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Low NO_x Burner Development Program

Final Report – 09/15/1996 – 09/30/2000

A. W. McClaine

September 2000

Work Performed Under Contract No. DE-FC07-96ID13470

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

By
Thermo Technologies
Waltham, MA

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Prepared for: U.S. Department of Energy

Prepared by: Thermo Technologies, a division of Thermo Electron Corporation
45 First Avenue
Waltham, MA 02454-9046

Technical contact: Andrew W. McClaine
Program Manager
(781) 622-1032
amcclaine@tecogen.com

Business contact: Frederick E. Becker
President
(781) 622-1059
fbecker@tecogen.com

NOTICE

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Title of Program:

Industrial Energy Conservation

Title of Project:

Low NO_x Burner Development Program

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September 1996 – September 2000

Project Objective

The project objective is to develop the Vortex Inertial Staged Air (VIStA) combustor and to demonstrate stable combustion over a broad turndown range with NO_x production of 9 ppm or less and CO production of 50 ppm or less.

Overall Summary

This report describes the work performed to develop and demonstrate the VIStA combustor. The development effort was planned for three phases. Laboratory testing at a 1.5 to 6 MMBtu/hr scale was performed at Thermo Power Corporation during the first phase. Also during the first phase, analytic modeling was performed to guide the design modifications evaluated in the experimental testing. Toward the end of the first phase, John Zink Company entered the program to participate in the design, evaluation, testing, and demonstration of a 30 MMBtu/hr combustor. The results of the second phase testing were to be used in the demonstration of the 30 MMBtu/hr combustor in a Koch Industries boiler.

The program proceeded into the second phase. Two models of the VIStA combustor were tested. Measurements of the first stage NO_x production were in the range anticipated to achieve the program goals, based on analytical modeling results. While testing the VIStA combustor at the John Zink facility, John Zink elected to discontinue the development of the VIStA combustor in favor of an alternative in-house concept. As a result, this program was terminated.

1 INTRODUCTION

NO_x formation in combustion processes is very complex. It is sensitive to temperature, local stoichiometry, and residence time. The NO_x produced is commonly attributed to three mechanisms:

- thermal NO_x resulting from fixation of molecular nitrogen by atomic oxygen at high temperatures in oxidizing atmospheres;
- prompt NO_x resulting from fixation of molecular nitrogen by hydrocarbon radicals in reducing atmospheres; and
- oxidation of nitrogen compounds organically bound in the fuel.

The general approach for controlling NO_x emissions therefore requires an understanding of the formation and destruction mechanisms that affect the process. Ideally, the combustion process should be optimized recognizing the interrelationship of the burner and furnace whether it is a boiler, an air heater or a process fluid heater. For utility-scale fluidized bed coal-fired boilers, this is carefully considered since the integration of the combustion and heat transfer mechanisms are integrally linked.

For liquid and gaseous fuels, however, the high volumetric heat release rates and combustion stability associated with these fuels have most often resulted in the design of the burner being engineered independent of the specific application. Low NO_x burners developed by most boiler and burner manufacturers generally are designed to achieve low emission levels by prolonging the combustion process through the way the air and fuel are introduced. The level of available oxygen is decreased in zones that are prone to high NO_x formation. Flue gas recirculation is used to reduce the flame temperature and the partial pressure of the oxygen. While these techniques are satisfactory for maintaining NO_x emissions down to 40 ppmv levels, more exacting approaches are required to limit prompt and thermal NO_x if single digit levels are to be attained.

Thermo Power Corporation and John Zink Company with funding support from the United States Department of Energy, worked together to develop and bring to the market a natural gas burner capable of meeting ultra-low emissions for boilers and process heaters without costly post-processing of exhaust gases. The design approach was to combine the individual techniques necessary to achieve ultra-low NO_x emissions into a single device, largely independent of the intended application, in sizes up to 120 MMBtu/hr. The specific objectives were to achieve NO_x emission levels of 9 ppmv and CO levels of less than 50 ppmv, both at 3% O_2. Additional goals included high turndown ratio, and low levels of unburned hydrocarbons or air toxics. The implementation of these combustion goals into a single, cost effective burner represents a very challenging problem with a very high payoff upon its success.

This report describes the approach, designs, and test data developed as a result of the work performed on the VIStA Burner Development Program. The work was planned for three phases with laboratory testing performed in the first phase, scale-up engineering in the second phase, and full-scale demonstration in the third phase. Thermo Power Corporation worked with John Zink into the second phase engineering development testing. As this work was proceeding, John Zink decided to pursue an alternative burner design for their product line. The development program was terminated at that point.

2 TECHNICAL APPROACH

2.1 Overview

The VIStA burner concept, shown in Figure 1, consists of two combustion stages. In the first stage, natural gas and part of the combustion air are premixed and tangentially admitted at high velocity into the combustion chamber through multiple ports at the head end of the combustor. By exploiting the radial pressure difference created by the vortex, part of the combustion products are taken out through tangential openings at the tail end of the combustion chamber, cooled, and returned into the combustor axially at a center opening via multiple recirculation tubes. Recirculation and cooling of the first stage combustion products is an important aspect of the VIStA technology. By controlling the stoichiometry, temperature, and residence time, hydrocarbon and nitrogen-bound compounds which contribute to prompt NO_x formation can be minimized. The cooled recirculated gases also reduce the oxygen concentration and temperature in the combustor, thereby reducing thermal NO_x formation. The cooled first stage combustion gases then enter the main combustion chamber where secondary air is introduced axially through an annular opening around the burner periphery. The secondary air stream is introduced in a manner that aspirates furnace gases into the annular space between the first stage combustion products and secondary air stream. This works to lower both the temperature and oxygen concentration in the secondary flame zone, thereby minimizing the final thermal NO_x formation.

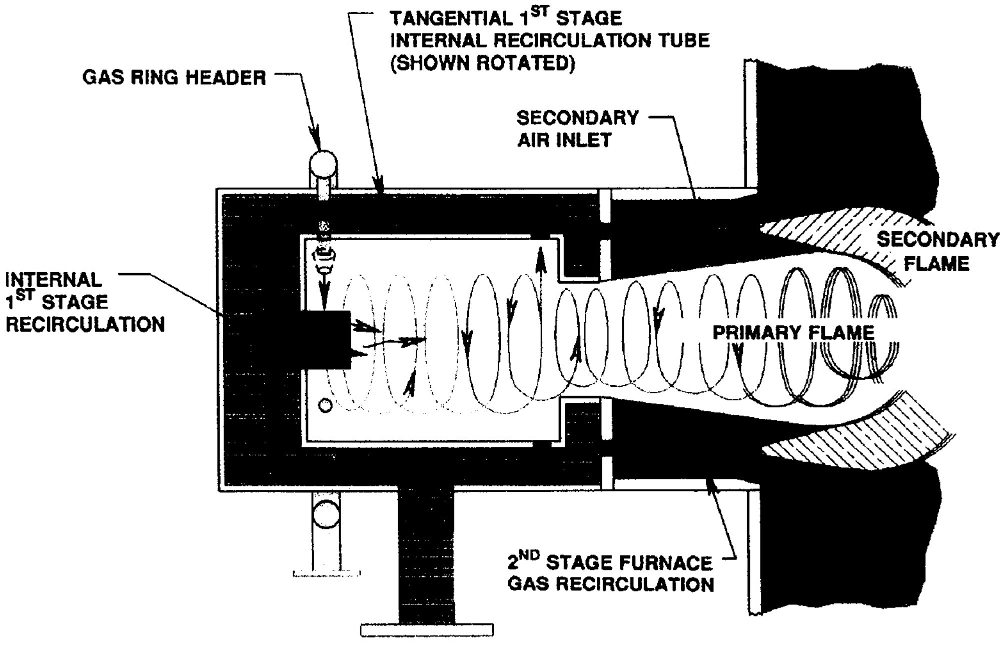


Figure 1 - Vortex Inertial Staged Air (VIStA) Burner

2.2 Inertial Vortex Reactor Description

The first stage of the VIStA burner uses a vortex to drive the recirculating combustion gas flow. A simplified first stage reactor geometry is depicted in Figure 2. The amount of recirculation is dependent on the radial pressure distribution across the reactor, which is dependent on gas velocity, gas density and reactor geometry. The pressure distribution can be determined from Euler's equation:

$$\frac{dP}{dr} = \rho \frac{V_T^2}{r}$$

where:

V_T	is the tangential velocity
r	is the distance from the reactor centerline
P	is the gas pressure
ρ	is the gas density

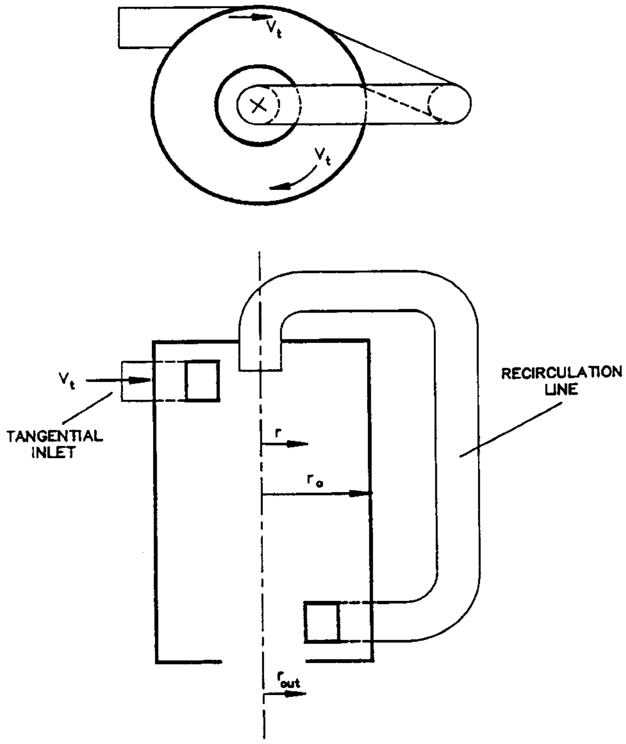


Figure 2 - Inertial Combustor Geometry

Integration of the above equation, coupled with the tangential velocity distribution in a vortical flow field, describes the pressure difference between the periphery and the centerline of the reactor as a function of inlet velocities and reactor geometry, as shown in Figure 3. This pressure difference can easily be several inches of water column resulting in high gas velocities in the recirculation line as well as high recirculation ratios. The recirculation line velocities and hence the gas recirculation ratios are strongly affected by the recirculation line geometry (length, diameter, number of turns, etc.) since these variables control the pressure drop through the recirculation line and therefore how effectively the reactor radial pressure distribution is converted to recirculation flow. In general, as the reactor size increases, the recirculation line pressure losses are reduced, and greater recirculation rates can be achieved.

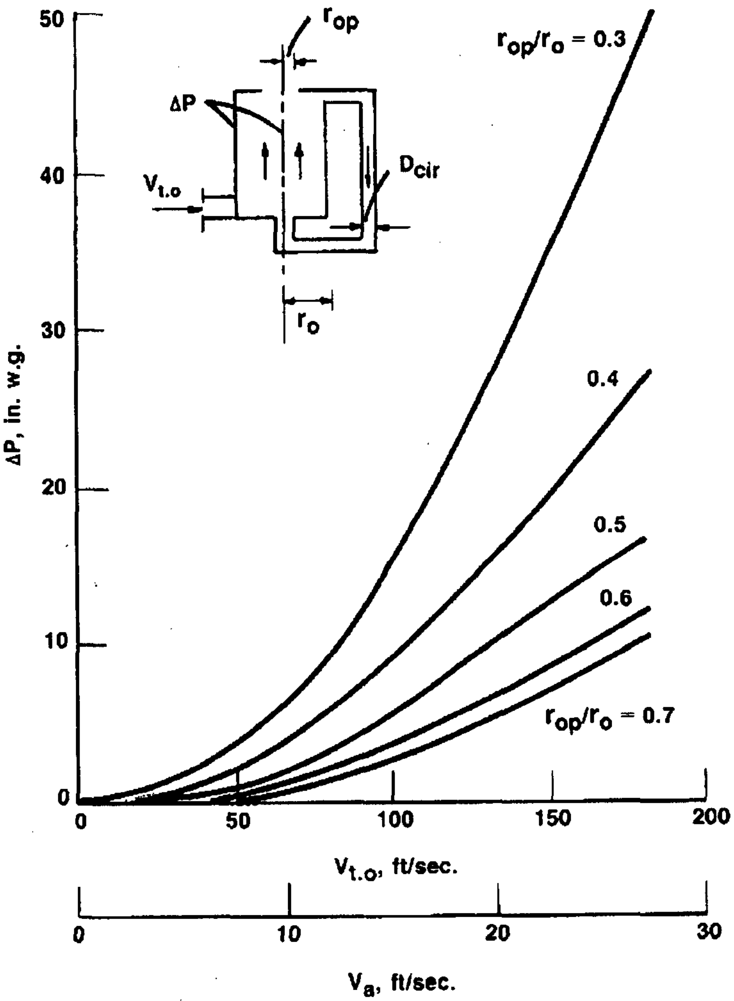


Figure 3 - Pressure Difference in Inertial Reactor

3 PROTOTYPE OVERVIEW

3.1 Sub-scale First Stage Burner Testing

The vortex inertial combustor has been under development for several years. Initial development of this burner was directed towards its use as a coal combustor. In 1995, a 250,000 Btu/hr sub-scale burner was tested with natural gas as a fuel to determine its potential as a natural gas burner. The results of these experiments were very encouraging. Figure 4 shows an isometric view of the combustor. The first stage inertial reactor had an internal diameter of 8.5 inches, an overall length of 19 inches, and a recirculation line inner diameter of 2.85 inches. Because of the relatively small size of the unit, a single air/fuel inlet and a single recirculation line were used. The second stage zone, as shown in Figure 4, was not intended to replicate the VIStA burner geometry but provide complete burnout of the gases exiting the first stage and permit evaluation of the overall NO_x performance. Recirculation ratios (recirculation mass flow rate divided by inlet flow rate) of nearly 90 percent were measured at inlet velocities above 50 ft/sec. Measurements of NO_x from the first stage indicated very low values of less than 2 ppm. NO_x levels of 10 ppm from the second stage were achieved with high excess air simulating the diluent effect of recirculation of furnace gases.

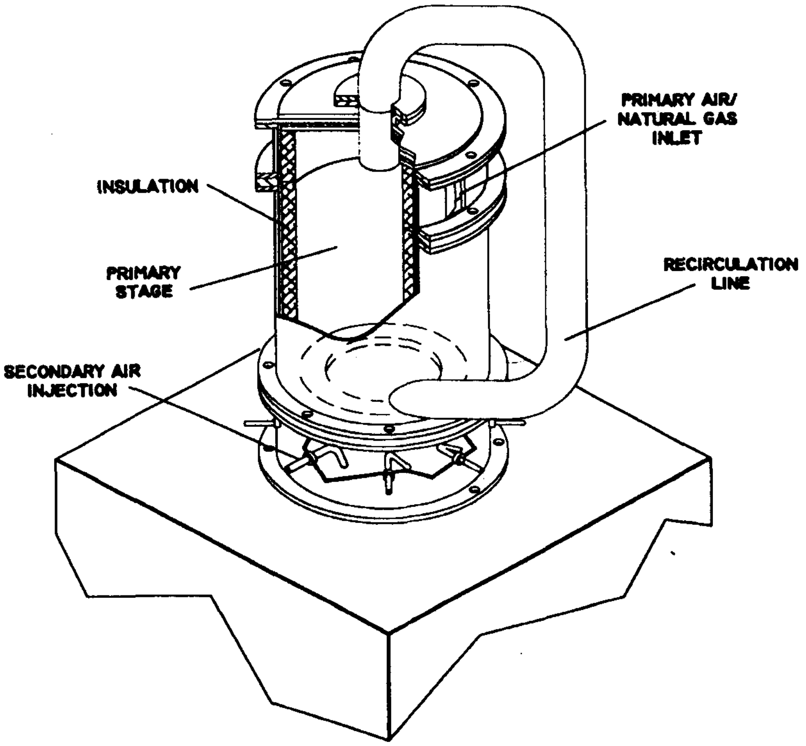


Figure 4 - Sub-Scale Combustor

3.2 Model 1 VIStA Burner First Stage

The next step in the development of the VIStA Burner was the fabrication and testing of the pilot-scale 3 MMBtu/hr VIStA burner prototype first stage. A drawing of the unit is shown in Figure 5. The photograph in Figure 6, displays the Model 1 VIStA burner first stage mounted with a burnout second stage on a package boiler used to quench the exhaust gases. The first stage combustor has two tangential premixed air/fuel inlets. Internal recirculation is provided through six recirculation tubes integrally cast into the combustor refractory. The combustor is air-cooled and the heated cooling air can serve as preheated combustion air for either the first or the second stage via external piping. During the initial tests, the second stage consisted of a simple mixing chamber, much like that used in the sub-scale testing, in which the secondary air was injected to burn out the first stage combustion products. The hot exhaust was ejected into a standard package boiler designed for an oil-fired burner.

Laboratory testing of this prototype showed recirculation in the first stage to be relatively independent of inlet momentum, with the fraction recirculated in the range of 55 to 60 percent. NO_x emission at the exit of first stage was measured to be less than 2 ppm.

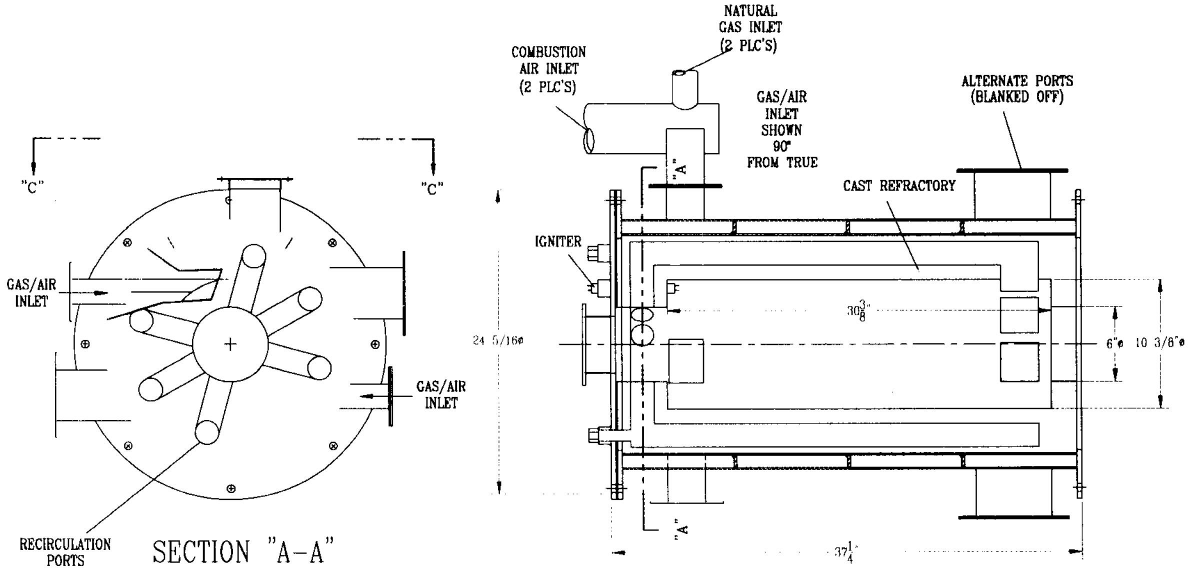


Figure 5 - Drawing of the Model 1 VIStA Burner

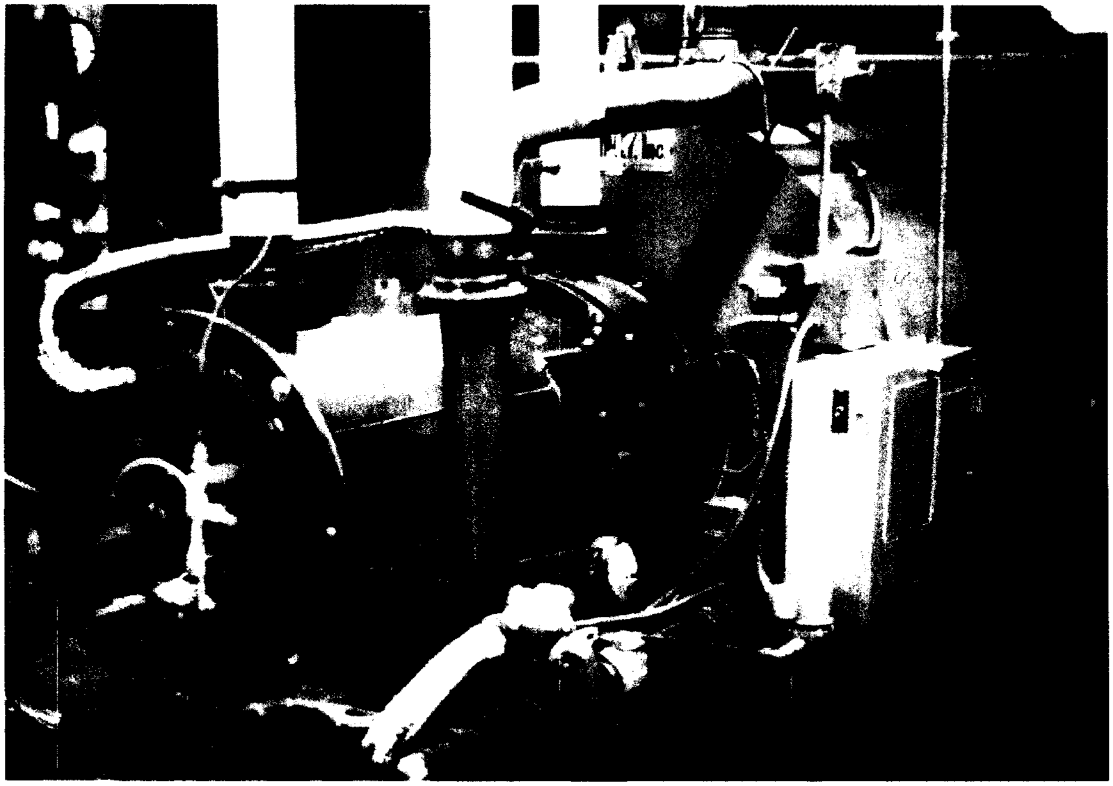


Figure 6 - Model 1 VIStA Burner with Simple Second Stage Mixing Chamber

3.3 Model 1 VIStA Burner Second Stage

As the initial tests of the Model 1 VIStA burner first stage were being performed, the second stage combustion section was designed and fabricated. The second stage combustion section is made up of a water cooled furnace section that is designed to simulate the radiant volume of a large scale boiler and an air injection section that is designed to be flexible for experimental variations. A drawing of this unit is shown in Figure 7. The second stage air injection is designed to aspirate furnace flue gas into the annular space between the first stage products and secondary air streams. Initially, the aspirated flue gas acts as a dividing layer between the first stage products and the secondary air stream. Later, as first stage products and secondary air mix, this flue gas serves to lower both temperature and oxygen concentration in the secondary flame zone. The prototype was built with the capability to inject secondary air from up to eight injectors in one of three ring diameters. The gas entering the second stage combustion zone is ducted through a six inch diameter nozzle that is replaceable to allow testing of other tube diameters.

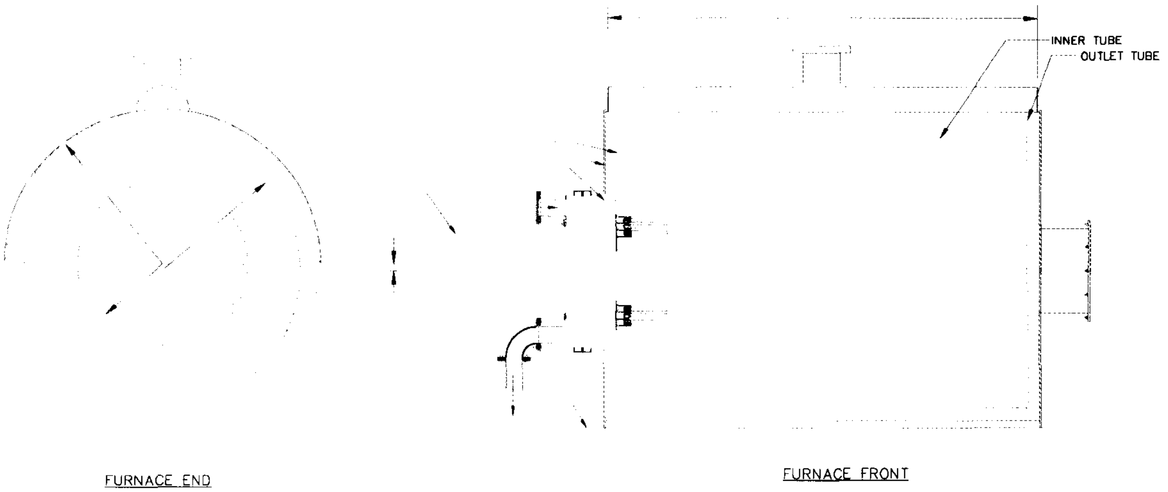


Figure 7 - Combustion Facility Furnace Section

Figure 8 is a picture of the 3 MMBtu/hr VIStA burner first and second stages along with the water-cooled furnace section. Laboratory testing of this prototype indicated recirculation rates in the first stage to be relatively independent of inlet momentum, ranging from 55 to 60 percent. NO_x emissions at the exit of first and second stages were measured to be approximately 2 and 25 ppmv respectively. Analytical modeling of the first and second stages predicted values to be in the range of 1 and 6 ppmv respectively.

One explanation for the higher measured values is the possible oxygen infiltration into the combustor at uncontrolled locations. Because of the construction technique of the burner and possible unidentified air infiltration leakage paths, the design and construction of a second, water cooled combustor rated at a nominal 6.0 MMBtu/hr input was begun. Water-cooling was incorporated to enable doubling of the volumetric specific heat release without resorting to excessively high cooling airflow requirements.

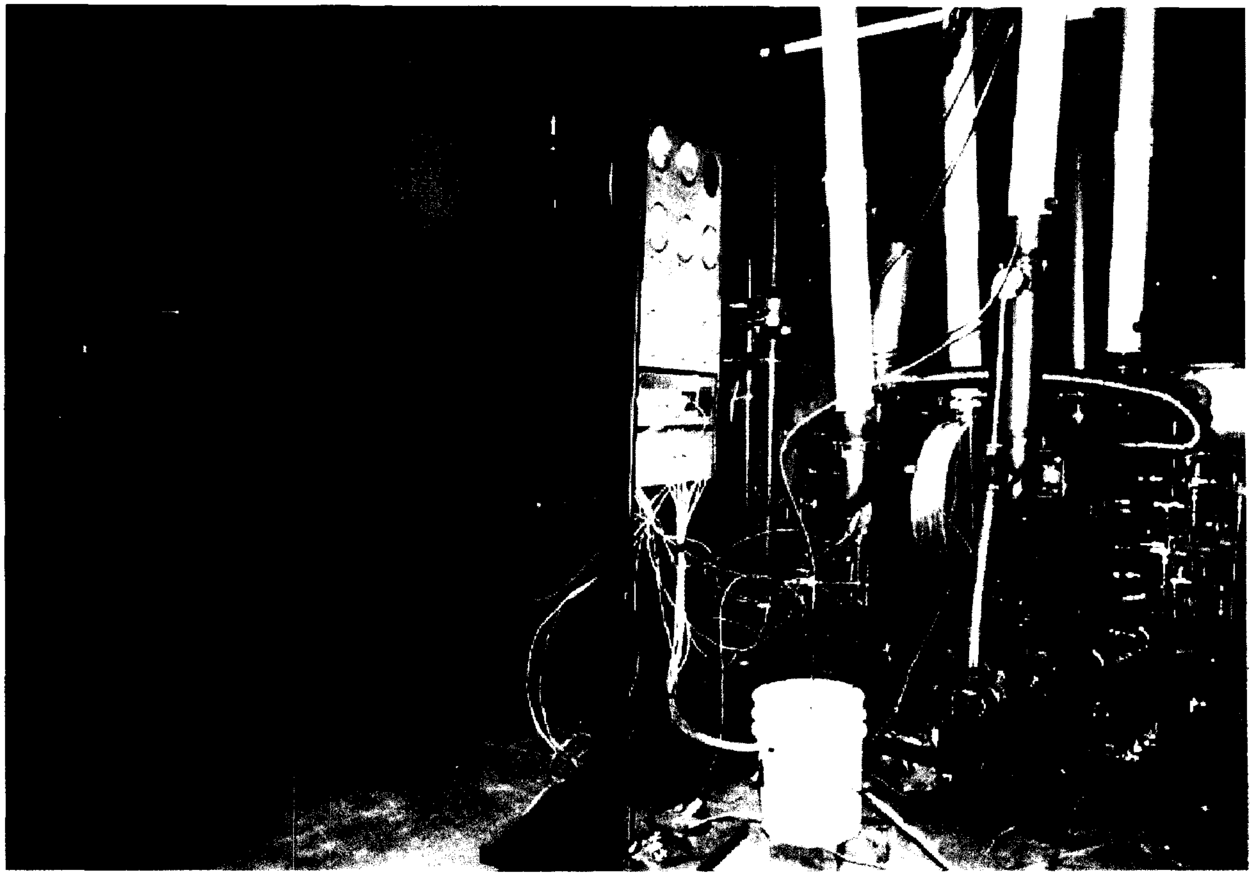


Figure 8 - VIStA Pilot Scale Experimental Burner Photograph

3.4 Model 2 VIStA Burner First Stage

Shown in Figure 9 is a photograph of the 6 MMBtu/hr VIStA combustor during installation in the Thermo Power combustion test facility. Figure 10 is a photograph of the combustor as it appeared during testing. The combustor is designed in five sections to provide experimental flexibility and to enable design modifications to be easily accommodated. The internal dimensions of the combustor, 10.4 in. in diameter by 30.0 in. long, are the same as the previous 3 MMBtu/hr unit. The number of recirculation tubes, however, were increased in number from 6 to 12, and their size doubled to 2.75 in. in diameter to increase the potential for recirculation. The combustor is water cooled and lined with a high thermal conductivity castable refractory to control the combustion gas-cooling rate. The refractory can be easily removed and replaced with alternative materials. The first stage incorporates four gas/air mixture injectors each with a damper and metering orifice to control the inlet velocity and stoichiometry. The long tubes at each injection point provide uniformity to the air intake to allow accurate measurement of the air flow rates. The design of the gas injectors was carefully engineered to provide a very uniformly mixed natural gas/air mixture prior to entering the first stage.

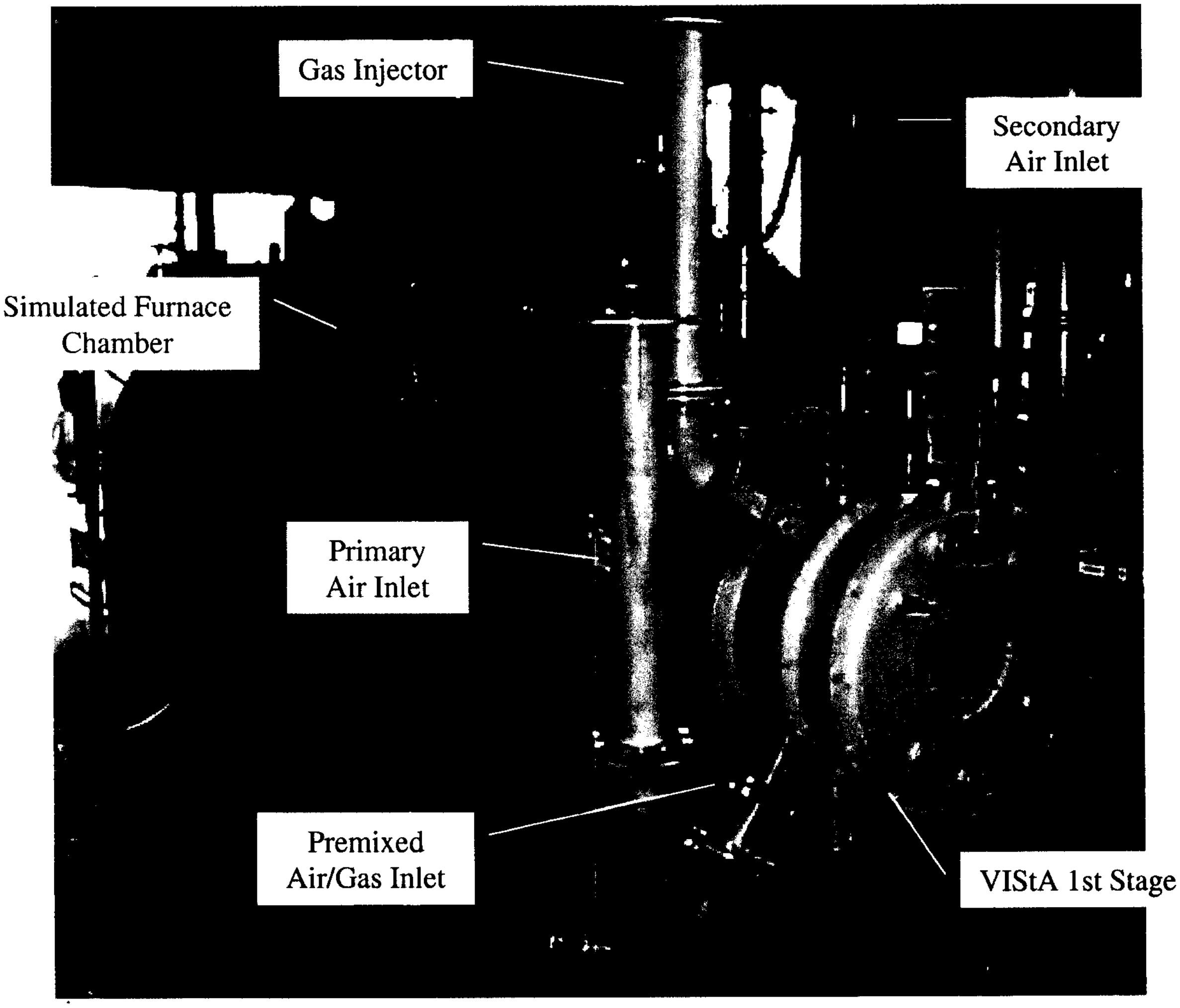


Figure 9 - Photograph of Experimental 6 MMBtu/hr VIStA Burner

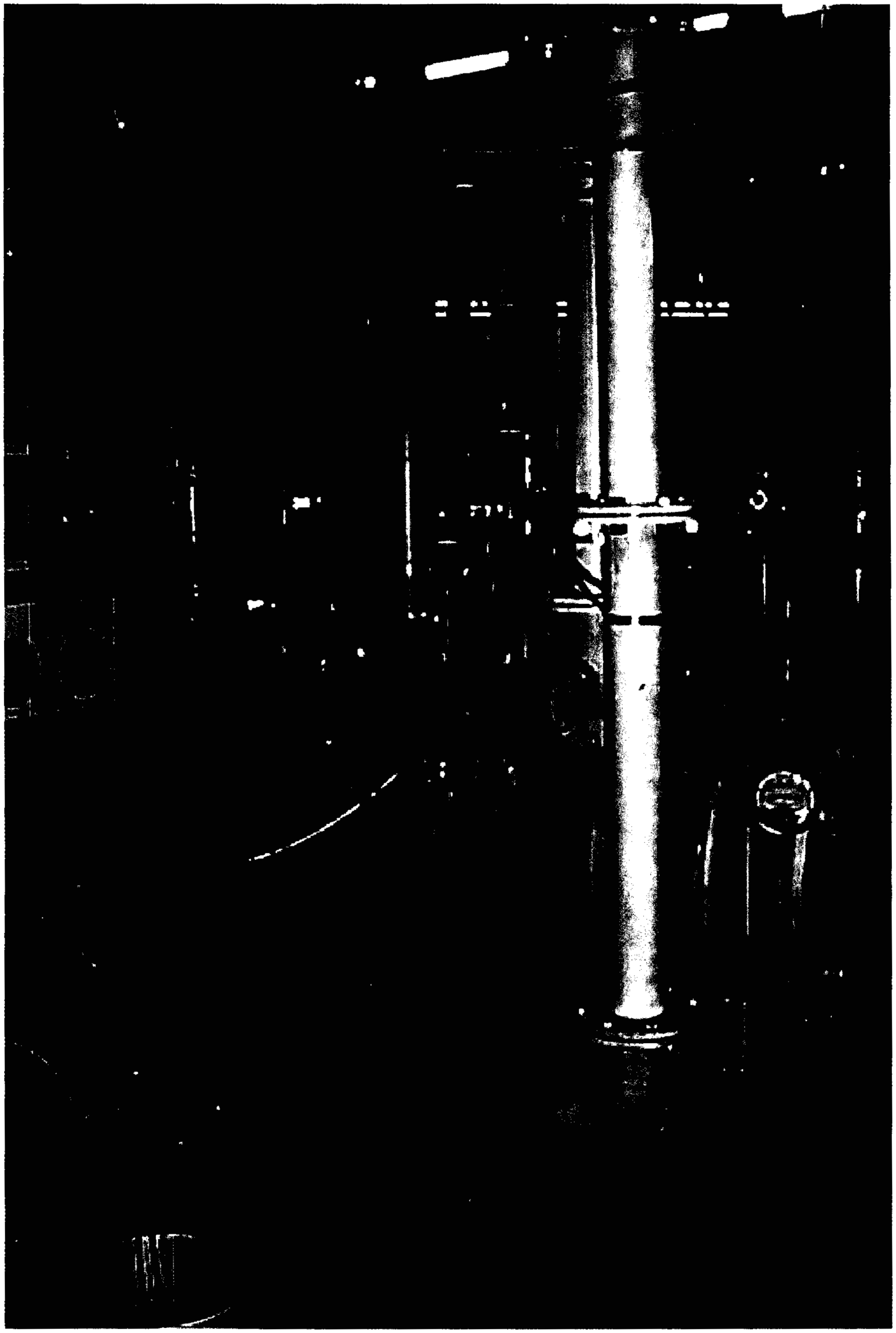


Figure 10 - Photograph of the VIStA Combustor Installed at Thermo Power Corporation's Waltham Laboratory

3.5 Model 2 VIStA Burner Second Stage

In addition to the modifications added with the first stage, modifications were made to the second stage air nozzle to introduce the secondary air as an annular stream, Figure 11, rather than as eight discrete jets for improved combustion uniformity. This nozzle configuration was used during the testing of the Model 2 VIStA Burner at Thermo Power Corporation. It was also used for the initial tests at John Zink's Test Facility.

Figure 11 - Photograph of the Annular Second Stage Air Injector

As testing progressed at John Zink's test facility, the second stage air injector was replaced with the injector shown in Figure 12. This injector uses the same exit area as the annular injector and thus has approximately the same inlet velocity. The individual jets penetrate further into the furnace however and create better jet pumping of the furnace gases than the annular sheet of secondary air. They also allow furnace gases to be carried from the outside of the jet into the region between the jet and the hot gases from the first stage. The annular sheet of the annular second stage air injector acts to prevent the passage of furnace gases into the zone between the sheet and the first stage gases. By entraining more furnace gas into the combustion zone, the oxygen concentration will be reduced in the zone and the production of NO_x will be reduced.

An additional improvement that has been suggested is to inject the secondary air downstream of the exit of the nozzle from the first stage. This will allow the jet from the first stage to better pump furnace gases into the zone between the primary gases and the secondary air. This will be a more difficult design however since we will need to have the secondary air injector jets set outside the hot gas jet. We decided to test the concept first with the sixteen-jet design, which required a simple modification to the secondary air injection system.

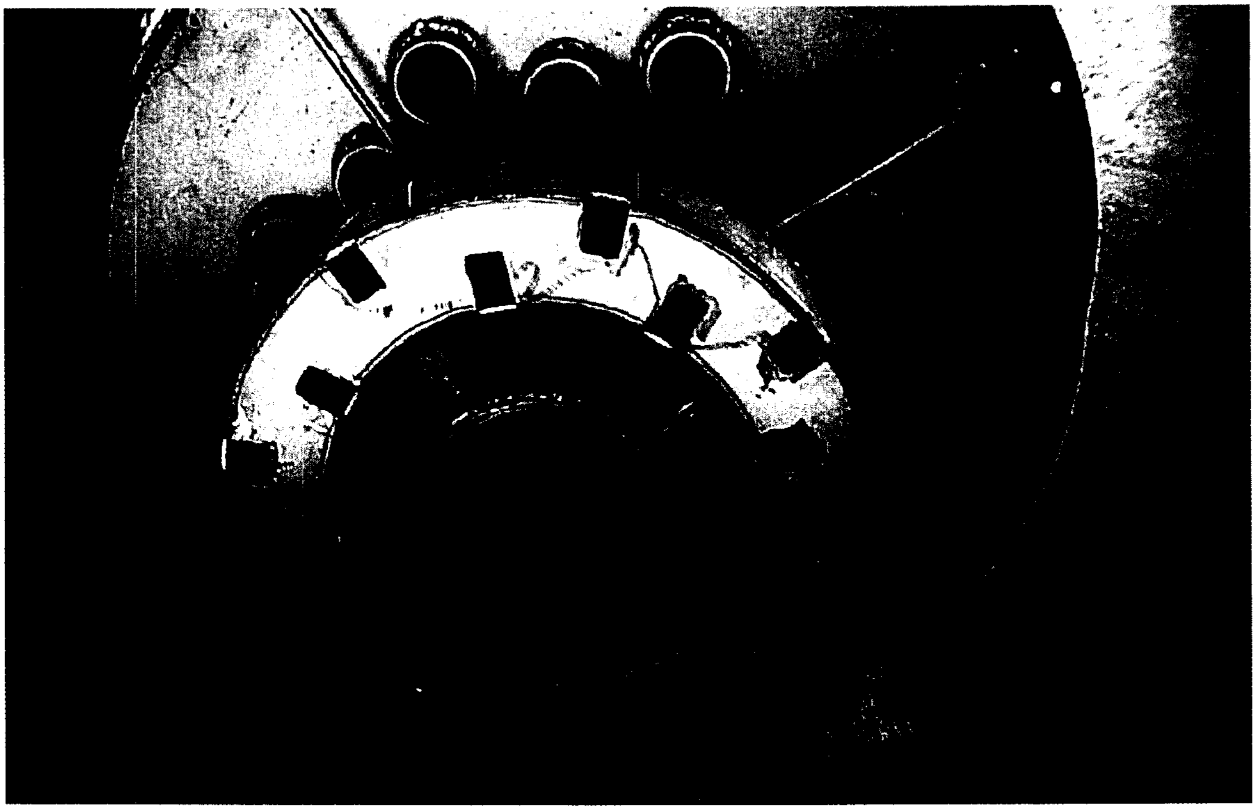


Figure 12 - Photograph of the Sixteen Jet Secondary Air Injector

4 DISCUSSION OF WORK PERFORMED

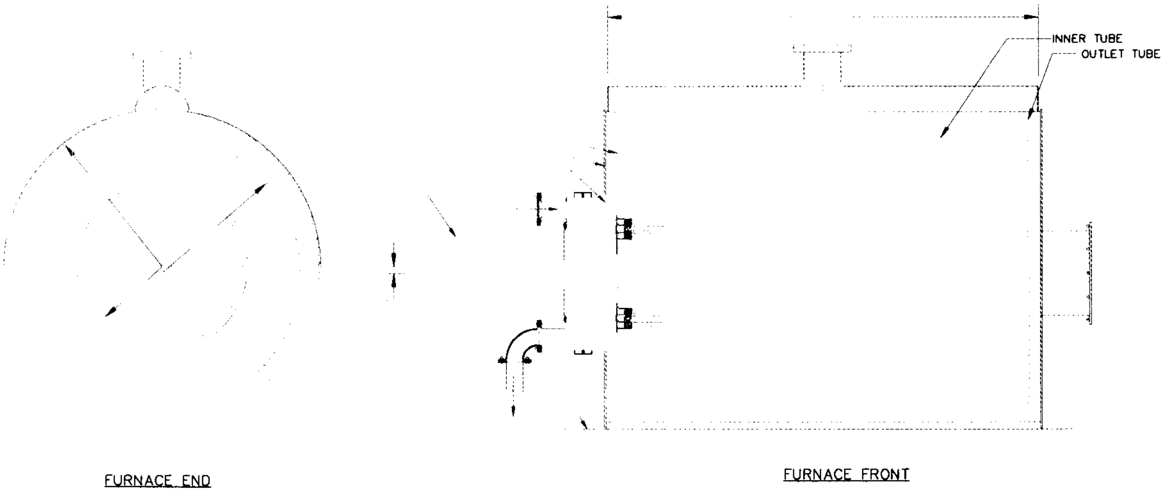
4.1 Advanced Combustor Design

In this task, designs needed for the testing of the Model 1 VIStA burner were prepared. Specifically, we prepared designs of the second stage air injector, the furnace section in which the secondary combustion occurred, and bayonet heat exchangers used to cool the recirculation gases in the first stage.

4.1.1 Design of Model 1 Second Stage Air Injection and Furnace Section

The model 1 second stage replaced the original burnout second stage that was designed only for the purpose of checking out the first stage. The model 1 second stage, shown in Figure 13, was designed to promote recirculation of flue gases within the furnace section. It was built with the capability to inject secondary air from up to 8 injectors in one of three ring diameters. Diameters of 15", 18", and 21" are available. The gas entering the second stage combustion zone was ducted through a 6" diameter tube. The second stage was designed so that the duct was replaceable. This allowed other tube diameters to be tested if required. The second stage was attached to the first stage and protruded into the furnace section.

The furnace section is a cylinder about 5'6" in diameter and about 8' long. It was placed between the combustor and the boiler. It is water-cooled using a teapot concept. The purpose of this section was to provide sufficient volume to allow flue gases to be recirculated back into the combustion zone.



FURNACE END

FURNACE FRONT

Figure 13 - Second Stage Air Injector and Furnace Section Designs

4.1.2 Water Cooled Nozzle

Since the temperatures leaving the first stage combustion zone are anticipated to be in the range of 1600 to 2200°F, the nozzle carrying gases from the first stage to the second stage must either be made of ceramic or it must be actively cooled. To provide the greatest experimental flexibility, an active water cooling technique was selected. A double walled design was selected to perform the water cooling. A design drawing for this nozzle is included in Figure 7 of Appendix E.

4.1.3 Water Cooled Bayonet Heat Exchangers

During the testing of the Model 1 VIStA first stage, bayonet heat exchangers were placed in the six recirculation tubes. These heat exchangers were constructed of 0.5" stainless steel tube. A 0.25" tube carried water to the tip of the heat exchanger. The water flowed back in the annular region between the two tubes to the exit. A Swagelock Heat Exchanger T-fitting was used to join the two tubes.

These heat exchangers allowed us to evaluate the effectiveness of cooling the recirculating gases. Our conclusion from the testing was that the recirculation tubes were a good place to cool the combustion gases. This information was used during the design of the Model 2 First Stage.

4.2 Computer Modeling

Computer modeling was performed to guide the experimental program and to aid in the scale-up analyses. Initial modeling was contracted from Reaction Engineering International. Succeeding modeling was performed at Thermo Technologies using Fluent, a computational fluid dynamic computer program leased from Fluent, Inc.

4.2.1 3-D Modeling at Reaction Engineering International

To begin the computer modeling of the VIStA burner, Reaction Engineering International (REI) was engaged to perform CFD and kinetic modeling of the model 1 first and second stages of the VIStA burner. The final report of their effort is included in Appendix D.

The results of their analysis showed the potential for significant reductions in the NO_x produced from the VIStA burner and identified the target NO_x and other emissions levels.

Reaction Engineering International found that NO_x production from the first stage should be below 2 ppm and that NO_x production in the second stage should be less than 10 ppm (adjusted for 3% Oxygen). The input conditions and predicted performance under various operating stoichiometries and wall cooling conditions are shown in Table 1. NO_x production in both stages is affected by the amount of heat removal. In particular, for cases 4 and 5 with adiabatic walls, overall NO_x levels of more than 200 ppm are produced as compared to single digit NO_x production in the cases with cooled walls.

Table 1 – REI Modeling Results

	FIRST STAGE				SECOND STAGE			
	Heat Removal	**Stoich-iometry**	**NO_x (ppm)**	**HCN (ppm)**	**Wall Temp.**	**Stoich-iometry**	**Inject Angle**	**NO_x (rel)**
Baseline	3%	0.6	0.2	11	650°F	1.15	0°	1.0
Case 1	0	0.6	1.2	46	650°F	1.15	0°	5.8
Case 2	5%	0.6	0.1	5	650°F	1.15	0°	0.4
Case 3	3%	0.65	1.4	22	650°F	1.15	0°	1.9
Case 4	0	0.6	1.2	46	adia.	1.15	0°	190.8
Case 5	3%	0.6	0.2	11	adia.	1.15	0°	80.8
Case 6	3%	0.6	0.2	11	900°F	1.15	0°	1.4
Case 7	3%	0.6	0.2	11	650°F	1.15	12.5° Inward	1.9

These results were quite encouraging except for the prediction of the production of HCN. The production of HCN had not been reported for tests of other fuel rich combustors. In addition, the existence of the fuel lean combustion in the second stage led us to believe that HCN, if produced, would be consumed in the second stage. However, preparations were made to measure the exhaust gases for HCN during the testing of the VIStA burner.

4.2.2 2-D Axi-Symmetric Modeling

Computer modeling, using the Fluent program, was performed at Thermo Power to evaluate the performance of the VIStA burner with variations in the design parameters. The modeling began with an analysis of the second stage performance with variations on the air injection diameter. The modeling indicated that the secondary air injection should be made within 18" of the nozzle centerline to obtain an acceptable CO burnout. The model geometry was expanded to include a coupled solution of both the first and second stages. This coupled solution eliminated uncertainties in the local chemistry at the inlet of the second stage.

The Fluent modeling of the 3 MMBtu/hr combustor was begun with simplified physics. Additional complexity was added throughout the analysis as required to improve the model. For instance, the initial model was performed with a simple 2 step combustion process ($CH_4 + 1.5O_2 \rightarrow CO + 2H_2O$, $CO + 0.5O_2 \rightarrow CO_2$) evaluation of the flow velocities within the system. As the modeling progressed, the combustion model was modified to account for a three step combustion process ($CH_4 + 0.5O_2 \rightarrow CO + 2H_2$, $CO + 0.5O_2 \rightarrow CO_2$, $H_2 + 0.5O_2 \rightarrow H_2O$). The model included radiation and convection heat transfer within the combustion zone, conduction heat transfer through the walls, and convection heat transfer to the coolant around the combustor. NO_x production was calculated in each case and varied with the changing combustion temperatures. The final model evaluated during this period, predicted 2 ppm NO_x and 242 ppm CO indicating that further attention needed to be paid to the second stage mixing. All modeling during this period was performed assuming an axi-symmetric two dimensional model.

Table 2 summarizes some of the results of the modeling performed during this period. The recirculation rate of 80% in the first stage using air is similar to the measured results of 60 to 70%. The model assumes an annular recirculation zone rather than discrete tubes. It indicates that at combustion temperatures, the recirculation rate in the first stage will decline.

Comparison between VIStA-3d and VIStA-3ha shows the effect of the chemistry assumptions. NO_x production declined probably due to reduced first stage temperature.

Modeling was also performed to simulate a competing low NO_x burner to compare the 2nd stage recirculation rates with those predicted for the VIStA burner. Second stage recirculation rates were predicted to be about 3.8% of the total flow rate compared to the 76% anticipated for the VIStA burner. The burner manufacturer claims that their recirculation rate is 10 to 25%. This result would indicate that the VIStA burner analysis is somewhat conservative. Overall the recirculation rate anticipated for the VIStA burner appears to be quite acceptable.

Table 2 - Summary of Analytical Results

Case	VIStA-2o	VIStA -3d	VIStA -3e	VIStA -3ha
Thermal Input (MMBtu/hr)	3	3	3	3
Fluid	Methane/Air 2 step	Methane/Air 2 step	Air	Methane/Air 3 step
secondary air injection radius	9"	7.5"	7.5"	7.5"
recirculation rate - 1st stage	29%	28%	80%	29%
recirculation rate - 2nd stage	90%	76%	140%	76%
NO (ppm)	9.12	9.11	-	2.3
CO (ppm)	53	43	-	242
Tpeak (K)	2083	2083	300	1957

4.2.3 Scale-up Analysis

4.2.3.1 Introduction

As part of the market evaluation task for this project, we had planned to perform an evaluation of the scaling of the VIStA burner and a conceptual design of the commercial scale burner. In working with John Zink, a large commercial scale of 200 MMBtu/hr was selected for evaluation. This section describes the evaluation performed for scaling the VIStA burner from the laboratory scale of 3 MMBtu/hr to 200 MMBtu/hr. Also reported is the conceptual design proposed for this large-scale combustor.

The scaling analysis was begun with an evaluation based on similarity parameters. This evaluation provided a rough scale for the burner. A conceptual design of the burner was prepared and the large-scale burner was then evaluated using the Fluent Computational Fluid Dynamics codes to predict the performance of the burner.

4.2.3.2 VIStA Burner Design Considerations

The VIStA burner concept consists of two combustion stages. In the first stage, natural gas and part of the combustion air are premixed and tangentially admitted at high velocity into the inertial reactor through multiple ports. By exploiting the radial pressure difference created in the reactor, part of the combustion products are taken out through tangential openings and returned into the combustor axially at a center opening via multiple recirculation tubes. The stoichiometry, recirculation rate, and residence time are controlled to reform the natural gas in this first stage thereby eliminating or minimizing the hydrocarbon and nitrogen-bound compounds which contribute to prompt NO_x formation. In the second stage, secondary air is introduced axially through tubes located concentrically around the burner periphery. The secondary air stream velocity is designed to entrain sufficient furnace gases into the annular space between the first stage products and secondary air stream so as to lower both the temperature and the oxygen concentration in the secondary flame zone thereby minimizing thermal NO_x formation.

Several design parameters are considered during the design of a VIStA burner unit: the residence time of the gas, the velocity of the combustion products leaving the first stage, the velocity of the secondary air, the pressure drop of the gases through the various components of the burner, and the recirculation rates of the gases within the first and second stage zones. These design parameters are constrained by the size of the boiler or furnace opening, and the acceptable size of the burner unit. Typical burner throat diameters are displayed in Figure 14. At 200 MMBtu/hr, a typical oil fired flare burner nozzle has a diameter of about 3.25 ft and a maximum refractory free opening of about 4.1 ft.

We have estimated that the distance between combustors in a large multi burner industrial boiler using 200 MMBtu/hr burners would be about 8 ft. Thus the maximum outside diameter of the VIStA burners would need to be less than 8 ft. We have assumed that the wind box for this size of boiler would be at least 5 ft deep.

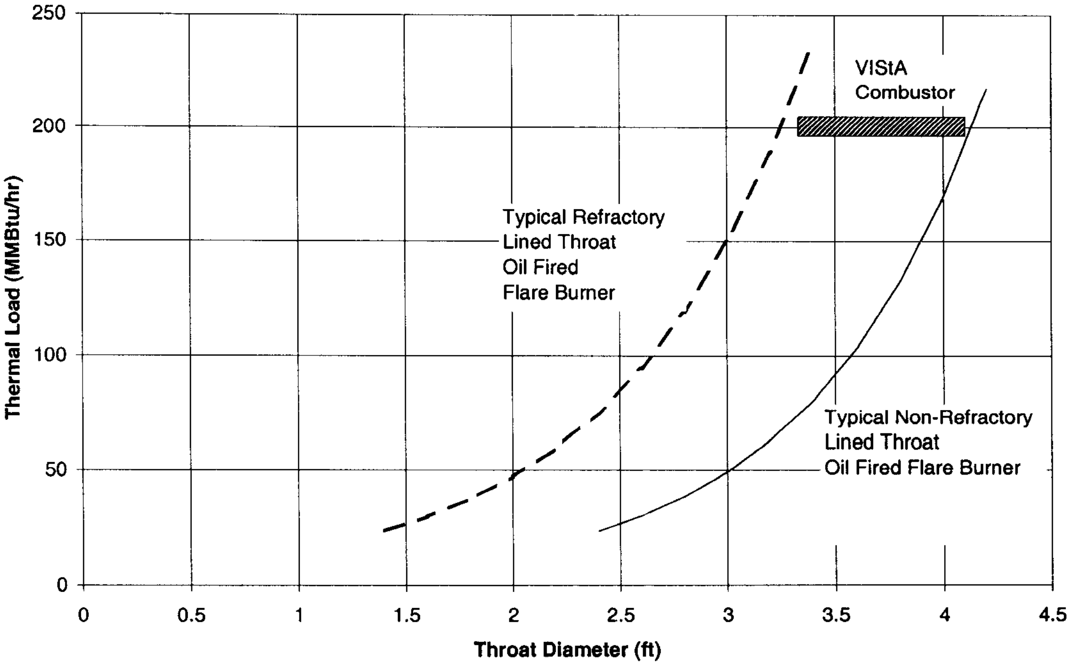


Figure 14 - Throat Diameter Available in Commercial Boilers

4.2.3.3 Scaling Analysis

The scaling analysis began with an evaluation of the size of the VIStA burners as the scale was increased. During this analysis, the heat release rate in the first stage was maintained constant and the velocities in the first and second stages were maintained constant. The baseline for this analysis was the design for the laboratory scale 3 MMBtu/hr burner.

The next step in the analysis was to test the assumption of using the 3 MMBtu/hr scale device. We tested this assumption by increasing the flow rate of the laboratory scale burner using the Fluent model. The flows in the Fluent model were increased to 6.7 MMBtu/hr without serious increases in the NO_x. NO_x levels were calculated to increase from 2.3 ppm to 2.8 ppm. CO was calculated to increase from 242 ppm to 646 ppm indicating that the design of the secondary air must be improved to meet the requirements for CO < 50 ppm. From this result, we concluded that the original baseline for the combustor was too conservative. Whereas we had been using a value of 1.2 MMBtu/hr/ft3 for the heat release rate in the first stage, we increased this value to 3.4 MMBtu/hr/ft3 in the latest scaling analysis. This would correspond with an 8.5 MMBtu/hr combustion rate from the laboratory scale unit.

Other criteria which constrain the scaled up design are the pressure drops in the gas/air inlet, the pressure drop in the nozzle separating the first and second stages, the pressure drop of the secondary air jet, and the residence time of the gas in the first stage. Pressure drops have been maintained in the 5 to 8 in. w.c. range. Residence times for an 8.5 MMBtu/hr combustor are calculated to be about 110 ms.

In addition to the design constraints mentioned above, if the combustor is to be used in retrofit applications, it will be constrained by the depth of the wind box, the diameter of the openings in the boiler or furnace, and the distance between the existing openings.

4.2.3.4 Computer Modeling

An axi-symmetric Fluent model was prepared of a 200 MMBtu/hr VIStA combustor to evaluate and explore its performance. Our first model was built to operate within the constraints mentioned above. Early results indicate that the NO_x emissions from this scale of burner could be about 25 ppm. As this value is a bit too high, we evaluated the results and modified the model. It appears that the heat release rate (3.4 MMBtu/hr/ft3) in this first case was a bit too high. If we base our scale-up on the 6.7 MMBtu/hr combustor, the heat release rate would be about 2.7 MMBtu/hr/ft3 and the residence time would be about 140 ms.

4.2.3.5 Commercial Unit Design

The first model explored with Fluent was 4 ft. long, with a combustion chamber 3.3 ft. in diameter and a nozzle 2.8 ft. in diameter. Inlet velocities were 100 ft/s for both the primary gas/air and the secondary air streams. Pressure drops in the primary stream are anticipated to be about 5 in. w.c. Pressure drops in the secondary air stream are anticipated to be 6 to 8 in. w.c. Pressure drop through the primary exhaust nozzle are expected to be about 5.4 in. w.c.

The combustor is designed with 4 inches of refractory liner around the primary combustion chamber and eight 8-inch diameter recirculation tubes spaced with a minimum of 2 inches between the tubes and the outer wall of the refractory. An additional 2 inches of space has been planned between the outer edge of the recirculation tubes and the outer wall of the combustor. For the Fluent analysis, the secondary air is carried via thirty-two 4-inch diameter tubes to an annular distributor with an outside diameter of 4.1 ft. The outside diameter of this combustor would be about 72 inches. This diameter can be reduced if necessary, to about 56 inches, by reducing the thickness of the refractory wall, the diameter of the recirculation tubes, and the distance between the tubes and the walls.

To reduce the heat release rate to 2.7 MMBtu/hr/ft3, we plan to increase the length of the combustor to 60 inches while maintaining the other dimensions of the combustor.

4.2.3.6 Conclusions

Analysis of the scaling of the 200 MMBtu/hr VIStA Burner using the Fluent model were completed. NO_x production meeting the target emissions levels was achieved with the removal of sufficient heat from the first stage.

The analysis was performed using a two-step calculation approach. The first stage performance was calculated and then radial profiles of the temperature, pressure, velocity, and composition of the exhaust gases leaving the first stage were taken from the model of the first stage and provided to the model of the second stage. Exhaust gas temperatures from the first stage were defined to determine the amount of heat which must be removed from the first stage to achieve the target emissions levels. A reduction in the first stage temperature of 300°K was sufficient to achieve the emissions targets. This corresponds to a heat removal from the first stage of 11.4%. NO_x production at this condition was 4.8 ppm and CO production was 0.22 ppb indicating complete burnout of the combustion gas.

A further refinement of this analysis was performed to evaluate the effect of using the heat removed from the first stage in the second stage air. We assumed that the first stage heat could be used to preheat the second stage air to 600°K. The injection of this heated air increased the NO_x production to 18 ppm with continued low CO production of 0.21 ppb. With no heat removal from the first stage, NO_x emissions were predicted to be 134 ppm. Additional secondary air injection strategies must be evaluated to determine if the second stage NO_x can be reduced further.

4.3 Fabrication and Testing

4.3.1 Cold Testing of the Model 1 Air Cooled First Stage

Several short tests were performed to evaluate the performance of the Model 1 first stage combustor design. The Tecogen combustor recirculates first stage combustion gases through tubes which are located outside the cylindrical combustor volume. See Figure 15. This recirculation is induced by the pressure difference between the inlet centerline and the exhaust circumference of the vortex created with the inlet air.

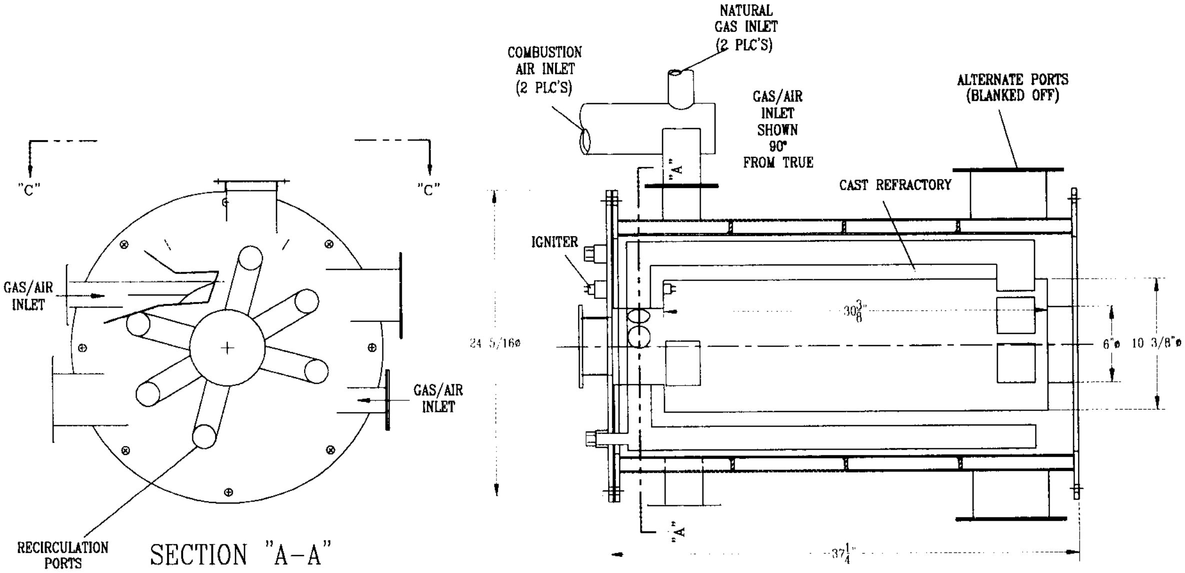


Figure 15 – Model 1 VIStA Burner Design

Cold flow measurements were made with a pitot tube in one of the recirculation tubes. These measurements showed about 50 to 70% recirculation, as shown in Figure 16. Recirculation was found to be relatively independent of the inlet momentum. Increases in recirculation rate were achieved by reducing the pressure drop within the recirculation tubes by installing a turning cone at the head end of the tube. Gains of 10% were observed. Figure 17 displays the measurements with and without the inlet cone. Measurements were made with air injection balanced between the two air injectors and with air injection from each of the injectors alone.

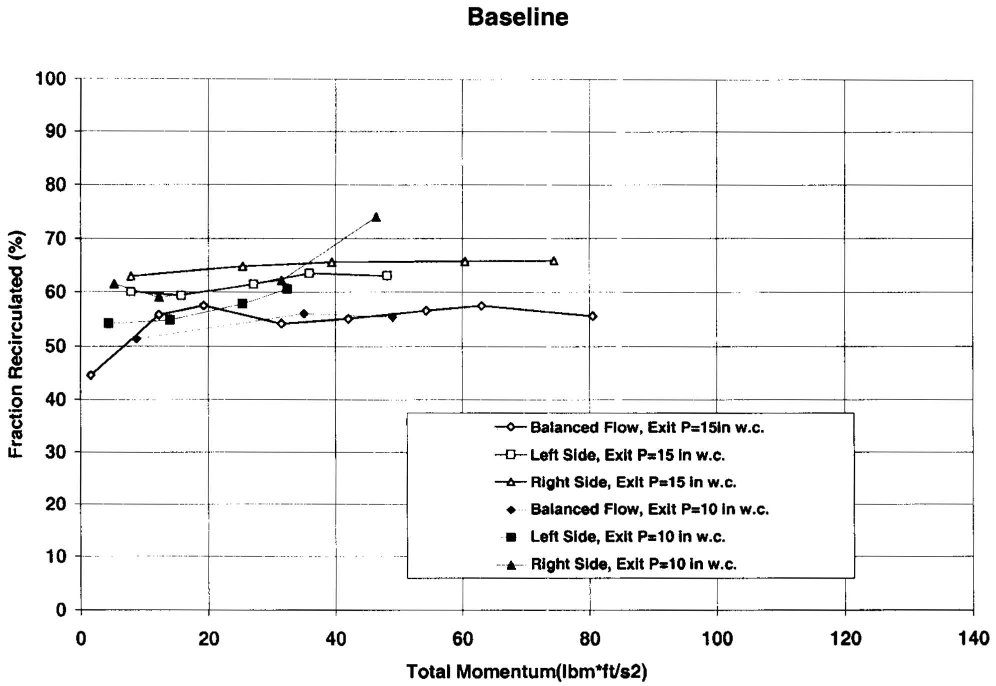


Figure 16 - Cold Flow measurements of the Recirculation Rate in the VIStA Combustor

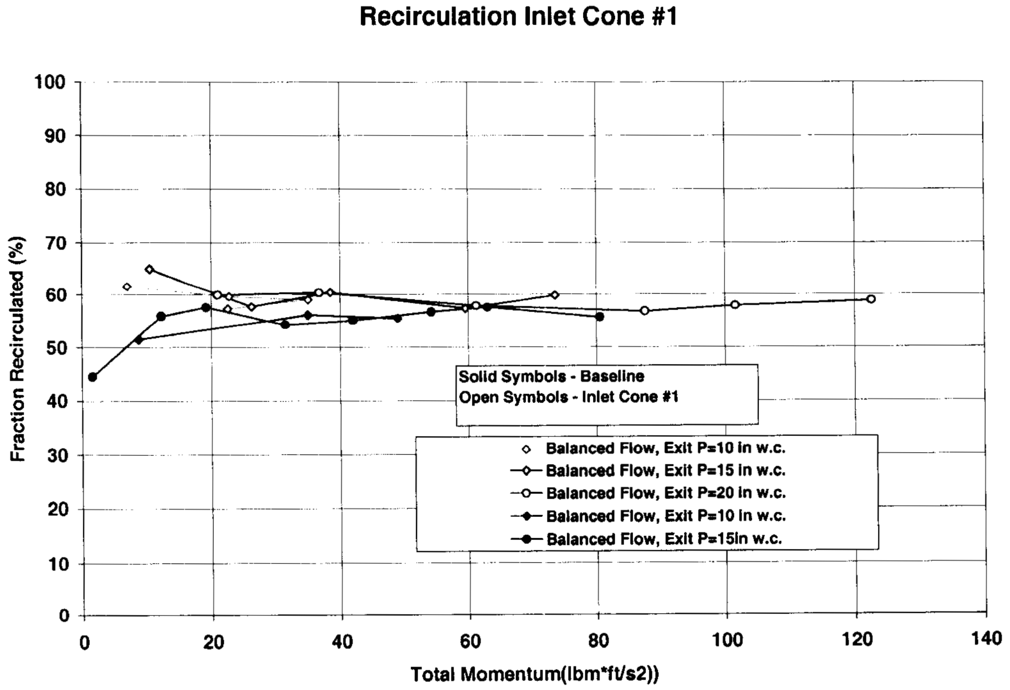


Figure 17 - Cold Flow Measurements of the Recirculation in the VIStA Combustor with Reduced Pressure Drop in the Recirculation Tubes

4.3.2 Recirculation Fluid Mechanics

The amount of internal flue gas recirculation in the first stage of the VIStA burner is dependent on the radial pressure distribution across the reactor, which is dependent on gas velocity, gas density and reactor geometry as shown. The pressure distribution can be determined from Euler's equation:

$$\frac{dP}{dr} = \rho \frac{V_T^2}{r} \quad \text{where:}$$

V_T is the tangential velocity

r is the distance from the reactor centerline

P is the gas pressure

ρ is the gas density

Integration of the above equation, coupled with the tangential velocity distribution in a vortical flow field, provides the pressure difference between the periphery and the centerline of the reactor as a function of inlet velocities and reactor geometries. Figure 18 gives the predicted differential pressure from centerline to combustor wall for the 6.0 MMBtu/hr combustor design based on this simplified equation. The pressure difference can easily be several inches of water column resulting in high recirculation flow rates depending on the size and geometry of the recirculation line.

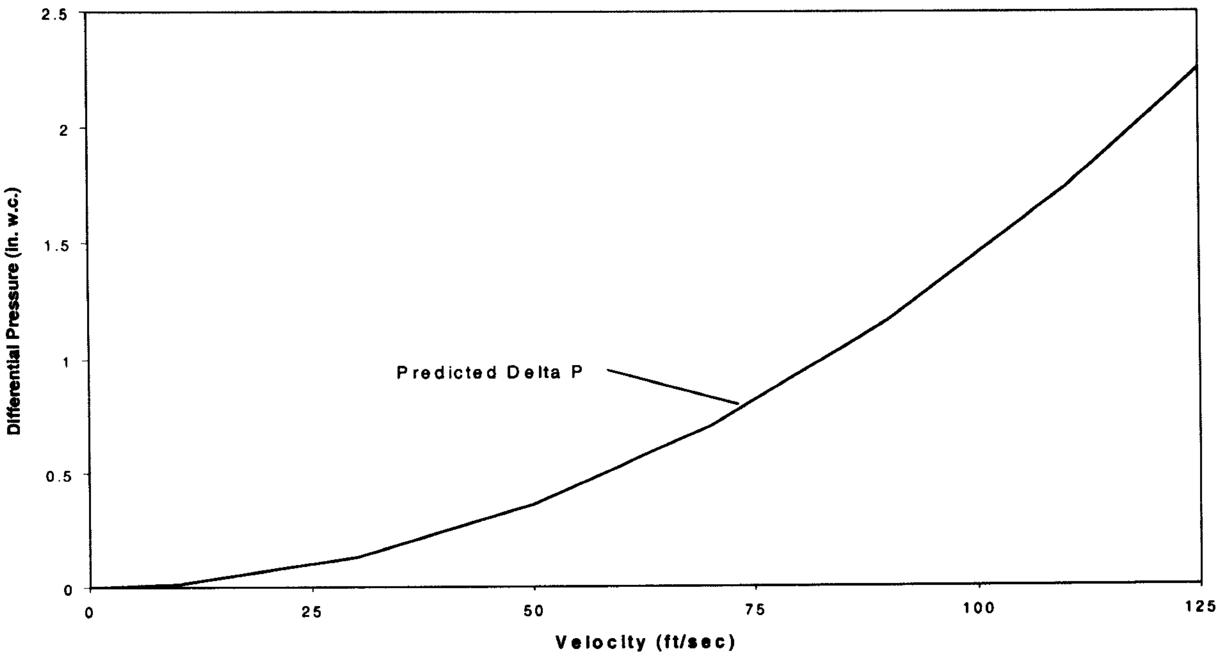


Figure 18 - Recirculation Driving Pressure

4.3.3 Cold Testing of the Model 2 Water Cooled First Stage

The recirculation line flow rate and hence the gas recirculation ratio is strongly affected by the frictional losses through the recirculation line (length, diameter, number of turns, etc.) and how effectively the radial pressure gradient is converted to a driving pressure. In general, as the reactor size increases, the recirculation line pressure losses are minimized, and greater recirculation rates can be achieved. To estimate the recirculation rates for the 6.0 MMBtu/hr combustor, computational fluid dynamics (CFD) modeling was performed using the Fluent computer codes. The modeling began with an evaluation of cold flow performance to judge whether the code would predict the recirculation rate measured during cold flow tests. An axi-symmetric model was designed based on the combustion chamber and recirculation tube volumes. The recirculation volume, which is made up of 12 tubes, was modeled as an annulus with the same cross-sectional area and hydraulic diameter.

Figure 19 shows the recirculation ratios as a function of the inlet momentum under ambient conditions. The inlet momentum is utilized here to normalize the inlet conditions for variations in flow rates and inlet geometries. The first set of calculated recirculation ratios fell short of the measured recirculation ratios with predictions of about 50% and measurements close to 80%. The second set of comparison cases was run with an increased inlet velocity to reflect the difference between discrete jets in the actual combustor and the axi-symmetric model. Recirculation rates were measured at hot conditions to be about a third of the cold recirculation rates. This ratio was confirmed by the axi-symmetric modeling using the inlet velocities which best matched the cold flow tests.

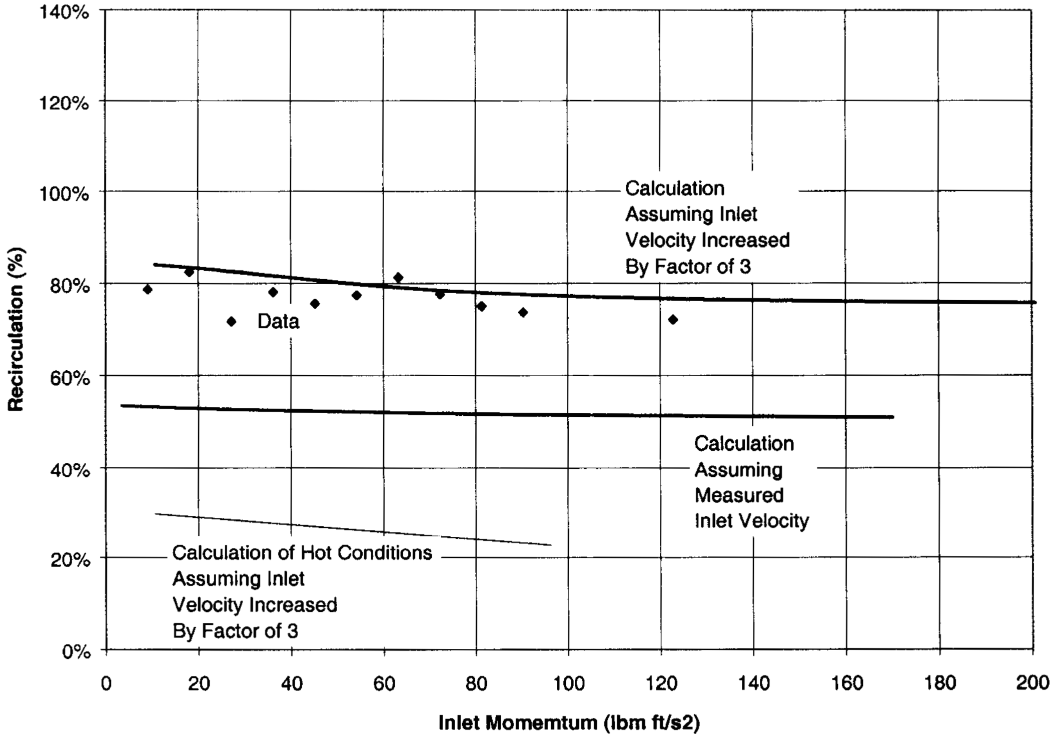


Figure 19 - Measured Recirculation Rates

4.3.4 Hot Testing of the 3 MMBtu/hr VIStA Burner

The system was checked out and run to demonstrate the performance of the first and second stages working together. Measurements were taken at thermal inputs ranging from 1 to 2 MMBtu/hr. Excessive pressure drop at the inlet of the combustor prevented the operation at the full 3 MMBtu/hr flow rate. Measurements were made of the emissions from the first and second stages. Measurements of NO_x in the first stage were between 1 and 2 ppm. Measurements of NO_x from the second stage were about 30 ppm. The NO_x measurement in the first stage were higher than anticipated for a premixed combustion of natural gas and air at the mixture ratios tested. We were concerned that the first stage section was experiencing some air infiltration through the refractory shell. The steel shell surrounding the combustion chamber was tack welded rather than seal welded and could allow air infiltration due to the reduced pressure in the combustion chamber.

4.4 Market Analysis and Commercial Unit Design

4.4.1 Market Needs

The market for industrial combustion equipment in the United States in the latter part of the 1990's and beyond will be shaped by the 1990 Clean Air Act Amendments (CAAA). Title I of the CAAA is designed to bring ambient air quality into attainment with the National Ambient Air Quality Standards (NAAQS) and requires that industrial expansion in non-attainment areas is accompanied by a net decrease in emissions. Some parts of Los Angeles are in "non-attainment" and do not meet the NO_2 NAAQS. "New sources" in NO_x non-attainment areas must use emission offsets and a tight level of control known as "lowest achievable emission rate" (LAER). A target no greater than 9 ppm is usually established. Selective catalytic reduction (SCR) is generally designated as the technology to meet LAER standards.

CAAA control requirements for ozone apply to over 100 ozone non-attainment areas which do not meet the ozone health standard and to "ozone transport regions" which may meet the standard but into which ozone can migrate. Much of the industrial USA is non-attainment for ozone: California, the Great Lakes, the Gulf Coast, as well as the North East. New sources in some ozone non-attainment areas will be subject to the same LAER NO_x target. Thus emission offsets and 9 ppm or lower NO_x emissions will be required. Further, the CAAA will affect smaller sources than previous regulations and consequently will impact industrial-scale furnaces and boilers directly. Of course, industry could opt for SCR systems. But because of the high cost of SCR systems, very low-emitting combustion equipment which does not generate typical pollution levels could be expected to capture the lion's share of the market. If available at a truly competitive cost, very low emission combustion equipment could be used even where it is not required.

4.4.2 Market Analysis

A 1997 McIlvaine report described the market for NO_x control technology as explosive for the next ten years. The report claims that the market for low NO_x burners, selective catalytic and noncatalytic reduction systems, reburn systems, instrumentation and controls, catalysts and chemicals to reduce NO_x will expand to \$2 billion per year within 10 years. It also says that the market for low NO_x burners will rise to more than \$1 billion in 1998.

The boiler market is one of the markets which offers great potential growth in the next few years. A research summary prepared by Joel Bluestein of Energy and Environmental Analysis, Inc. describes the boiler market as consisting of 33,000 units greater than 10 MMBtu/hr with 2.1 million MMBtu/hr total capacity. This report goes on to say that natural gas and byproduct fuels make up more than half of this installed capacity and that sales of natural gas industrial boiler have increased in recent years at the expense of oil and coal. Gas is expected to maintain it dominant market share for several years.

As a result of the increasing markets for low NO_x burners and the boiler market is indicating that old equipment is being replaced, John Zink is pursuing opportunities in these markets.

John Zink envisions a seven step commercialization process:

- Continue to verify the market potential of the VIStA burner.
- Field test the full scale burner.
- Gather and analyze the data provided by this test.
- Use the operating data to develop scale factors for a range of burners (currently projected to be 25 MMBtu/hr to 200 MMBtu/hr)
- Develop burner standards using PRO/Engineer. PRO/Engineer is a highly advanced mechanical design software package which provides three dimensional solid models. Models can be programmed to provide a means of modifying a set of drawings for various sizes of units. This minimizes to opportunities for human error in the design process.

- Develop burner literature describing the features and benefits of the VIStA burner. Use PRO/Engineer to prepare product renderings for the product literature.
- Introduce the burner to the market

4.5 Host Site Agreement

A scaling analysis was performed to evaluate the size and anticipated performance of a VIStA combustor at a 200 MMBtu/hr scale. The analysis results indicate that the combustion chamber can be as small as 3.3 ft. in diameter and 5 ft. long. External dimensions of the burner can be between 4.5 and 6 ft. in diameter and 5.5 to 6 ft. Long.

A letter of commitment to participate in the Phase 2 and 3 development of the VIStA burner was received from John Zink. A project plan for the completion of the development was prepared. This project plan formed the basis for the preparation of a proposal which was prepared for the Phase 2 and Phase 3 work. This proposal was submitted to DOE during the second week of September 1997.

4.6 Fabricate Water Cooled VIStA Burner

4.6.1 Design

The first stage of the 3 MMBtu/hr Low- NO_x burner was redesigned in order to improve emissions performance while simultaneously reducing the burner pressure drop, without changing the geometry of the burner chamber. The new first stage is intended to be fired at rates up to 6 MMBtu/hr.

The burner first stage re-design involves several improvements:

- Increasing the amount of internal gas recirculation, through increasing the number and diameter of the internal recirculation passageways.
- Reducing the temperature of the increased internal gas recirculation, by changing from air-cooled to water-cooled recirculation passageways.
- Eliminating cooling air leakage by modifying the fabrication technique.
- Improving premixing of the natural gas and primary air, utilizing an alternative mixing arrangement.
- Improving swirl in the first stage combustion chamber, by doubling the number of premixed gas/air injector ports.
- Using a modular approach, where the burner is comprised of three (3) mating sections, so that portions of the burner can be readily changed without changing the entire burner.
- Moving the ignition pilot location, to enable more reliable burner ignition.

All of the planned design improvements were incorporated in the revised design. Figure 20 illustrates the resultant overall layout drawing.

The design includes 12 recirculation tubes. The recirculation tubes communicate with the main combustion area via ducts formed in the refractory end caps. The gas/air mixture will be directed into the main combustion zone through four injectors located equidistant around the circumference of the combustor and directed so that the gas/air mixture will enter the main combustion zone tangential to the combustor refractory walls. The combustor design is relatively simple and will be constructed with eight flanges and four spool sections. The center two spool sections will be water-cooled. The two end spool sections will incorporate water cooling on the outer surface to minimize the stresses on the joints between the flanges and the spools.

The dimensions of the main combustion zone are the same as the dimensions of the main combustion zone of the Model 1 first stage. This allows us to evaluate the effect on the performance of the water-cooling. It also allows us to compare Model 2 performance with the performance measured using the Model 1 combustor. The recirculation zone volume has been increased substantially in the Model 2 combustor.

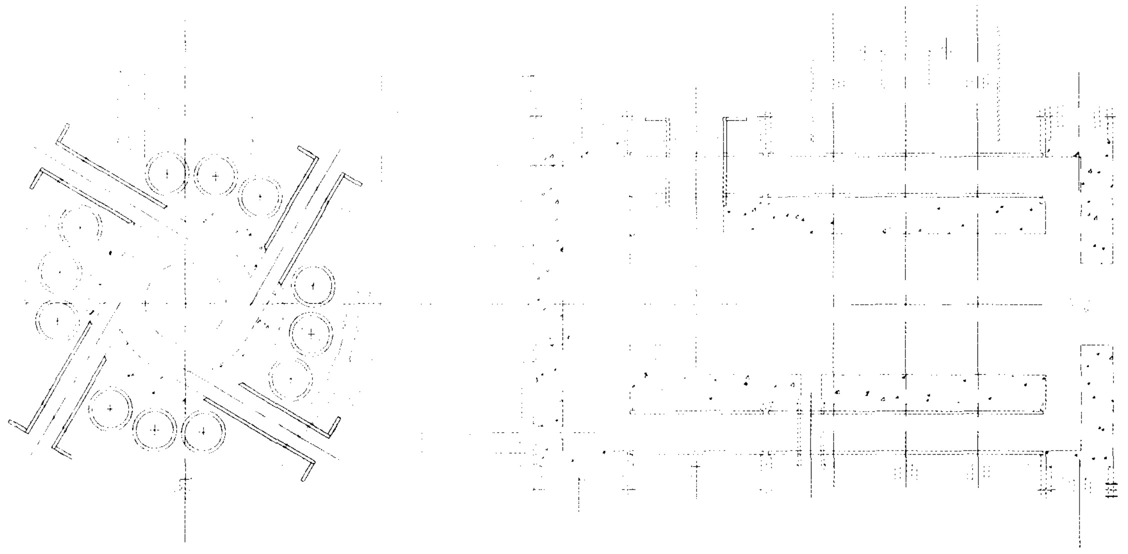


Figure 20 - Water Cooled VIStA Burner Design

As this design is scaled up, the main combustion volume can be increased substantially without large increased in overall diameter of the combustor because the volume will increase with the square of the radius.

Upon completion of the steel fabrication, castable refractory will be installed in all the sections. Then the combustor will receive its final assembly. Modifications to the support system to provide the higher pressure gas will be completed prior to receiving the welded burner.

A minor focus of the project involved verifying that the auxiliaries needed for the larger-gas and air flow rates are sufficient. As a part of that examination, the natural gas delivery pressure feeding the test rig was found to be insufficient for the increased flow associated with the new firing rate. Subsequently, several alternative solutions to this gas supply deficit were explored. Initially, these alternatives involved:

- Complete re-piping of the existing low-pressure natural gas line to reduce the line losses.
- Installing and utilizing an existing natural gas booster pump that could draw sufficient gas volume and deliver sufficient pressure to the test burner.
- Re-activating an existing high-pressure natural gas service to this building, then piping from this existing gas service to the test burner.

As the design effort to increase the gas pressure evolved, a fourth alternative was realized. This alternative involved connecting to an existing medium-pressure natural gas line that could satisfy the gas delivery requirements of the burner. This fourth alternative was determined to be the preferred, low-cost choice.

The design of the new first stage of the VIStA burner continued through January and February, 1998. The original plan was to rely on engineer drawings to describe the new design to the fabrication shops. The differences of the new burner were enough to warrant the production of a set of mechanical design drawings however. The preparation of these drawings took place during January and February.

During the month of February 1998, bids on the fabrication of the new first stage combustor were received. Changes on the first stage design drawings were incorporated in preparation of final selection of the fabricator. The contract was awarded in March.

4.6.2 Fabrication

Fabrication of the new first stage of the burner was completed in June 1998. The sections were hydro-tested to assure that welds were tight and then they were delivered to Thermo Power Corporation.

The first step in the installation was to install the refractory liners for the four sections. Figure 21 through Figure 24 display the sections with the refractory installed. Rounded edges were used at several junctions to reduce the pressure drop of the flowing hot gases.

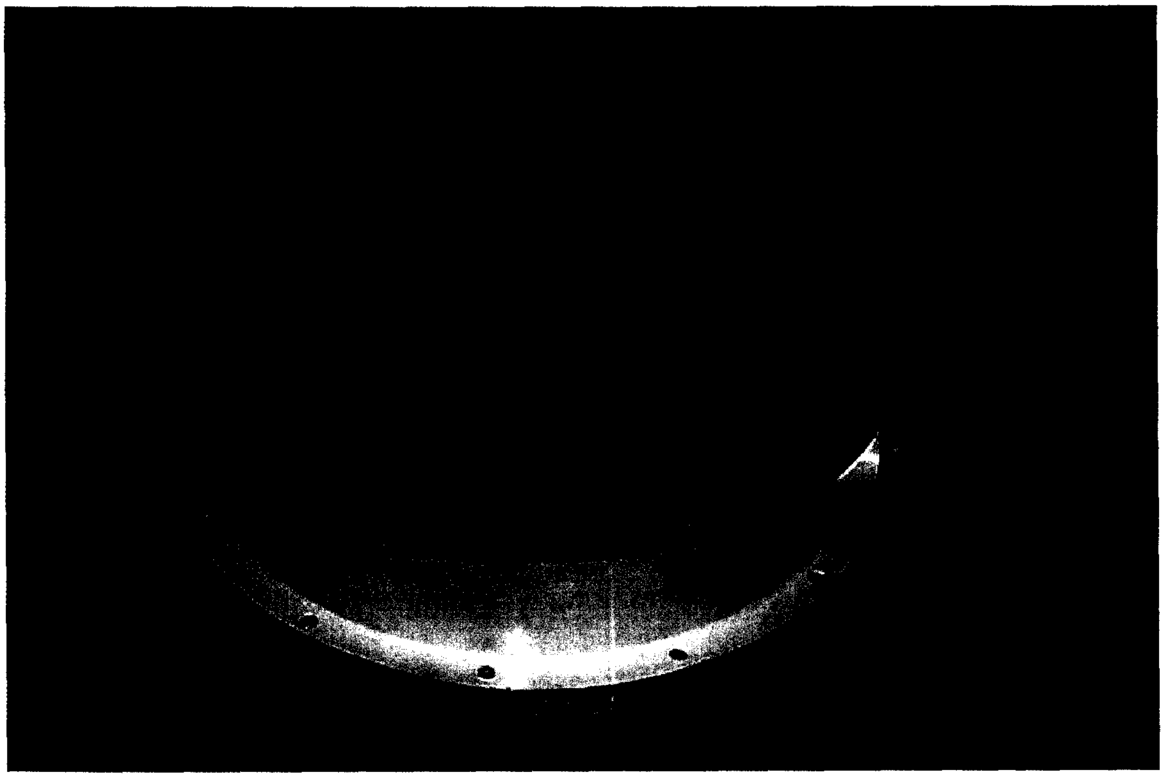


Figure 21 - Head End Section with Refractory Liner

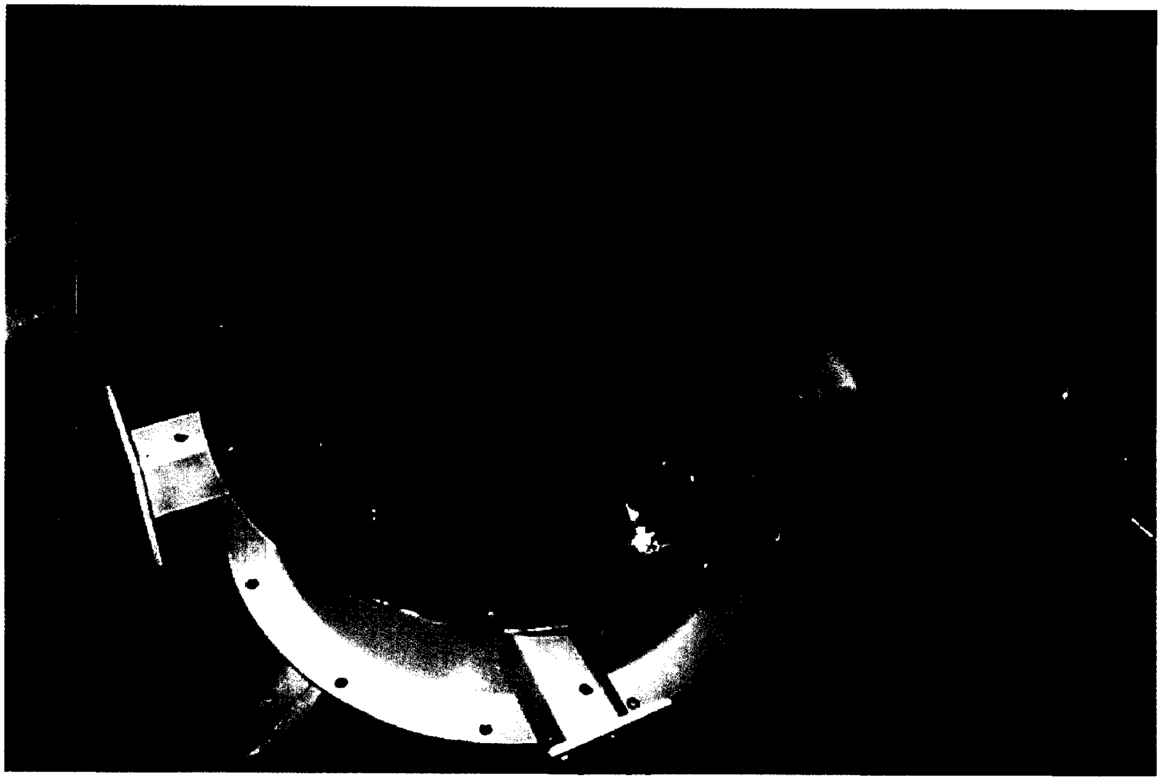


Figure 22 - Injector Section Head with Refractory Liner

Figure 23 - Barrel Section Exhaust with Refractory Liner

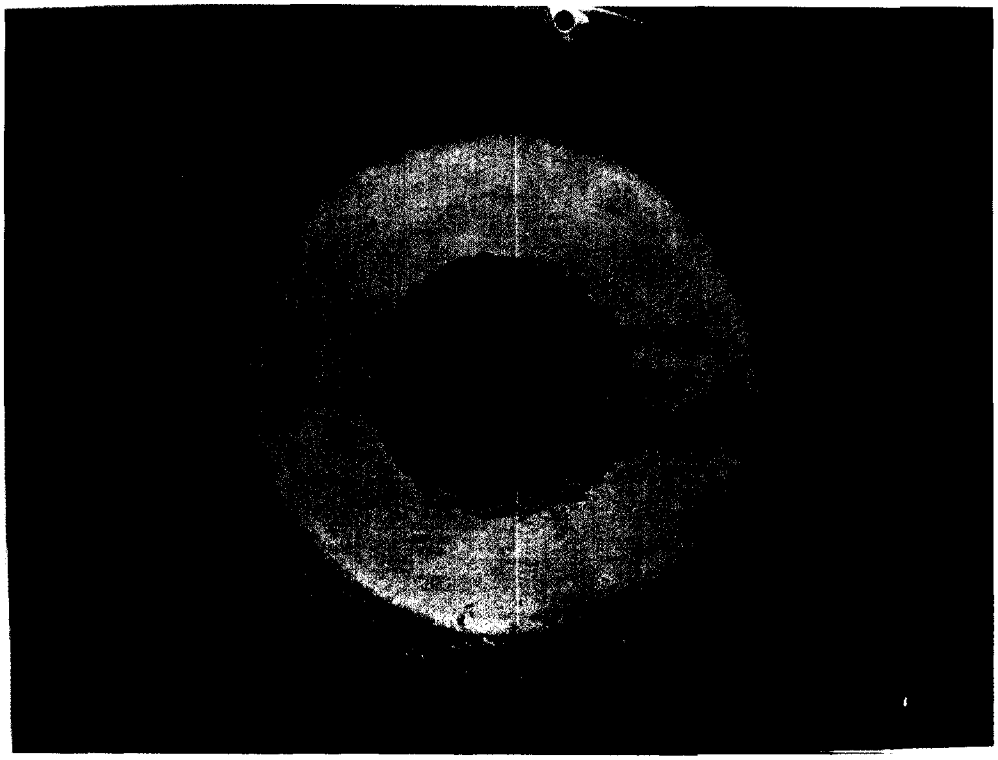


Figure 24 - Nozzle Section Upstream Side with Refractory

The next step in the installation was to assemble the sections and attach them to the second stage section which was already installed on the furnace section. Then connections were made to the steam removal ducting, the water cooling system, and the gas and air supply. Figure 25 shows the assembly at the end of June 1998 with the steam ducting being installed.

Figure 26 displays the model 2 VIStA burner during its installation. In this picture, the head end of the combustor is located to the right of the picture. The four injectors are attached to gas mixing sections, which will in turn be connected to air metering sections. The two secondary air ports, located at the downstream end of the combustor, have air metering sections attached. The burner is connected to the secondary air section which is mounted in the furnace section of the Thermo Power Corporation combustion test facility.

The second stage injector was modified to provide an annular jet of secondary air around the central partially burned exhaust gases coming from the first stage. This second stage was cold tested to determine the air flow rates as a function of the furnace pressure. These measurements confirmed that the new design would be able to supply sufficient air to meet the new 6 MMBtu/hr combustion target.

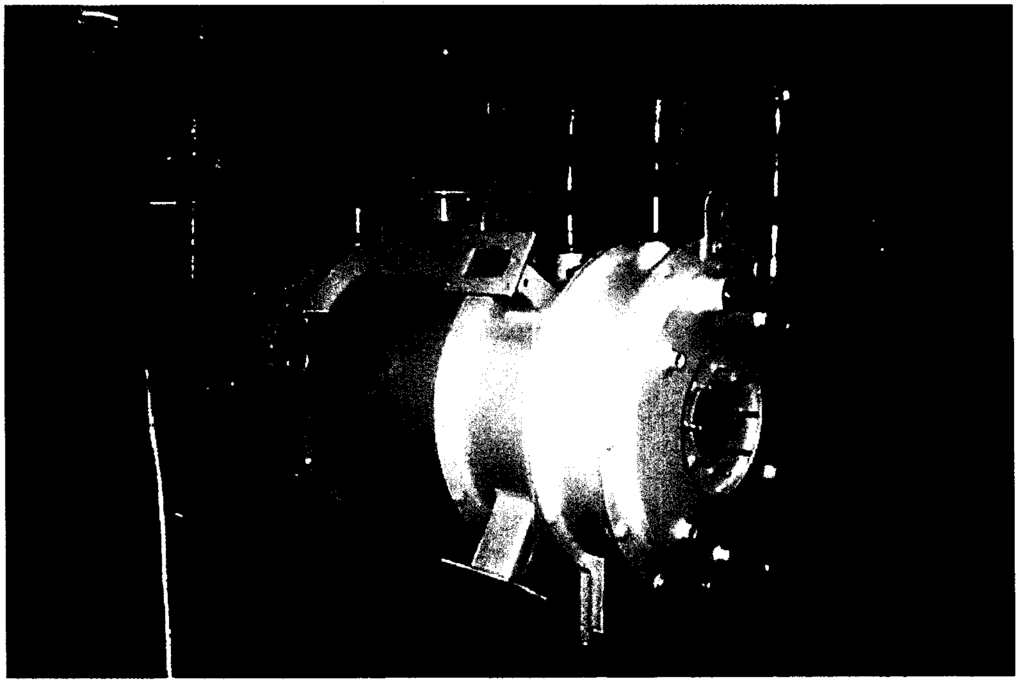


Figure 25 - VIStA Burner Installed on Second Stage Section

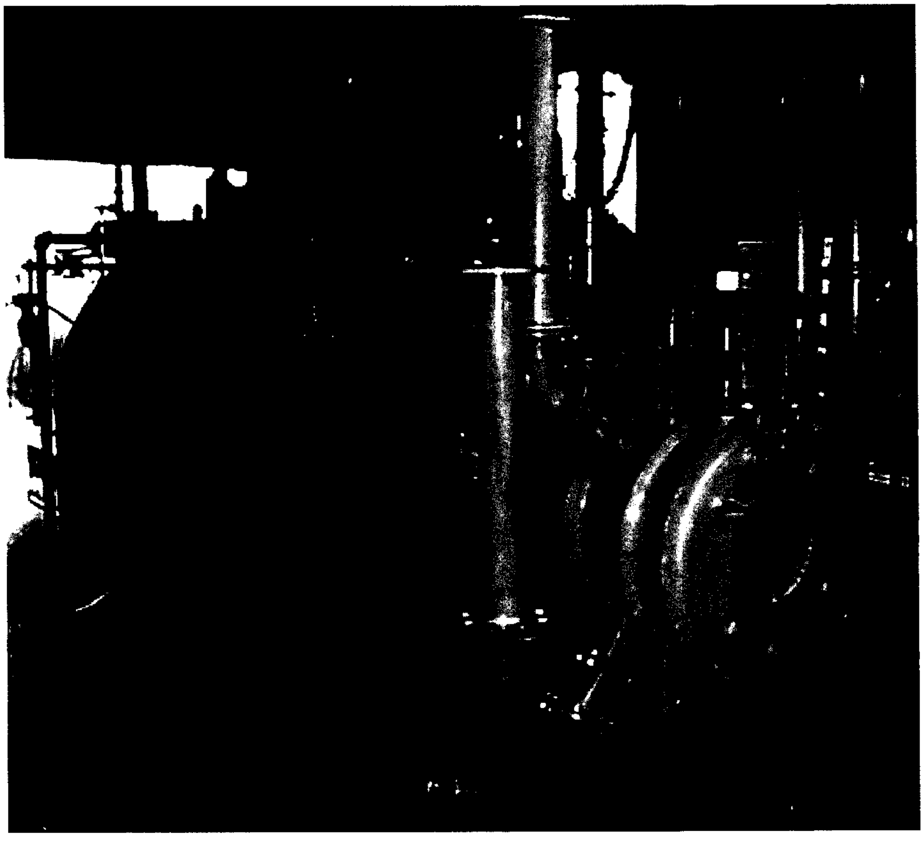


Figure 26 - Model 2 VIStA Burner During Installation

4.6.3 Improved Gas/Air Mixer Design

Design work was performed on the first stage gas/air mixers for the burner. In discussions with John Zink, the team concluded that individual mixers for each injector would provide the most scaleable burner because this would minimize the amount of combustible mixture in the system.

Modeling using the Fluent program was performed on a commercially available gas/air mixer and on a Thermo Power Corporation mixer design. We found that the Thermo Power Corporation design performed the mixing function in a shorter distance and with lower pressure drop.

4.7 Test Water Cooled VIStA Burner

4.7.1 Test Plans

Test plans and data collection needs were discussed in preparation for the test program. Testing was planned to begin with a shakedown period to assure that the system was operating properly and that the combustion safety system was working correctly. These tests were followed with a series of tests performed at a 2 MMBtu/hr firing rate to compare the performance of the new first stage to that of the original first stage. Cold flow measurements of the flow in the recirculation tubes was also to be made to compare to the earlier measurements.

Upon completion of this test series, the flow rate of the burner was to be increased in steps while monitoring the NO_x and CO production.

4.7.2 First Round of Testing of the VIStA Model 2 Burner

Initial testing of the 6 MMBtu/hr VIStA Burner, focused on characterizing the baseline first stage emissions, turndown, and combustion stability. During this testing, second stage emissions were also determined but no attempt was made to optimize the second stage operation.

The results of the testing at Thermo Technologies are summarized in the following figures showing the measured NO, NO_x, and CO as a function of the first stage stoichiometry. Figure 27 and Figure 28 display the data measured over several days of testing. Figure 29 displays the measured NO_x data versus the combustor thermal input. From the scatter in Figure 29, it is apparent that the thermal input may not be the most important factor. In Figure 30 and Figure 31, the data has been replotted to display the effect of thermal input on the NO/ NO_x versus first stage stoichiometry plot. Figure 32 displays that the CO is typically low for this configuration of the VIStA combustor.

Initial testing of the Model 2 VIStA Combustor demonstrated that the combustor can operate over the full range of interest from 1.5 to 6 MMBtu/hr while producing low NO in the first stage and low NO_x and CO in the second stage. NO production in the first stage was measured as low as 1.5 ppmv. NO_x in the second stage was measured in the 23 to 40 ppmv range with CO measurements consistently below 30 ppmv. (Accurate measurement of CO was found to require 10 to 20 minutes of stable operation while the CO instrument stabilized at its final value. Our experimental method was to wait for it to reach a value below 30 ppmv before continuing on to the next condition. When we did give the instrument enough time, the CO measurements were typically below 10 ppmv). The low measured CO production rates are interpreted to be a direct result of the improved secondary air mixing resulting from the modification of the secondary air injector. The CO measurements with the 8 injection tubes during the testing of the model #1 VIStA combustor were about 150 ppm. The secondary air injector tubes were replaced with an annular secondary air injection system for the Model #2 VIStA combustor tests and the CO production has dropped to values of about 10 ppmv when the analyzer is given enough time to equilibrate.

Measurements were also made of HCN and ammonia using a chemical sampling system produced by Sensidyne. These are tubes of chemically treated particles that change color when contacted by the chemicals of interest. The column of the particles shows a longer region of color change depending on the concentration of the chemical being measured.

HCN measured with a first stage stoichiometry of 0.6 and 0.7 at 3.2 MMBtu/hr was about 5 ppm in the first stage and 4 in the second stage. HCN measured with a first stage stoichiometry of 0.6 and 5 MMBtu/hr was about 10 ppm for both the first and second stages. Sampling was performed for ammonia at the first stage stoichiometry of 0.6 and 3.2 MMBtu/hr. No ammonia was detected. The minimum detection level was 500 ppb.

We are encouraged that the measured HCN is not as high as predicted by REI. The REI baseline predictions were made for the Model #1 VIStA combustor at 3 MMBtu/hr with a baseline first stage stoichiometry of 0.6 and 3% first stage heat loss. This model also used a secondary air injection made up of 8 injector tubes located around the first stage nozzle exhaust. These predictions estimated that the HCN for the baseline operating condition would be 11 ppmv in the first stage and 7.8 ppmv in the second stage. Increasing the heat loss would reduce the HCN in the first stage to 5 ppmv and in the second stage to 3.9 ppmv. At adiabatic conditions, the HCN would increase to a high of 46 ppm in the first stage and 24 ppm in the second stage. Other modeling indicated that the second stage HCN could be reduced by decreasing the heat extraction in the second stage or by improving the second stage mixing. Both of these options would increase the NO_x production and decrease the CO production.

Equilibrium thermochemical calculations predict HCN concentrations of 1 to 4 ppbv so the HCN production is probably a non-equilibrium effect.

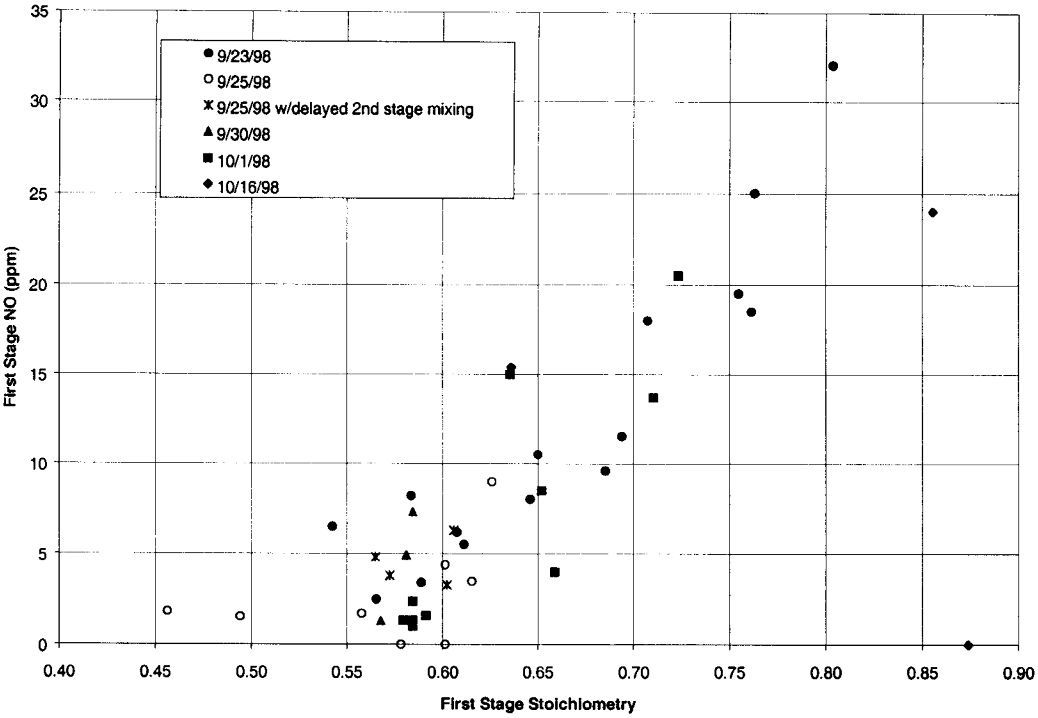


Figure 27 - First Stage Measured NO

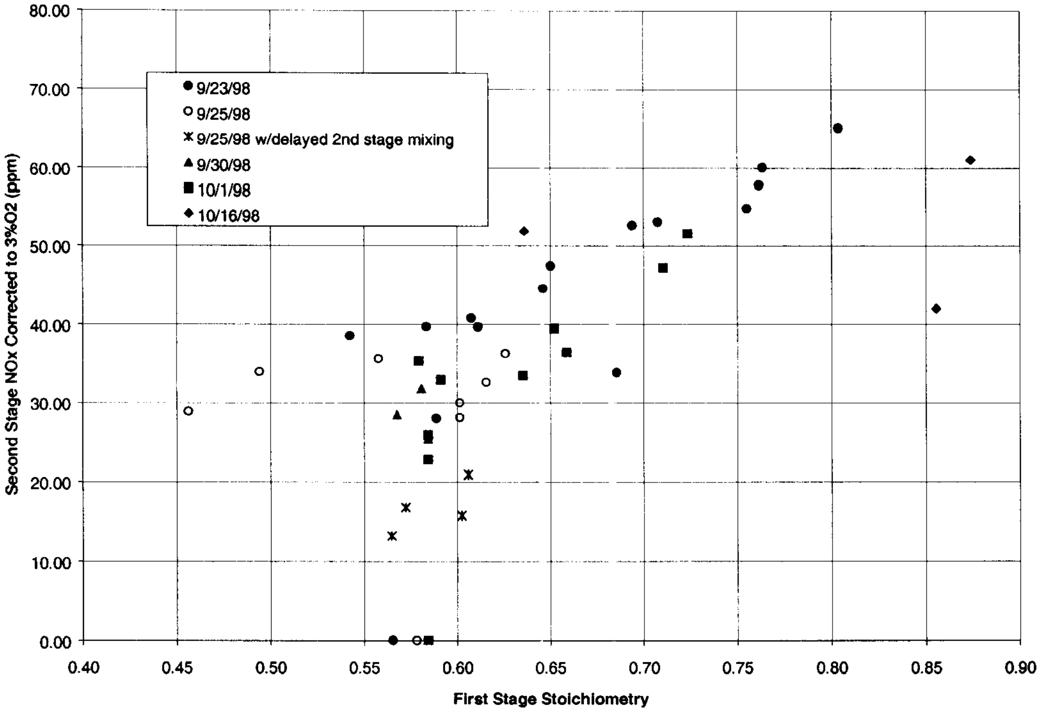


Figure 28 - Second Stage NOx Corrected for 3% O2

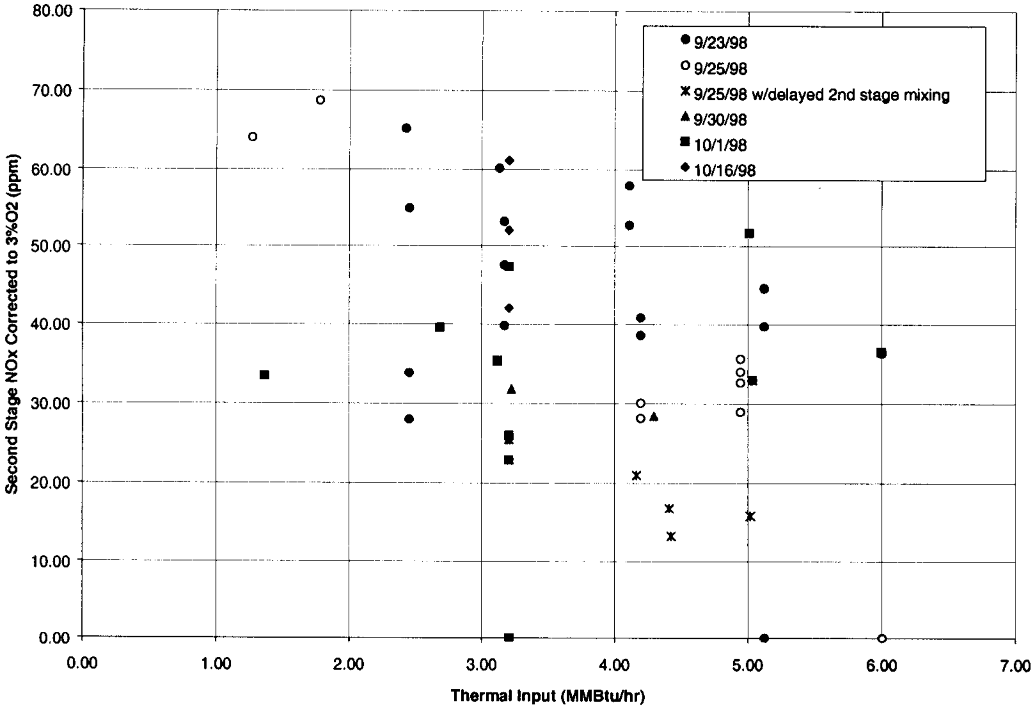


Figure 29 - Second Stage NOx presented as a Function of Thermal Input

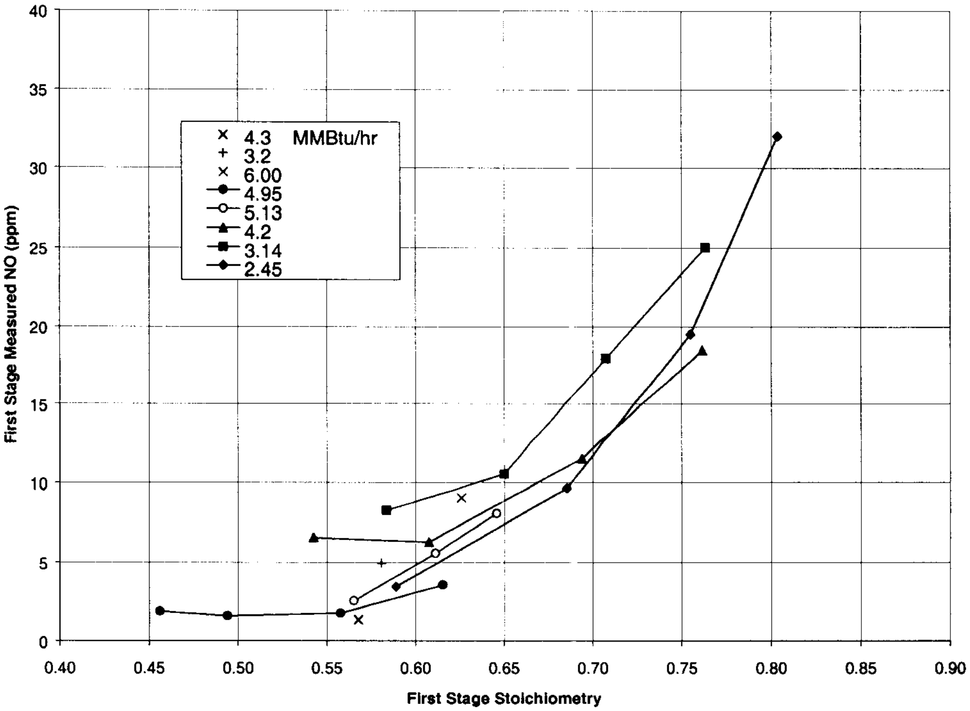


Figure 30 - First Stage NO Showing Effect of Thermal Input

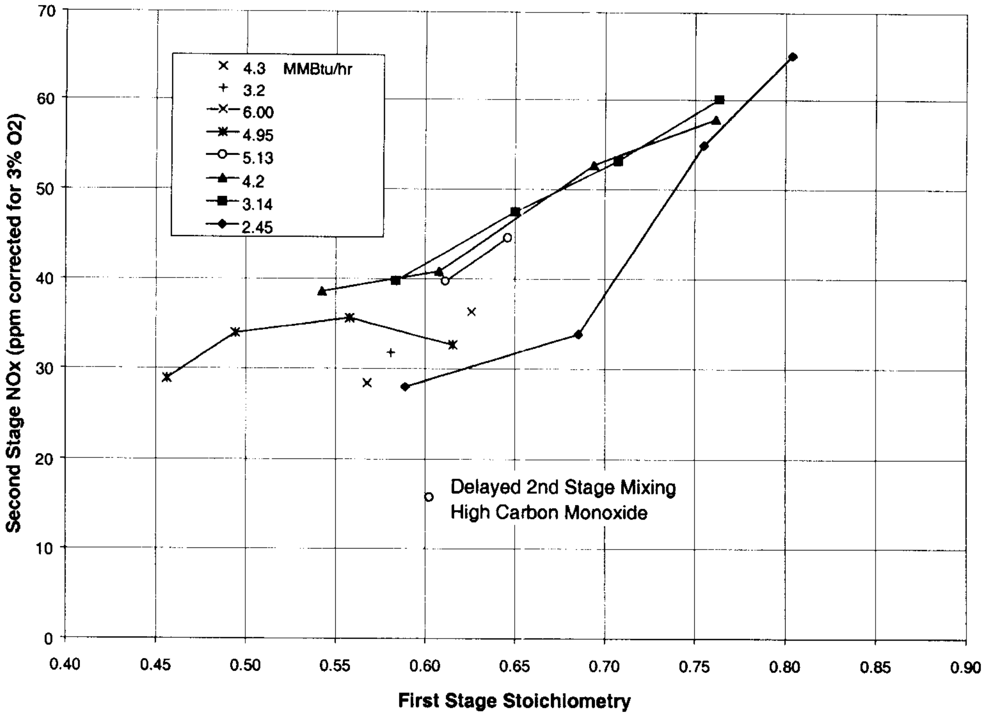


Figure 31 - Second Stage NOx Showing Effect of Thermal Input

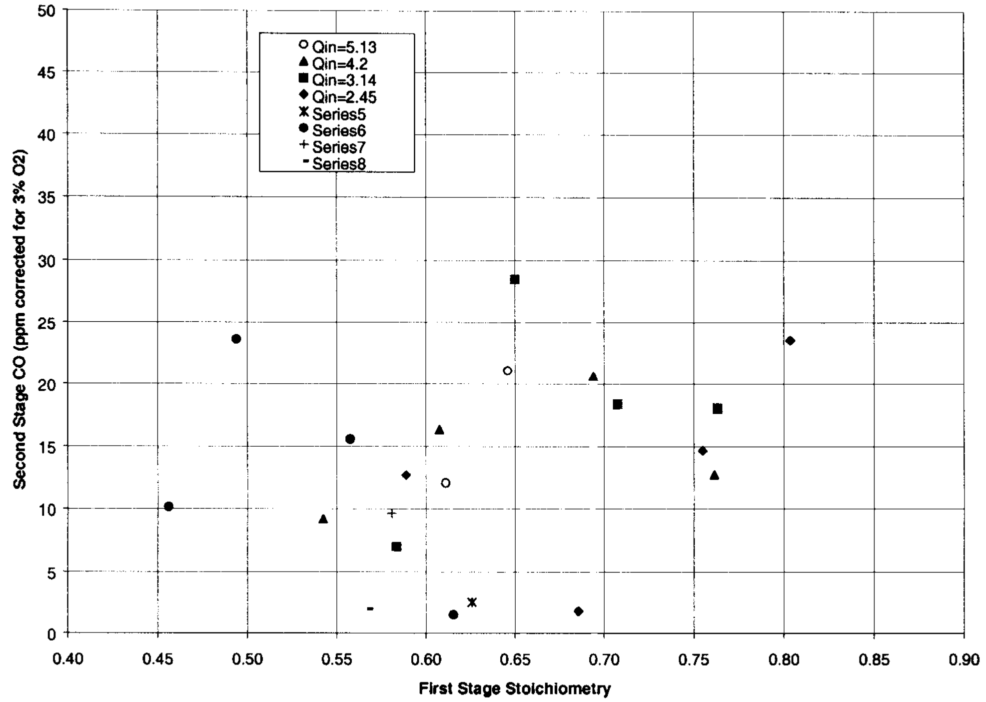


Figure 32 - Second Stage CO Corrected for 3% O2

4.7.3 Moving to John Zink

In early 1999, the 6 MMBtu/hr VIStA burner was disassembled and shipped to the John Zink Company test facility. John Zink reassembled it in their facility and modified the flame safety system to use equipment that is commonly used by John Zink.

A test plan was prepared for the anticipated tests. This plan was forwarded to DOE and approved. The plan is as follows:

- Install the burner as it is, conduct baseline testing i.e. repeat 5 –10 old data points

  Purpose: check out hook up and familiarize personnel with the test set up, verify equipment and measurement

- Add tile step and install refractory with lower heat conductivity

  Purpose: stabilize the burner for desired operating conditions, if possible with equal air supply to all injectors

  Test variables:

heat release	1, 3, 6 MMBtu/hr
primary air stability limit	0.8
Number of recirculation tubes	6, 12
Total test points	< 20

- Add center gas tip and replace shroud with a refractory tile

  Purpose: reduce NO_x emissions, avoid hot metal surface of shroud

  Test variables:
  heat release,
  primary air and fuel gas split (center tip, injector gas)

  Note: Adjust the amount of center gas until the stoichiometry of the injectors is just above the stability limit and the overall stoichiometry in the primary zone is as low as 0.5

- If easy to modify, investigate the effect of shape and form of the primary zone outlet on the NO_x and stability.

  Purpose: it may turn out as a critical scaling parameter

- After the primary zone is stable and the emissions after the primary zones are promising the secondary zone should be modified

  Change from annulus to 8 separated air jets

  Vary arrangement and jet angle

  Purpose: apply air staging to avoid further NO_x emissions,

  Note: discrete jets allow higher flue gas entrainment and better air injection control as an annulus, also swirl can be simulated by turning the tips

4.7.4 Testing at John Zink Test Facility

During the tests performed with the 6 MMBtu/hr VIStA burner at the John Zink facility problems were experienced with burning in the injector ports, overheating and melting of nozzle components, and unsymmetrical flow in the burner. Based on inspection by Thermo Power Corporation, several repairs were recommended.

The John Zink personnel evaluated several of the issues planned for the test program. They installed a barrier in the combustion zone to provide an additional flame holder, they evaluated centerline gas injection, and they reduced the size of the nozzle connecting the first and second stages. Throughout these tests, the burner failed to run as it had been running at the Thermo Power Corporation laboratory. Inspections by Thermo Power Corporation identified that the flame holder on the lower left injector was misaligned and that the igniter placed in the upper left injector was probably aggravating non-symmetric flow observed during the tests.

During the early June 1999 tests, the burner was operated at a stoichiometries of 0.7 and 0.8 with 4 injectors and at a stoichiometry of 0.6 with the 4 tangential injectors and a center injector. First stage NO_x matched the data measured at Thermo Power Corporation at the stoichiometries of 0.7 and 0.8.

During these tests, the following issues were identified:

- Recirculation was not consistent in the recirculation tubes. Thermocouple measurements in two tubes indicated that the flow was in the correct direction in the left tube and the wrong direction in the right tube.
- Need to operate at about phi=0.6 to achieve the low NO_x required. Operation below a stoichiometry of 0.6 was not possible. The flame went out. Yet operation below a stoichiometry of 0.6 was routinely performed at the Thermo Power Corporation laboratory.
- Flame holder on #1 injector is on the wrong side of the injector. Flame holders had been installed on the lower left and upper right injector ports as a means of maintaining ignition at the head end of the burner. The flame holder on the lower left port was observed to be pressing against the wall forcing the injector flow in a radial rather than tangential flow direction. This also would contribute toward the unsymmetrical flow observed in the recirculation tubes.
- Recirculation tube measurements are valuable. The recirculation tube measurements implemented by John Zink were quite useful. They consisted of two thermocouples spaced at a distance of several inches along the centerline of the recirculation tube. We would suggest that these thermocouples be supported with a three-leg spring made of 10-gauge wire to keep the thermocouples centered in the tubes. This will assure that the centerline temperatures are being measured and will eliminate the concern that the thermocouples may be measuring temperatures close to the wall. The system can be constructed using a tube with the two thermocouples placed at the desired distance from one another. As the tube is installed through the head end opening, the three-leg wire spring can be installed in the head end plenum before being positioned into the recirculation tube.
- Damper design needs to be improved. The damper design in the existing model was intended to allow changes to be made in the inlet flow velocities while burning. The design was not implemented properly and the dampers are hard to set.

- Pilot design needs to be improved. The pilot flame was moved from a location on the barrel of the burner to the upper right injector port to assure ignition during the John Zink test. This location causes unsymmetrical flow in the burner and may be the cause of the unsymmetrical flow in the recirculation tubes.
- Pilot in #3 injector could be improved to improve momentum transfer to vortex. Our recommendation is to replace the flame holder in this injector and to return the pilot flame to the barrel section. We would continue to use a flame sensor on the centerline of the first stage.
- Fix or change the nozzle between the first stage and second stage. The nozzle between the first and second stage must be rebuilt so that it does not leak. We recommend a design similar to that which we used originally.
- Second stage design needs to be improved. The second stage could not be evaluated during these tests due to leaks in the nozzle joining the first and second stage. Measurements of the second stage performance during the testing at Thermo Power Corporation had indicated that the second stage flame was too hot.

The goal of the first stage continues to be the partial reformation of the natural gas to CO and H2, and the removal of some heat in the first stage. There are four methods to operate the first stage:

- 4 cold injectors – adjust dampers for maximum momentum
- 2 hot injectors/2 cold injectors
- 4 hot injectors
- Along with one of the proceeding methods, add centerline gas to jet to the wall

We recommend operation with 2 hot injectors/2 cold injectors. This method provides a sufficient ignition source to maintain the flame at the head end of the burner. We have not observed that the introduction of gas on the centerline of the burner has any positive effect.

Several questions remain to be addressed.

- What is the optimum design for the second stage air injector?
- What is the optimum location and shape of the flameholder and igniter to maximize the strength of the vortex?
- What is causing reversed flow in the right recirculation tube? Does the flow return to normal with symmetrical injection of the gas/air mixture at the head end?
- What is the effect of using two hot/2 cold injectors on the vortex strength and the recirculation?
- Should all the injectors be the same design? Should they be all hot, all cold, or mixed?
- How can we accelerate the reformation reactions at the head end?
- What is the effect of wall insulation at the head end and in the reaction chamber?

The following issues were recommended to be performed prior to the next test series.

- Check the recirculation tubes for blockage.
- Check head and tail plenums for blockage that may be redirecting gas flow.
- Instrument all or more of the recirculation tubes. Use centering spring to keep the thermocouples centered in the tube and away from the wall.
- Instrument a suction pyrometer to sample gas from the nozzle entrance. We used a silica tube through the wall at the nozzle end. Through this tube we were able to measure the temperature and the gas composition at the nozzle entrance.

4.7.5 Final Test Set at John Zink

The final set of tests were performed at the John Zink test facility during October of 1999. On the second day, leaks were observed in the secondary air injector plenum causing secondary air injection into the inlet of the nozzle separating the first stage from the second stage. Figure 33 displays the weld failure responsible for these leaks. When the combustor was evaluated, refractory loss was observed from the first stage. Figure 34 displays the loss of refractory from the first stage inlet section.

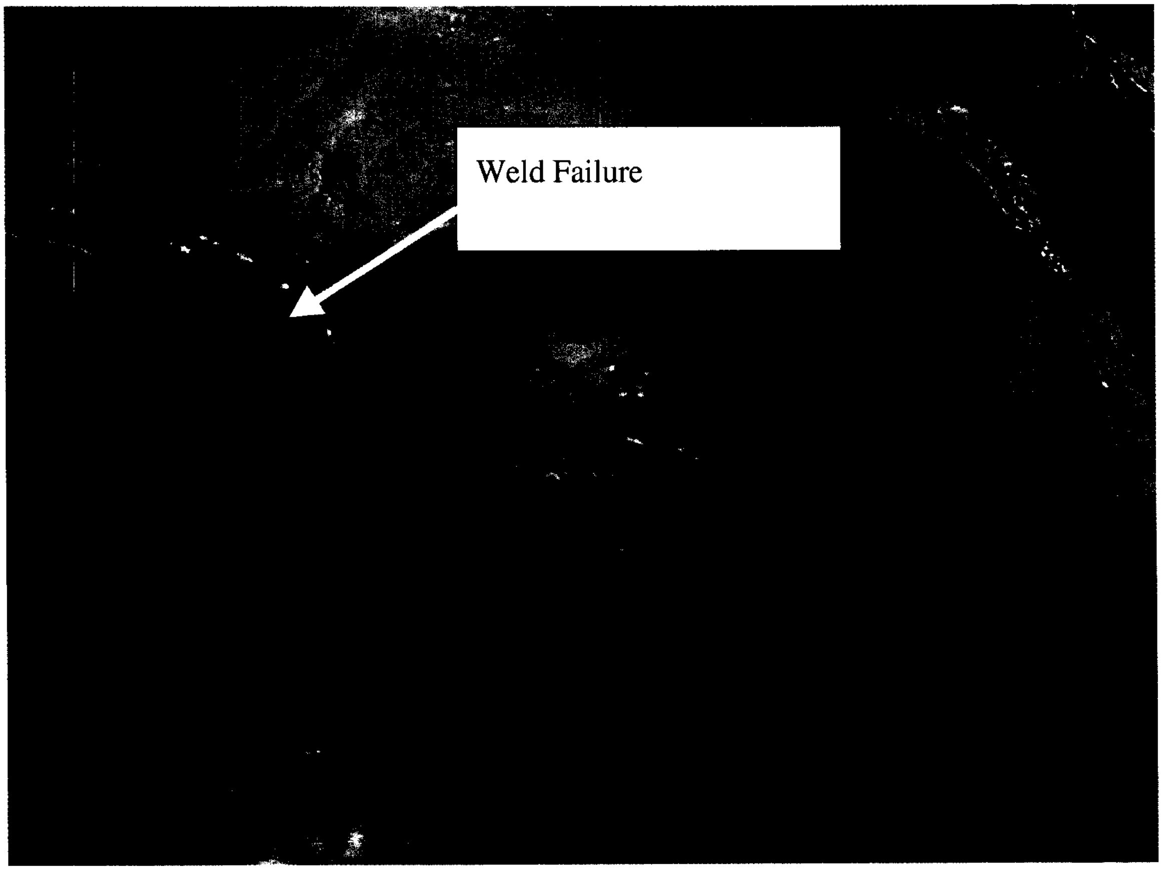


Figure 33 - Weld Failure on the Secondary Air Plenum at the Upstream End of the Nozzle

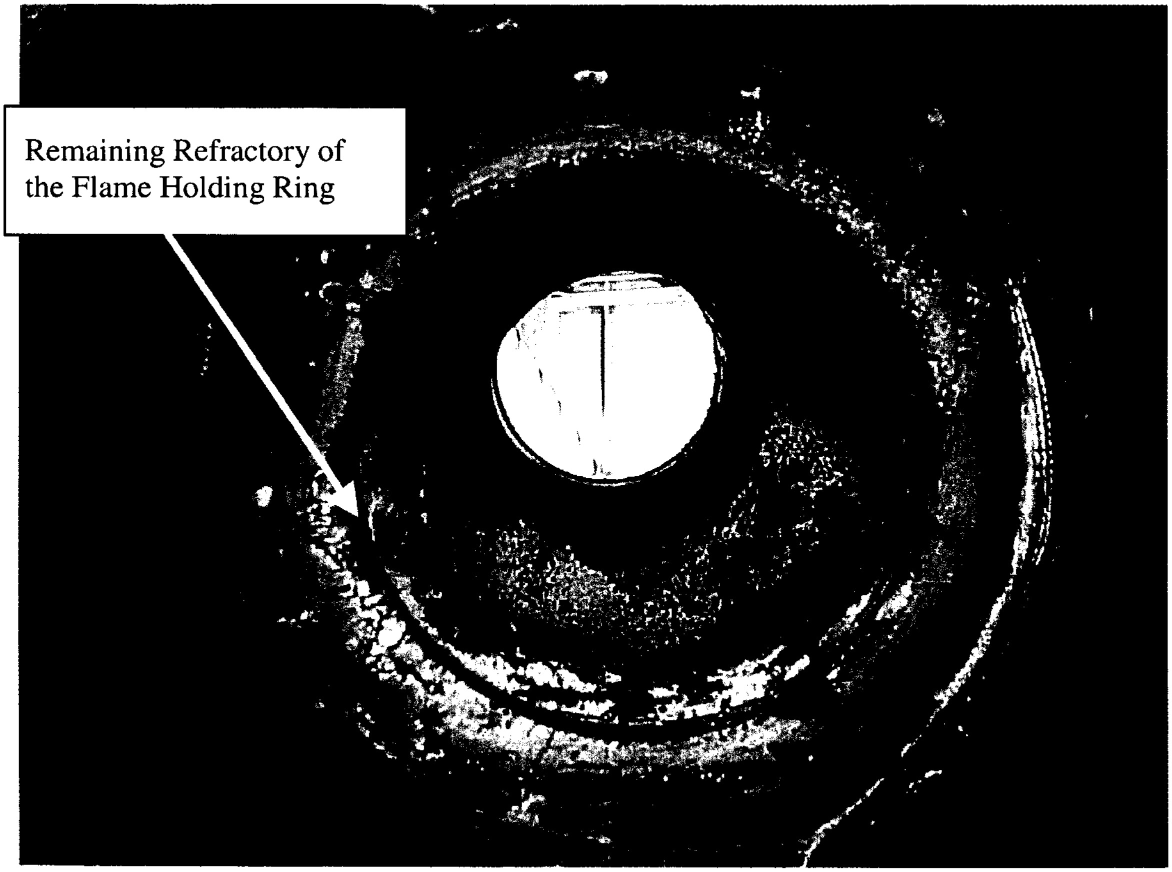


Figure 34 – Loss of Refractory Flame Holder Ring

During inspection, the John Zink personnel also observed that the flame holder ring, that had been installed to improve the flame retention at the head end of the combustor, had almost entirely disappeared.

4.7.6 Data Analysis

Data collected from these tests is shown in Figure 35 through Figure 38. (Note that first stage NO_x was measured rather than first stage NO as in the Thermo Power tests). The conclusions resulting from these tests are that the NO_x produced in the first stage appears to follow the same trend line as the NO produced during the Thermo Power tests (Figure 35). The NO_x produced in the second stage, using the new second stage injector, appears to be lower than the trend line (Figure 36). The lowest NO_x production is still around 30 ppm however. CO production continues to be low (Figure 37). Figure 38 displays that the overall NO_x production may be reduced with increased size.

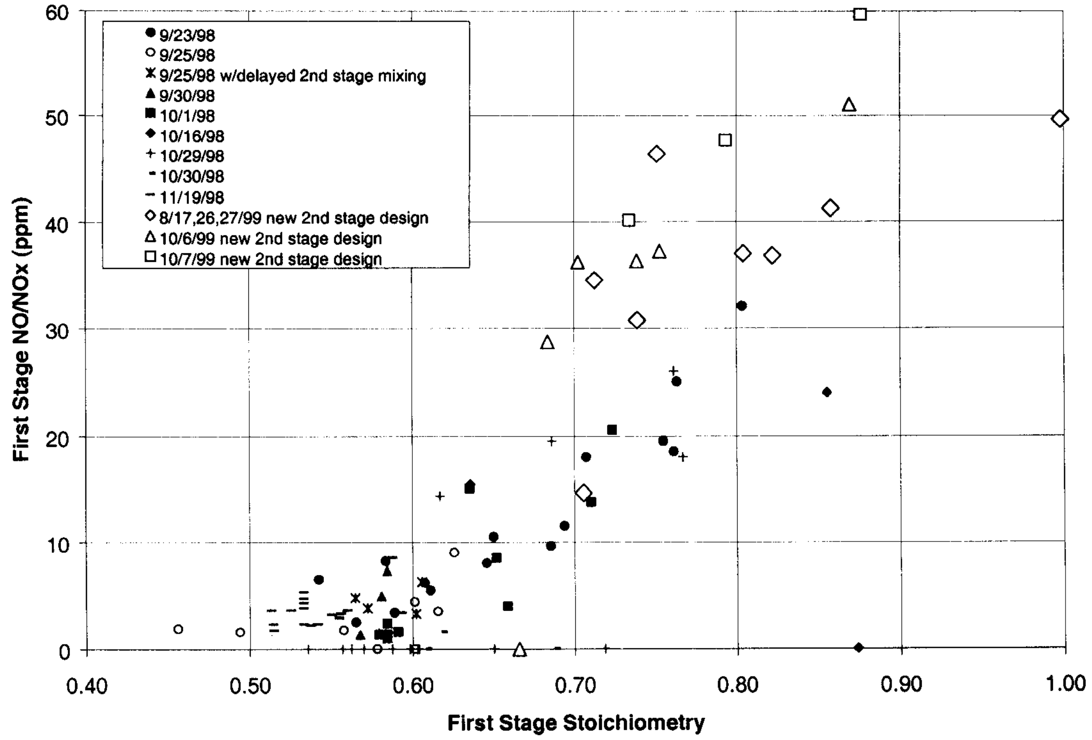


Figure 35 – First Stage NO/ NO_x vs First Stage Stoichiometry

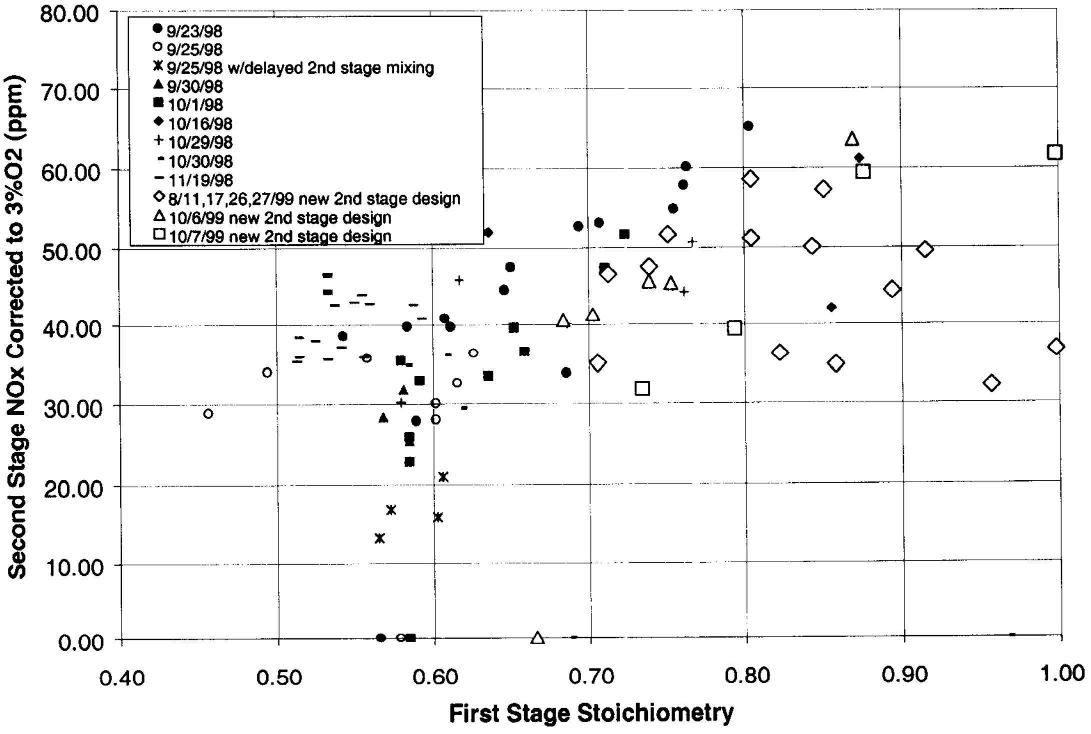


Figure 36 – Second Stage NO_x vs First Stage Stoichiometry

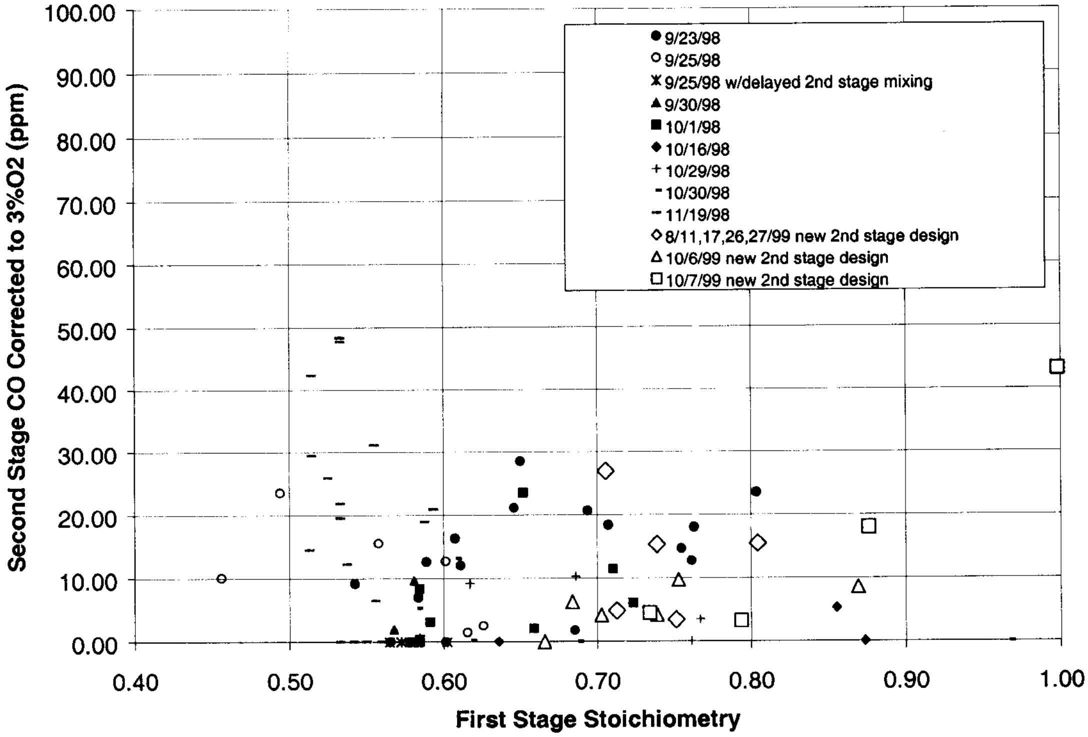


Figure 37 – Second Stage CO vs First Stage Stoichiometry

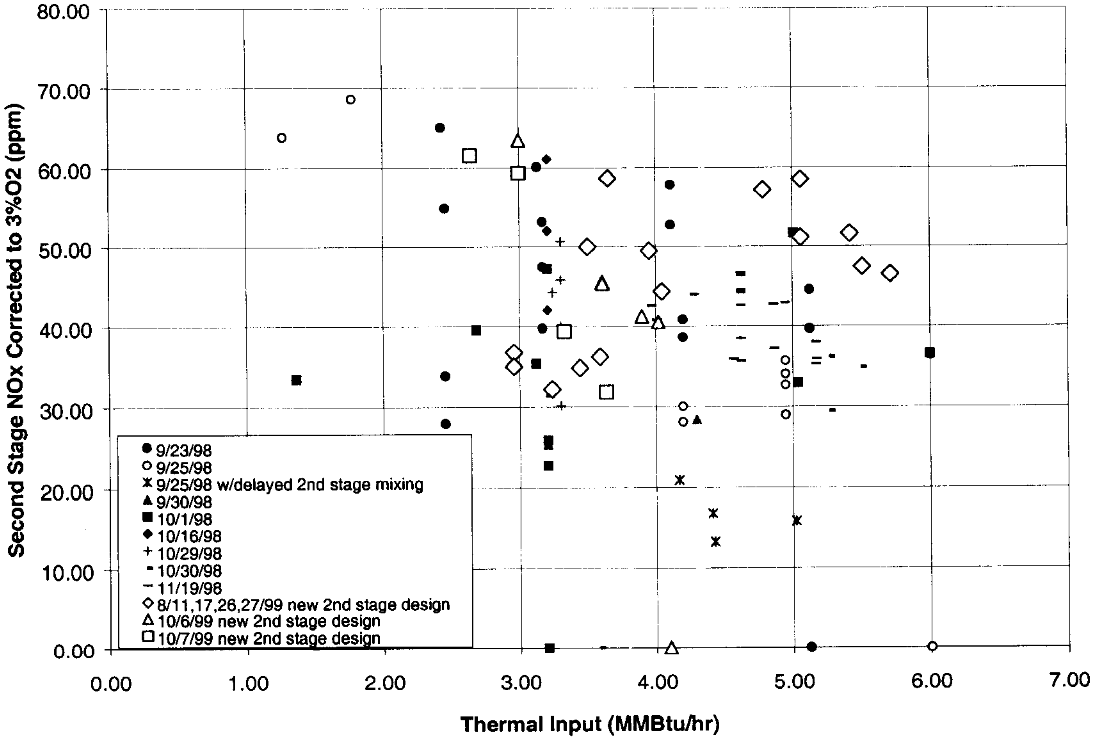


Figure 38 – Second Stage NO_x vs Total Thermal Input

4.8 Design of a 30 MMBtu/hr Burner

Drawings prepared for the fabrication of the model 2 VIStA burner were forwarded to John Zink for their review. John Zink has assembled a team made up of fabrication, manufacturing, modeling, and test engineers to support this development effort. This team was charged with reviewing the model 2 experimental VIStA burner drawings for commercial manufacturability.

The John Zink design team reviewed the drawings of the Model #2 VIStA combustor and recommended several areas of design evaluation. These areas include the design of the second stage and the design of the injection section of the first stage. They have recommended that the second stage be made of discrete jets of air rather than the continuous annular sheet of air. The discrete jets are better at entraining furnace flue gases into the combustion zone because the flue gases can penetrate inside the annular zone. Penetration of the sheet does not occur.

The recommendations for the first stage are intended to help better stabilize and hold the flame at the head end of the first stage combustor. Additional modeling was recommended to better define these recommendations.

Further evaluation was postponed until data had been collected from the John Zink test facility. The program was terminated before any further evaluation and design was performed.

5 CONCLUSIONS

During the course of this work, we have learned that it is very important to provide a thoroughly premixed gas to the first stage combustion zone. During the initial tests of the Model 1 combustor, regions of poor mixing result in sheets of stoichiometric mixtures that burned at high temperatures and produce high NO_x concentrations.

We have found that we need to provide as high an inlet velocity as possible at the head end inlets of the primary combustion zone. High velocities promote a strong vortex that provides a strong recirculation through the recirculation tubes. High velocities also result in high pressure drops however, so our testing has typically been performed at pressure drops across the combustor that are acceptable to the industry. This limits the vortex strength and forces us to compromise on the combustor performance.

One of the design elements of the current 6 MMBtu/hr burner is to cool the recirculating gases as much as possible before returning them to the combustion zone. This provides a radiation absorption zone within the core of the combustor that helps to cool the first stage combustion zone. We had planned to insulate the recirculation tubes to compare the performance of the system with reduced first stage cooling. This option has not yet been tested.

Once the gas/air mixture is in the combustor, it is important to get it hot at the head end so that the partial reduction reactions can begin taking place. This allows us to make maximum use of the combustion volume and it minimizes the combustion volume required for the burner. We have addressed this issue by operating two of the four gas/air injectors at stoichiometries of 0.8 and two of the injectors at lower stoichiometries. The resulting mixture is intended to be at a stoichiometry of about 0.6 to minimize the NO_x production. This strategy requires a decision about how much gas each injector should carry. We have tested with all the injectors supplying the same gas flow rate and with the hot injectors supplying half the gas that the cold injectors are supplying. Our results indicate that the lowest NO_x production occurs when all the injectors supply the same gas flow rate.

Another strategy for getting the inlet gas/air mixture hot is to insulate the head end of the combustion chamber. This will allow the refractory to operate at a higher temperature and to transfer more heat to the gas/air mixture. This strategy has been evaluated by building the vortex finder with insulation board. The stability of the first stage combustion zone appeared to be improved with this design option. Insulating the head end of the combustion zone has not yet been tested.

Finally, we have explored the option of injecting some of the gas into the first stage axially along the centerline of the combustor. The rational for this strategy is that gas will reduce any NO_x formed in the partial combustion of the gas/air mixture. In addition, the gas flow rate may induce additional recirculation through the recirculation tubes. This strategy has been used during most of the testing at John Zink. One possible problem with this strategy is that the reducing environment may actually create some NO_x. In earlier tests in Waltham, we noted that the NO_x is reduced as we reduce the first stage stoichiometry but that it started to increase at stoichiometries below about 0.55. A modification to this strategy might be to inject a gas/air mixture along the centerline.

APPENDIX A - List of Papers delivered

McClaine, Andrew, Frederick Becker, Anthony Litka, Ronald Breault, and Kailash Shukla of Thermo Power Corporation and Jaiwant D. Jayakaran, Roger Poe, and Christoph Strupp of John Zink Company, "VIStA Combustor for Very Low NO_x Emissions in Furnaces and Boilers", 1999 Fall International Symposium of the American Flame Research Committee, San Francisco, California, October 3-6, 1999

Becker, Frederick, Ronald Breault, Anthony Litka, Andrew McClaine and Kailash Shukla of Thermo Power Corp and Jaiwant D. Jayakaran and Christoph Strupp of John Zink Company, " Status Report on the Development of the VIStA Combustor for Very Low NO_x Emissions in Furnaces and Boilers", 1998 American and Japanese Flame Research Committees International Symposium, Maui, Hawaii, October 11-15, 1998

Breault, Dr. Ronald, Kailash Shukla, Fred Becker, and Andrew McClaine of Thermo Power Corp. and Jaiwant D. Jayakaran of John Zink Company, "Status Report on the Development of the VIStA Low NO_x Burner", 20th Task Leaders Meeting of the International Energy Agency Program of Research in Energy Conservation and Emissions Reductions in Combustion, Ottawa, Ontario, July 26-30, 1998

Breault, Dr. Ronald, Kailash Shukla, Fred Becker, and Andrew McClaine of Thermo Power Corp. and Jaiwant D. Jayakaran of John Zink Company, "VIStA Combustor for Very Low NO_x Emissions in Furnaces and Boilers", American Flame Research Committee 1997 International Symposium on Combustion Technologies for Improving Productivity and Product Quality, Chicago, Illinois, September 21-24, 1997

Breault, Dr. Ronald, Kailash Shukla, Fred Becker, and Andrew McClaine of Thermo Power Corp. and Jaiwant D. Jayakaran of John Zink Company, "Status Report on the Development of the VIStA Low NO_x Burner", 19th Task Leaders Meeting of the International Energy Agency Program of Research in Energy Conservation and Emissions Reduction in Combustion, Capri, Italy, September 14-17, 1997

APPENDIX B - Patents awarded

6,089,855	July 18, 2000	Low NO_x Multistage Combustor

APPENDIX C - Statement of Work

Objective of Project: The project goal is to develop and test an advanced combustion burner to achieve nitrogen oxide emission levels of 9 ppm or lower and carbon monoxide levels of 50 ppm or lower (both corrected and reported for 3% excess oxygen) under acceptable operating conditions. Determination of the feasibility will be made for a full-scale unit.

Scope of Work: The scope of this research is to develop and test an industrial low NO_x burner for existing gas-fired boilers and industrial processes. Pilot scale tests (nominally 3 MMBtu/hr firing rate) will be perform to evaluate the concept burner system. Market and economic estimates will be used to confirm the potential for commercial viability.

During Phase II, a 30 MMBtu/hr scale VIStA burner will be designed, manufactured, and tested at the John Zink test facility. During Phase III, this unit will then be packaged and shipped to a John Zink host site where it will be demonstrated for a period of up to 6 months.

Statement of Objectives

Phase I - Laboratory Development

Task 1 - Advanced Combustor Design

The participant will use a burner scaled up from a 250,000 Btu/hr reactor previously tested as the first stage (inertial reactor) of a staged burner. A second stage combustor will be designed, fabricated, and installed between the first stage combustor and the boiler. Factors to be included in the design include axial pressure drop, heat release rate, reactor temperature, and residence time. An analytical model (previously developed) of the inertial reactor will be modified for use in the design of the second stage combustor. The model will be used to help determine parametric behavior of the effects of reactor geometry variables, fluid dynamic parameters on emissions, turndown, and flame stability.

The design of the reactor will include modularity to allow flexibility in varying key geometric parameters. Specific goals will be to minimize nitrogen-bound compounds at the exit of both the inertial and secondary reactor, high turndown ratio (10 to 1), and good flame stability to permit high amounts of external flue gas recirculation.

Task 2 - Computer Modeling

Fluid dynamic computational modeling and chemical kinetics modeling will be performed prior to testing (Tasks 3) to help guide the experimental set-up. The model shall consider the parameters controlling the composition of the partially reacted products of combustion produced by the inertial vortex reactor, these shall include: the fuel/air ratio, the degree of recirculation, and the level of heat extraction. A reacting CFD model will be used to model the second stage flame. The reactor geometry variables to be included are: diameter, length, partition opening, inlet nozzle area, nozzle angles, and internal recirculation flow area. The process variables include: fuel flow, primary, and secondary air flows, inlet velocities, cooling rate, internal recirculation rate, and external recirculation rate. Test data collected under Task 3 will also be used as input boundary conditions to improve the modeling code.

Task 3 - Fabrication and Testing

The participant will complete the design, fabrication, and assembly of a pilot scale Inertial Vortex Staged Return Flow burner. A test plan will be written that will define the testing parameters and DOE approval of the plan received prior to initiating tests. The plan will detail the test variables, goals, instrumentation, data collection systems, and test analysis procedures. An estimated 25 days of testing shall be carried out over a two-month period. The test schedule shall be identified. Included in the testing will be variations of normal operating parameters such as excess air, combustion air temperature, turndown, internal inertial reactor recirculation rate, overfired air (OFA), and flue gas recirculation (FGR) rate. Modifications to the burner to optimize configuration will be made. The burner process and geometric variables will be varied, as applicable, and their effect on heat release rates, radiation transfer, pollutant formation and noise conditions shall be determined. Conventional diagnostics including suction pyrometers, thermocouples, flow meters, and gas analyzers will be used to measure the gas and wall temperature, and O_2, CO_2, CO, HC, and NO/NO_x emissions. A data acquisition system will be used to collect all digital readouts. The data will be use to optimize the burner for Phase II activities. Identification of the scaling laws for the design of a 100 MMBtu/hr prototype burner will be made.

Task 4 - Market Analysis and Commercial Unit Design

A market analysis will be conducted for an advanced ultra-low NO_x combustor. A preliminary commercial design and manufacturer's cost will be prepared.

Task 5 - Host Site Agreement

Guidelines for identifying a host site will be determined. They will include sites located in non-attainment areas, multi-burner facilities, heat delivery rates, availability/load factors, outage plans/schedule, back-up fuels, cost sharing, commitment of plant personnel, and others. A review of regulatory or permitting actions for retrofit will be defined. A host site recommendation will be submitted to DOE which will include a summary of the conceptual and feasibility analysis, a rationale, for selecting the specific host site, and description of agreements with the host site owner.

Task 6 - Reporting/Project Management

A final report will be written and submitted to DOE for approval that fully presents the project research and the potential for the Inertial Vortex Stage Return Flow (IVSR) Very Low NO_x Burner. The report will include a plan for Phase II prototype burner development. Review comments will be incorporated and a camera-ready final report will be submitted. A review meeting will be held to determine project status and the advisability of project continuation. The participant will provide management functions necessary to maintain the budget and schedule within established limits, seek identification and resolution of technical, environmental, safety health, and administrative issues and maintain communications with all project participants, DOE and its technical representatives.

Task 7 - Fabricate Water Cooled VIStA Burner

Thermo Power will fabricate the water cooled VIStA burner designed as part of the design task. This will involve completion of the design drawings, soliciting quotations, fabrication, installation, and checkout. The design of the apparatus will be modified to allow for an increased thermal input of 6 MMBtu/hr.

Task 8 - Test Water Cooled VIStA Burner

Thermo Power will test the water cooled VIStA burner in the Thermo Power test facility to evaluate its ability to efficiently burn its fuel while producing NO_x and CO of less than 9 ppm and 50 ppm respectively.

Phase II - Scale-Up Design, Fabrication, and Testing

Task 9 - Continued Laboratory Testing

The first step in the scale-up of the 3-6 MMBtu/hr VIStA burner will be to complete the laboratory testing of the 3-6 MMBtu/hr burner to resolve any issues remaining after the completion of the preceding Phase 1 tasks. In particular, the VIStA burner will be operated with a backup fuel to assure that it can burn the backup fuel reliably. In addition, modifications to the secondary air injection design and the gas/air mixer design may be explored to understand improved design concepts. Most commercial burners used in the petroleum industry require a backup fuel capability. The use of a backup fuel must be tested prior to performing the scale-up design. The secondary air injection design is a critical part of the successful reduction of NO_x from any gas burner. Additional laboratory testing will be performed to evaluate other design issues as the design of the 30 MMBtu/hr burner progresses. The 6 MMBtu/hr burner will be shipped to the John Zink Company who will perform additional developmental effort. A test plan will be developed outlining the parameters to be studied, the tests to be conducted, ant the overall approach to lowering the NO_x emission observed. DOE will be provided the opportunity to review the document prior to commencing the tests.

Task 10 - Design of a 30 MMBtu/hr Burner

The participant will model a 30 MMBtu/hr scale VIStA burner to aid in the burner design. A preliminary design will be prepared in conjunction with the modeling to define the design criteria. A mechanical design of the 30 MMBtu/hr VIStA burner will then be performed which will result in fabrication drawings for the burner.

Task 11 - Fabrication of a 30 MMBtu/hr VIStA Burner

The fabrication drawings prepared in the previous task will be used to prepare a cost estimate of the burner. Modifications to the design will be made to correct fabrication difficulties and to reduce fabrication costs where fabrication difficulties would result in high costs of manufacture. A 30 MMBtu/hr VIStA burner will then be manufactured.

Task 17 - Demonstration of 30 MMBtu/hr VIStA Burner

The 30 MMBtu/hr VIStA burner will be shipped to the host site and installed in the host site boiler for testing. The burner/boiler will be instrumented to monitor the performance of the burner and boiler during the demonstration period. The performance of the burner/boiler will be monitored over a period sufficient to assure that the unit performs satisfactorily. The data collected will be analyzed and test reports written to record the performance of the system.

Task 18 - Marketing Preparations

Scaling studies will be reviewed to define the specific sizes of the VIStA burners which will be offered for sale based on the results of the 30 MMBtu/hr tests and demonstration. Sizes ranging from 10 MMBtu/hr to 200 MMBtu/hr are anticipated. Standardization studies will be performed to determine the mechanical standardization, which can be achieved with the VIStA burner. Marketing materials will be prepared.

Task 19 - Phase III - Reporting/Project Management

A final report will be written and submitted to DOE for approval that fully presents the project research and the potential for the Vortex Inertial Stage Air (VIStA) Very Low NO_x Burner. Review comments will be incorporated and a camera-ready final report will be submitted.

The participant will prepare and deliver papers on the results of the project to the International Energy Agency and to the American Flame Research Committee meeting.

The participant will provide management functions necessary to maintain the budget and schedule within established limits, seek identification and resolution of technical, environmental, safety, health, and administrative issues and maintain communications with all project participants, DOE, and its technical representatives.

APPENDIX D – Reports from Reaction Engineering International

APPENDIX E – Drawings

APPENDIX D – Reports from Reaction Engineering International

REACTION
ENGINEERING
INTERNATIONAL

May 6, 1997

Kailash C. Shukla
Thermo Power Corporation, Tecogen Division
45 First Avenue
P.O. Box 9046
Waltham, MA 02254-9046

Dear Mr. Shukla,

Enclosed please find our report of predictions of emissions for the first stage of Tecogen's Vortex Inertial Staged Air (VIStA) burner. Predictions for the second stage using the second stage furnace geometry provided by Tecogen are in progress and will be sent upon their completion.

If you have any questions concerning the simulations, feel free to contact either myself or Dr. Heap.

Sincerely,

Marc Cremer

Marc Cremer, Ph.D.
Senior Engineer

77 West 200 South, Suite #210 • Salt Lake City, Utah 84101
(801) 364-6925 • FAX (801) 364-6977

1.0 Introduction

This report describes the results of REI's computer simulations of the Tecogen designed Vortex Inertial Staged Air (VIStA) burner. Predictions for the first stage of the burner are included in this report.

These simulations were performed using REI's three-dimensional turbulent reacting flow code, BANFF. This code provides full coupling between the turbulent fluid mechanics, radiative and convective heat transfer, and combustion chemistry occurring within the burner. Finite-rate chemistry governing the formation of both prompt and thermal NOx is included so that predictions of NOx and HCN emissions can be obtained. Thermal NOx kinetics are assumed to be governed by the extended Zeldovich mechanism and prompt NOx is formed through a mechanism involving HCN.

2.0 Simulated Conditions

As stated in task 1 of the statement of work, we simulated first stage conditions and emissions as a function of several key operating parameters. In particular the parameters considered were:

- Heat loss
- Stoichiometry
- Inlet velocity

Conditions were varied in terms of the baseline simulation. Conditions which were imposed for the baseline case were:

- 3% Overall heat loss (based on a total heat release rate of 3MMBtu/hr)
- Stoichiometric ratio = 0.6, premixed CH_4 and air at 300 K.
- Inlet velocity corresponding to given inlet cross-sectional area (2.75 in. by 0.875 in.)

In addition to the baseline case, four parametric cases were simulated as follows:

1) No heat loss (adiabatic walls)
2) 5% heat loss
3) Stoichiometry = 0.65
4) 10% reduction in inlet velocity (cross-sectional area changed to 2.48 in. by 0.875 in.)

Heat loss through the burner walls was accounted for by the specification of a thermal resistance and a backside fluid temperature, rather than through the *a priori* specification of a fixed wall temperature. Adiabatic walls were modeled by assignment of a "large" thermal resistance while finite thermal resistances were used to obtain non-zero heat loss.

The overall first stage stoichiometry was varied through proper adjustment of the mass flow rate of the inlet air while keeping that of the fuel constant. In all cases, the fuel was taken to be pure methane (CH_4) gas and was assumed to be premixed with air. The inlet temperature was fixed at 300 K.

3.0 Results

The color contour plots which are included show the predicted conditions inside the first stage of the VIStA burner as a function of position for the baseline case (3% overall heat loss). The properties shown are velocity magnitude, gas temperature, and NOx, HCN, and CO concentrations. Key observations regarding the flow field and gas temperature distribution within the first stage are:

- The vortical flow field induced by the inlet geometry produces recirculation of approximately 25% of inlet mass
- Extraction of heat from the recirculation tubes produces a relatively cool core of gas within the combustion chamber enclosed by relatively hot gas against the walls
- The vortical flow induced by the inlet geometry persists to the outlet of the first stage

Table I compares the predicted outlet emissions for the burner first stage for the baseline case and each of the parametric cases.

Table I: Predicted Average Outlet Emissions from Tecogen VIStA Burner

	FIRST STAGE EMISSIONS		
SIMULATION	**NOx**	**HCN**	**CO**
Baseline- 3% Overall Heatloss	0.2ppm	11ppm	8.0%
Adiabatic first stage	1.2ppm	46ppm	8.3%
5% Heat Loss in first stage	0.1ppm	5ppm	7.9%
Stoichiometry = 0.65	1.4ppm	22ppm	6.9%
10% increase in first stage inlet velocity	0.2ppm	10ppm	8.0%

Regarding the emissions estimates, notable observations from these simulations are:

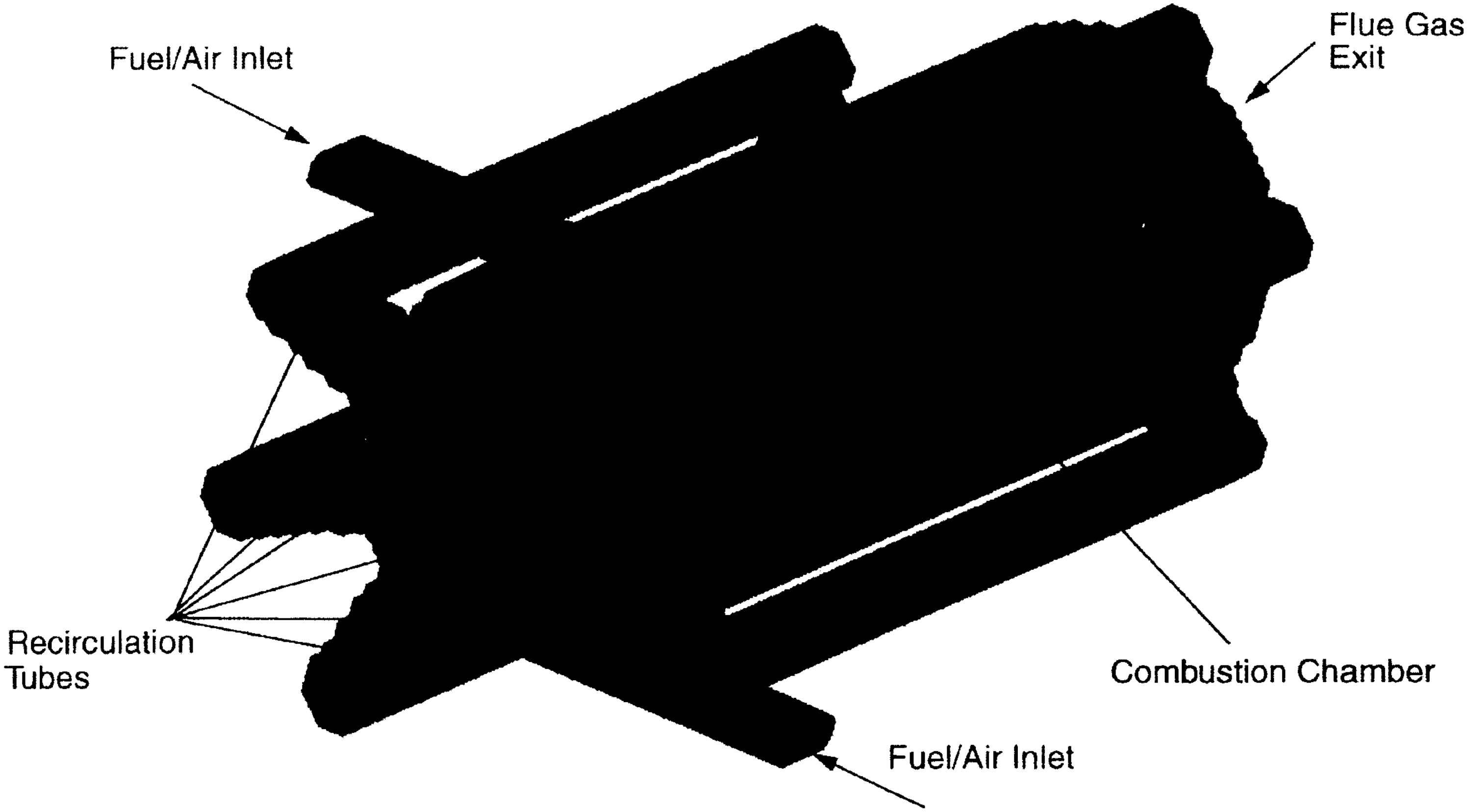
- NOx emissions are very low (order 1 ppm or less) for all cases considered
- HCN levels decrease with increasing heat loss
- NH_3 levels were less than 1 ppm in all cases
- NOx and HCN increase with a slight increase in stoichiometry
- 10% increase in inlet velocity has no effect on exit NOx, HCN, and CO levels

The low levels of NOx predicted here are consistent with the rich conditions that were simulated (low O atom concentrations and relatively low temperature). An increase in NOx with stoichiometry is consistent with the corresponding increase in temperature and availability of O atoms. In addition, a reduction of NOx with increased heat loss is reasonable due to the corresponding drop in temperature.

The observed trends seen in HCN concentration is likely explained in terms of the effect of temperature and residence time in the first stage. The elevated levels of HCN with higher temperature is a result of the enhanced rate of HCN formation coupled with a relatively short residence time within the first stage. The equilibrium level of HCN at a stoichiometry of 0.6 is approximately 0.03 ppm; so, superequilibrium levels of HCN are clearly obtained. The short residence accompanied by a slow rate of reduction of HCN to N_2 is the likely cause for the trends observed in these simulations.

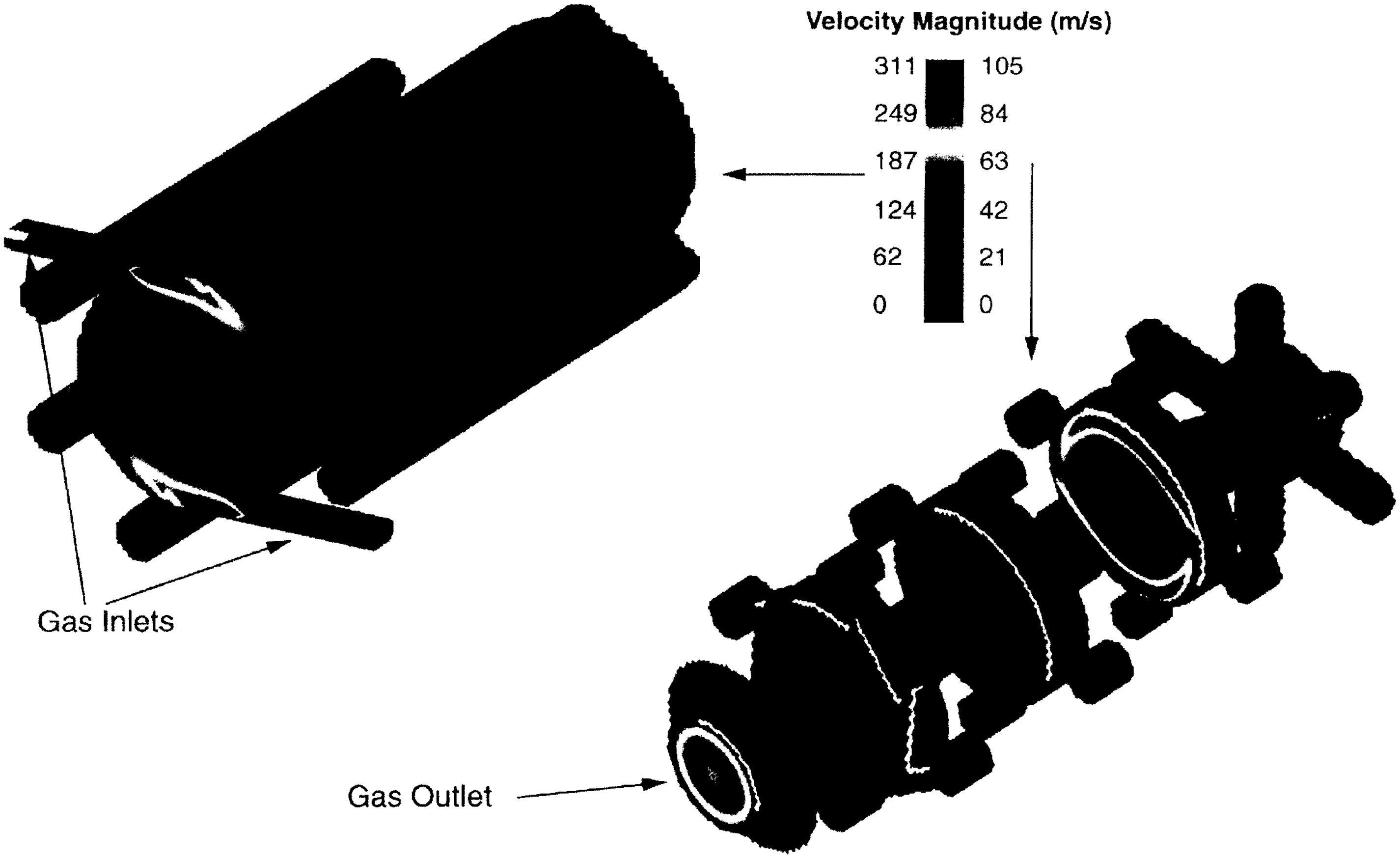
Predictions of simulations of the burner second stage using the furnace geometry provided by Tecogen are in progress and will be relayed to Tecogen when they are complete. If you would like to discuss any of the predictions presented here or have any questions related to the simulations, please feel free to contact us.

First Stage Burner Geometry



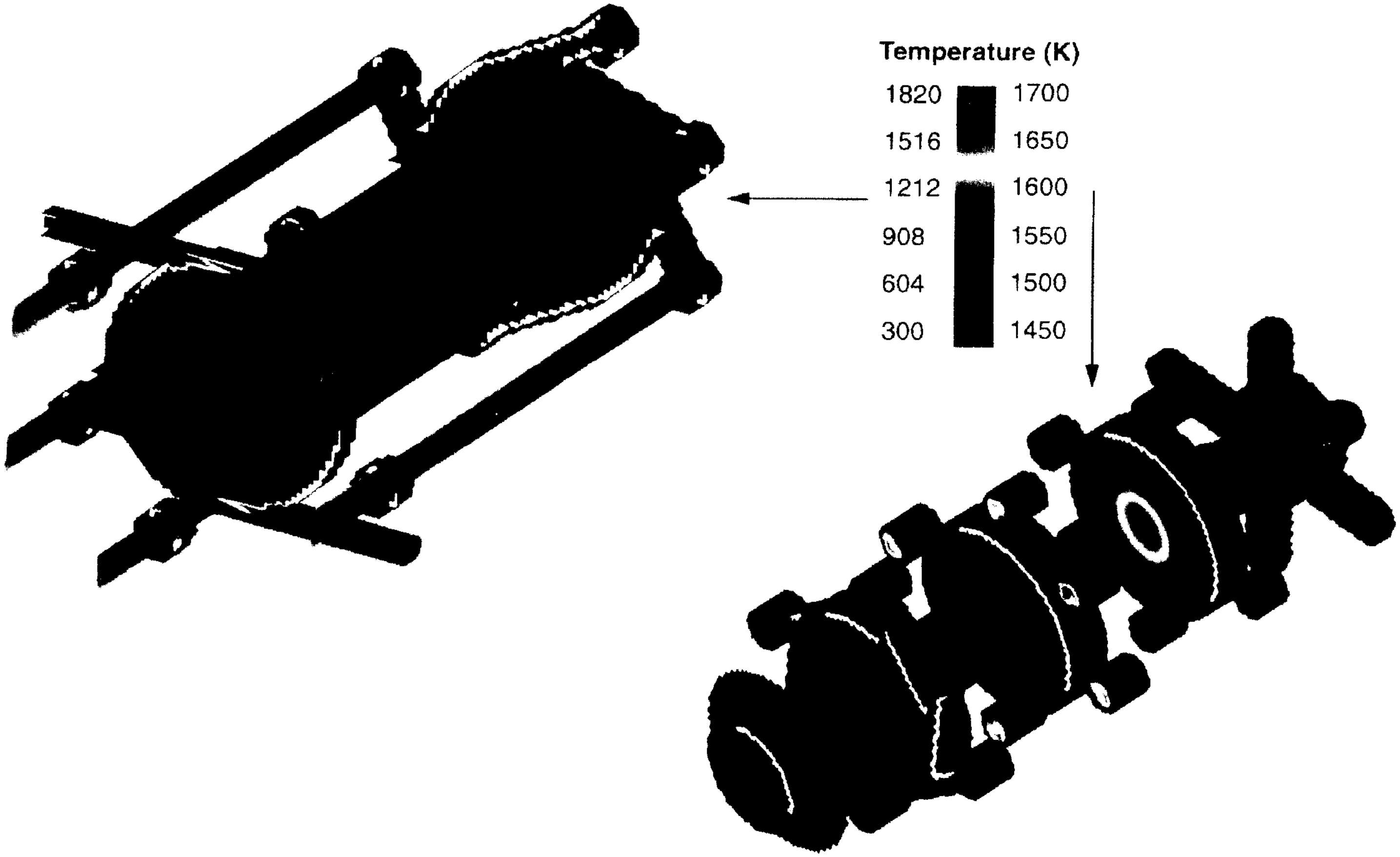
First Stage Vortical Flow Field

Baseline Case - 3% Overall Heat Loss



First Stage Gas Temperature

Baseline Case - 3% Overall Heat Loss



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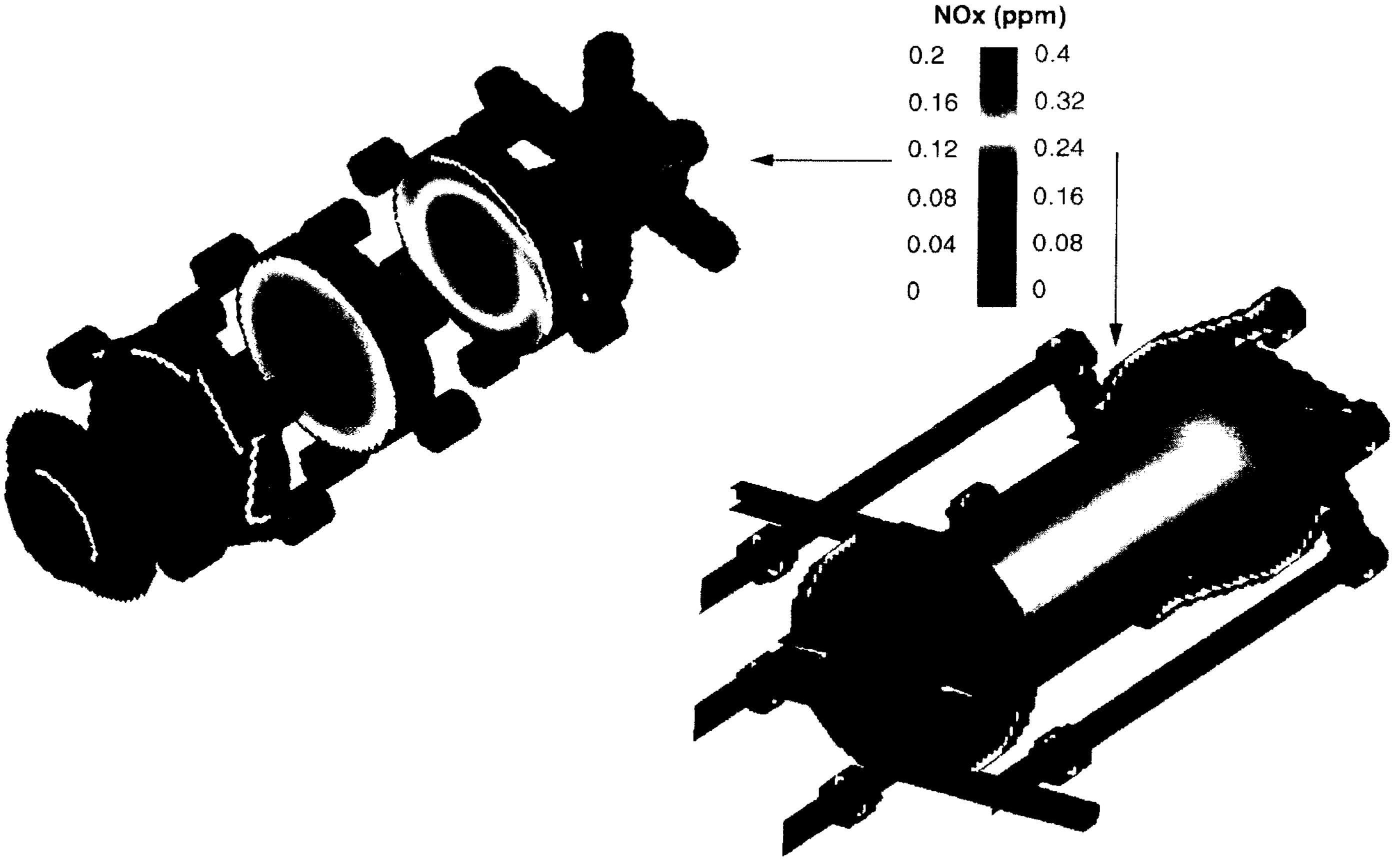
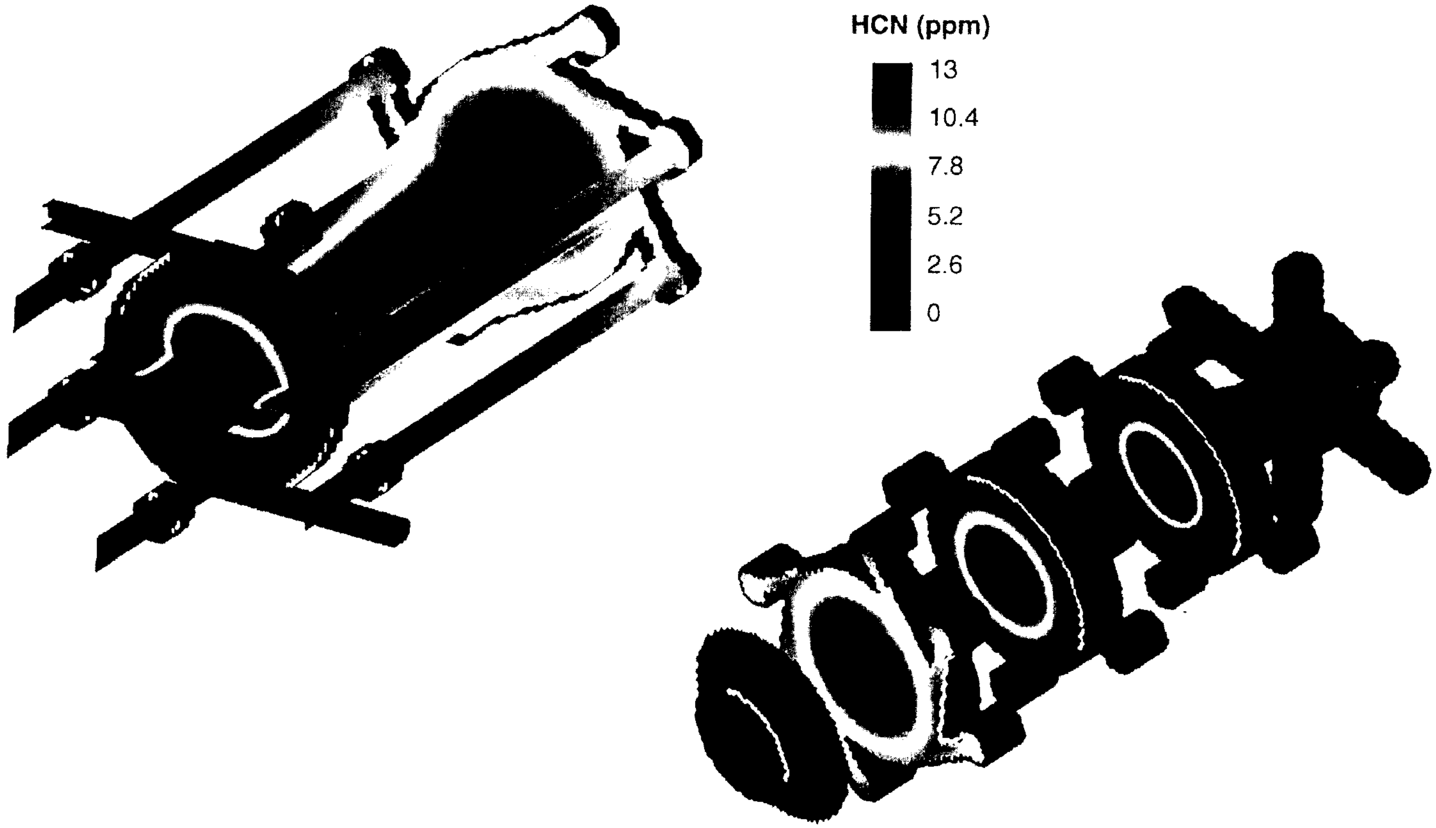
First Stage NOx Emissions

Baseline Case - 3% Overall Heat Loss



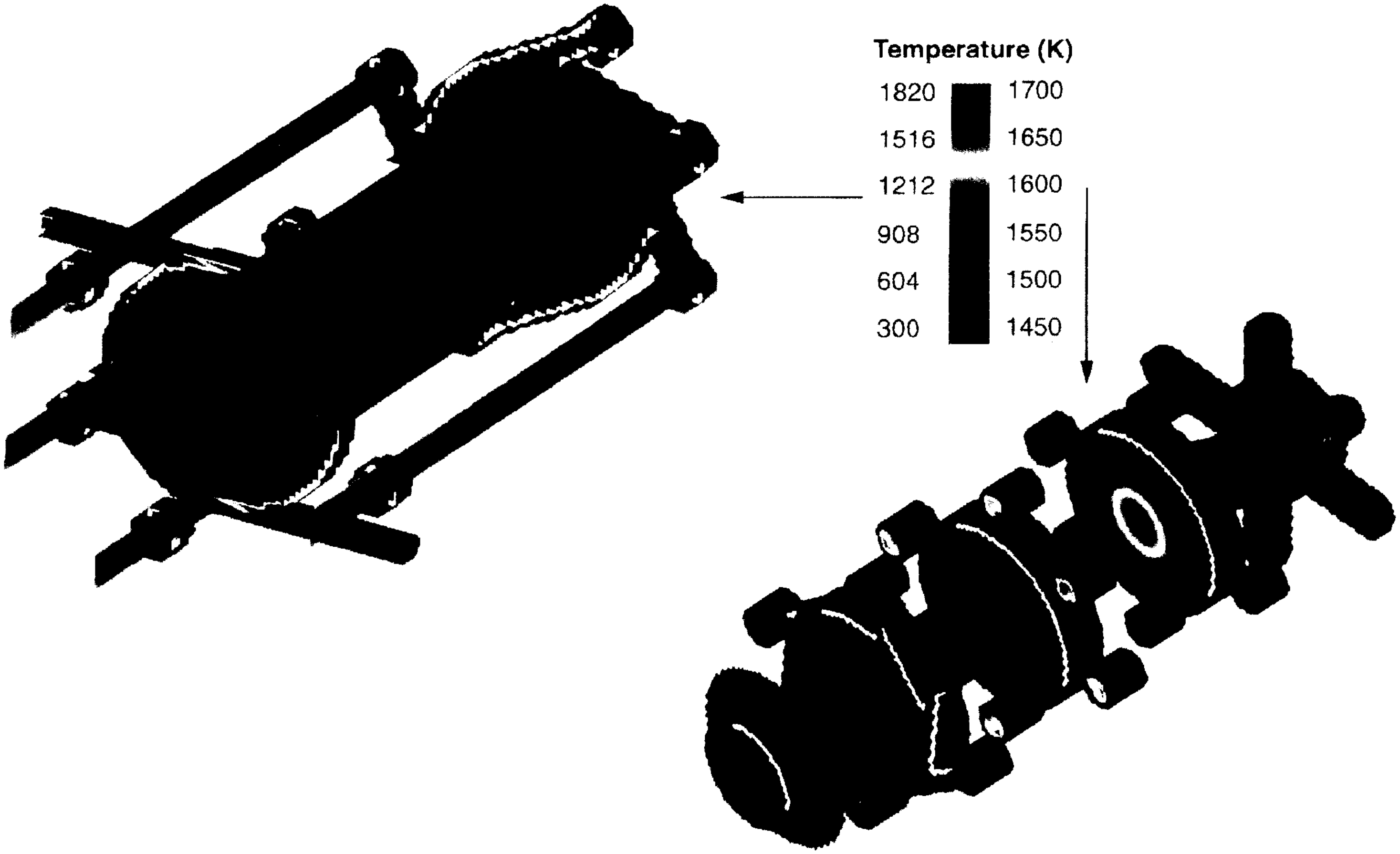
First Stage HCN Emissions

Baseline Case - 3% Overall Heat Loss



First Stage Gas Temperature

Baseline Case - 3% Overall Heat Loss



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June 9, 1997

Kailash C. Shukla
Thermo Power Corporation, Tecogen Division
45 First Avenue
P.O. Box 9046
Waltham, MA 02254-9046

Dear Mr. Shukla,

Enclosed please find our report of predictions of emissions for the second stage of Tecogen's Vortex Inertial Staged Air (VIStA) burner. These predictions were based on the second stage furnace geometry provided by Tecogen and on the results of the first stage predictions which were previously reported to you.

If you have any questions concerning the simulations, feel free to contact either myself or Dr. Heap.

Sincerely,

Marc Cremer

Marc Cremer, Ph.D.
Senior Engineer

77 West 200 South, Suite #210 • Salt Lake City, Utah 84101
(801) 364-6925 • FAX (801) 364-6977

1.0 Introduction

This report describes the results of REI's computer simulations of the 2nd Stage of the Tecogen designed Vortex Inertial Staged Air (VIStA) burner. Predictions for the first stage of the burner were included in a previous report.

These simulations, as well as those completed for the 1st stage, were performed using REI's three-dimensional turbulent reacting flow code, BANFF. This code provides full coupling between the turbulent fluid mechanics, radiative and convective heat transfer, and combustion chemistry occurring within the burner. Finite-rate chemistry governing the formation of both prompt and thermal NOx is included so that predictions of NOx and HCN emissions can be obtained. Thermal NOx kinetics are assumed to be governed by the extended Zeldovich mechanism and prompt NOx is formed through a mechanism involving HCN.

2.0 Simulated Conditions

Simulations for the first stage included a baseline case with four additional parametric cases. Outlet conditions from the first stage computations were used to specify inlet conditions for the second stage computations. Parameters which were considered in the first stage simulations included heat loss, stoichiometry, and inlet velocity. Additional variables which were considered in the second stage simulations included heat loss from the second stage furnace and the orientation of the second stage air inlets.

Conditions were varied in terms of the baseline simulation. Conditions which were imposed for the baseline case were:

- 3% Overall heat loss in the first stage (based on a total heat release rate of 3MMBtu/hr)
- 650 °F second stage furnace wall temperature
- Stoichiometry: First stage, 0.6; Overall, 1.15
- 1 set of 8 equally spaced straight air inlets at R=9 in.

Parametric cases for the second stage simulations were as follows:

Case 1) No heat loss from the first stage (adiabatic walls)

Case 2) 5% heat loss from the first stage

Case 3) First stage stoichiometry = 0.65; 1.15 overall

Case 4) Adiabatic first and second stage

Case 5) Adiabatic second stage

Case 6) Second stage furnace wall temperature, T=900 °F

Case 7) Second stage air inlets angled 12.5° toward centerline

Heat loss through the burner walls was accounted for either by the specification of a thermal resistance and a backside fluid temperature or through the specification of a fixed wall temperature. The baseline simulations for the second stage furnace assumed a fixed furnace wall temperature of T=650 °F (~ 39% heat loss).

In all cases, the overall stoichiometry was fixed at 1.15. Variation of stoichiometry in the first stage while keeping the overall stoichiometry fixed involved proper adjustment of the distribution of inlet air between the first and second stages while keeping the mass flow rate of the fuel constant. In all cases, the fuel was taken to be pure methane (CH_4) gas and was assumed to be premixed with air. The inlet temperature was fixed at 300 K.

3.0 Results

The color contour plots which are included show the predicted conditions inside the second stage furnace as a function of position. The properties shown are velocity magnitude, gas temperature, equivalence ratio, and CO, NOx, HCN concentrations. Properties are plotted for the baseline case as well as for case 7 (angled air inlets). For overall comparison, gas temperature is plotted for all cases.

A notable observation from these plots is the relatively slow rate of mixing between the second stage air and the rich first stage products. This can be observed in the figure showing equivalence ratio for the baseline case in which the rich core of first stage products persists at the exit of the second stage. This causes high levels of CO there. Increasing the rate of mixing by angling the air inlets towards the rich core significantly helps to alleviate the high levels of CO at the exit.

The assumed furnace wall temperature for the baseline case was T=650 °F. The plots of HCN and NOx for this case indicate that at the relatively low temperatures existing in the second stage, NOx emissions are largely governed by oxidation of HCN rather than by formation through the thermal mechanism. Thermal NOx becomes much more significant with lower second stage heat loss, as the results in Table I indicate.

Table I compares the predicted outlet emissions for the second stage for the baseline case and each of the parametric cases.

Table I: Predicted Average Outlet Emissions from Tecogen VIStA Burner

	FIRST STAGE EMISSIONS			SECOND STAGE EMISSIONS		
SIMULATION	**NOx**	**HCN**	**CO**	**NOx**	**HCN**	**CO**
Baseline	0.2ppm	11ppm	8.0%	3.6ppm	7.8ppm	848ppm
Case 1	1.2ppm	46ppm	8.3%	20.8ppm	24ppm	748ppm
Case 2	0.1ppm	5ppm	7.9%	1.4ppm	3.9ppm	943ppm
Case 3	1.4ppm	22ppm	6.9%	6.8ppm	16.3ppm	268ppm
Case 4	1.2ppm	46ppm	8.3%	687ppm	0.5ppm	4470ppm

Table I: Predicted Average Outlet Emissions from Tecogen VIStA Burner

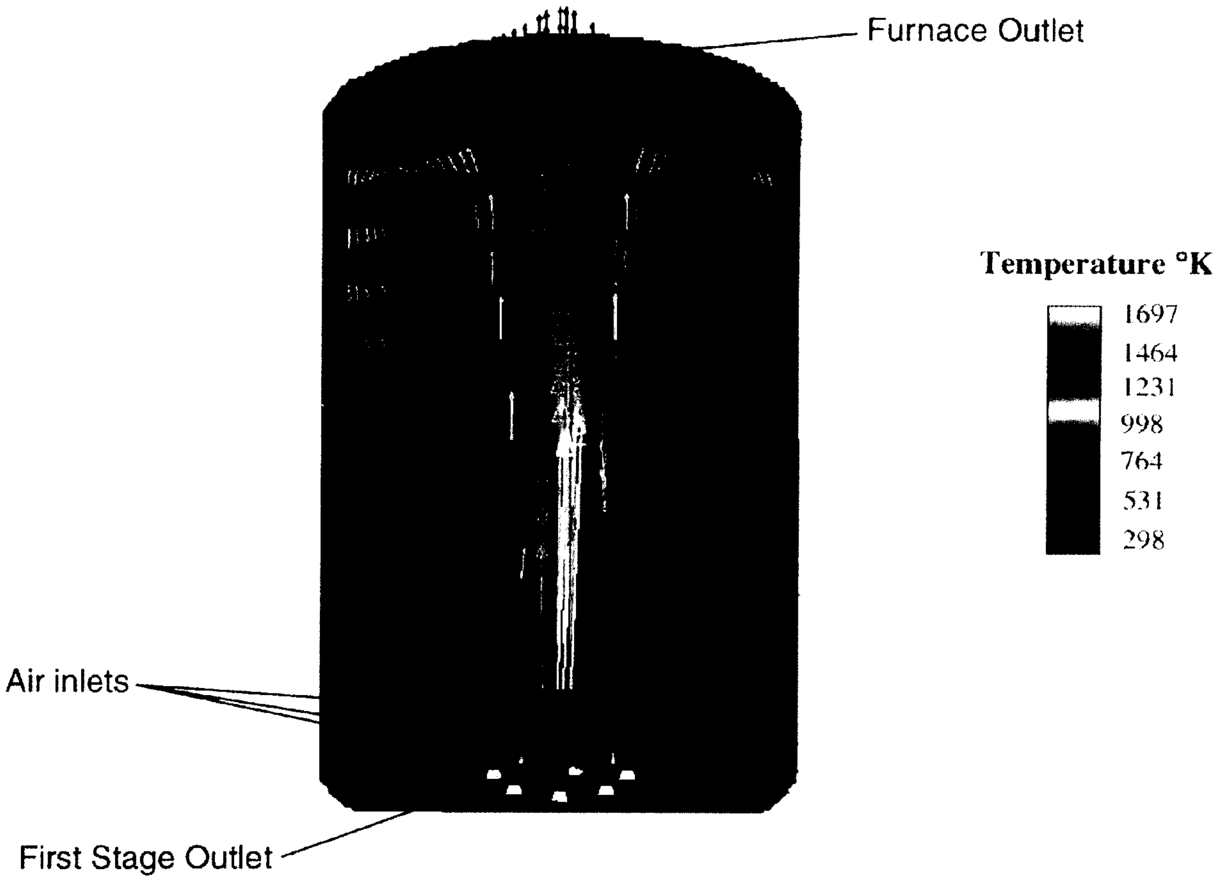
	FIRST STAGE EMISSIONS			SECOND STAGE EMISSIONS		
SIMULATION	**NOx**	**HCN**	**CO**	**NOx**	**HCN**	**CO**
Case 5	0.2ppm	11ppm	8.0%	291ppm	0.6ppm	3786ppm
Case 6	0.2ppm	11ppm	8.0%	5.0ppm	6.6ppm	923ppm
Case 7	0.2ppm	11ppm	8.0%	6.9ppm	5.0ppm	236ppm

Regarding the emissions estimates, notable observations from these simulations are:

- NOx emissions are very low for the baseline case (3.6 ppm)
- CO emissions are relatively high (848 ppm for the baseline case)
- Enhancing the rate of mixing between the air and first stage flue-gas (by angling the air inlets) reduces outlet CO by approximately 75%
- 3% overall heat loss from the first stage reduces second stage total fixed nitrogen (TFN) by 75% (44.8 ppm to 11.4 ppm)
- Increasing first stage stoichiometry from 0.6 to 0.65 reduces second stage CO but increases TFN
- Second stage NOx emissions are sensitive to second stage heat loss (3.6 ppm for 39% heat loss, 5 ppm for 35% heat loss, 291 ppm for 0% heat loss)

If you would like to discuss any of the predictions presented here or have any questions related to the simulations, please feel free to contact us.

Second Stage Burner and Furnace Geometry



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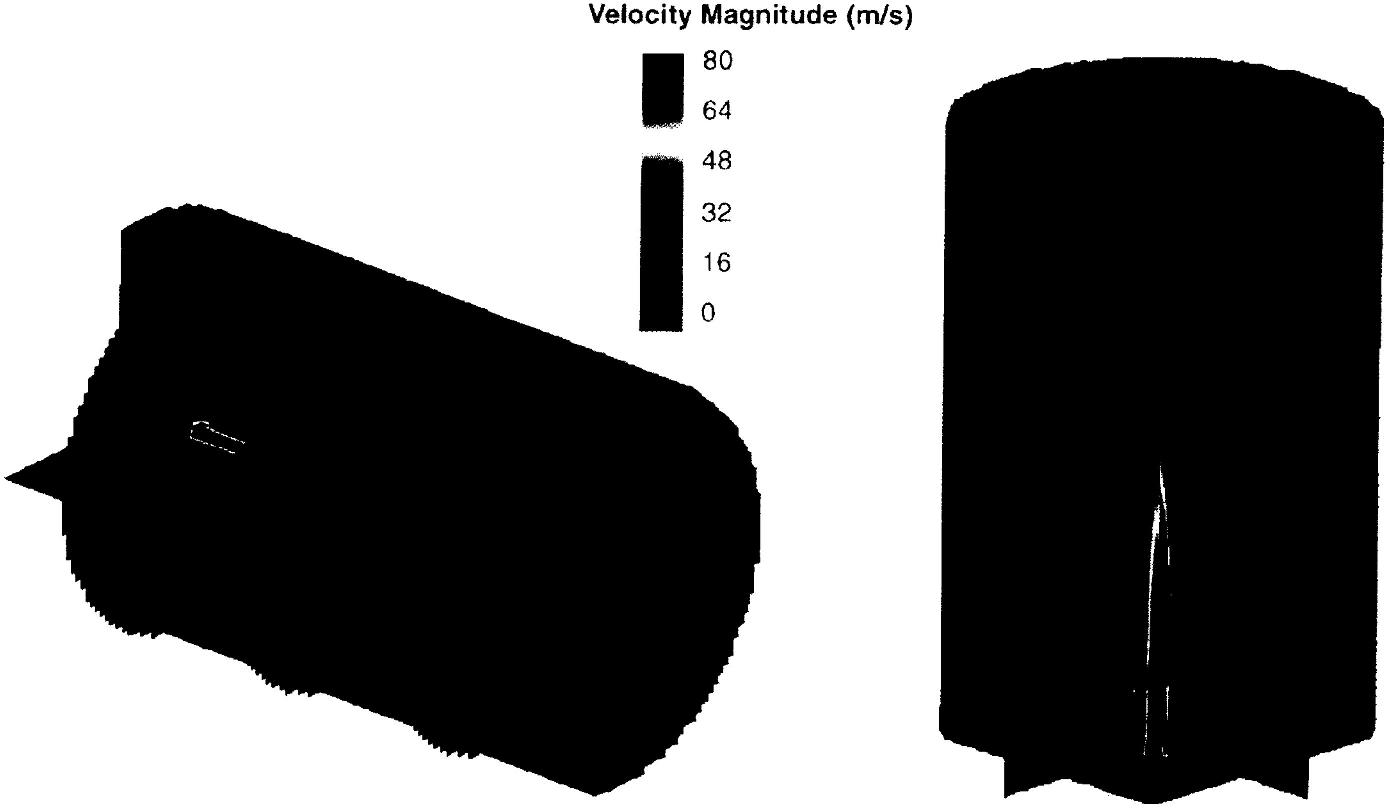
■ VIStA Burner - Second Stage ■

Second Stage Gas Velocity

Baseline Case - Straight Air Nozzles



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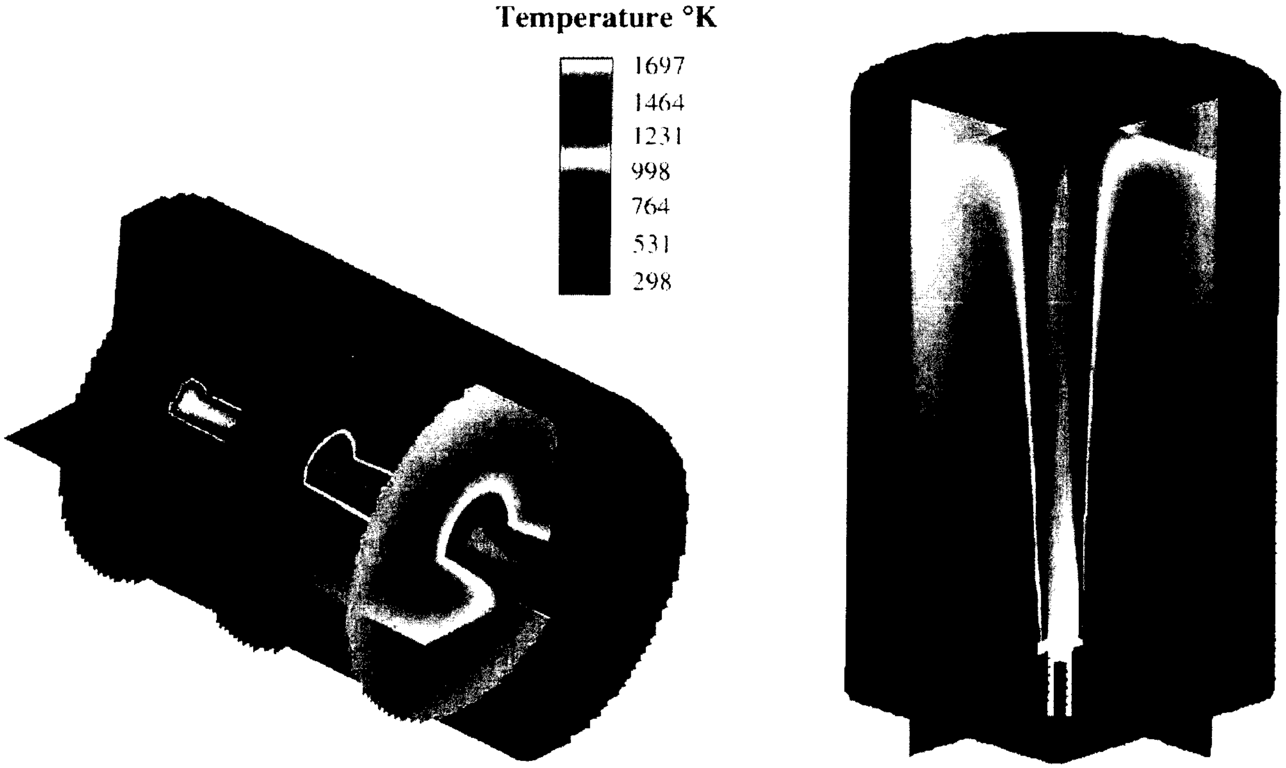
Second Stage Gas Temperature

Baseline Case - Straight Air Nozzles



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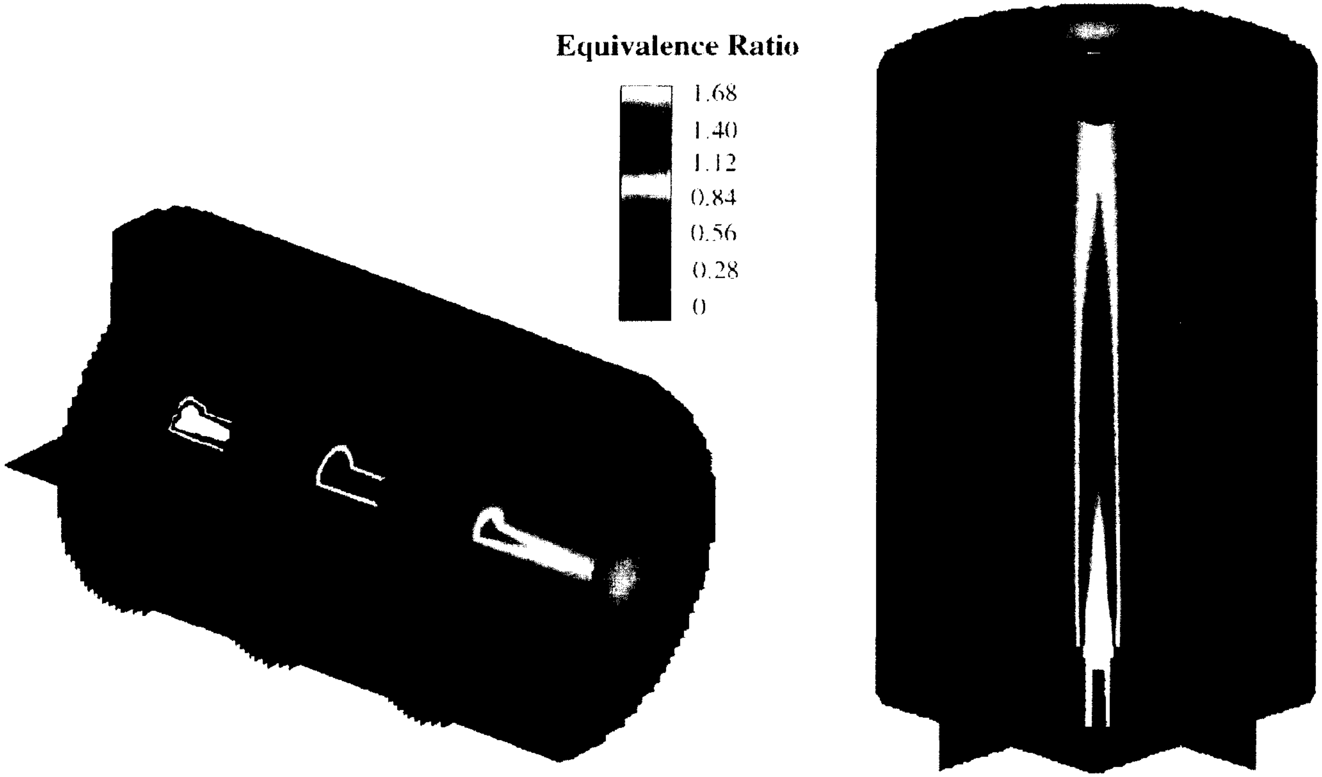
Second Stage Equivalence Ratio

Baseline Case - Straight Air Nozzles



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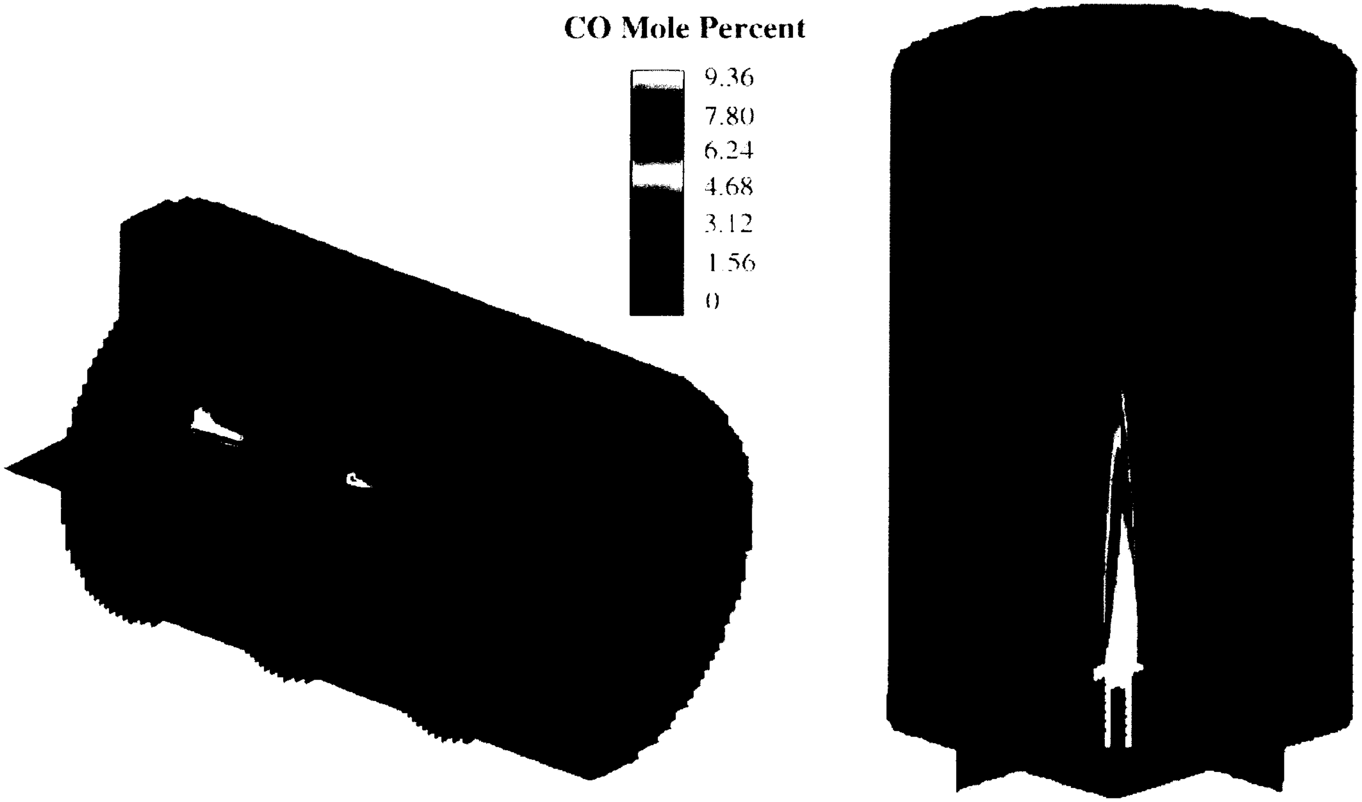
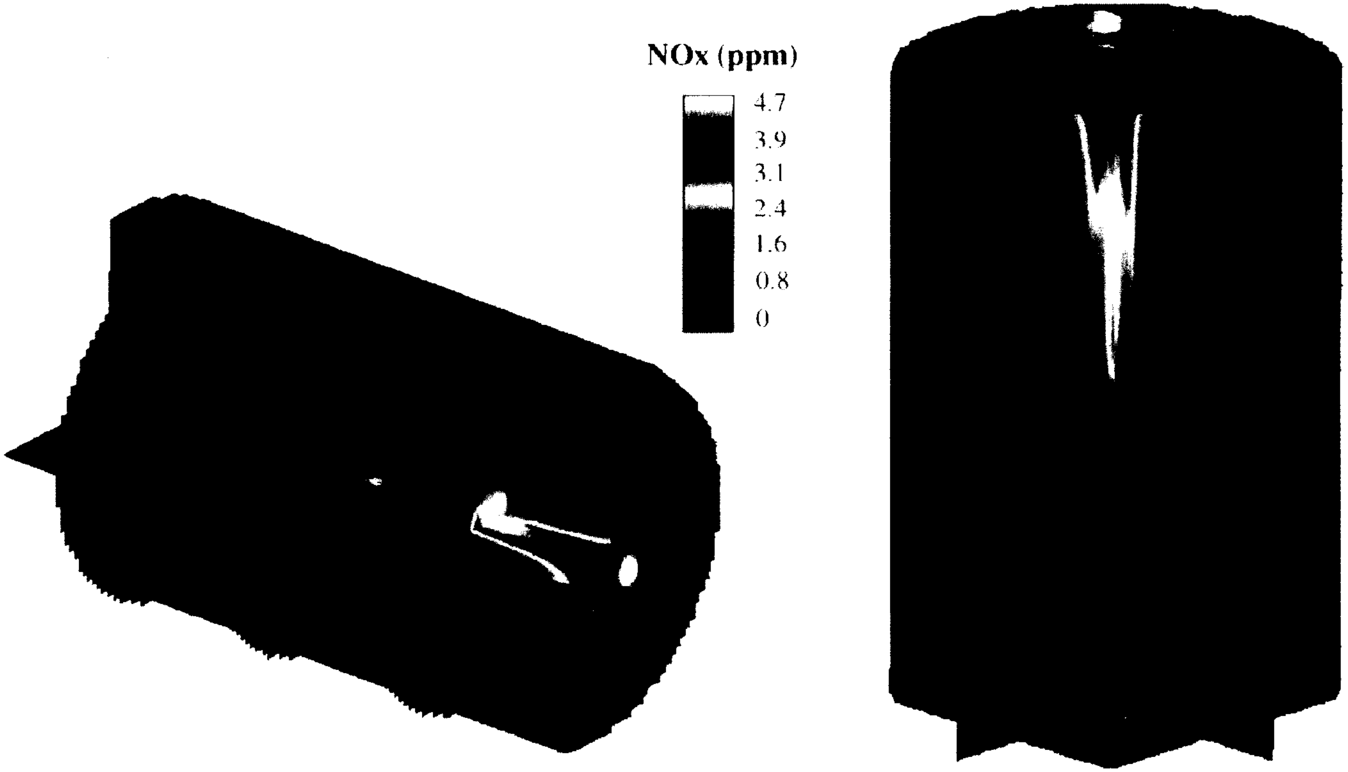
Second Stage CO Concentration

Baseline Case - Straight Air Nozzles



Second Stage NOx Concentration

Baseline Case - Straight Air Nozzles



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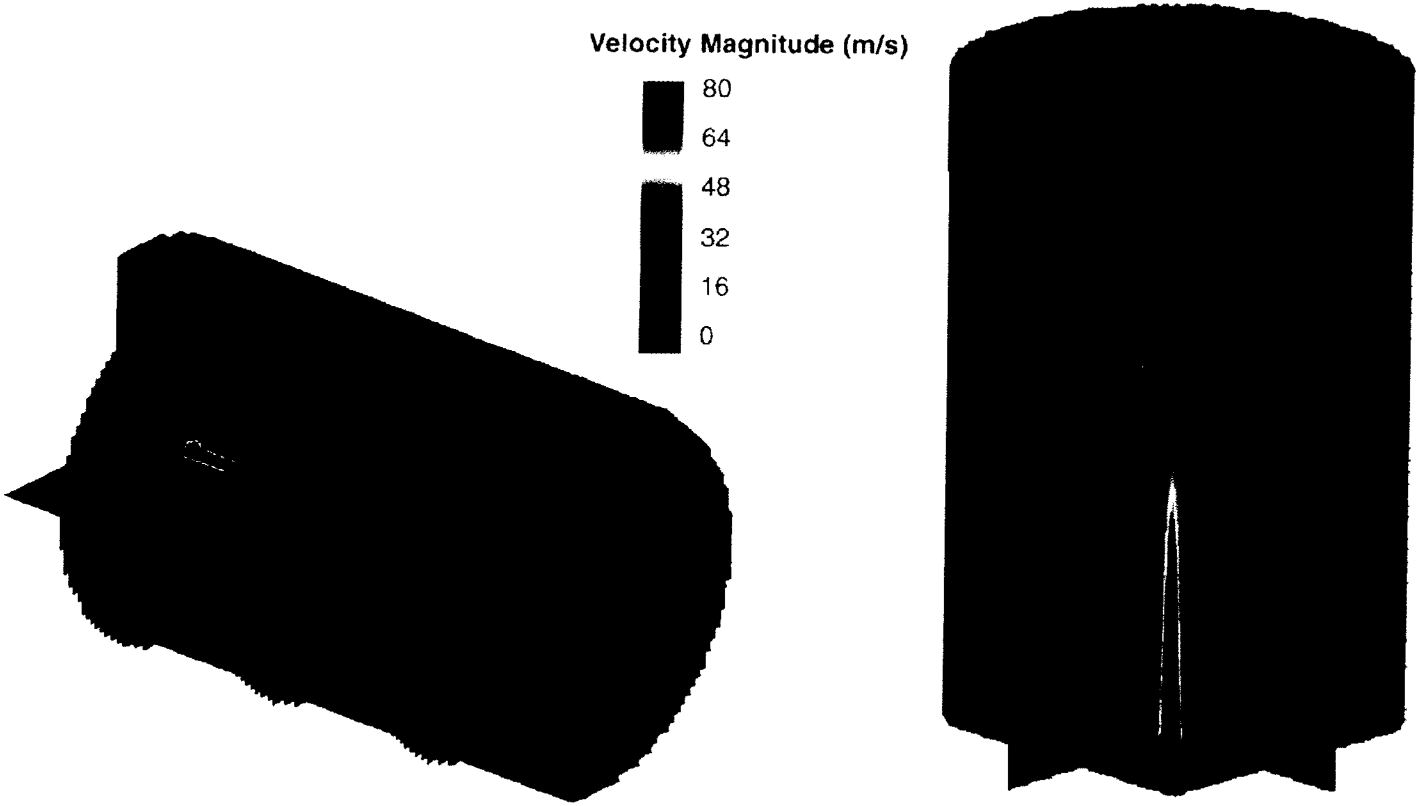
Second Stage Gas Velocity

Parametric Case - Angled Air Nozzles



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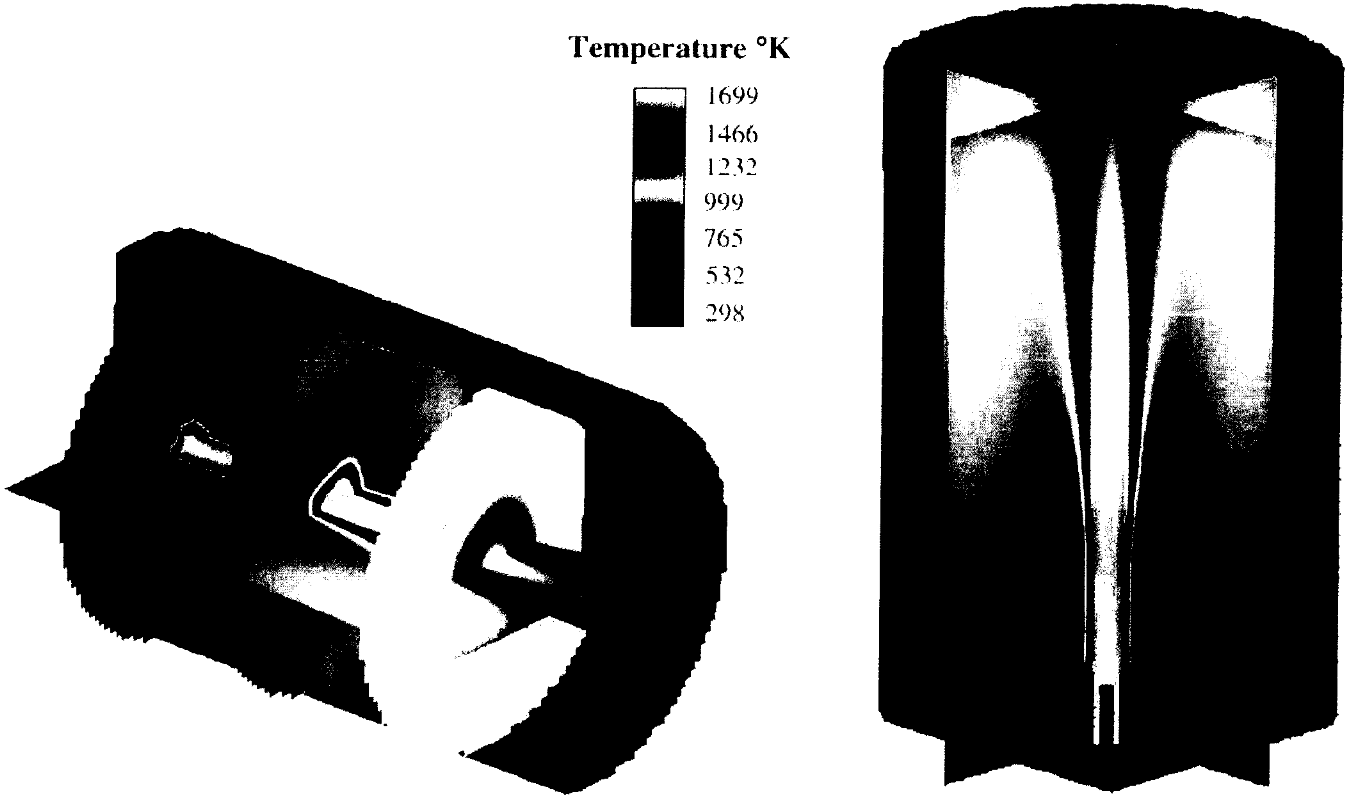
Second Stage Gas Temperature

Parametric Case - Angled Air Nozzles



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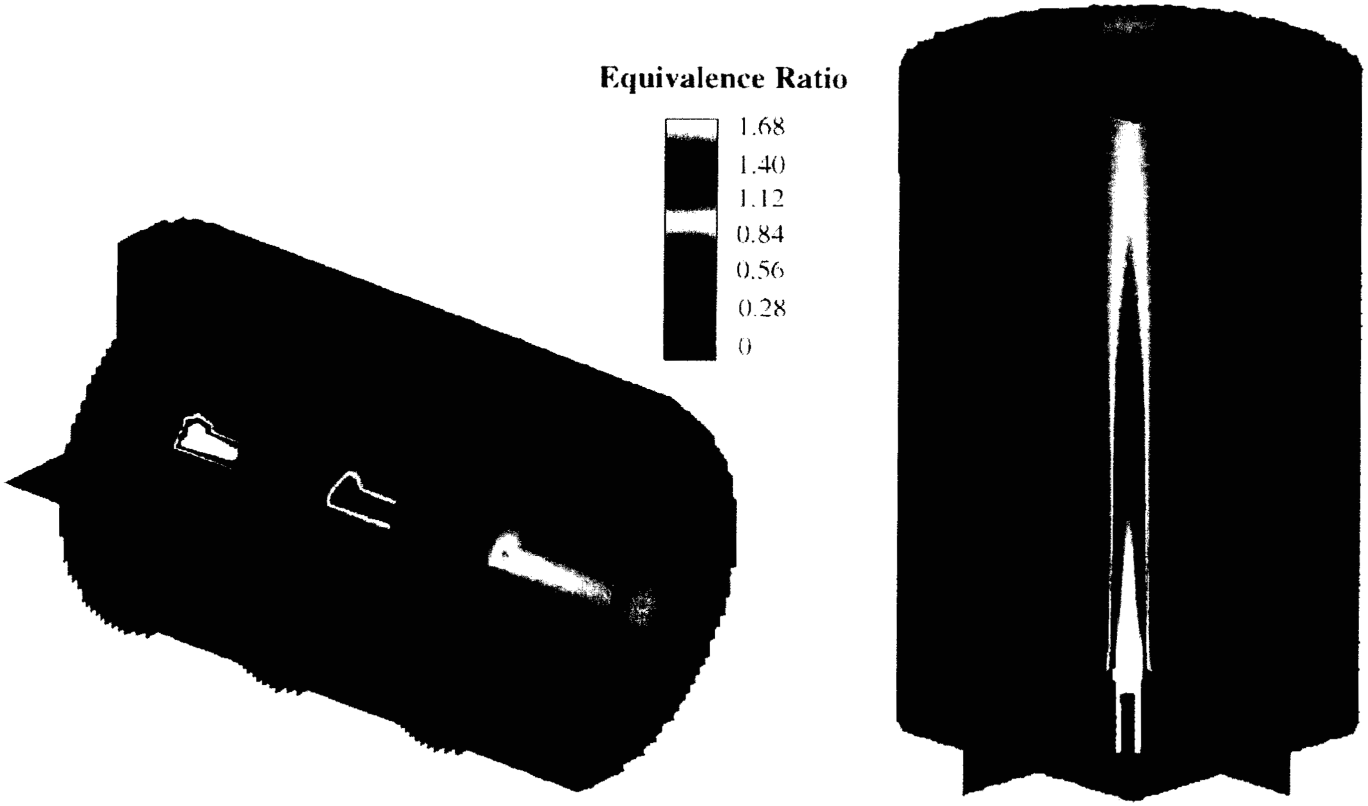
■ VIStA Burner - Second Stage ■

Second Stage Equivalence Ratio

Parametric Case - Angled Air Nozzles



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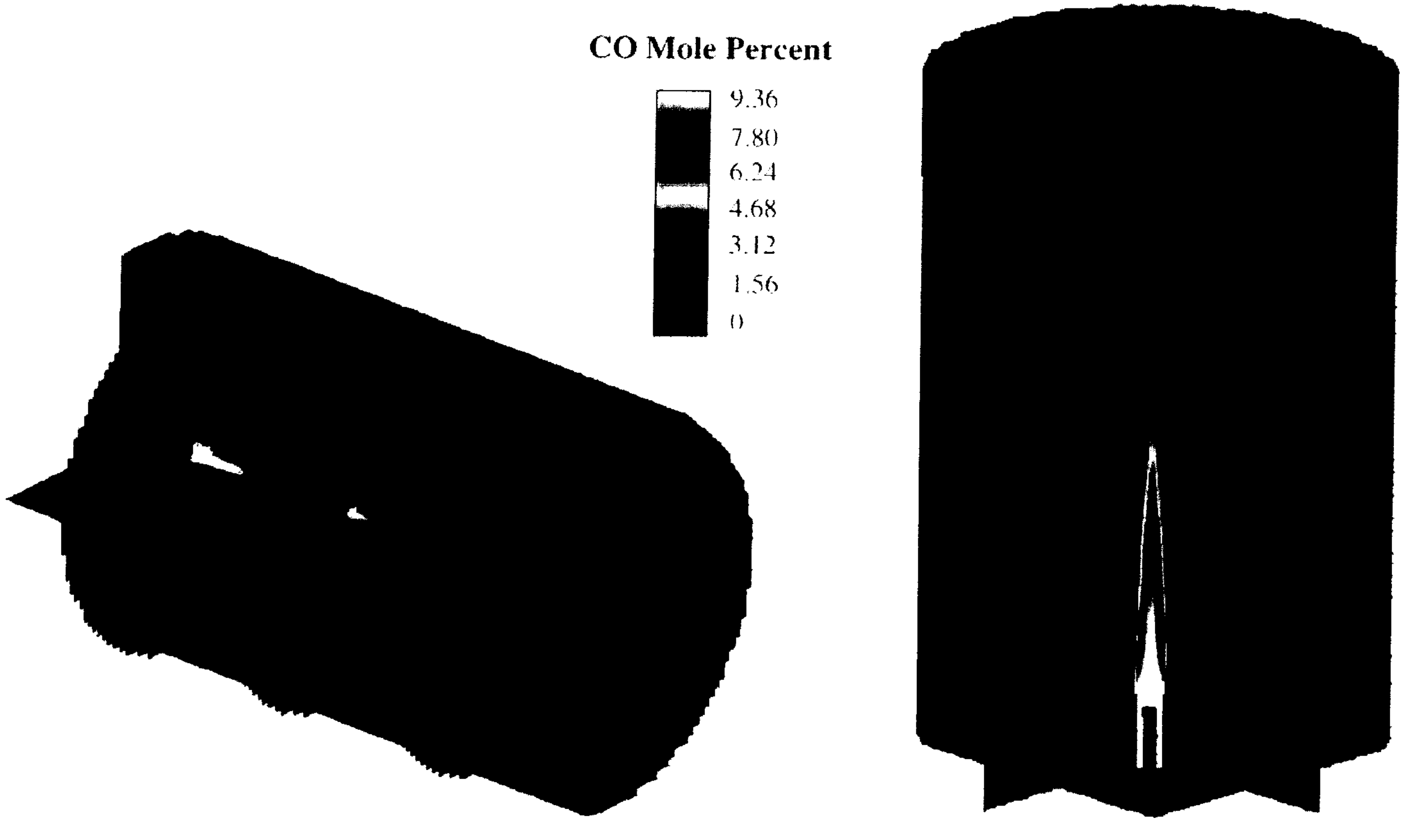
Second Stage CO Concentration

Parametric Case - Angled Air Nozzles



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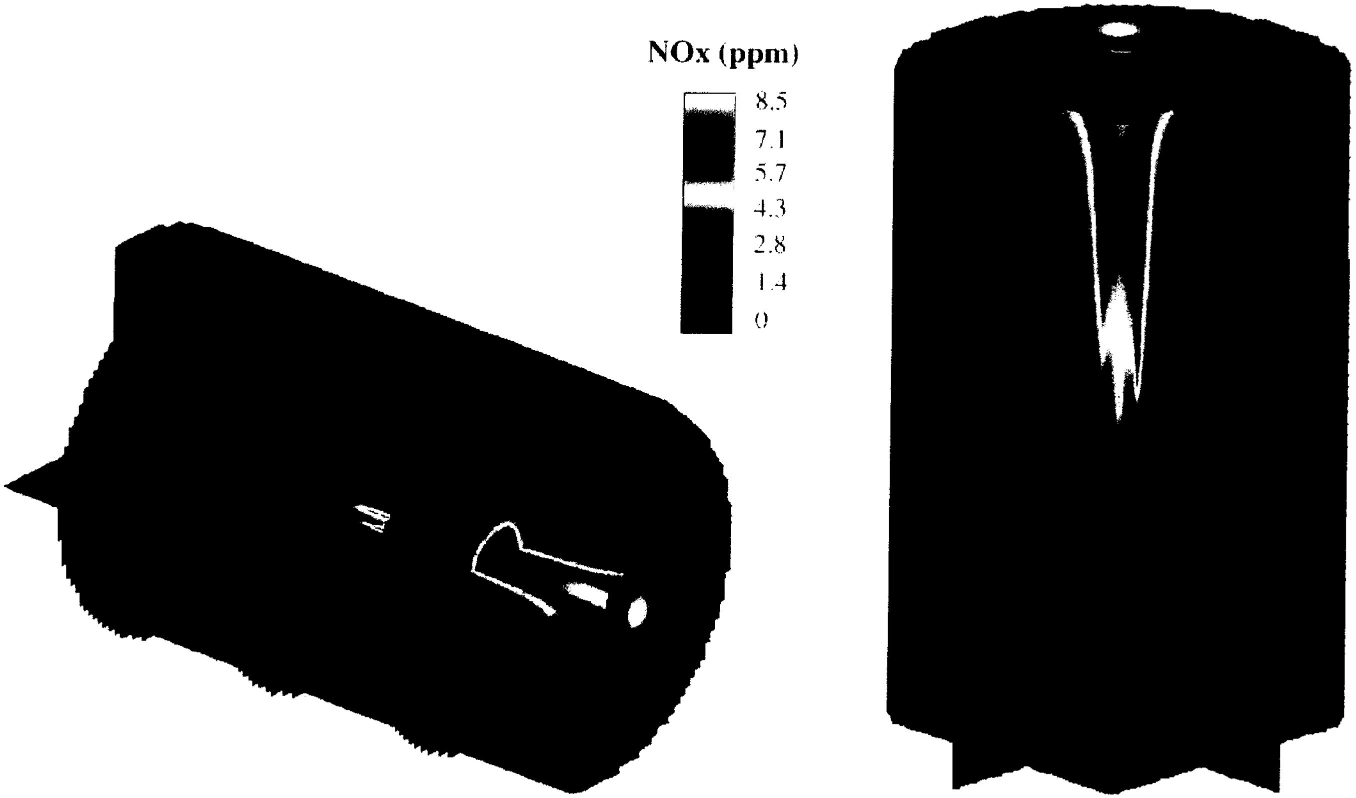
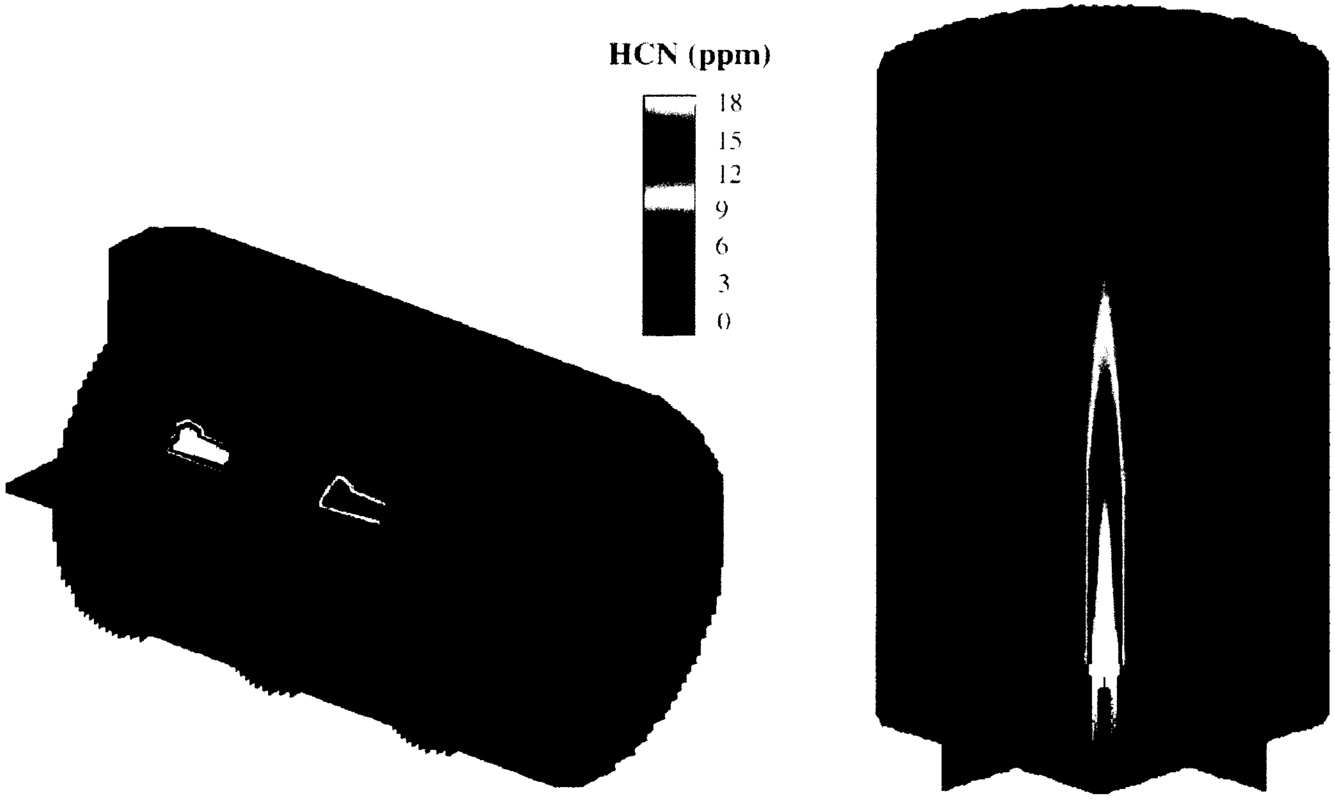
Second Stage NOx Concentration

Parametric Case - Angled Air Nozzles



Second Stage HCN Concentration

Parametric Case - Angled Air Nozzles



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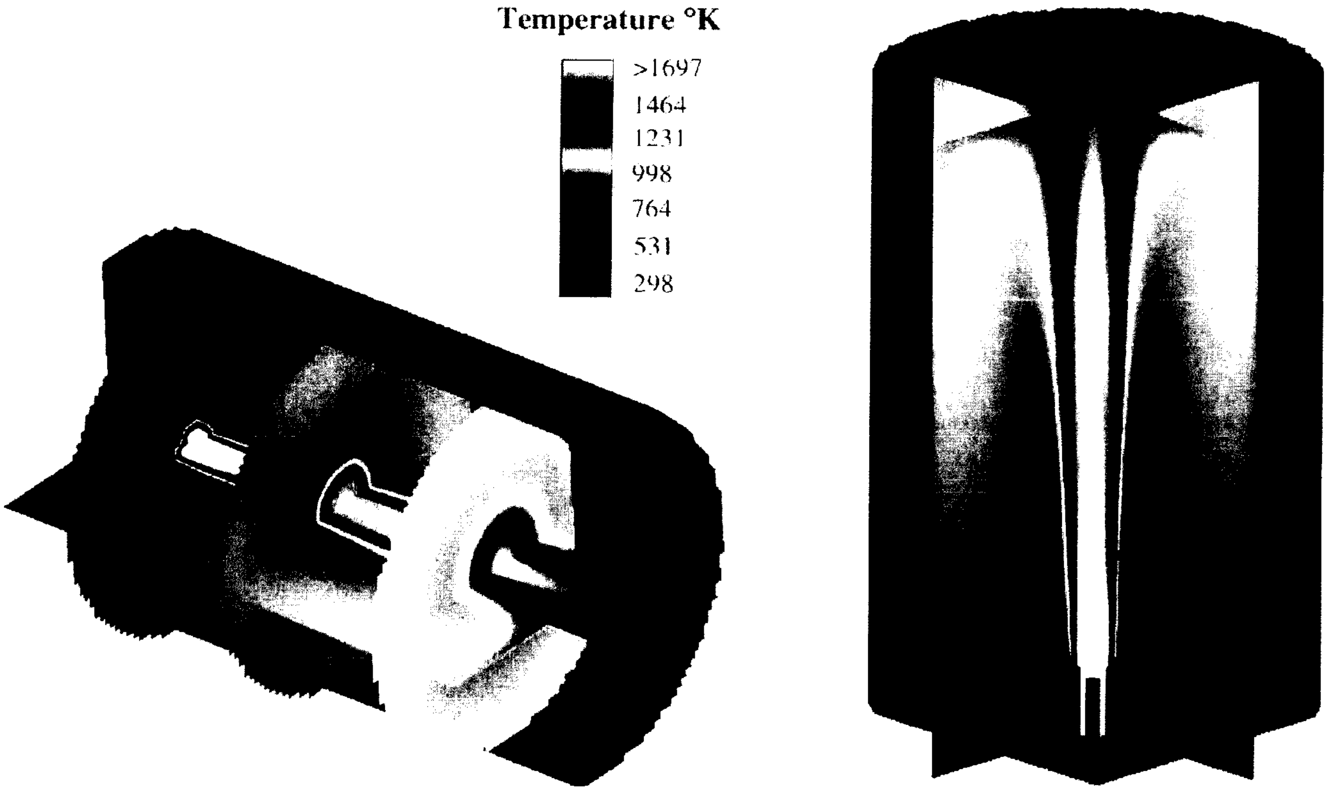
Second Stage Gas Temperature

Case 1 - Adiabatic First Stage



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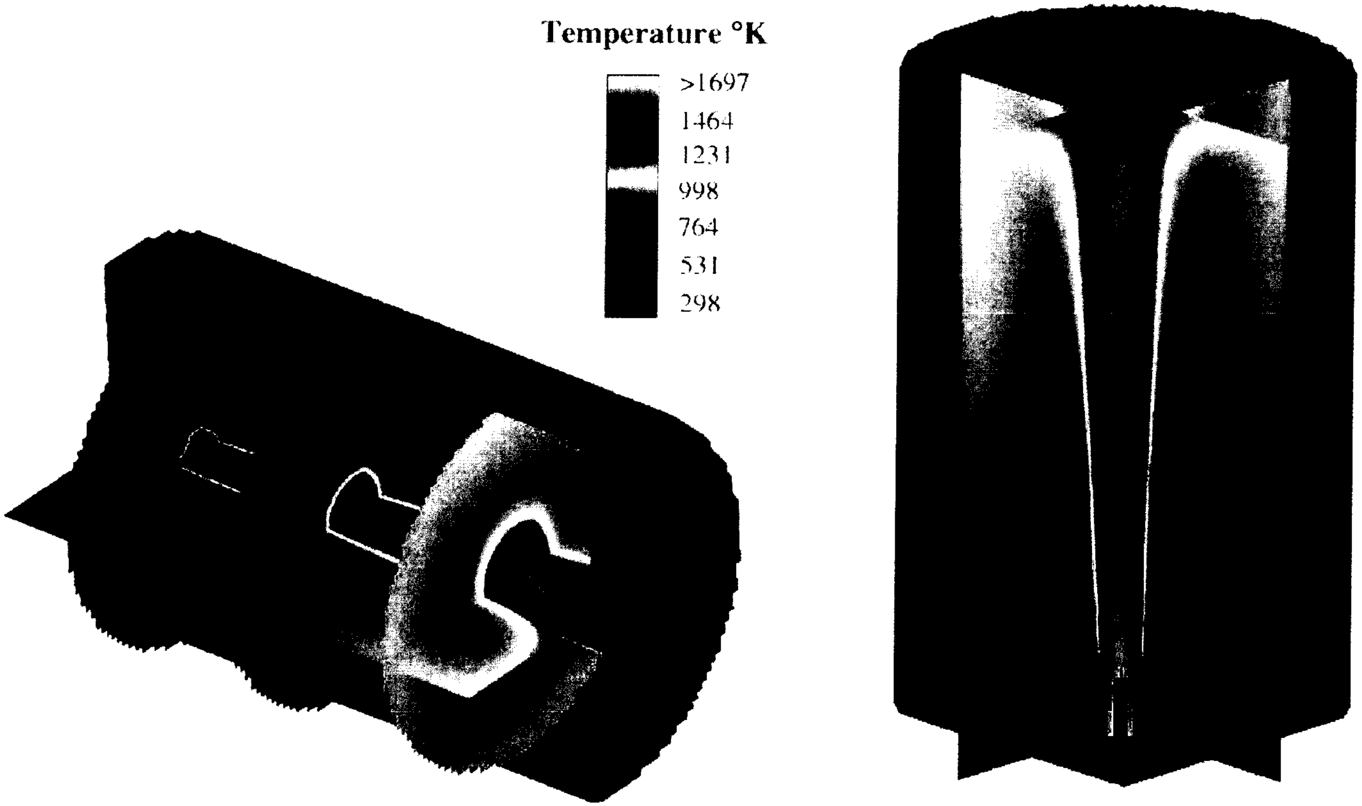
Second Stage Gas Temperature

Case 2 - 5% Heat Loss from First Stage



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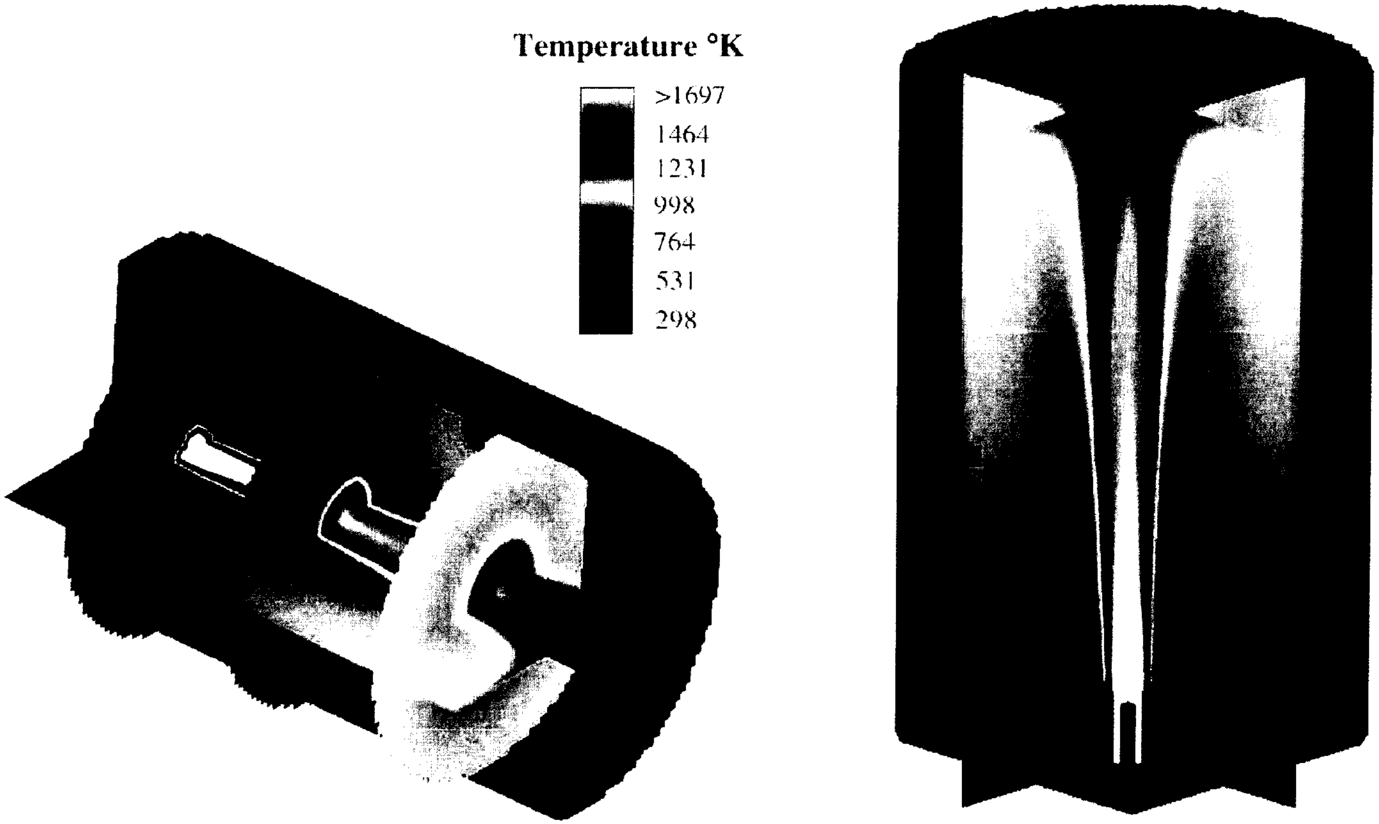
Second Stage Gas Temperature

Case 3 - First Stage Stoichiometry=0.65



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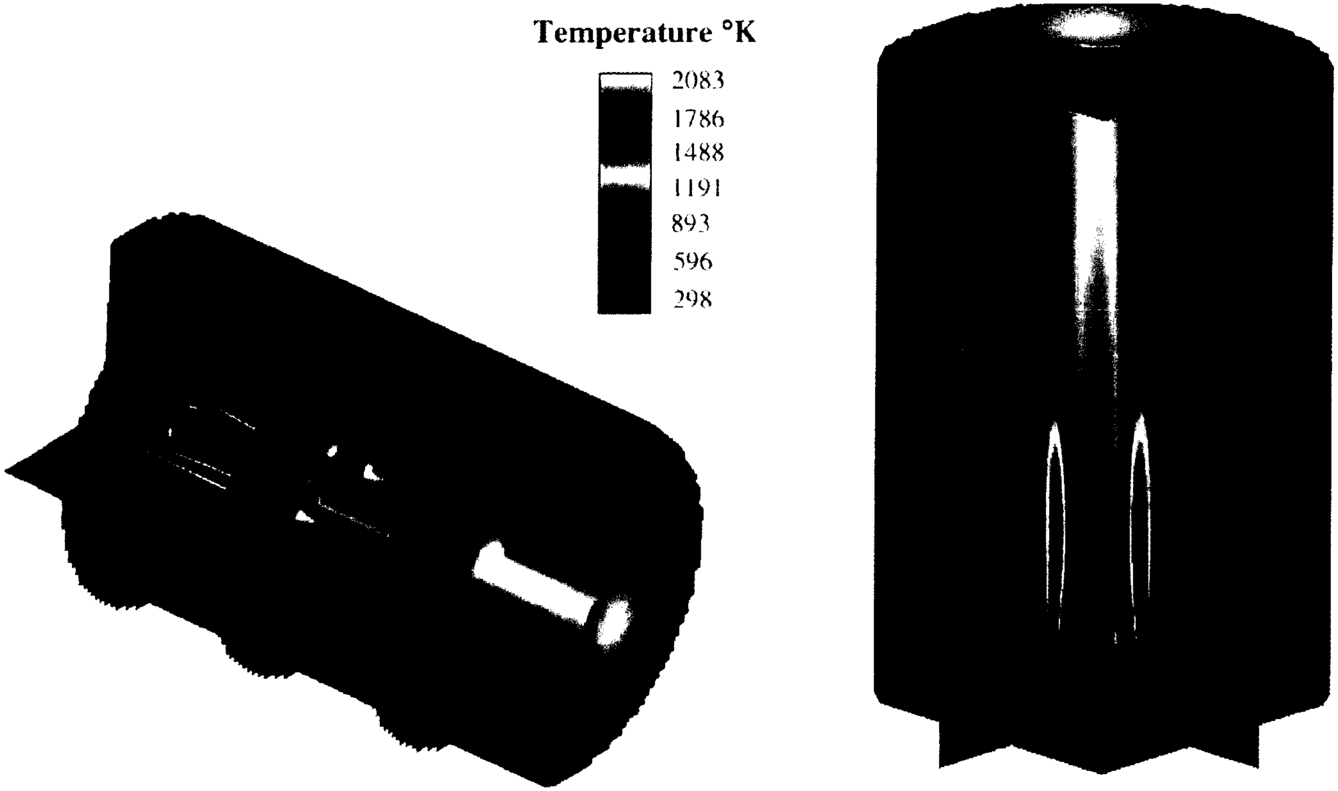
Second Stage Gas Temperature

Case 5- Adiabatic Second Stage



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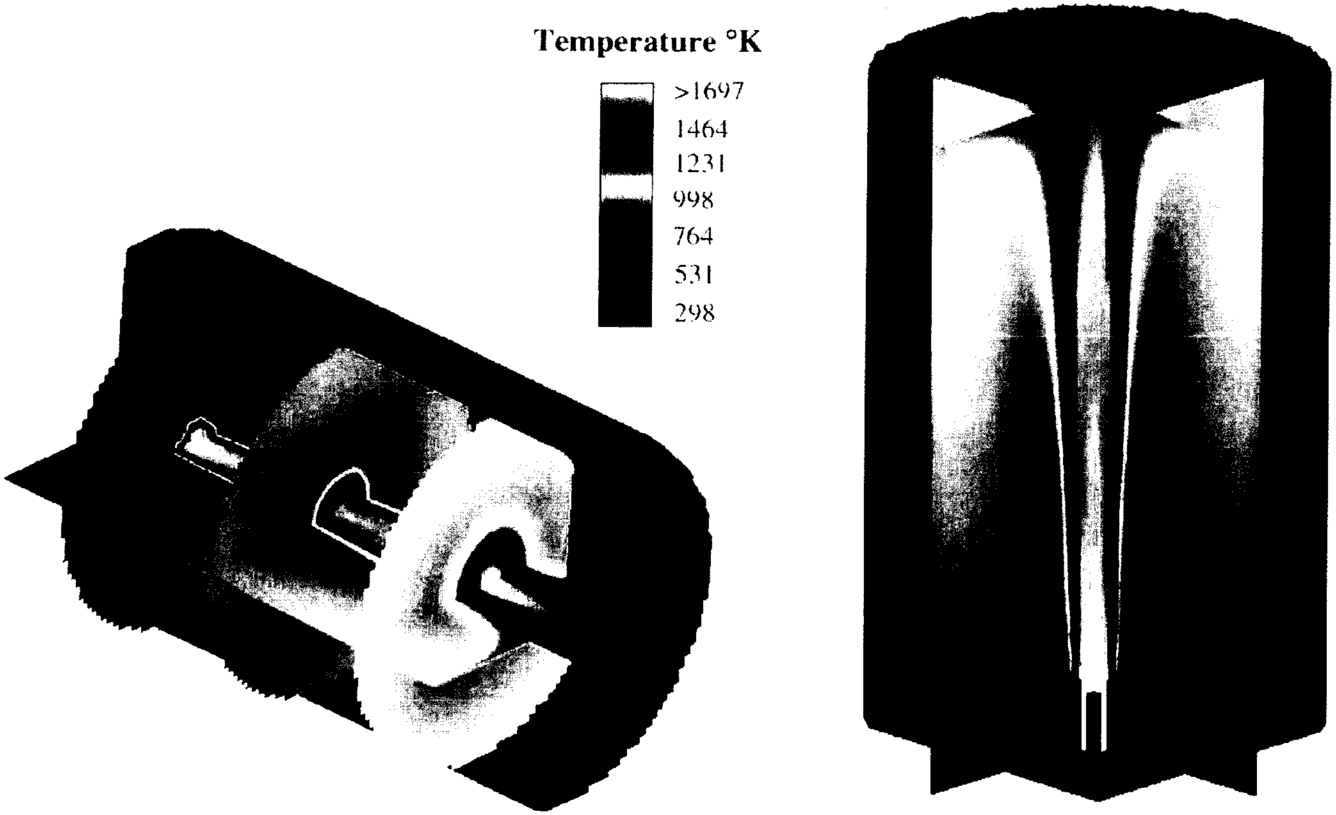
Second Stage Gas Temperature

Case 6 - Furnace Wall T = 900 °F



APPENDIX E - Drawings

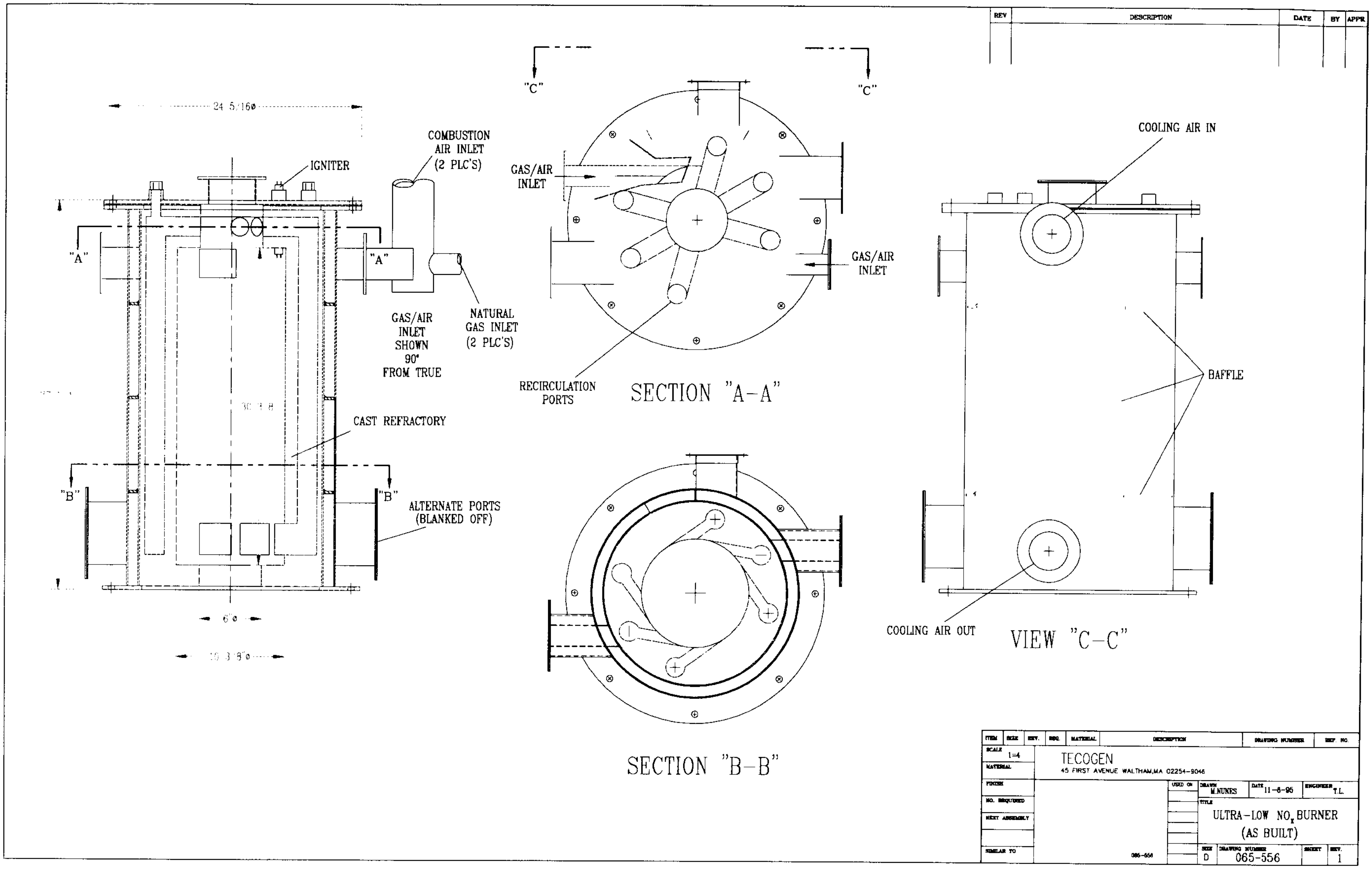


Figure 1 - VIStA Model 1 Assembly Drawing

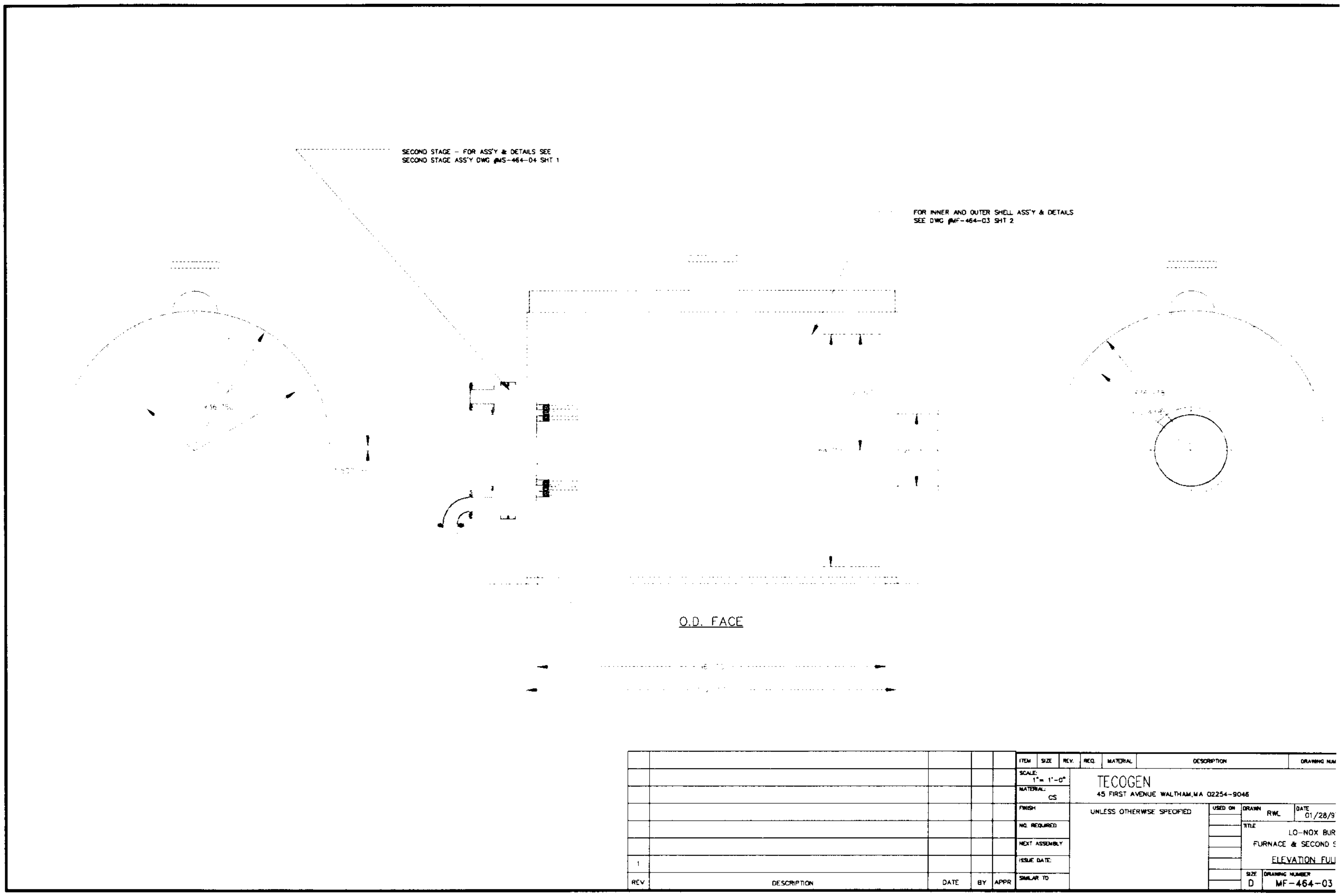


Figure 2 - Second Stage Assembly Including Furnace Section and Secondary Air Injection

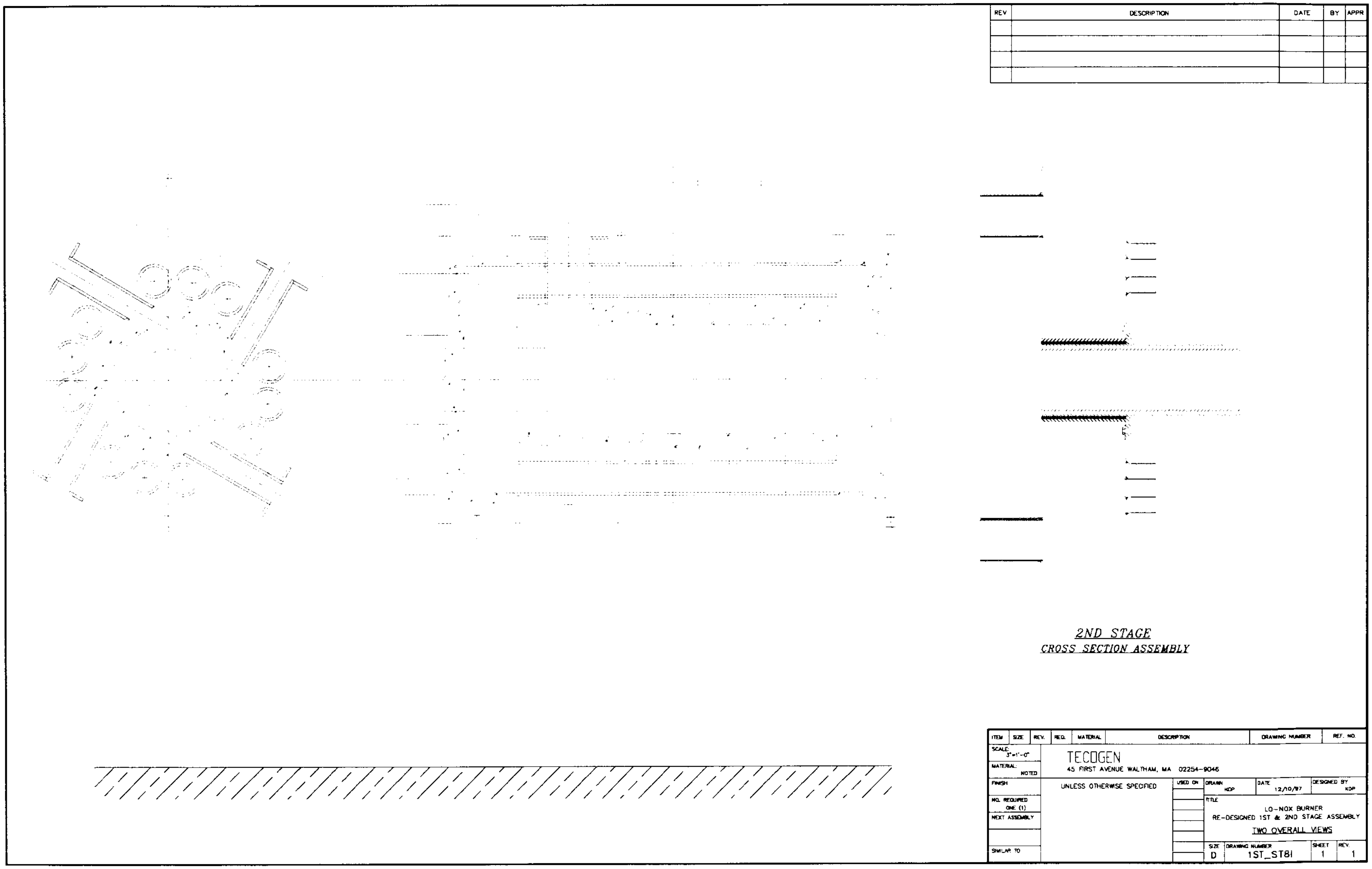


Figure 3 - VIStA Model 2 Design

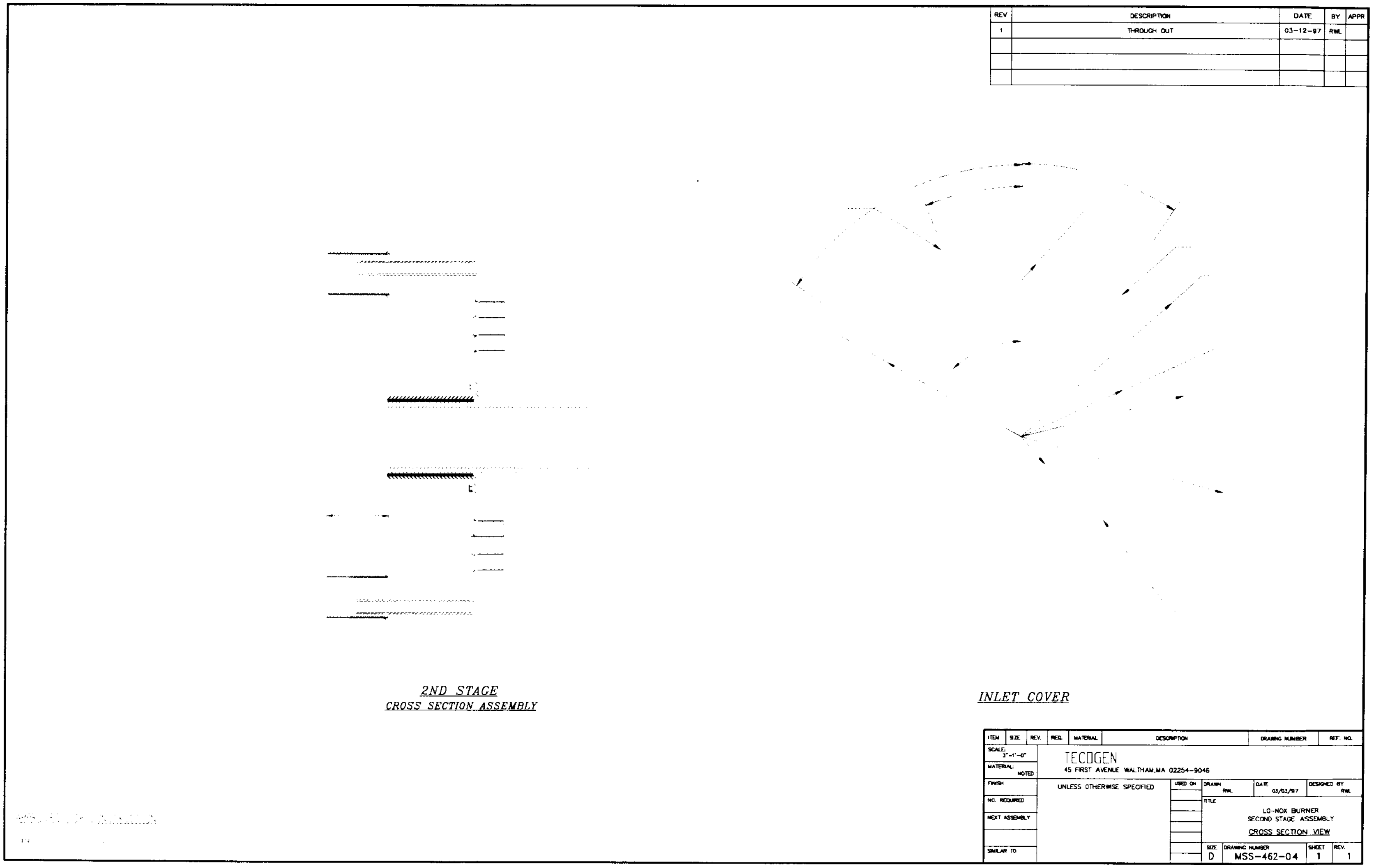


Figure 4 – Secondary Air Injector Cross-Section Assembly and Inlet Cover Detail

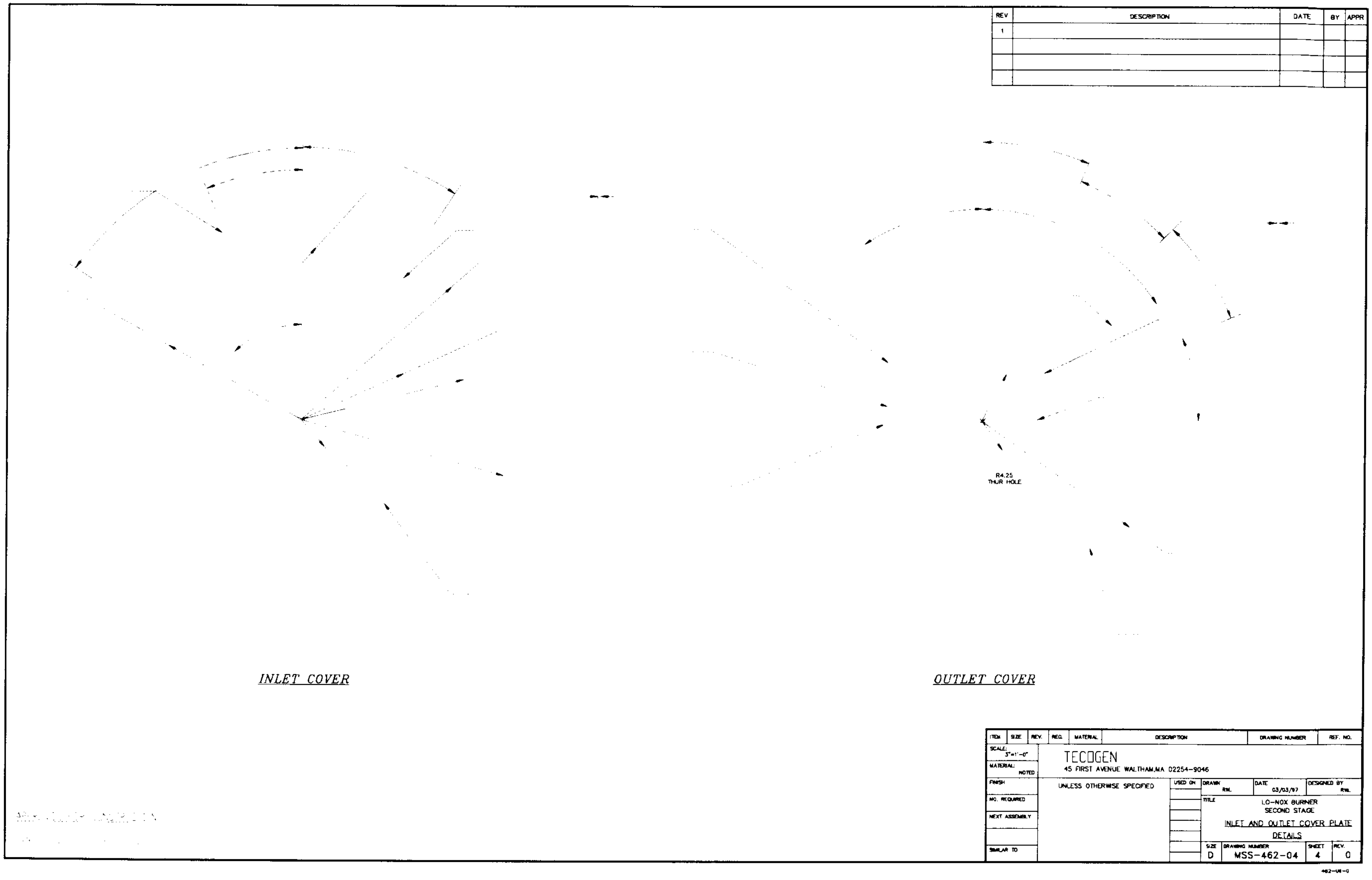


Figure 5 - Secondary Air Injector Inlet and Outlet Cover Details

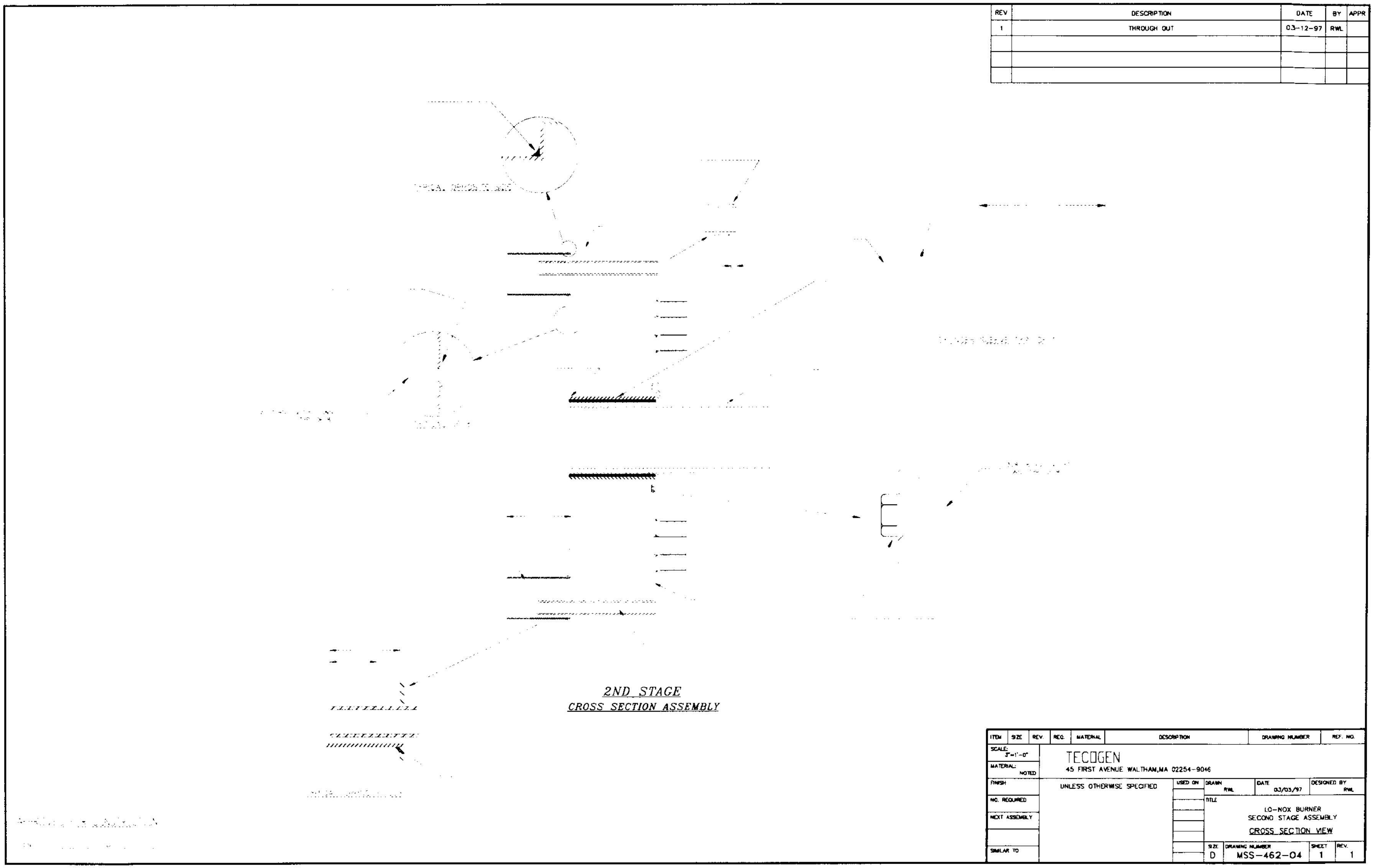


Figure 6 - Secondary Air Injector Welding Detail

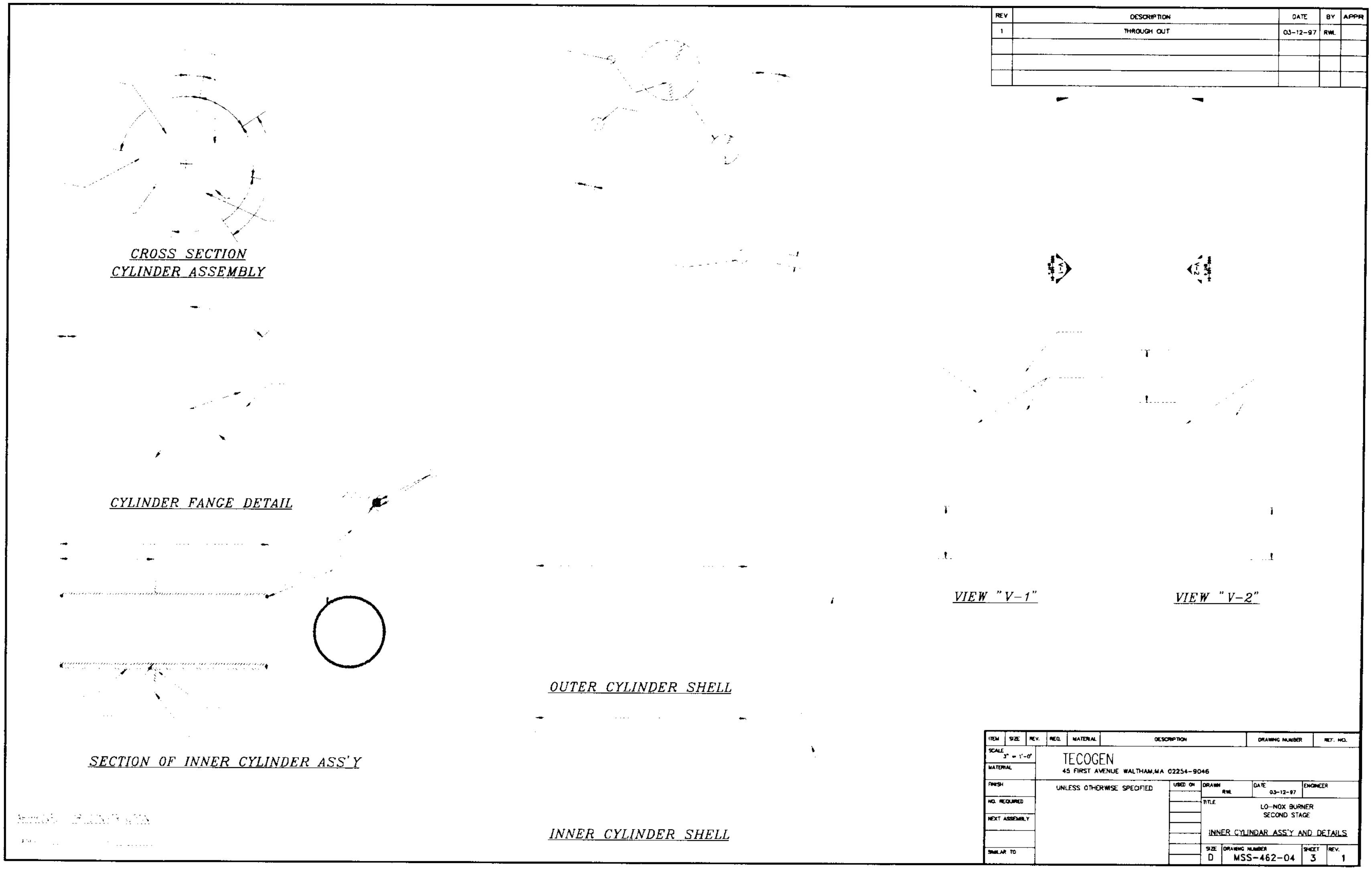
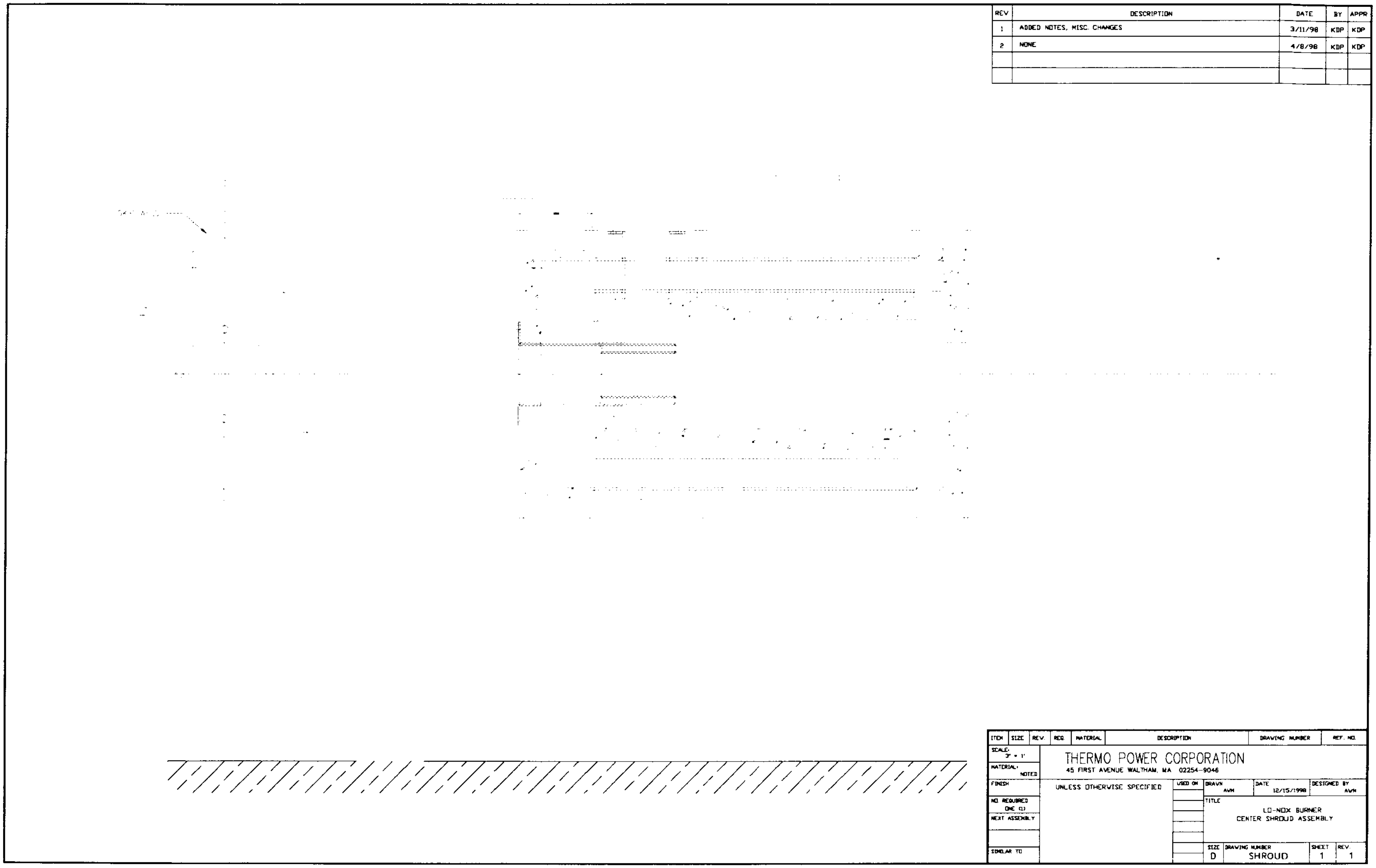


Figure 7 - Low NOx Burner Second Stage Nozzle



REV	DESCRIPTION	DATE	BY	APPR
1	ADDED NOTES, MISC. CHANGES	3/11/98	KDP	KDP
2	NONE	4/8/98	KDP	KDP

ITEM	SIZE	REV.	REQ.	MATERIAL	DESCRIPTION	DRAWING NUMBER	REF. NO.

SCALE: 3" = 1'
MATERIAL: NOTED
FINISH
NO. REQUIRED ONE (1)
NEXT ASSEMBLY
SIMILAR TO

THERMO POWER CORPORATION
45 FIRST AVENUE WALTHAM, MA 02254-9046

UNLESS OTHERWISE SPECIFIED
USED ON
DRAWN AWM
DATE 12/15/1998
DESIGNED BY AWM
TITLE LO-NOX BURNER
CENTER SHROUD ASSEMBLY
SIZE D
DRAWING NUMBER SHROUD
SHEET 1
REV. 1

Figure 8 - Recirculation Shroud Assembly in Combustor

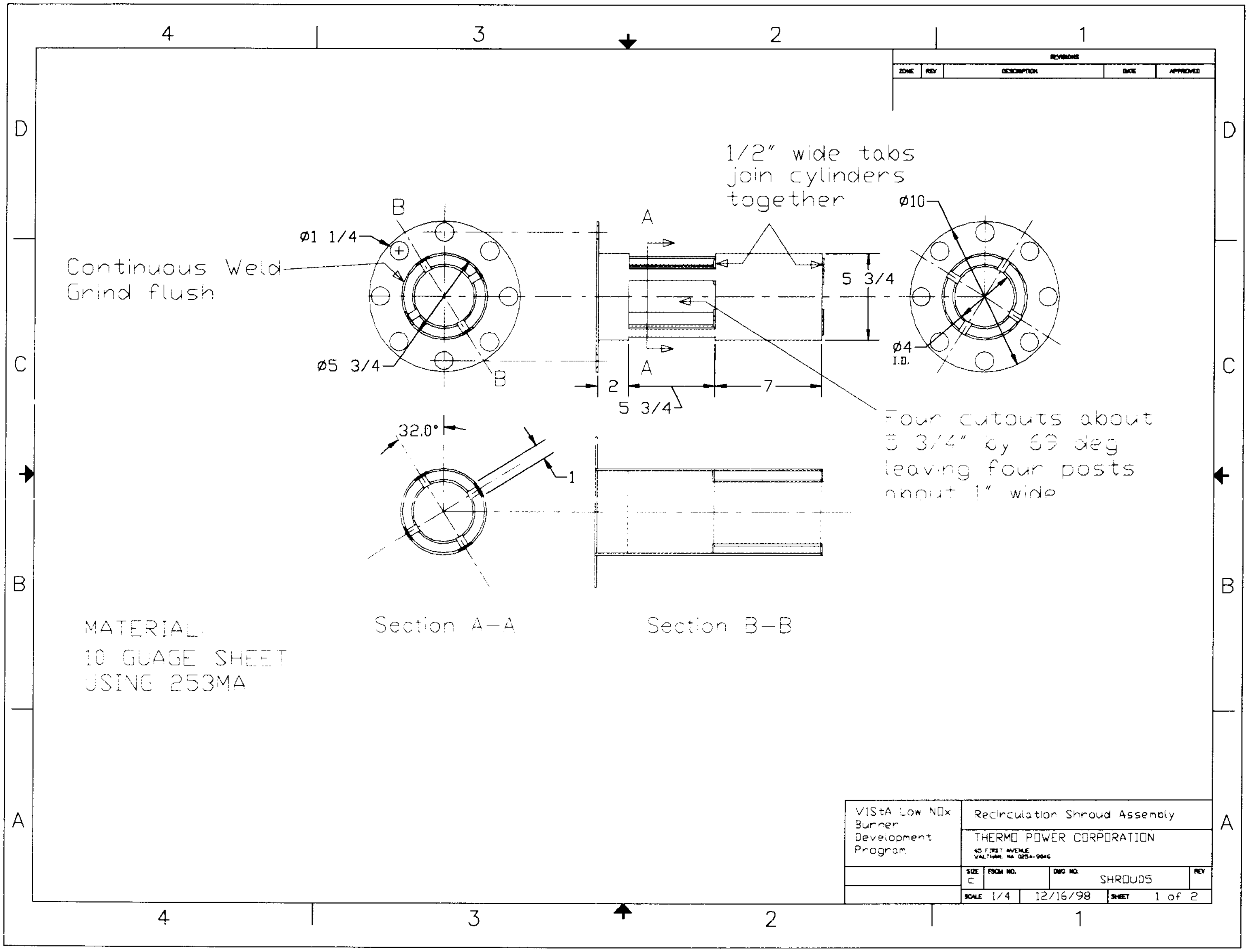


Figure 9 - Recirculation Shroud Assembly

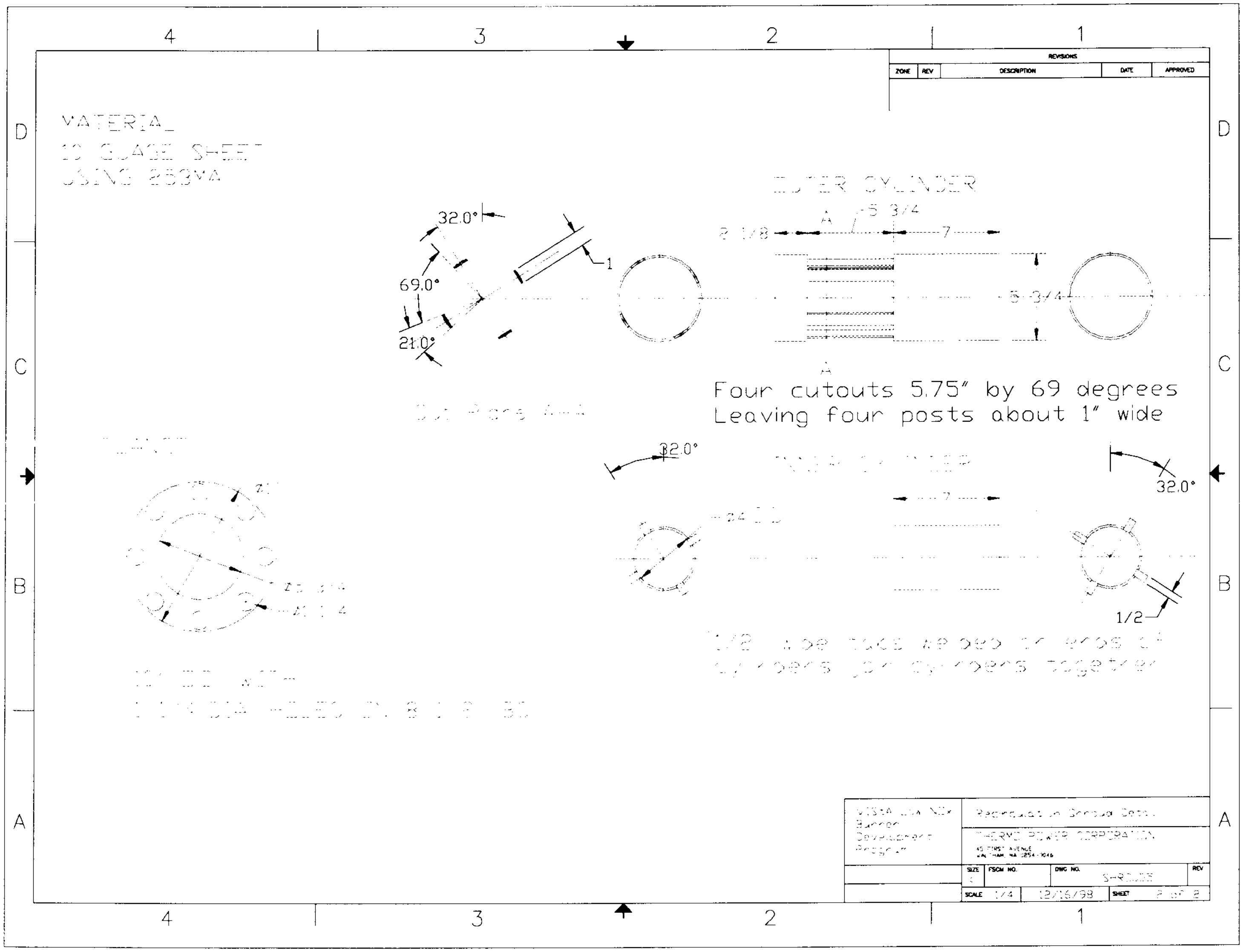


Figure 10 - Recirculation Shroud Detail

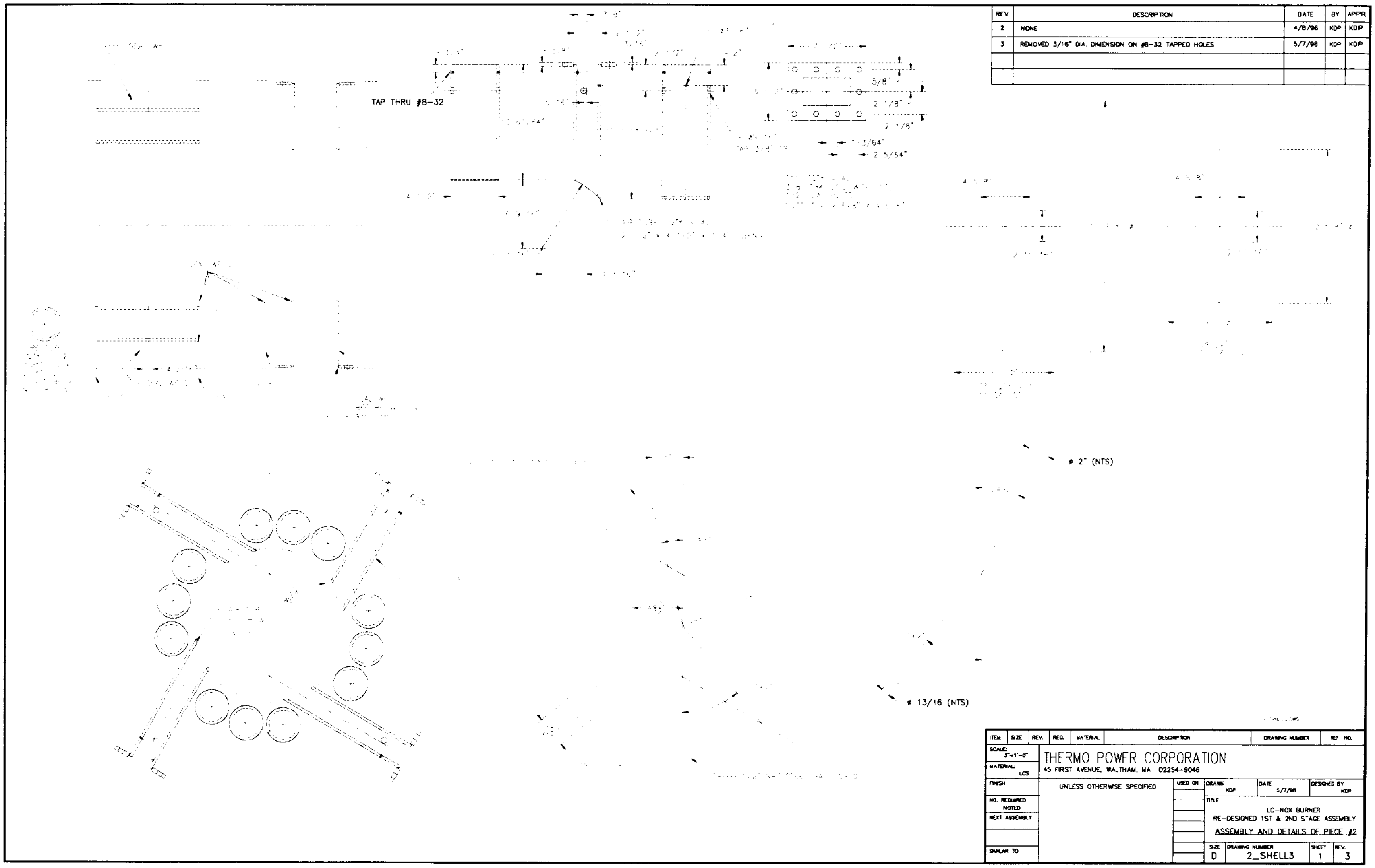


Figure 11 - Model 2 VIStA Burner First Stage Details

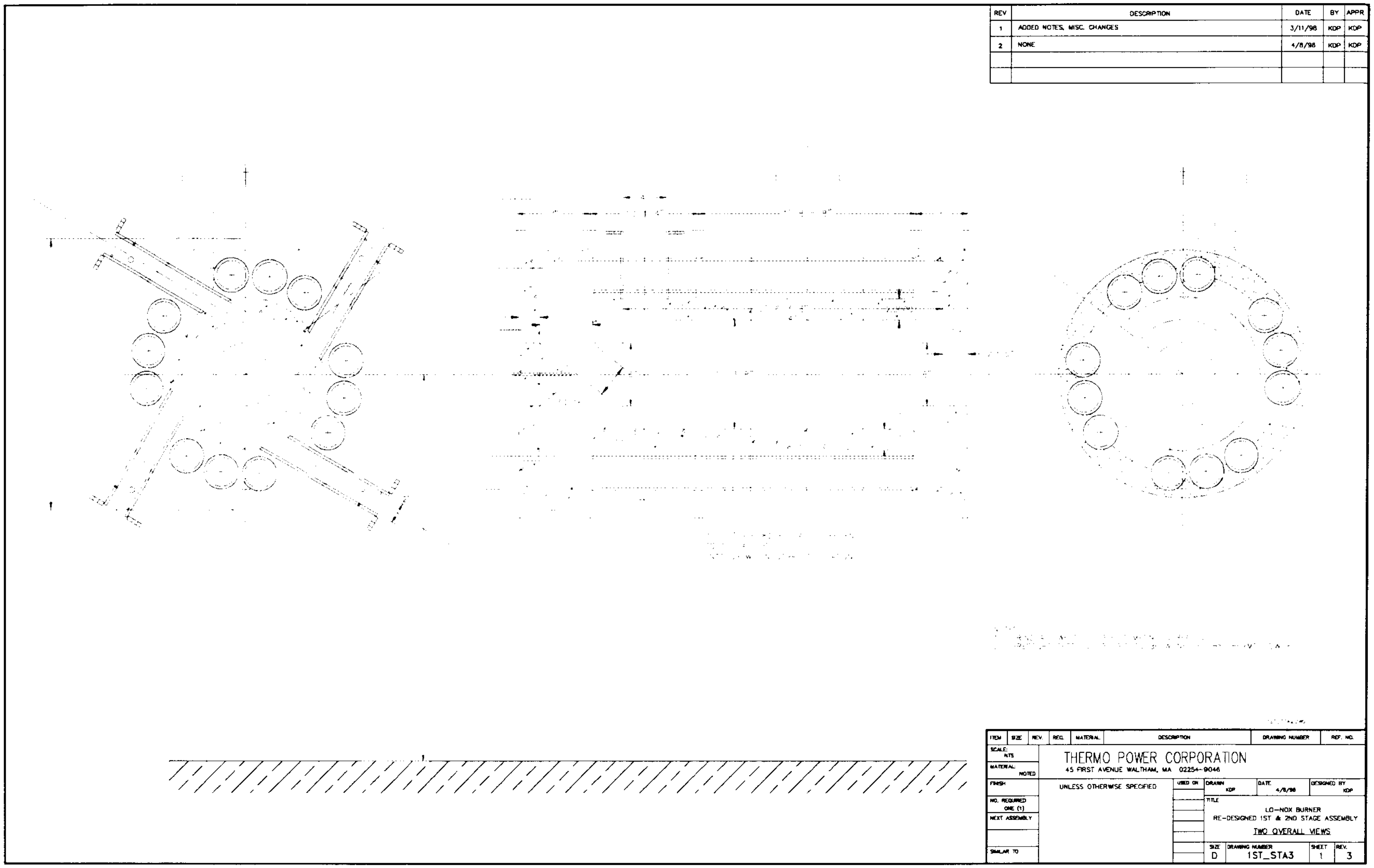


Figure 12 - Model 2 VIStA Burner First Stage Refractory

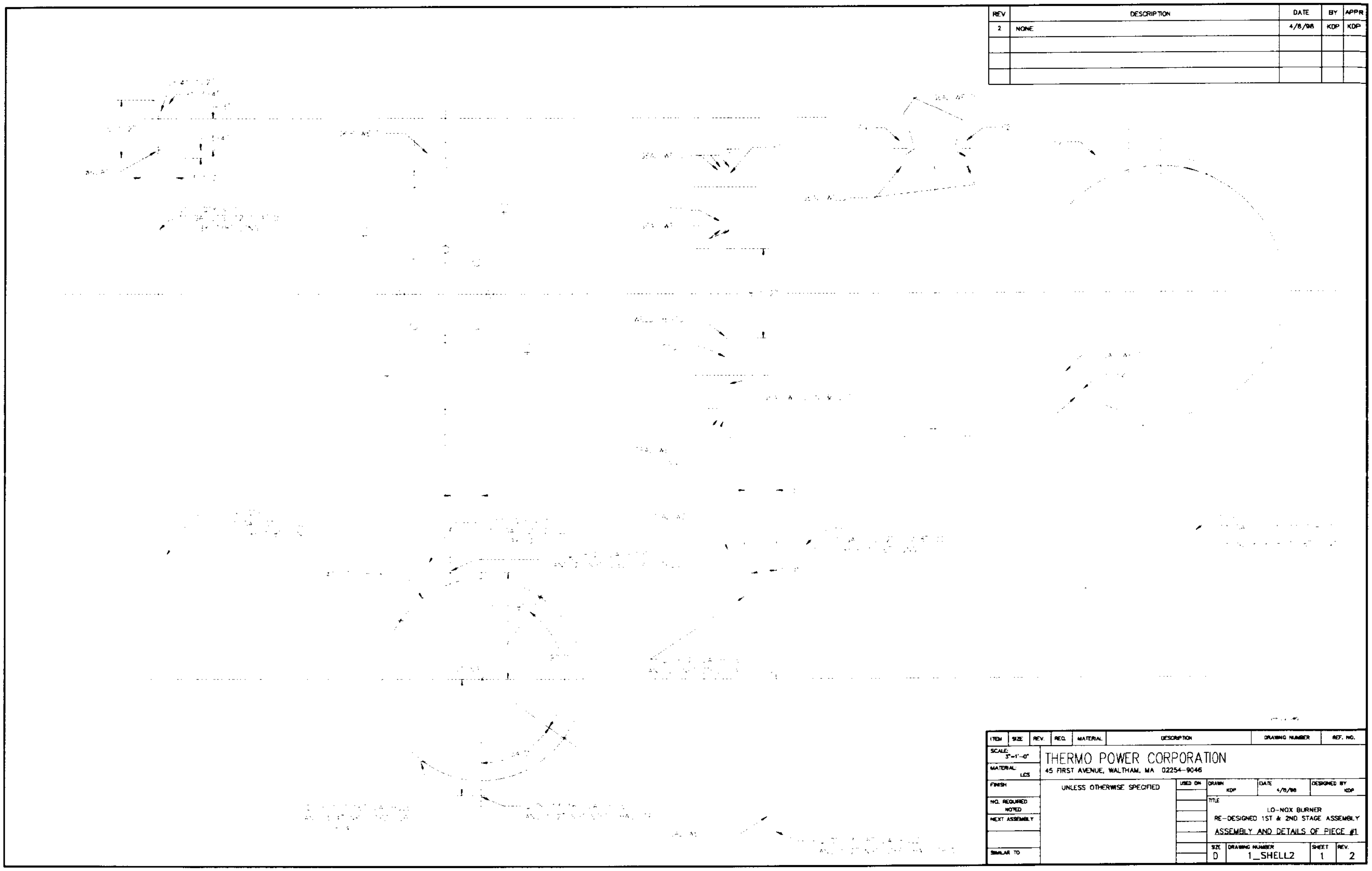


Figure 13 - Model 2 VIStA Burner First Stage Details

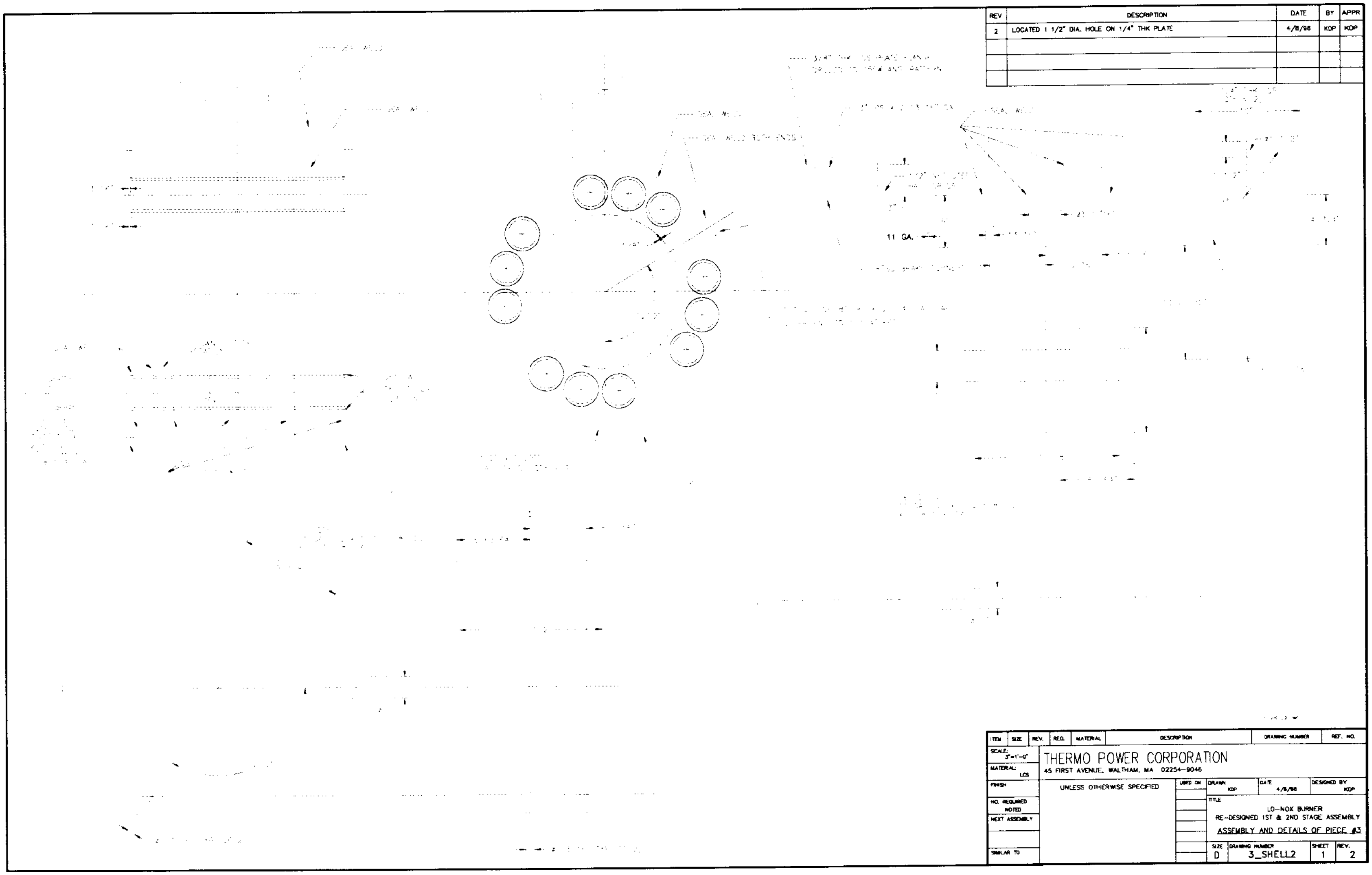


Figure 14 - Model 2 VIStA Burner First Stage Details

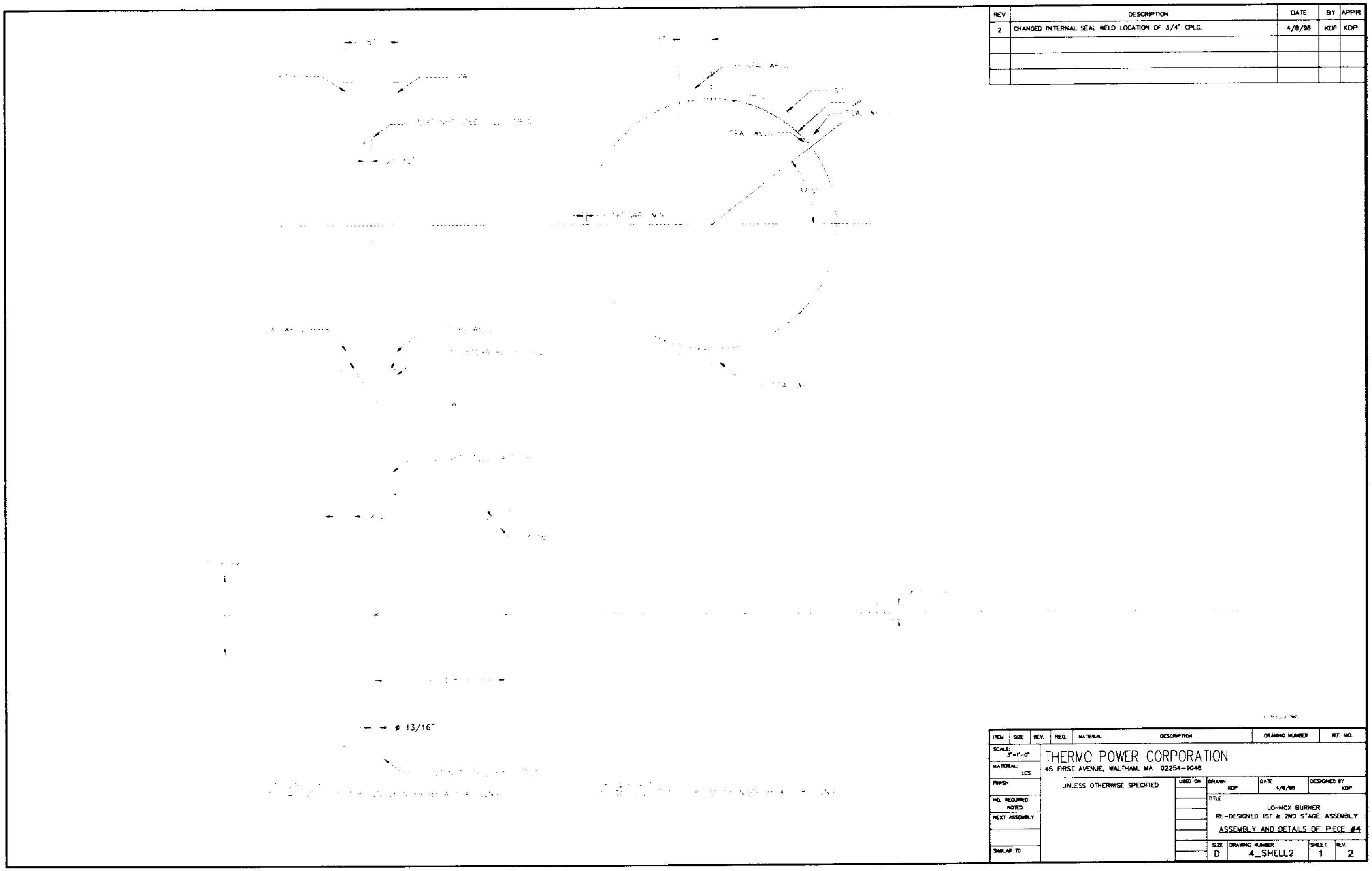


Figure 15 - Model 2 VIStA Burner First Stage Details

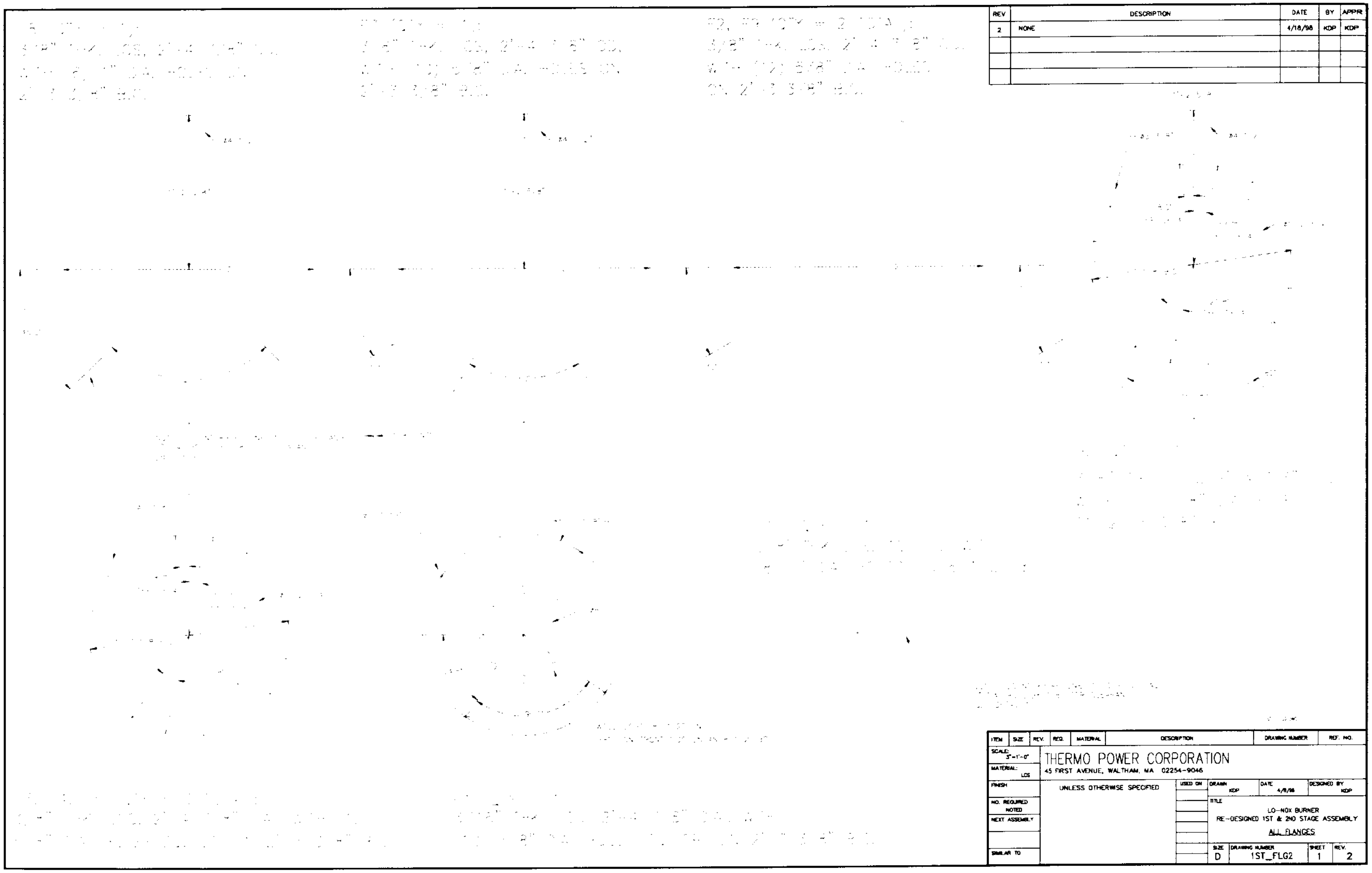


Figure 16 - Model 2 VIStA Burner First Stage Details

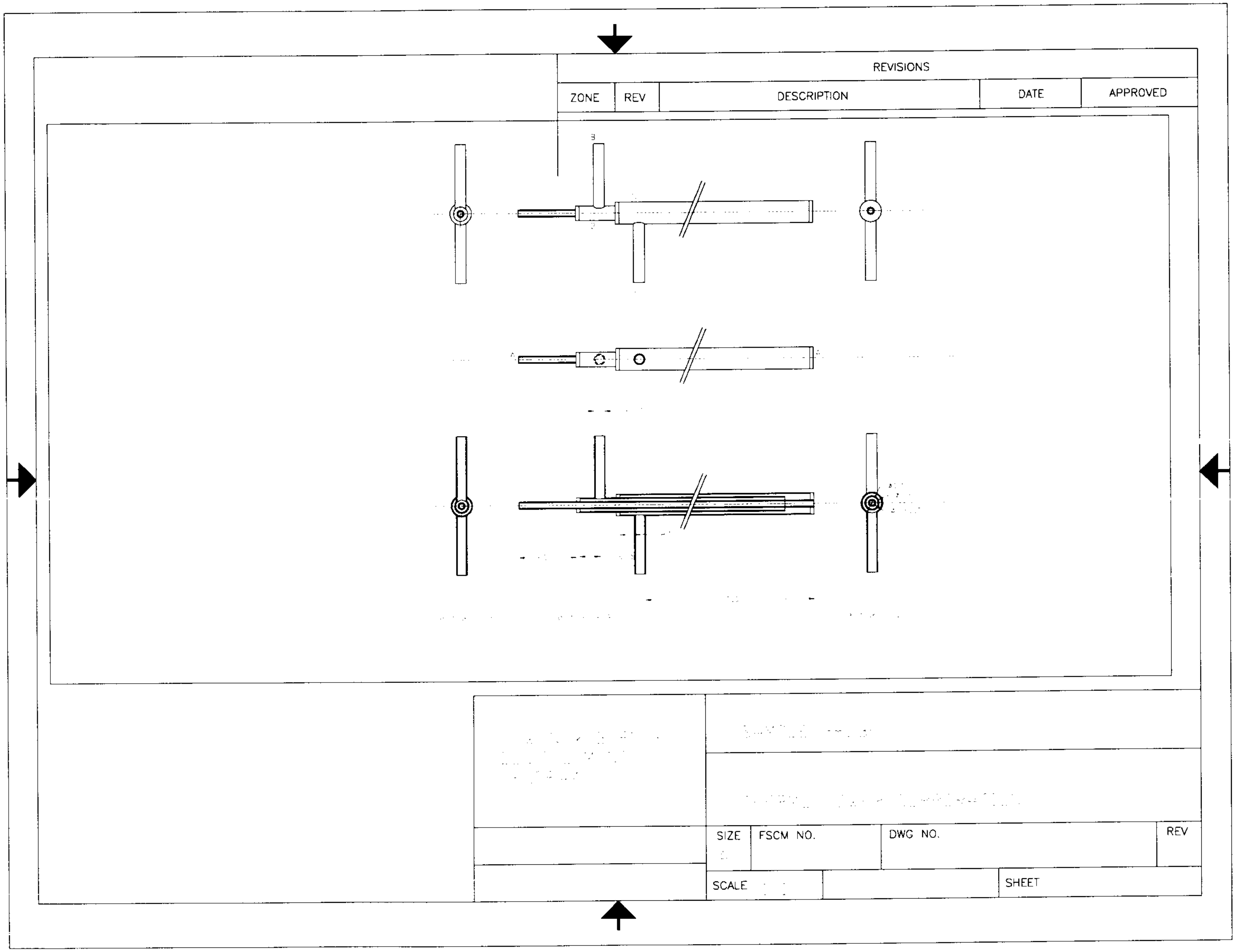


Figure 17 - Water Cooled Sample Probe Design Details