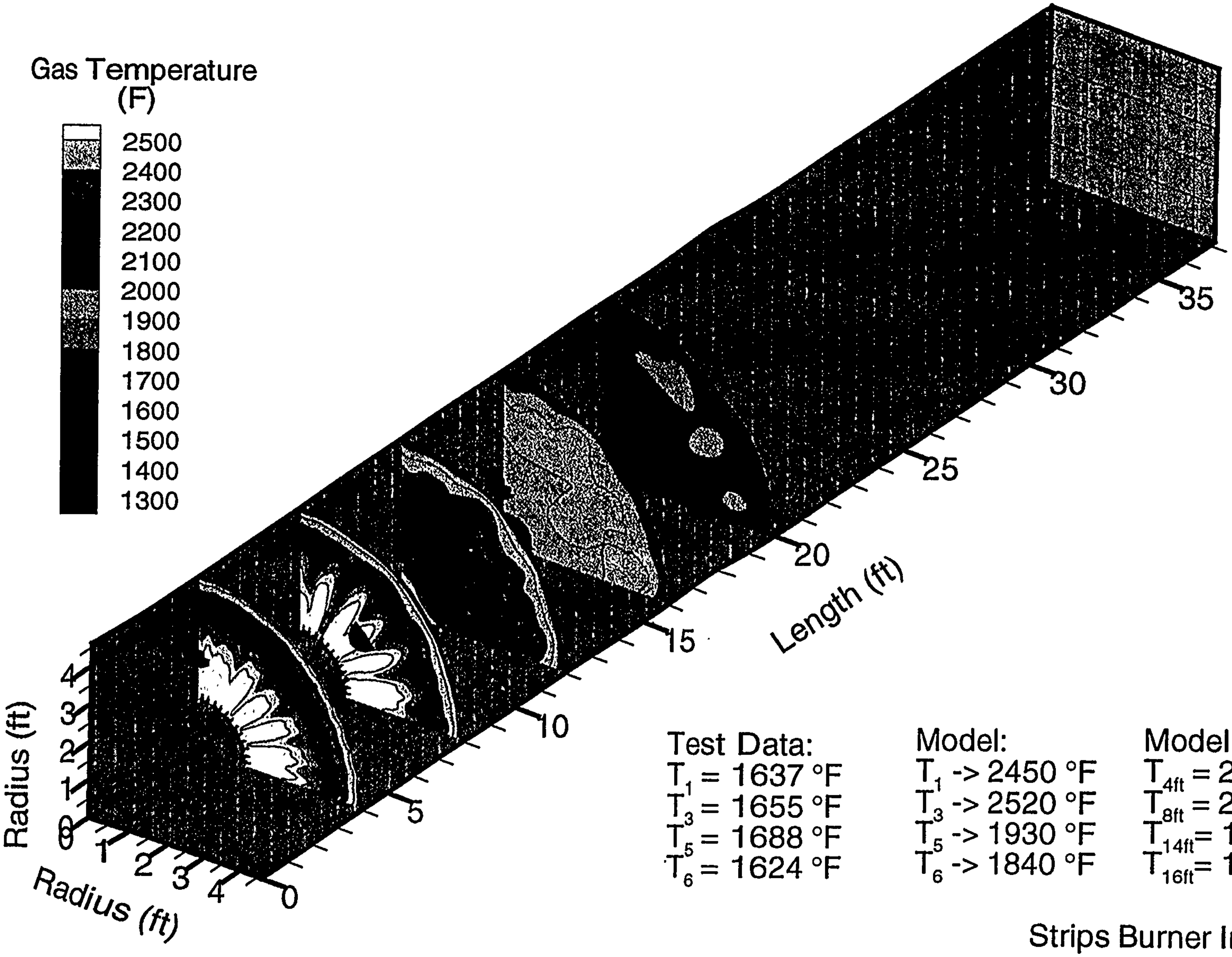


Model: T_{ave}= 2156 °F

Data: T_1 = 1637 °F

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Gas Temperatures



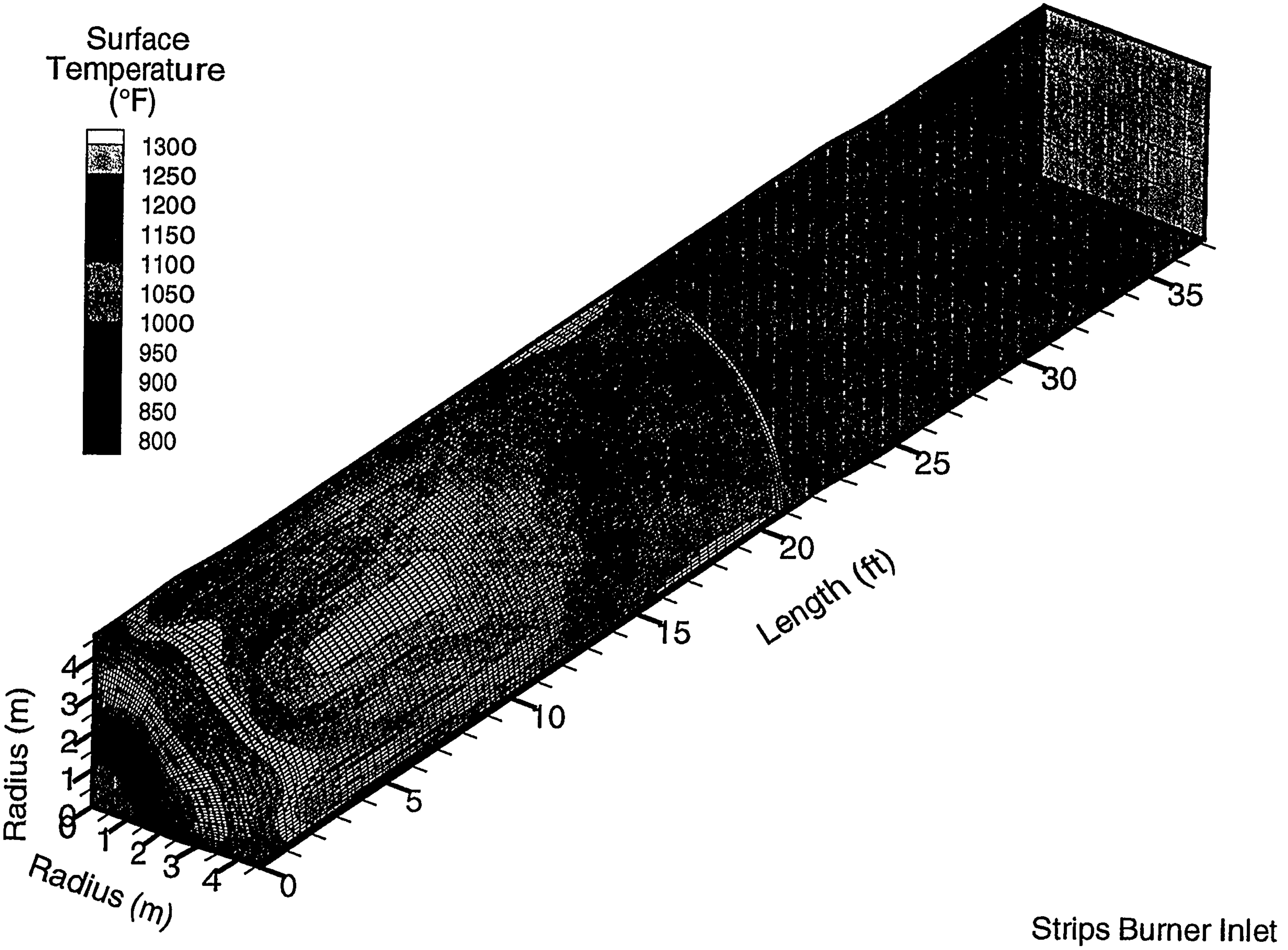
Test Data:	Model:	Model Ave:
T_1 = 1637 °F	T_1 -> 2450 °F	T_{4ft} = 2159 °F
T_3 = 1655 °F	T_3 -> 2520 °F	T_{8ft} = 2140 °F
T_5 = 1688 °F	T_5 -> 1930 °F	T_{14ft} = 1923 °F
T_6 = 1624 °F	T_6 -> 1840 °F	T_{16ft} = 1852 °F

Strips Burner Inlet

(a)

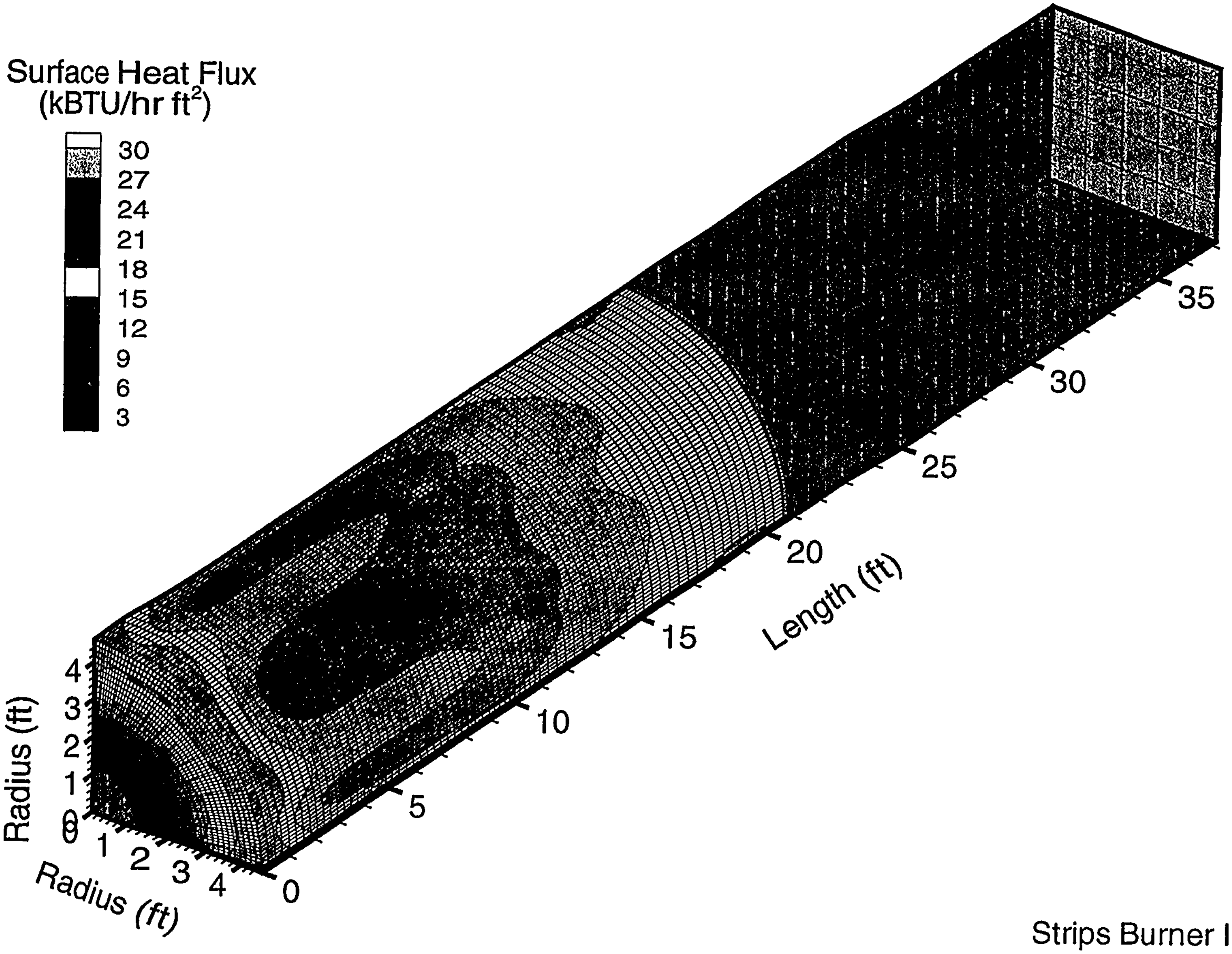
Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Surface Temperatures



Alzeta Burner Project, Cymric Model - Stage 2

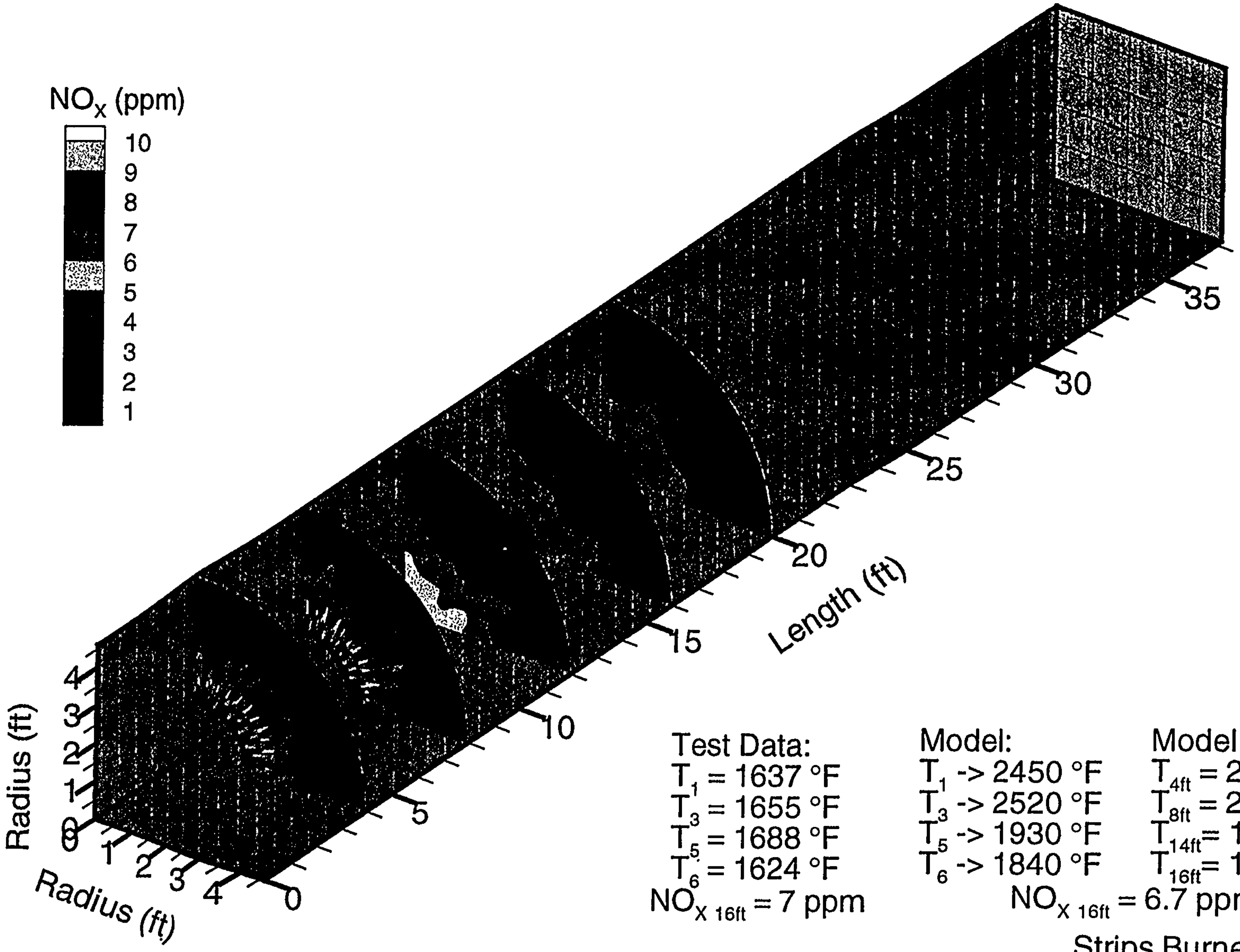
Option 3 - Furnace Heat Flux



Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace NO_x Levels

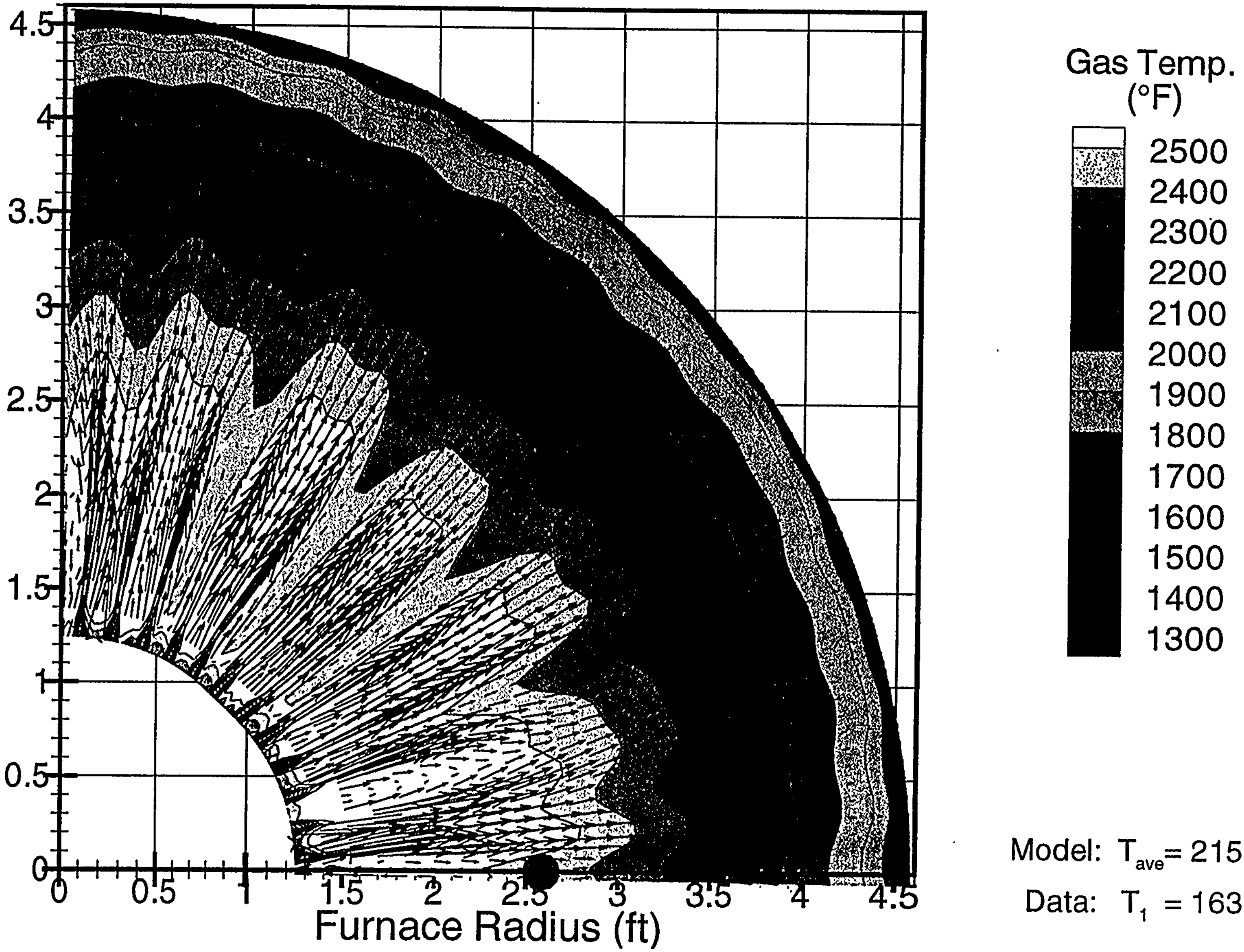


Test Data:	Model:	Model Ave:
T_1 = 1637 °F	T_1 -> 2450 °F	T_{4ft} = 2159 °F
T_3 = 1655 °F	T_3 -> 2520 °F	T_{8ft} = 2140 °F
T_5 = 1688 °F	T_5 -> 1930 °F	T_{14ft}= 1923 °F
T_6 = 1624 °F	T_6 -> 1840 °F	T_{16ft}= 1852 °F
$NO_{X\ 16ft}$ = 7 ppm	$NO_{X\ 16ft}$ = 6.7 ppm	

Strips Burner Inlet

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Location at 4 feet

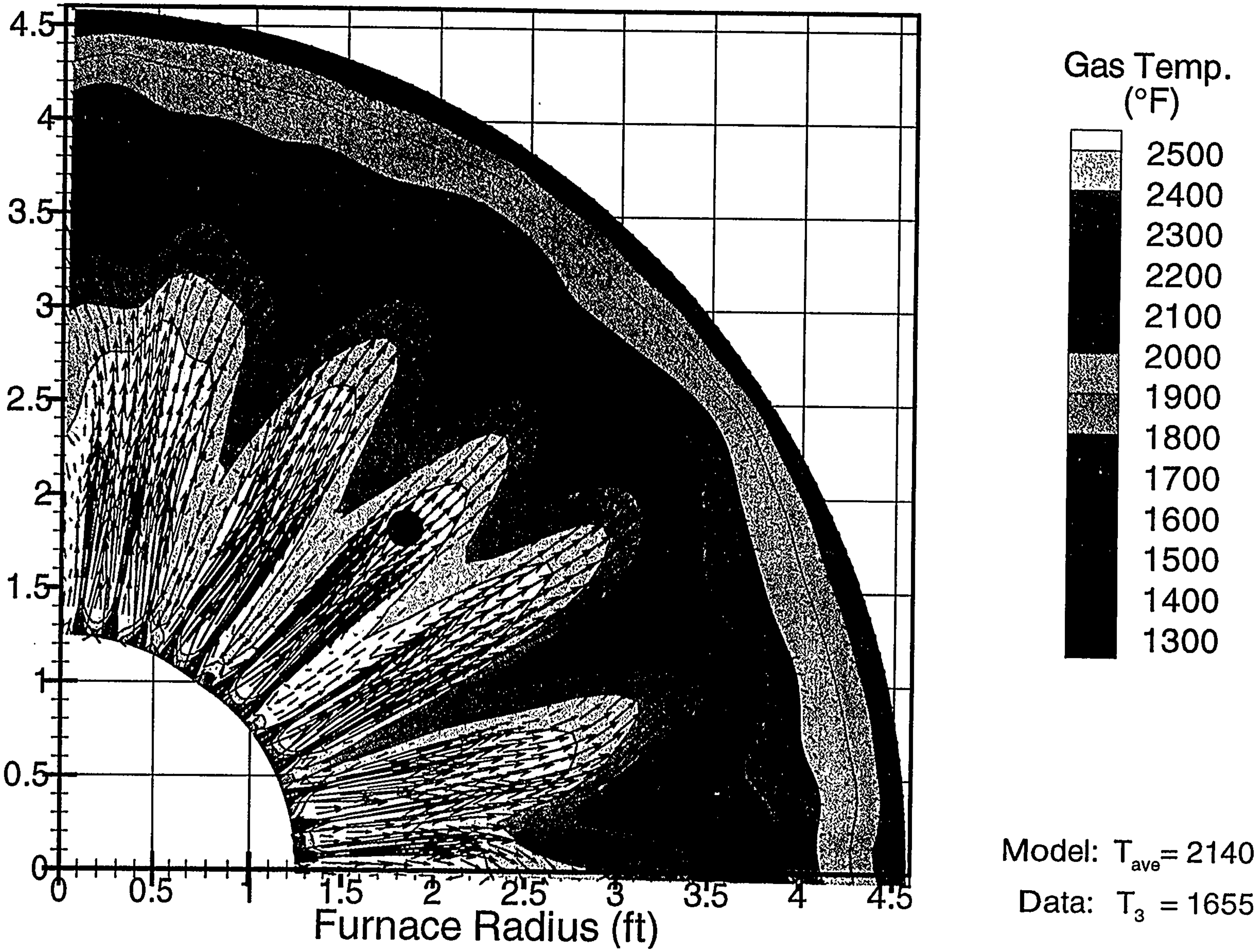


Model: T_{ave} = 2159 °F

Data: T_1 = 1637 °F

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Location at 8 feet

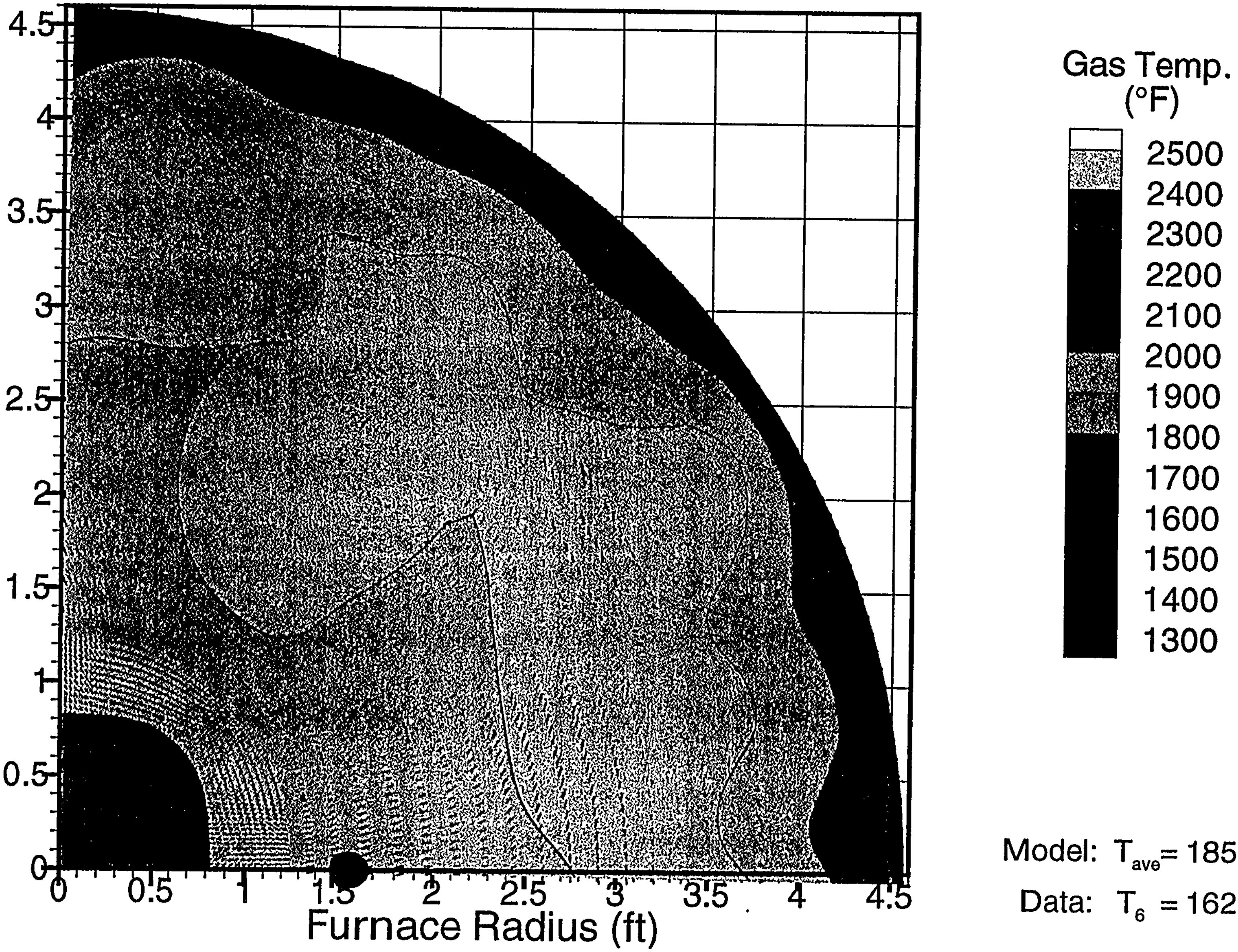


Model: T_{ave} = 2140 °F

Data: T_3 = 1655 °F

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Location at 16 feet



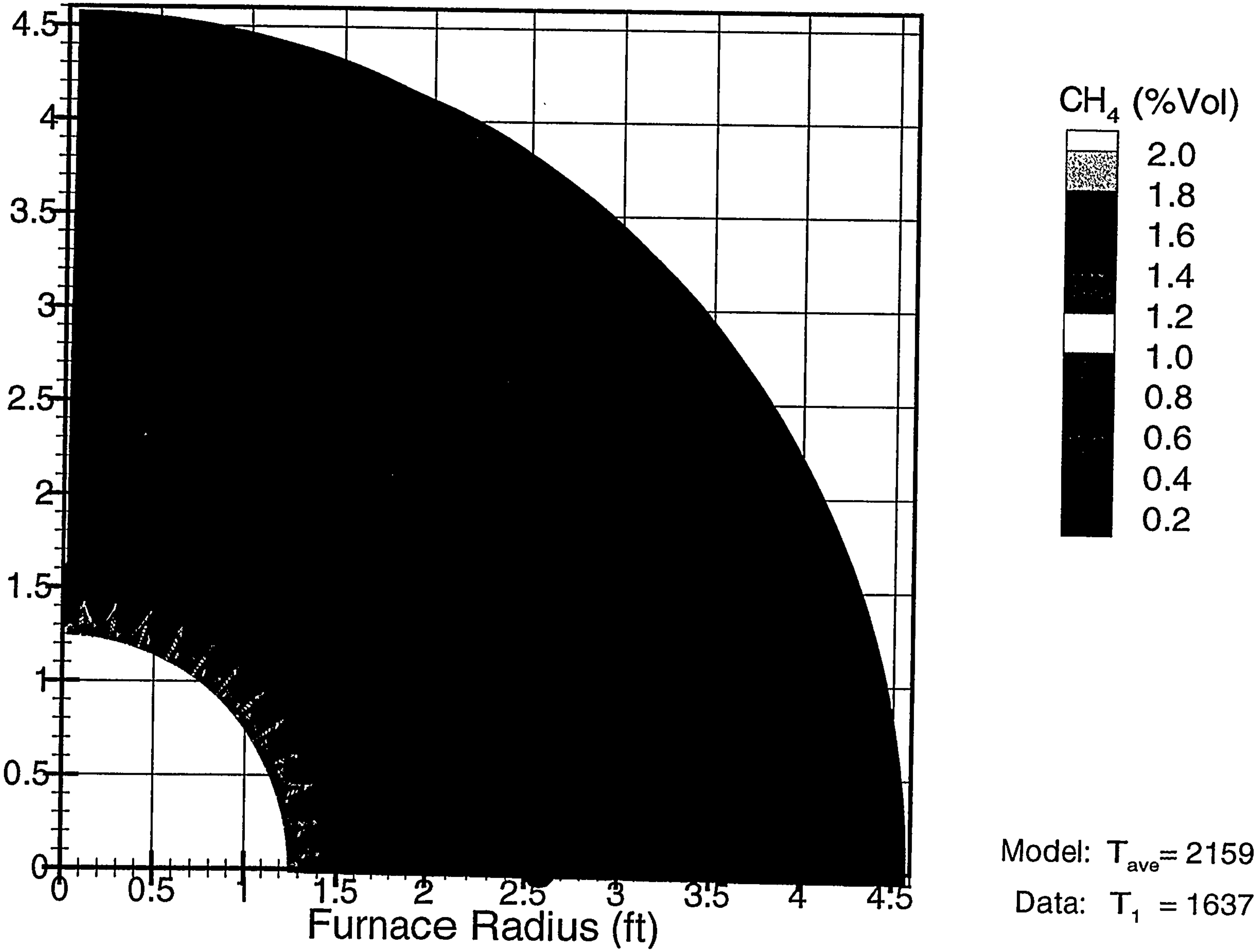
Model: T_{ave} = 1852 °F

Data: T_6 = 1624 °F

⑨

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Location at 4 feet

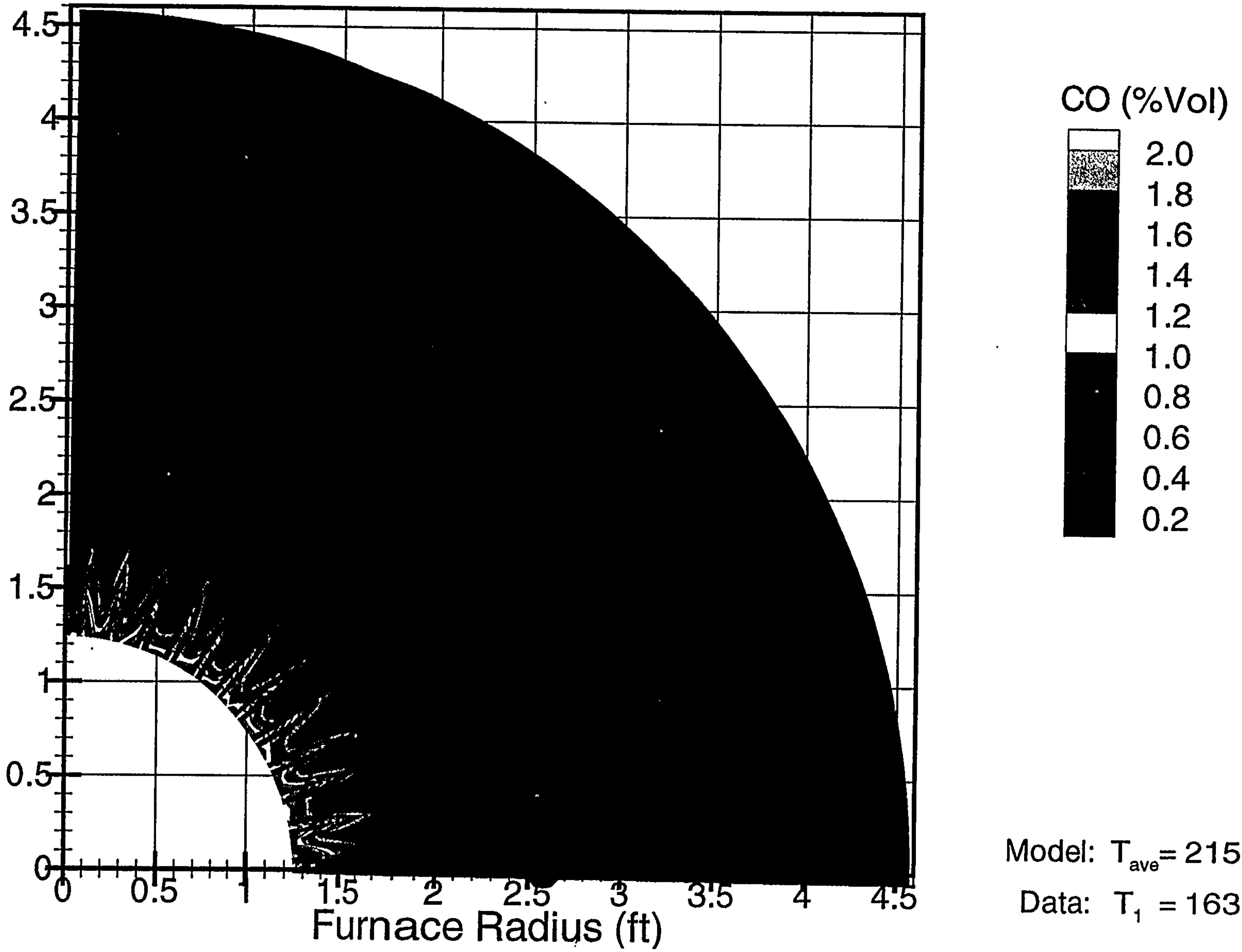


Model: T_{ave}= 2159 °F

Data: T_1 = 1637 °F

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Location at 4 feet

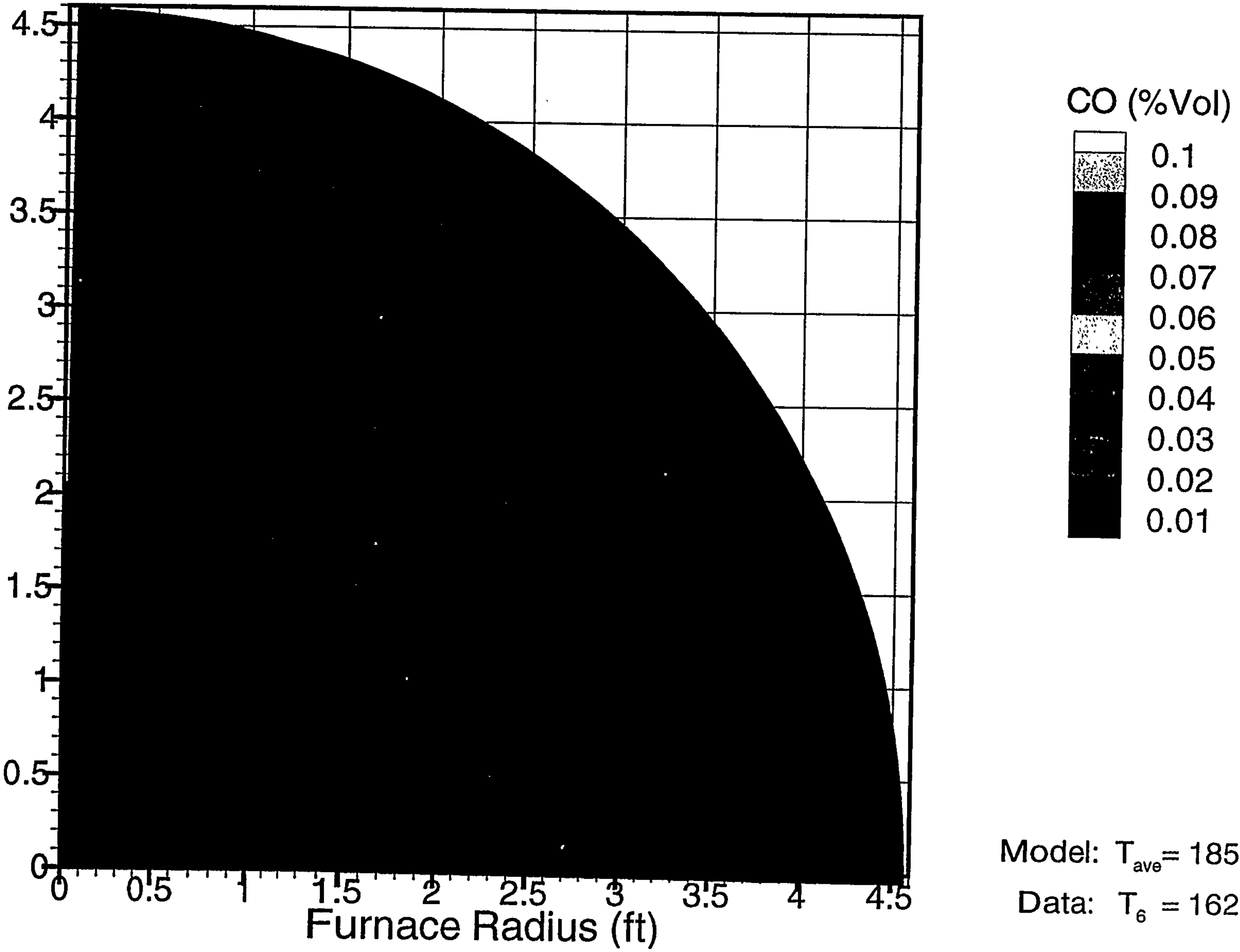


Model: T_{ave} = 2159 °F

Data: T_1 = 1637 °F

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Location at 16 feet



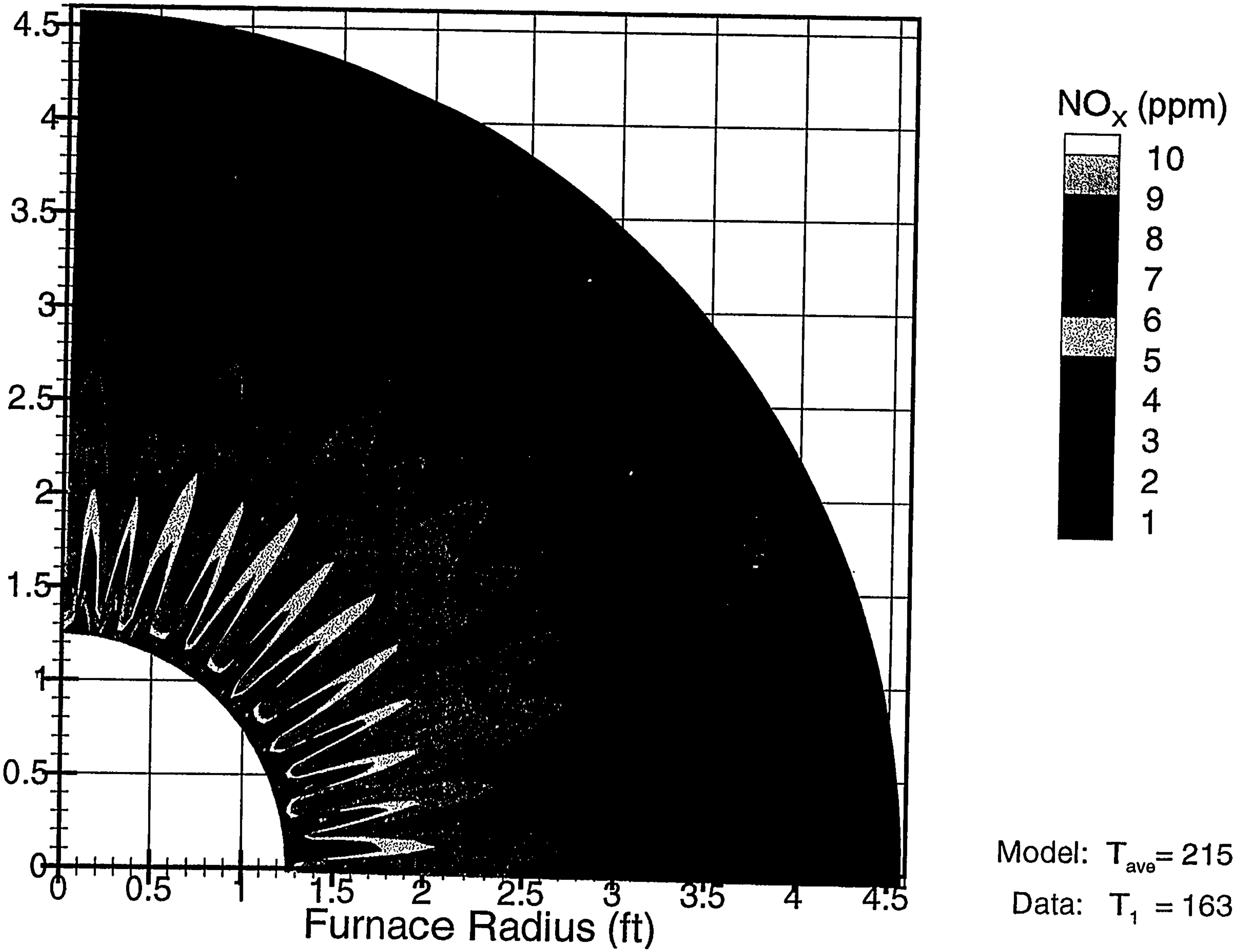
Model: T_{ave}= 1852 °F

Data: T_6 = 1624 °F

ⓙ

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Location at 4 feet



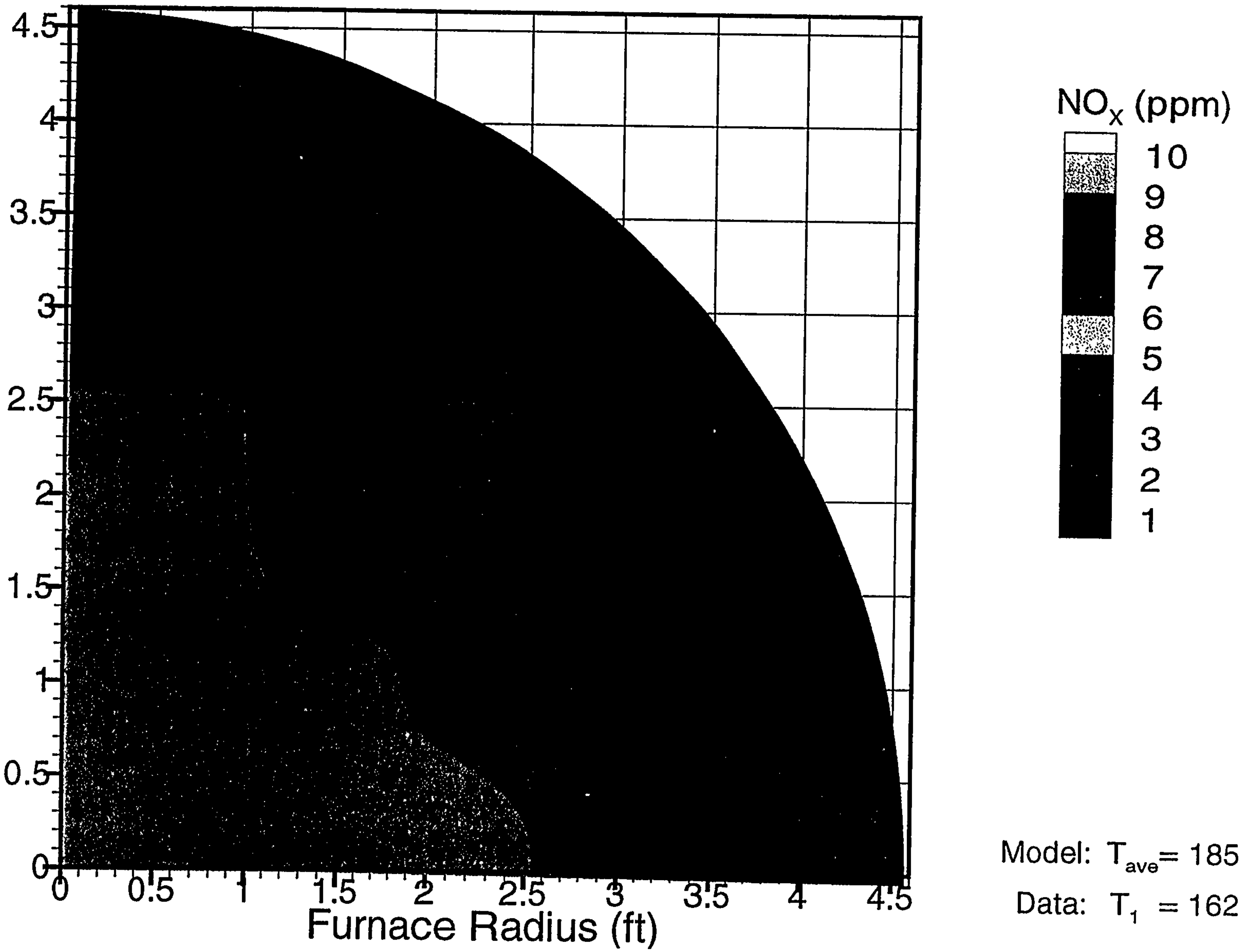
Model: T_{ave} = 2159 °F

Data: T_1 = 1637 °F

(K)

Alzeta Burner Project, Cymric Model - Stage 2

Option 3 - Furnace Location at 16 feet



Model: T_{ave} = 1852 °F

Data: T_1 = 1624 °F

Case	Description	Furnace Gas Temperature (°F)				NO_x (ppm)	Average Heat Flux (kBTU/hr-ft^2) <33ft (<21ft)
		4 feet	8 feet	14 feet	16 feet		
Test	Test Point Data	1637 °F	1655 °F	1688 °F	1624 °F	7	?
Alzeta	Spreadsheet Ave Data	2009 °F	2089 °F	1993 °F	1925 °F	--	16.1 (19.5)
Base	Model Point Data	2500 °F	2500 °F	1740 °F	1660 °F	--	--
	Model Average Data	2161 °F	2143 °F	1942 °F	1873 °F	13.6	14.5 (18.9)
Option 1	Model Point Data	2500 °F	2500 °F	1740 °F	1660 °F	--	--
	Model Average Data	2158 °F	2140 °F	1918 °F	1853 °F	8.1	15.4 (18.7)
Option 2	Model Point Data	2500 °F	2490 °F	1860 °F	1760 °F	--	--
	Model Average Data	2156 °F	2136 °F	1925 °F	1861 °F	7.6	? (18.7)
Option 3	Model Point Data	2450 °F	2520 °F	1930 °F	1840 °F	--	--
	Model Average Data	2159 °F	2140 °F	1923 °F	1852 °F	7.1	? (19.0)

Table: Stage Two Summary Results

Alzeta Burner Project, Cymric Model - Stage 2

Temperature Data Results