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Research & Development Division

Cost-Effective Control of NO_x with Integrated Ultra Low-NO_x Burners and SNCR

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COST-EFFECTIVE CONTROL OF NO_X WITH INTEGRATED ULTRA LOW-NO_X BURNERS AND SNCR

FINAL REPORT

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1 EXECUTIVE SUMMARY

1.1 INTRODUCTION

Under sponsorship of the Department of Energy's National Energy Technology Laboratory (NETL), McDermott Technology, Inc. (MTI), the Babcock & Wilcox Company (B&W), and Fuel Tech teamed together to investigate an integrated solution for NO_x control. The system was comprised of B&W's DRB-4Z™ low-NO_x pulverized coal (PC) burner technology and Fuel Tech's NO_xOUT®, a urea-based selective non-catalytic reduction (SNCR) technology. The technology's emission target is achieving 0.15 lb $NO_x/10^6$ Btu for full-scale boilers.

Development of the low-NO_x burner technology has been a focus in B&W's combustion program. The DRB-4Z™ burner (see Figure 1.1) is B&W's newest low-NO_x burner capable of achieving very low NO_x. The burner is designed to reduce NO_x by diverting air away from the core of the flame, which reduces local stoichiometry during coal devolatilization and, thereby, reduces initial NO_x formation. Figure 1.2 shows the historical NO_x emission levels from different B&W burners. Figure 1.2 shows that based on three large-scale commercial installations of the DRB-4Z™ burners in combination with OFA ports, using Western subbituminous coal, the NO_x emissions ranged from 0.16 to 0.18 lb/10^6 Btu. It appears that with continuing research and development the Ozone Transport Rule (OTR) emission level of 0.15 lb $NO_x/10^6$ Btu is within the reach of combustion modification techniques for boilers using western U.S. subbituminous coals. Although NO_x emissions from the DRB-4Z™ burner are nearing OTR emission level with subbituminous coals, the utility boiler owners that use bituminous coals can still benefit from the addition of an SNCR and/or SCR system in order to comply with the stringent NO_x emission levels facing them.

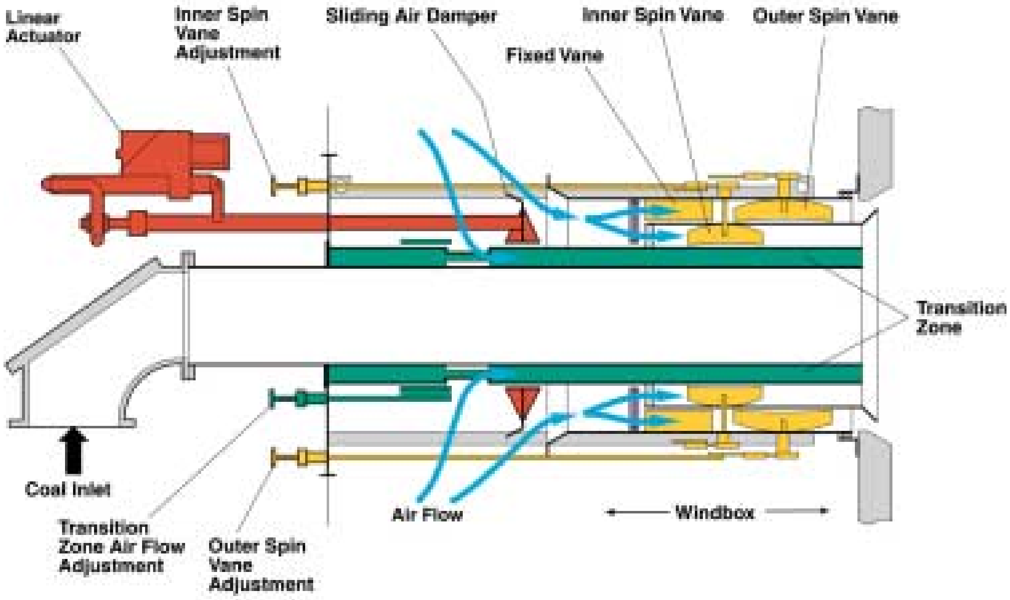


FIGURE 1.1. THE B&W LOW-NO$_X$ DRB-4Z™ COAL-FIRED BURNER

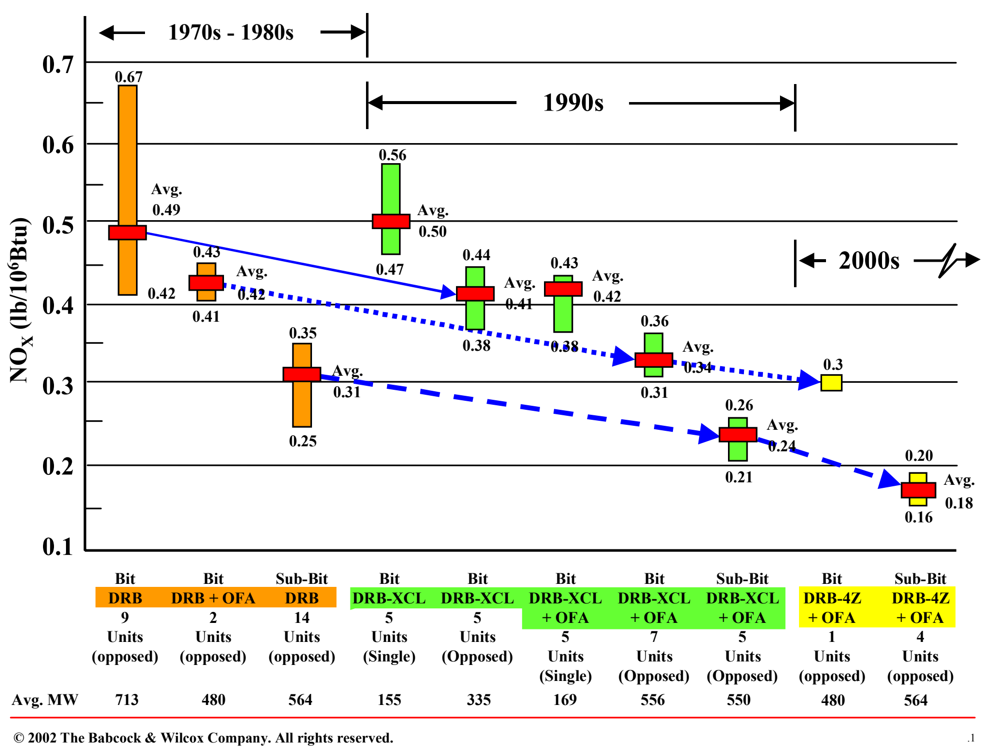


FIGURE 1.2. B&W LOW-NO$_X$ BURNER ADVANCEMENTS

1.2 EXPERIMENTAL FACILITY

Large-scale testing was conducted in B&W's 100-million Btu/hr Clean Environment Development Facility (CEDF) (see Figure 1.3) that simulates the conditions of large coal-fired utility boilers. The one-of-a-kind facility is equipped with one near full-scale burner. The CEDF is constructed with water walls and is insulated with refractory to simulate the thermal conditions of the middle row burner in a commercial boiler.

A wide range of commercially available utility coals including Spring Creek, a Montana high-volatile subbituminous coal from Powder River Basin (PRB) region, Pittsburgh #8 high- volatile bituminous coal, and Middle Kittanning medium-volatile bituminous coal were tested. Under the most challenging boiler temperatures at full load conditions, the DRB-4Z™ burner alone (without air staging) achieved NO_x emissions of 0.26 lb/10^6 Btu (187 ppm @ 3% O_2) for PRB coal, 0.30 (215 ppm @ 3% O_2) for Pittsburgh #8, and 0.40 (287 ppm @ 3% O_2) for Middle Kittanning coal (see Figure 1.4). The NO_x variations with fuel can be explained with the fuel ratio (fixed carbon over volatile matter, FC/VM) and fuel nitrogen content. Fuel ratios for Spring Creek, Pittsburgh #8, and Middle Kittanning were 1.26, 1.19, and 2.38 respectively. In addition, the lower fuel nitrogen content (as shown in Table 1.1) and higher moisture with the Spring Creek coal reduced the overall NO_x emissions.

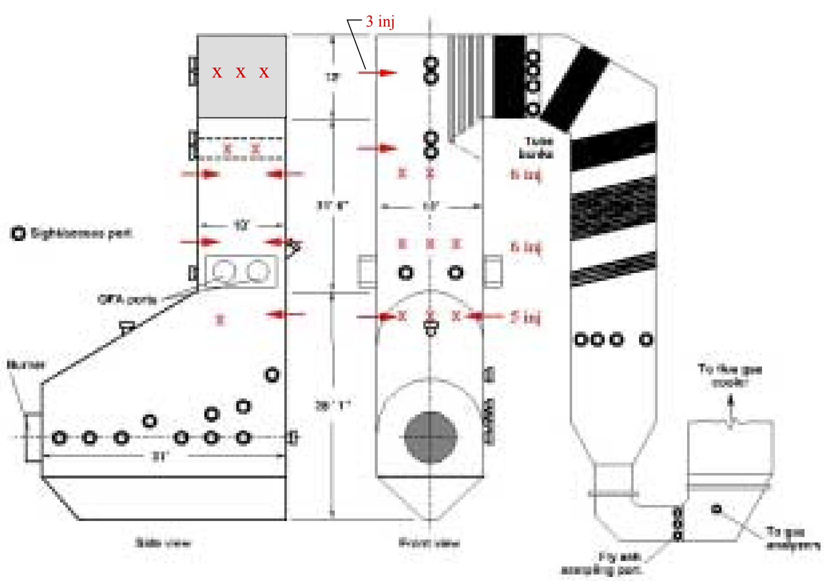


FIGURE 1.3. SNCR LOCATIONS

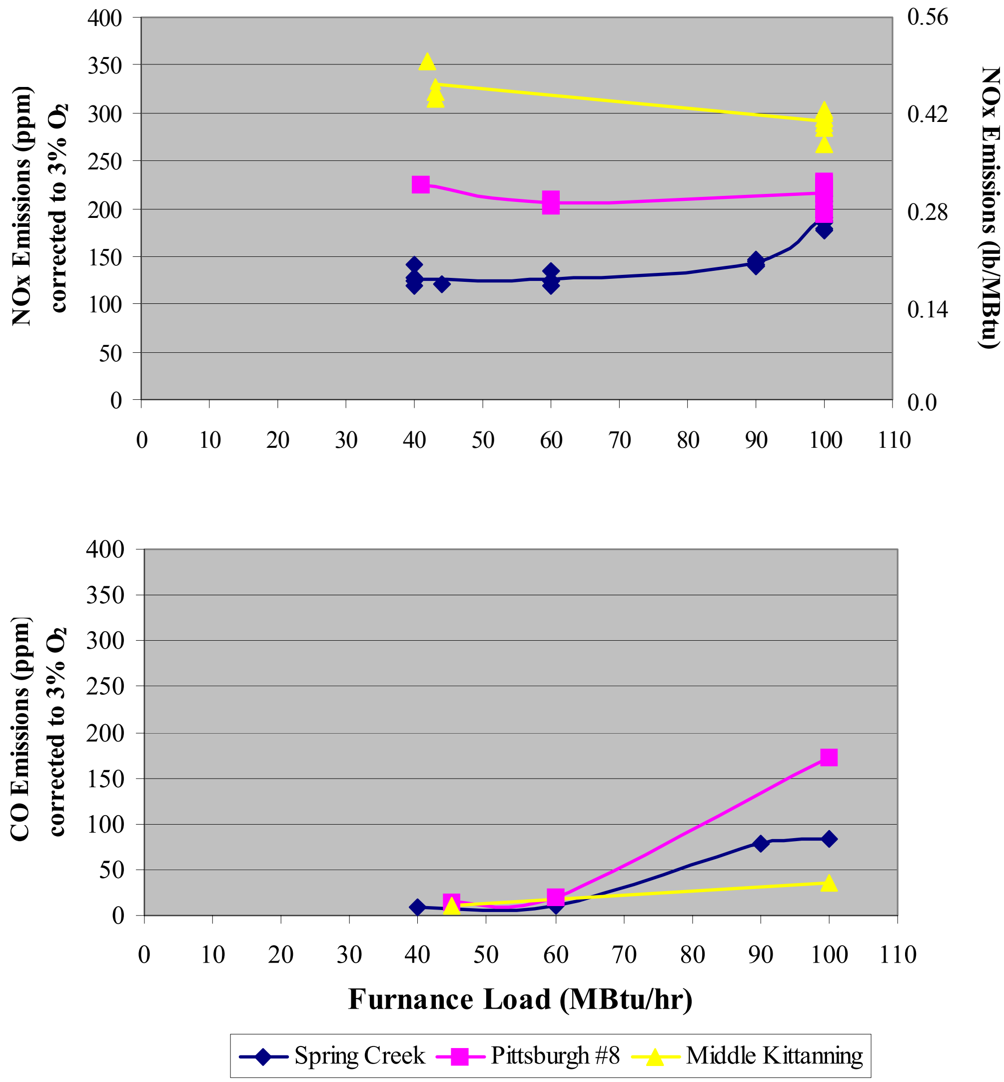


FIGURE 1.4. EFFECT OF FURNACE LOAD ON NO_X AND CO EMISSIONS WHILE FIRING THE BASELINE PLUG-IN DRB-4Z^{TM} BURNER WITH THE TEST COALS

TABLE 1.1. REPRESENTATIVE COAL ANALYSES

	Subbituminous *Spring Creek*	High-Volatile Bituminous *Pittsburgh #8*	Medium-Volatile Bituminous *Middle Kittanning*
PROXIMATE (as rec'd)			
Fixed Carbon (%)	39.10	44.00	47.31
Volatile Matter (%)	31.05	36.82	19.89
Moisture (%)	26.21	12.87	9.55
Ash (%)	3.64	6.31	23.25
Fixed Carbon/Volatile Matter	1.26	1.20	2.38
ULTIMATE (as rec'd)			
Carbon (%)	53.10	65.45	57.16
Hydrogen (%)	3.78	4.52	3.43
Nitrogen (%)	0.64	1.12	0.96
Sulfur (%)	0.23	3.10	1.20
Oxygen (%)	12.40	6.62	4.44
As-Fired Moisture (%)	13.56	1.95	1.06
Heating Value (Btu/lb) (as rec'd	9110	11733	10054

In order to determine the optimum SNCR port locations, numerical modeling and measurements of in-furnace temperature and gaseous species were performed. Figure 1.5 illustrates the temperature profiles (in degrees F) with the Spring Creek coal at different loads. CEDF temperature profiles increased with Middle Kittanning coal due to its lower volatile content and more char to burn in the boiler. Figure 1.3 shows the SNCR port locations at 4 different elevations. Fuel Tech Parametric tests showed that at the full load conditions urea injection in the upper two rows was the most effective.

A tanker truck with the urea-based injection reagent was located outside the CEDF building. A portable trailer was set in this location to monitor and control the aqueous urea injection. The NO_xOUT solution was pumped from the storage tank to the CEDF. Hoses were run from the storage tank to a trailer and from the trailer to three distribution modules located close to the injection ports on the CEDF. Hoses were run from the distribution panels to each injection port. Compressed air lines were connected to each injection port.

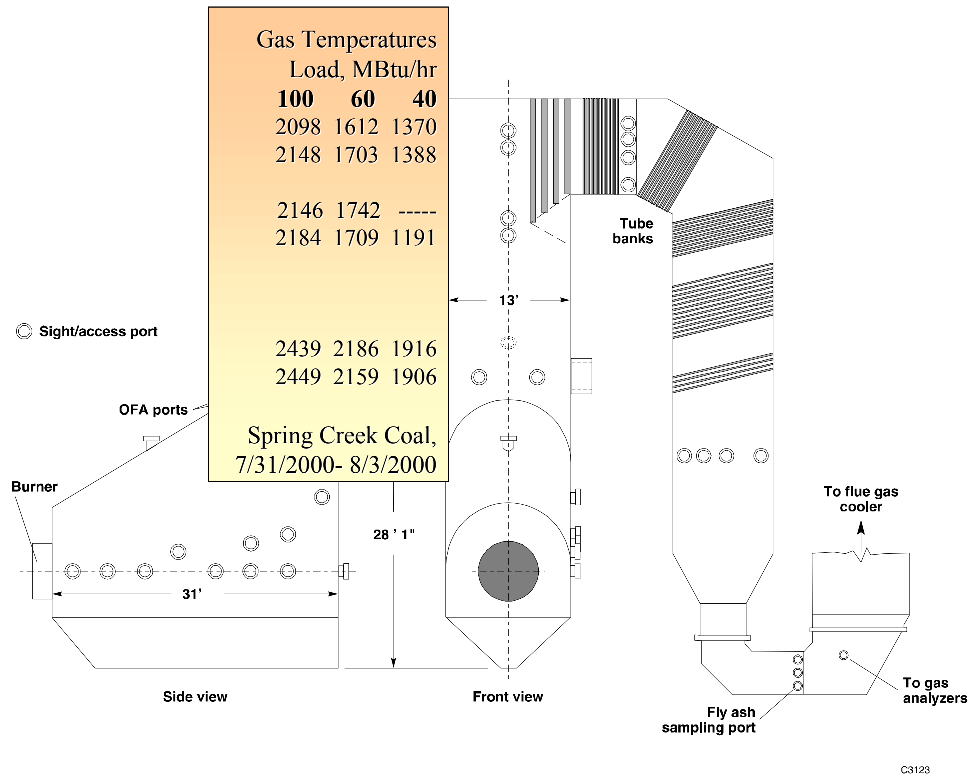


FIGURE 1.5. TEMPERATURE (IN DEGREES F) MAPPING OF CEDF FOR SPRING CREEK COAL

1.3 RESULTS

The baseline DRB-4Z™ NO_x levels at full load were reduced by the SNCR system (configured with wall injectors only) to 0.19 lb/10^6 Btu (136 ppm @ 3% O_2) for western subbituminous, 0.22 (158 ppm @ 3% O_2) for Pittsburgh No. 8, and 0.32 (230 ppm @ 3% O_2) for Middle Kittanning coal (see Figure 1.6). The NO_x reduction was 25% for western subbituminous, 26% for Pittsburgh No. 8, and 18% for Middle Kittanning coal. These data indicate that a nominal 25% NO_x reduction is feasible from a low-NO_x combustion system firing western subbituminous and eastern high volatile coals with a baseline NO_x of 0.2 to 0.3 lb/10^6 Btu. For units firing coals with lower volatile content such as Middle Kittanning, the boiler temperatures could be a limiting factor thus resulting in a NO_x reduction of 15-20%.

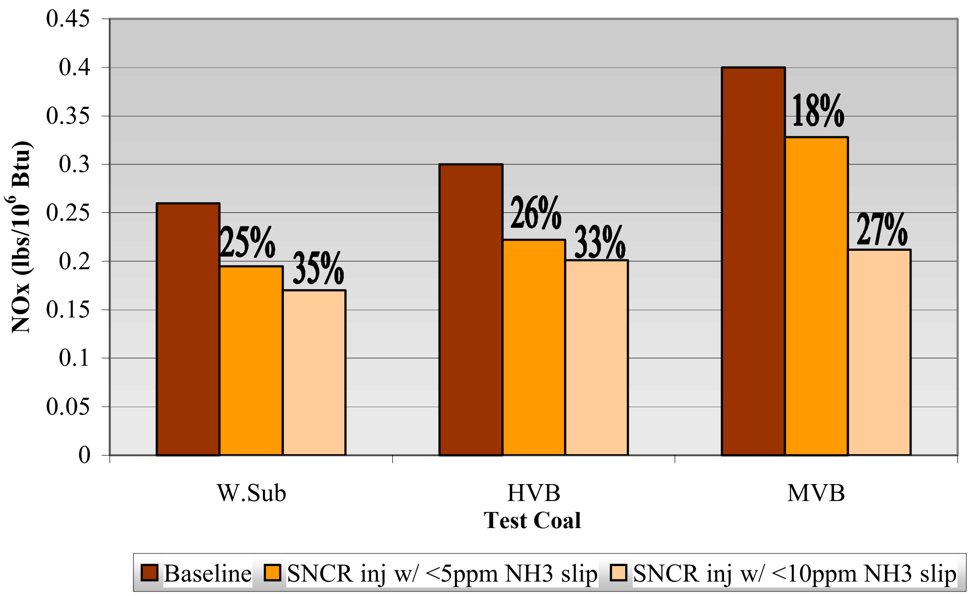


FIGURE 1.6. THE EFFECT OF SNCR INJECTION ON NO_x EMISSIONS FOR THE PLUG-IN DRB-4Z™ BURNER FIRING THE TEST COALS AT 100 MILLION BTU/HR

Under the more favorable reduced load conditions, NO_x emissions were lower for both baseline (burner only) and SNCR operation. Baseline NO_x emissions of 0.17 lb/10^6 Btu (122 ppm) for PRB coal at 60 million Btu/hr were reduced to 0.13 lb/10^6 Btu (93 ppm) by SNCR. The lowest NO_x of 0.09 lb/10^6 Btu (65 ppm) was achieved at a 40 million Btu/hr firing rate. These data were obtained while the ammonia slip was below 5 ppm. Higher reductions were possible when the ammonia slip was between 5 to 10 ppm.

In summary, testing has provided insight into utilizing SNCR in ultra low NO_x burner conditions and produced preliminary results that are positive. The DRB-4Z™ low-NO_x burner produced low NO_x without air staging (no OFA). Additional NO_x reduction could be obtained by air staging. Significant NO_x reductions were demonstrated from very low baselines by SNCR while controlling ammonia slip to less than 5 ppm. Improved performance may be possible with convective pass injection at full load.

1.4 ECONOMICS

To demonstrate the application and benefits of various NO_x control options, their cost-effectiveness was calculated for a reference 500 MWe wall-fired, coal-burning boiler. Three integrated NO_x control options were considered in this evaluation with the goal of reducing the baseline emissions from 0.5 to 0.15 lb $NO_x/10^6$ Btu. Also, the SCR-only scenario as specified in the DOE's program solicitation represents the base case for comparing with the costs of other cases. The options included:

1. LNB with OFA
2. LNB with OFA plus NO_xOUT®
3. SCR-only systems.
4. NO_xOUT Cascade®

A fifth case could have been the use of LNB with OFA and a smaller SCR but this scenario was outside of the scope of this project. The low-NO_x burner in combination with OFA was considered a potential technology for boilers using PRB coal. The LNB/OFA plus NO_xOUT® was considered when burner NO_x level is 0.2 lb/10^6 Btu. Also, Fuel Tech investigated the NO_xOUT Cascade® for cases with high reagent injection rates (burner $NO_x \geq 0.3$ lb/10^6 Btu) where ammonia slip can be reduced with a catalyst (see Table 9.2). In some of the CEDF tests, the SNCR system was forced to slip 10-20 ppm ammonia. There was no catalyst available in the CEDF to promote reaction between ammonia and NO_x which is the basis for NO_xOUT Cascade® technology. For the purpose of this economic analysis, the NO_xOUT Cascade® NO_x reduction was estimated based on the Fuel Tech's experience.

Table 1.2 compares the capital costs of different options. The SCR capital cost is a strong function of retrofit difficulties such as availability of space for SCR reactor, and the need for fan modification or new forced draft fan since SCR may increase the pressure drop beyond the capability of the existing fan. Low-NO_x burner cost is also very site specific and depends on many factors such as adequacy of air and coal measurements in the boiler, pulverizer performance and boiler control. Although, the DRB-4Z™ low-NO_x PC burner has been specifically developed for retrofit applications with potentially high throat velocity, the potential need for pressure part modifications impacts the cost of equipment. For these reasons a range of capital costs reported here which is according to multiple commercial installations of low-NO_x burners and SCR systems. The SNCR capital and operating costs were based on commercial experience of Fuel Tech. Our study demonstrated that the estimated capital costs of the LNB with OFA and LNB with OFA plus NO_xOUT® options were substantially 71 to 93% and 60 to 87% lower than the SCR-only case, respectively. The cost of NO_xOUT Cascade® is lower because it is assumed that the NO_xOUT Cascade® will be an in-duct system and therefore cost saving over a standard SCR system can be realized.

TABLE 1.2. INTEGRATED SYSTEM ECONOMICS FOR A 500 MW BOILER

	Capital Cost (million $)	**Operation Cost** ($/year)	**Annual Levelized Cost** ($/ton of NO_x Removed)
LNB+OFA	5 to 10 (10 to 20 $/kW)	166,000 *UBC + pressure loss*	139 to 247
LNB+OFA+SNCR	9 to 14 *4 SNCR* *5-10 LNB+OFA*	761,447 *595,447 urea cost* *166,000 LNB+OFA*	293 to 444
SCR	35 to 70 (70 to 140 $/kW)	760,000 *500,000 ammonia* *260,000 other*	897 to 1652
NO_xOUT Cascade®	15.7 (33 $/kW)	2,157,493 *Urea*	740

Our analysis shows that the DRB-4Z™ low-NO_x burner in combination with OFA has the lowest levelized cost (72 to 91% less than SCR). Since low-NO_x burners are more cost-effective on a $/ton of NO_x basis than SNCR or SCR technologies in general, there is a great incentive in using them in combination with post-combustion NO_x control methods. LNB/OFA plus the NO_xOUT® combination cost is $ 293 to $ 444 per ton of NO_x removed when the low-NO_x burner emissions are 0.20 lb/10^6Btu which is 50% to 82% lower than the SCR cost ($897 to $1,652 per ton of NO_x). NO_xOUT Cascade® levelized cost is close to the lower range of SCR due its lower capital cost. As stated earlier, it has been assumed that the catalyst can be placed in-duct and a separate reactor is not necessary. It should be mentioned that these costs are site specific and the results may change from unit to unit.

1.5 CONCLUSIONS & RECOMMENDATIONS

- Substantial NO_x reductions were achieved with an unstaged DRB-4Z™ low-NO_x burner and SNCR; however, they fell somewhat short of the OTR limit at the CEDF.

- At the full load conditions using SNCR and firing western subbituminous coal NO_x reduction of 25% was achieved from a baseline of 0.26 lb/10^6 Btu (no OFA).

- Additional NO_x reduction could be achieved through the use of air staging with the ultra low-NO_x DRB-4Z™ burner and SNCR. Based on several large-scale PRB coal-fired commercial installations of the DRB-4Z™ burners in combination with OFA ports, the NO_x emissions ranged from 0.16 to 0.18 lb/10^6 Btu. It is expected that OTR NO_x emission level of 0.15 lb/10^6 Btu can be met with DRB-4Z™ burners plus OFA and SNCR using PRB coal.

- The side effects from the use of the ultra low-NO_x DRB-4Z™ burner and the NO_xOUT system seem to be manageable during the test period, but ammonia slippage of even 5 ppm poses some risk for air heater pluggage etc. in commercial operation.

- Additional work should be performed to look at the effect of a water-cooled lance in front of the superheater tubes. This arrangement has been commercially tested; it produces very fine urea particles released at more favorable temperatures, and provides better mixing between urea and flue gas, which offer better distribution and potential for reduced ammonia slip.

2 BACKGROUND

Coal-fired electric utilities are facing a serious challenge with regards to curbing their NO_x emissions. At issue are the NO_x contributions to the acid rain, ground level ozone, and particulate matter formation. Substantial NO_x control requirements could be imposed under the proposed Ozone Transport Rule, National Ambient Air Quality Standards, and New Source Performance Standards.

McDermott Technology, Inc. (MTI), Babcock & Wilcox (B&W), and Fuel Tech have teamed together to evaluate an integrated solution for NO_x control. The system is comprised of an ultra low-NO_x pulverized coal (PC) burner technology plus a urea-based, selective non-catalytic reduction (SNCR) system capable of meeting a target emission limit of 0.15 lb $NO_x/10^6$ Btu and a target ammonia (NH_3) slip level targeted below 5 ppmV for commercial units. The MTI/Fuel Tech approach combines the best available combustion and post-combustion NO_x control technologies. More specifically, B&W's DRB-4Z™ ultra low-NO_x PC burner technology has been combined with Fuel Tech's NO_xOUT® (SNCR) system and jointly evaluated and optimized in a state-of-the-art test facility at MTI. Although the NO_xOUT Cascade® (SNCR/SCR hybrid) system was not tested directly in this program, its potential application for situations that require greater NO_x reductions has been inferred from other measurements (i.e., SNCR NO_x removal efficiency plus projected NO_x reduction by the catalyst based on controlled ammonia slip). MTI analysis shows that the integrated ultra low-NO_x burner and SNCR system has the lowest cost when the burner emissions are 0.25 lb $NO_x/10^6$ Btu or less. Based on several full-scale results the DRB-4Z™ burner with overfire air (OFA) can achieve 0.16-0.2 lb/10^6 Btu firing PRB coal. The NO_x level with bituminous coal was 0.3 in one commercial installation. At burner NO_x emission level of 0.20 lb/10^6 Btu, the annual levelized cost per ton of NO_x removed is 60 to 87% lower than the SCR cost.

Large-scale testing was conducted in B&W's Clean Environment Development Facility (CEDF). Testing in the CEDF provided the premise for the evaluation and optimization of the integrated NO_x control system at conditions representative of pulverized coal-burning utilities. Past experience has shown that a large prototype, 100 million Btu/hr burner design can be readily scaled with minimal risk for commercial retrofit where a typical burner size is about 150 to 200 million Btu/hr. It is anticipated that a commercial offer can be made around the 2003 timeframe.

A wide range of commercially available utility coals including western sub-bituminous, high-volatile bituminous, and medium-volatile bituminous were tested with the DRB-4Z™ ultra low-NO_x PC burner.

2.1 NO_X REGULATIONS

Minimizing the deleterious effects of acid rain, ground level ozone, and aerosol nitrates requires substantial reductions in NO_x emissions at the point source. Coal-burning power plants can implement compatible NO_x compliance strategies to meet the current and future regulations. For example, Title IV (acid rain control) compliance of 0.46 lb/10^6 Btu can be satisfied with the installation of low-NO_x burners in wall-fired utilities. But compliance with the proposed Title I (ozone transport) could require additional NO_x control technologies such as SCR (Selective Catalytic Reduction) or SNCR (Selective Non-Catalytic Reduction). In 1995, the twelve Northeastern States forming the Ozone Transport Commission (OTC) issued a memorandum of understanding that calls for significant reductions from the 1990 figures. Similarly, the Environmental Protection Agency (EPA) has published its final Ozone Transport Rule (OTR) for reducing ground-level ozone. The new rule affects 19 states in the ozone transport region plus the District of Columbia. It requires each to develop a State Implementation Plan (SIP) for curbing the NO_x emissions from utility boilers during the ozone season (May 1 – September 30) to an average of 0.15 lb $NO_2/10^6$ Btu starting on May 31, 2004. The SIP is based on a total NO_x emissions allocation to the state. The state then allocates a NO_x credit/allowance to each source. Utilities can use trading in order to comply. In our view, the 0.15 lb $NO_2/10^6$ Btu level can be met in a cost-effective manner many for coal-burning utilities by combining the best available combustion and post-combustion NO_x control technologies, namely ultra low-NO_x burner and SNCR and/or SCR processes.

2.2 AVAILABLE OPTIONS

Switching from high-sulfur eastern bituminous coals to western sub-bituminous coals is becoming more attractive to utilities searching for near-term reduction of NO_x emissions from existing low-NO_x burners. Western sub-bituminous coals are more reactive than bituminous coals and contain more moisture and less sulfur. Western subbituminous coals typically contain less nitrogen than bituminous coals but there are some Western subbituminous coals that contain over 1% nitrogen. Unburned carbon, SO_x, and NO_x levels from the combustion of sub-bituminous coals are generally lower than those measured for eastern bituminous coals. Post-combustion reduction of NO_x for western sub-bituminous coal-fired units via SNCR or SCR processes can be particularly challenging for three reasons. First, removal efficiencies can be low due to low combustion-generated NO_x concentrations. Second, the combustion of high-moisture content western sub-bituminous coals generates high water vapor levels in the flue gas that have a slightly inhibiting effect on NO_x removal efficiency. Third, western sub-bituminous coals generally have higher alkali content and lower ash fusion temperature than other coals, and, as such, ash deposition and fouling on heat transfer surfaces can be further exacerbated by the SNCR process due to potential formation of ammonium salts (e.g., sulfate and bisulfate) since these deposits happen at lower temperatures typical of boiler heaters. On the other hand, higher alkali concentrates in the gas-phase could enhance the SNCR process by reducing NH_3 slip and N_2O emissions[1]. Formation of alkali sulfates from burning western sub-bituminous coals may also inhibit NO_x removal by masking SCR catalysts.

Economic analyses[2] have shown that ultra low-NO_x burners can minimize the post-combustion NO_x control requirements and costs for pre-NSPS as well as post-NSPS retrofits. Air staging marginally reduces the NO_x emission levels and may not be necessary when an ultra low-NO_x burner is combined with SNCR or SCR technologies. Presently, no vendor has a commercial burner for wall-fired boilers that can achieve 0.15 lb $NO_x/10^6$ Btu even with a western sub-bituminous coal. B&W's unstaged DRB-4Z™ burner generated only 0.26 and 0.3 lb/10^6 Btu when fired at 17% excess air in a 100 million Btu/hr test facility with a PRB and a Pittsburgh #8 eastern high-volatile bituminous coal, respectively. (Based on general large-scale commercial installation of DRB-4Z™ burners in combination with OFA ports, using PRB coal, the NO_x emission ranged from 0.16 to 0.18 lb/10^6 Btu.) Development of a small throat (plug-in) version of the DRB-4Z^{TM} design is even more cost-effective for retrofit applications. However, very little was known about the combined performance of ultra low-NO_x burners with SNCR and/or SCR systems. This program addressed issues concerning the integration of ultra low-NO_x burner and SNCR and/or SCR technologies prior to field deployment. The program involved process optimization and testing in B&W's state-of-the-art 100 million Btu/hr facility. Testing in the 100 million Btu/hr unit versus field-testing has the main advantage of characterizing the combined ultra low-NO_x and SNCR technologies under well-controlled and commercially representative conditions. Additionally, a range of coals that typify the fuels consumed in power plants directly affected by the Ozone Transport Rule could be tested to provide cost-effective solutions for those utilities.

3 PROJECT OBJECTIVES

The objective of this project was to develop an environmentally acceptable and cost-effective NO_x control system that could achieve less than 0.15 lb $NO_x/10^6$ Btu for a wide range of coal-burning commercial boilers.

The system was comprised of an ultra low-NO_x PC burner technology plus a urea-based, selective non-catalytic reduction (SNCR) system. In addition to the above stated NO_x limit of 0.15 lb/10^6 Btu, ammonia (NH_3) slip levels were targeted below 5 ppmV for commercial units. Furthermore, the system was to have a negligible impact of balance-of-plant issues, be applicable to a wide range of boiler types and configurations, and to maintain performance over a wide range of coals. Testing was performed in the 100 million Btu/hr Clean Environment Development Facility (CEDF) in Alliance, Ohio. It was expected that NO_x emissions in some commercial units could be higher than in the CEDF due to flame interactions, hotter furnaces, coal property variations, imperfect mixing of NO_x reducing reagent with flue gas, etc. Therefore, to ensure that NO_x emissions of 0.15 lb/10^6 Btu or lower can be attained in the field, the CEDF target was initially set at 0.125 lb $NO_x/10^6$ Btu or less. Later, we determined by adding refractory to the CEDF, the temperature environment reached the hottest boiler in the range of commercial boilers. Therefore, similar CEDF NO_x levels could be achieved in the commercial boilers.

4 MODELING APPLICATION FOR ULTRA LOW-NO_X PC BURNER AND NO_XOUT® PERFORMANCE OPTIMIZATION

4.1 BURNER AND FURNACE SIMULATIONS

4.1.1 INTRODUCTION

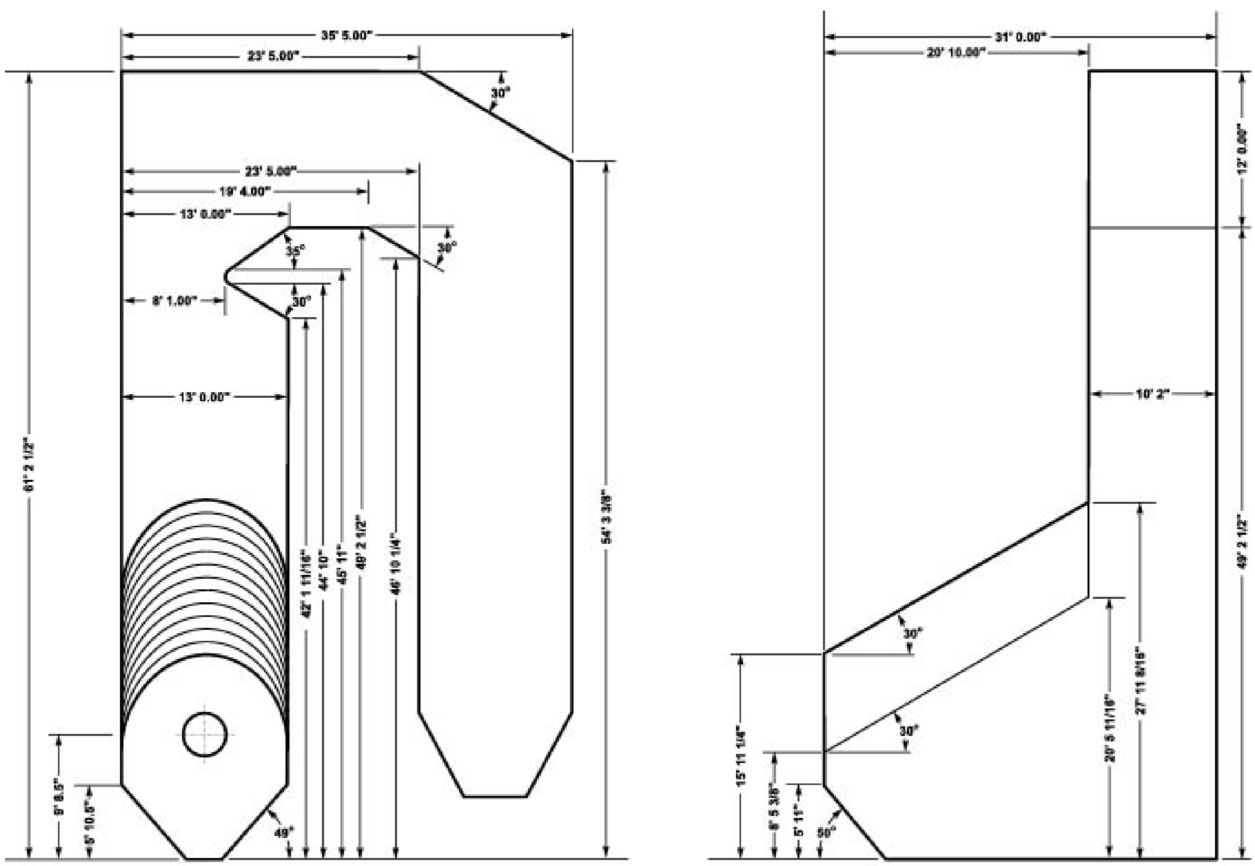
The objective of the burner and furnace simulation models was to generate data sets for the determination of the optimum location for SNCR urea injection in the CEDF. MTI's proprietary flow and combustion modeling code, COMO was used to model the plug-in DRB-4Z™ burner firing three coals. Each coal has been modeled at three loads, 40, 60 and 100 million Btu/hr.

4.1.2 BACKGROUND

COMO (Combustion Model) is a numerical model for predicting turbulent, reacting or non-reacting flow in complex geometries[3,4]. The algorithm is built around a cell-centered, finite volume formulation of the steady, incompressible Navier-Stokes equations and the solution of radiative heat transfer by the discrete ordinates method[5]. Mass and momentum equations are solved on a nonstaggered grid using a projection method; pressure-velocity coupling is achieved using Rhie and Chow interpolation[6]. Turbulence is considered using the k-ε turbulence model[7]. Advection terms are treated using a bounded, high resolution scheme to insure bounded, non-oscillatory solutions in regions of high gradients. For reacting flows, additional transport equations are solved for energy and constituent species. Chemical reactions may be modeled using either a two-step, global mechanism or general multi-step, detailed mechanisms. The model is applicable to unstructured discretizations in either two or three dimensions.

4.1.3 Model Input

The single-burner CEDF furnace and convection pass shown in Figures 4.1 and 4.2 were modeled with COMO, Version 8.10.57. The model is based on as-built furnace dimensions and refractory specifications. The facility geometry was modeled from the burner outlet to the exit of the convection pass, including the tube banks, with 80504 elements using an unstructured mesh generated in Fluent Inc.'s grid generation software GAMBIT version 1.2.4. The model geometry for the plug-in DRB-4Z^{TM} burner firing Decker coal was modified by the removal of the coal nozzle insert which was included in the models for Middle Kittanning and Pittsburgh #8. Tube banks 2A/2B were modeled as a single bundle as were 4A/4B.



CEDF Side Elevation (Relative to Convection Pass) CEDF Front Elevation (Relative to Convection Pass)

Figure 4.1. CEDF Single Burner Geometry

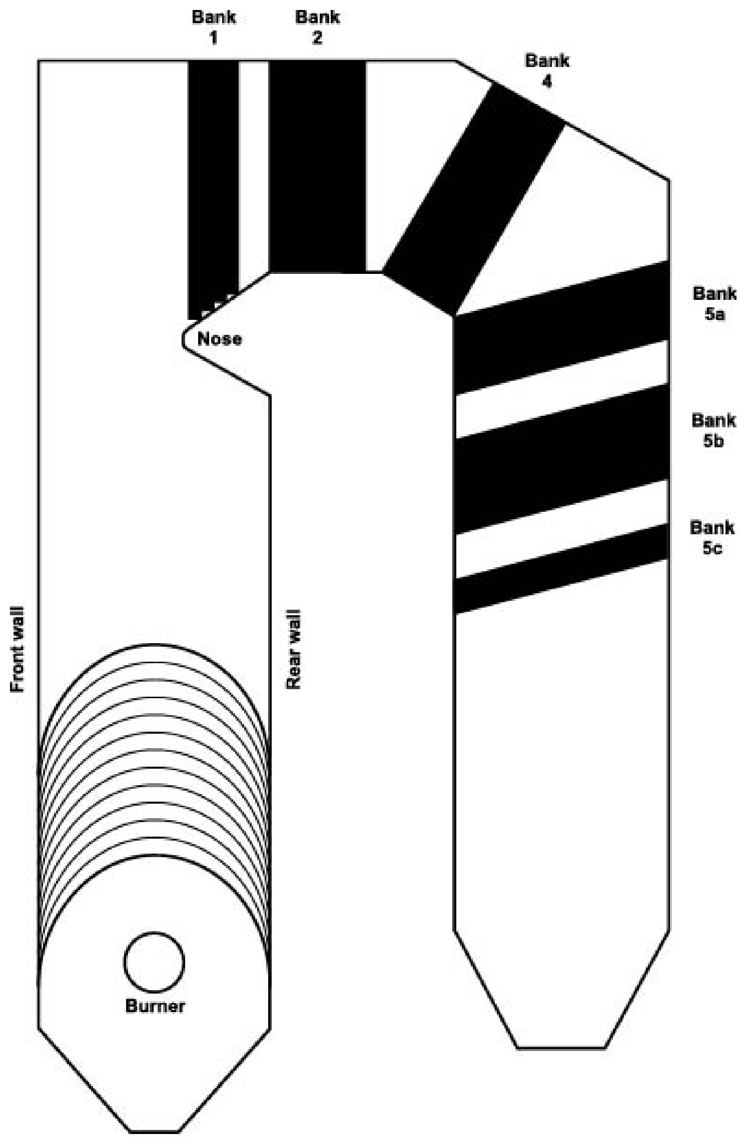


FIGURE 4.2. CEDF CONVECTION PASS ARRANGEMENT

The refractory conductances were obtained from the CEDF design specifications. A uniform surface emissivity of 0.7 was used for tube banks since aging and ash deposits are assumed to have reduced surface emissivity from the original installed values. The bottom of the hopper was modeled with a zero heat flux boundary condition with an emissivity of 0.7. Inertial resistance coefficients were estimated through tube bank correlations from Idelchik[8] and are listed in Table 4.1.

TABLE 4.1. CEDF TUBE BANK RESISTANCE COEFFICIENTS

	X1 (Pa/m)	**X2** (Pa/m)	**X3** (Pa/m)
Bank 1	0.8779	0.0	4.4535
Bank 2A/2B	1.9690	0.0	8.7002
Bank 4A/4B	4.1858	0.0964	2.6361
Bank 5A	3.5359	1.9741	0.3254
Bank 5B	3.5666	1.9823	0.3268
Bank 5C	3.5872	2.0874	0.3441

Coal particle combustion was modeled with a combination of Eulerian and Lagrangian particle transport models. The smallest seventy percent of the distribution (< 71 microns) was modeled using Eulerian transport and the largest thirty percent (> 71 microns) modeled using Lagrangian transport. The combined transport model balances the strengths of the transport models since small particles have negligible slip and are well approximated by Eulerian transport and larger particles are not accurately represented by the Eulerian model. The value of 71 microns was chosen to represent the largest part of the distribution which corresponds to unburned carbon losses. The as-fired coal properties used in the model are listed in Table 4.2, respectively. Coal devolatilization and char oxidation rate parameters were approximated by values for Pittsburgh #8[9].

TABLE 4.2. PULVERIZED COAL PROPERTIES

Ultimate Analysis	**Decker** *As-fired (%)*	**Middle Kittanning** *As-fired (%)*	**Pittsburgh #8** *As-fired (%)*
Carbon	59.00	78.16	72.20
Hydrogen	4.10	4.63	5.02
Sulfur	0.56	0.83	4.34
Oxygen	11.25	3.41	6.16
Nitrogen	0.97	1.37	1.29
Ash	5.11	10.30	8.49
Moisture	19.00	1.30	2.50
HHV (MJ/kg, as-fired)	23.63	31.98	30.49

Model velocity initialization was performed by post-processing model results from a 3D model of the plug-in DRB-4Z™ burner performed earlier. The burner vane configuration was modeled with a 30° inner vane angle and a 45° outer vane angle. The primary and transition air zones were modeled as uniform-nonswirling flows. A coal nozzle insert was included in the model for the Middle Kittanning and Pittsburgh #8 coals to increase the primary air velocity. An air separation model was implemented in the CEDF model.

The pulverized coal size distribution was obtained through an average of 5 sieved size distributions, MTI chemical analyses C23326-C23330. A continuous distribution was obtained by fitting a Rosin-Rammler distribution to the average size distribution.

Nitric oxide was determined by post-processing the flow field. Nitrogen bound in the coal was assumed to be evolved as 80% HCN/20% N_2. The following reactions are included in the global NO_x model.

Global Reactions in NO_x Model

$$\text{Fuel –N} \rightarrow HCN$$
$$HCN + O_2 \rightarrow NO$$
$$HCN + NO \rightarrow N_2$$
$$NO + CH_i \rightarrow HCN$$

4.1.4 RESULTS

The CEDF temperature values at the three elevations are tabulated in Table 4.3. It is encouraging that predictions are reasonably close to measurements after several intervening test campaigns since refractory conductances may have changed due to spalling, slagging and refractory replacement.

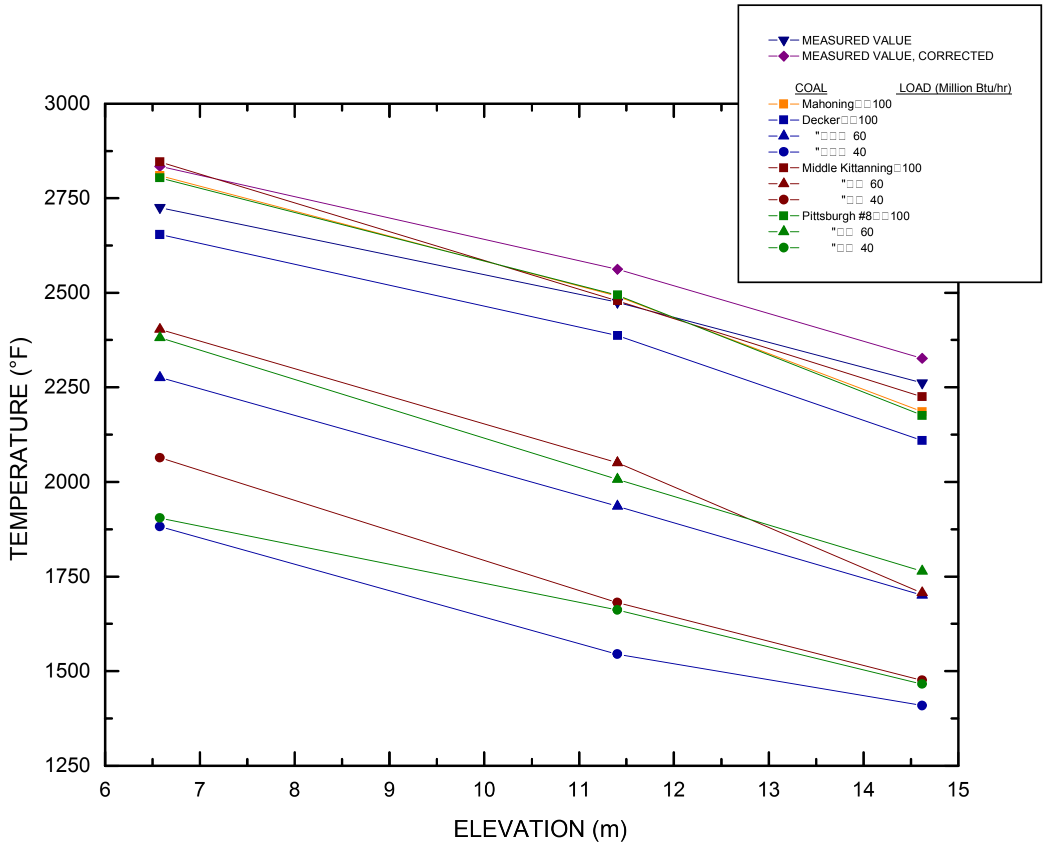


FIGURE 4.3. GAS TEMPERATURE IN THE CEDF FURNACE SHAFT

TABLE 4.3. CEDF MODEL TEMPERATURES

	Decker	**Middle Kittanning**	**Pittsburgh #8**
Temperature (K)			
Position 1 (6.5786 m)			
100 million Btu/hr	2654	2846	2804
60 million Btu/hr	2276	2403	2381
40 million Btu/hr	1882	2064	1905
Position 2 (11.4046 m)			
100 million Btu/hr	2387	2479	2494
60 million Btu/hr	1936	2051	2007
40 million Btu/hr	1545	1681	1662
Position 3 (14.6177 m)			
100 million Btu/hr	2110	2225	2176
60 million Btu/hr	1701	1707	1764
40 million Btu/hr	1409	1476	1466

Model results firing Pittsburgh #8 at full load are shown in Figures 4.4 - 4.9. Figure 4.4 shows temperature contours and velocity vectors at a coordinate plane through the burner centerline. Figure 4.5 shows temperature contours at a coordinate plane midway through the convection pass. Figure 4.6 shows contours of oxygen mole fraction through the burner centerline plane. Figures 4.7 and 4.8 show CO contours through burner centerline planes and convection pass planes, respectively. Figure 4.9 shows NO contours through the burner centerline plane.

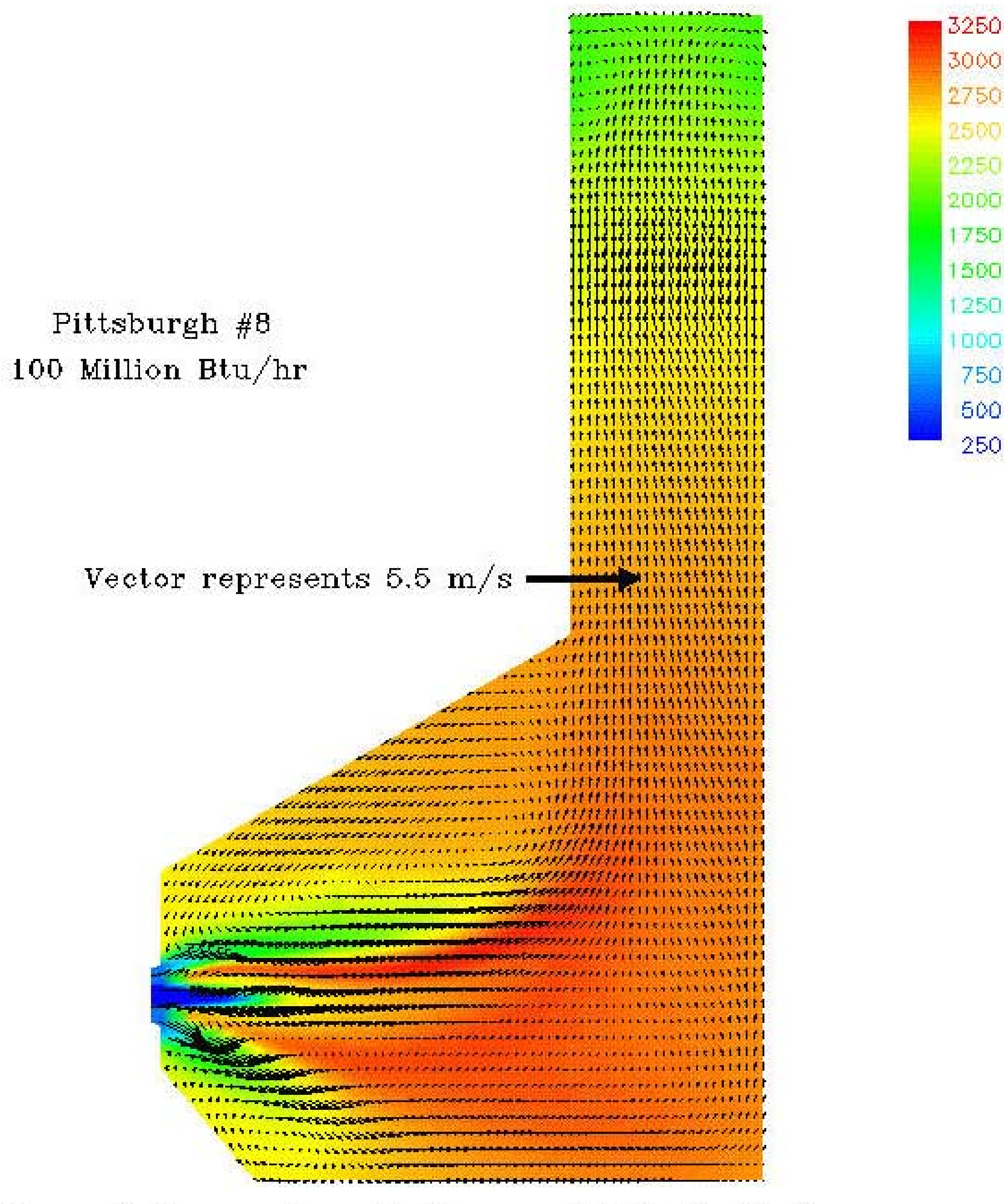


FIGURE 4.4. CEDF TEMPERATURE CONTOURS AND VELOCITY VECTORS WITH PITTSBURGH #8 COAL AT 100 MILLION BTU/HR

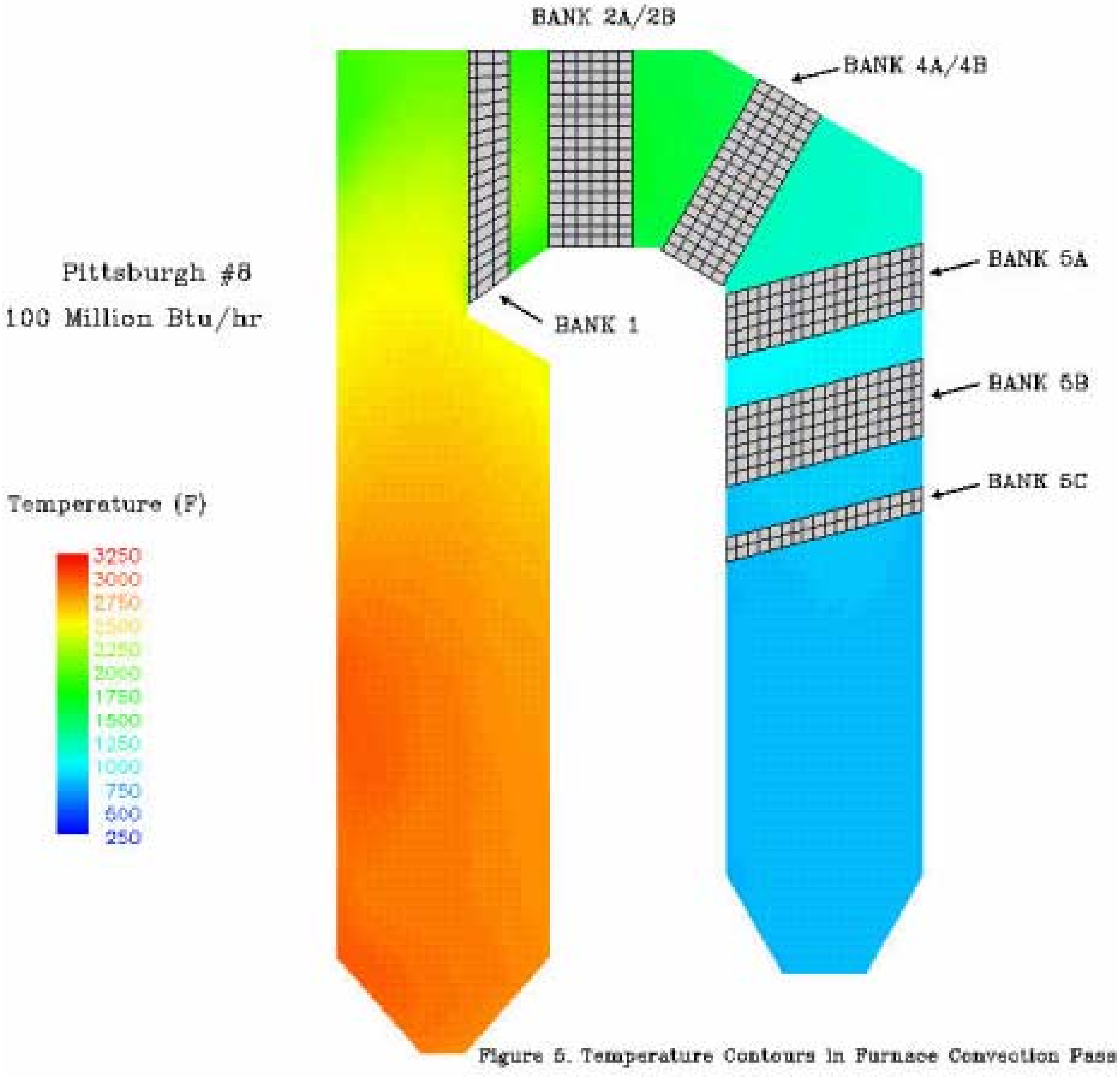


FIGURE 4.5. CEDF TEMPERATURE CONTOURS IN FURNACE CONVECTION PASS WITH PITTSBURGH #8 COAL AT 100 MILLION BTU/HR

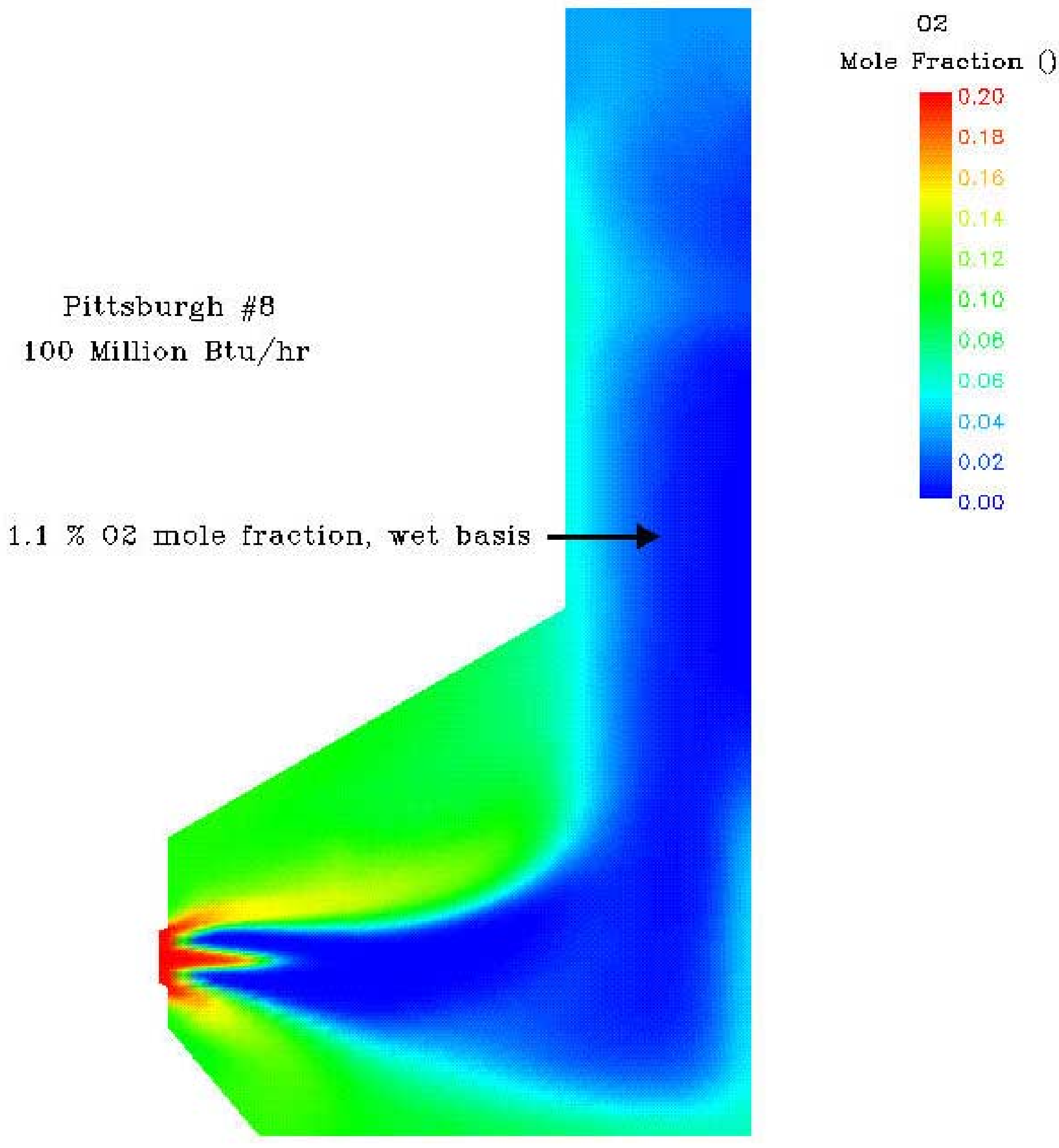


FIGURE 4.6. CEDF CONTOUR OF OXYGEN MOLE FRACTION WITH PITTSBURGH #8 COAL AT 100 MILLION BTU/HR

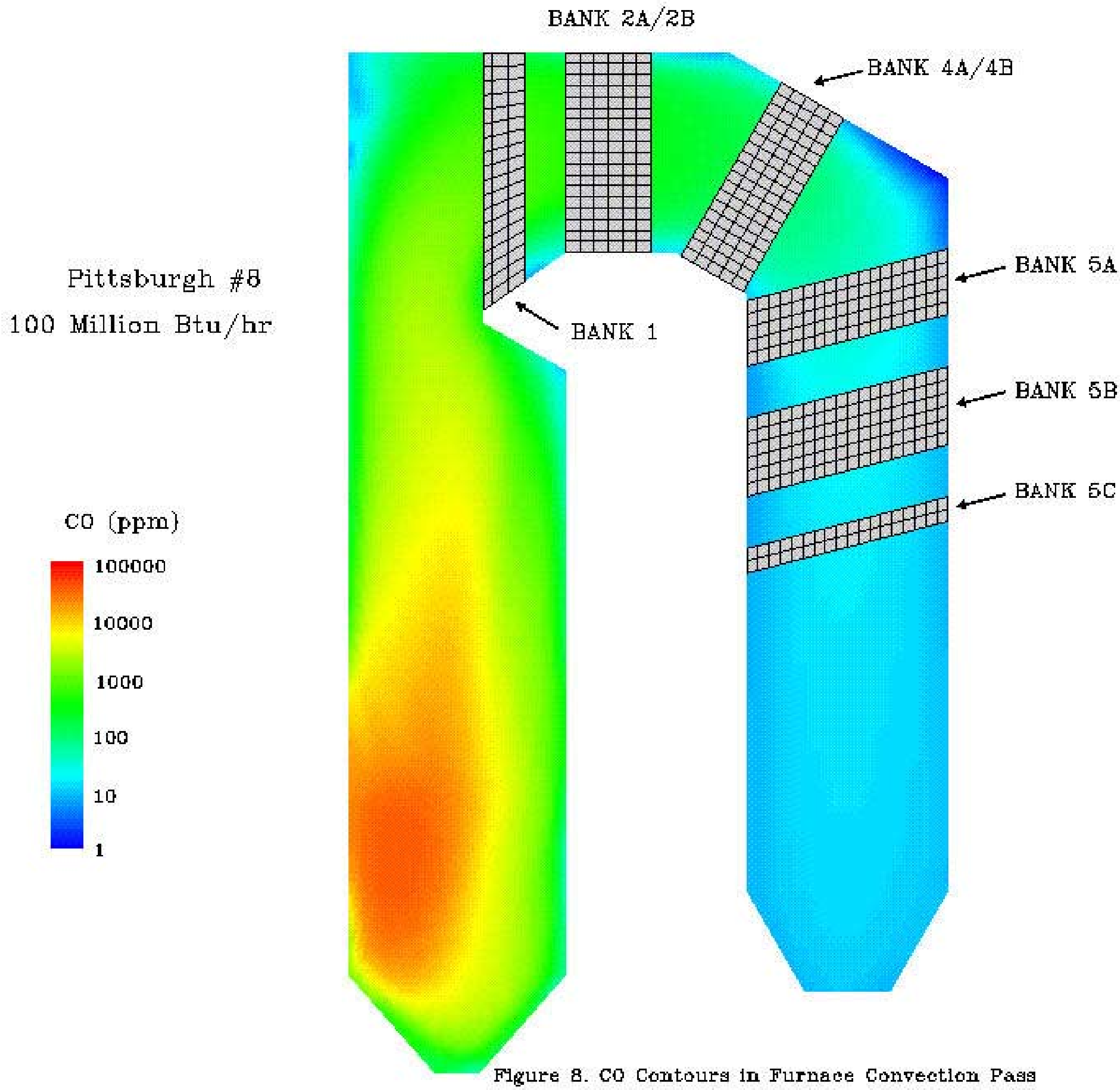


FIGURE 4.7. CEDF CONTOURS OF CO CONCENTRATIONS WITH PITTSBURGH #8 COAL AT 100 MILLION BTU/HR

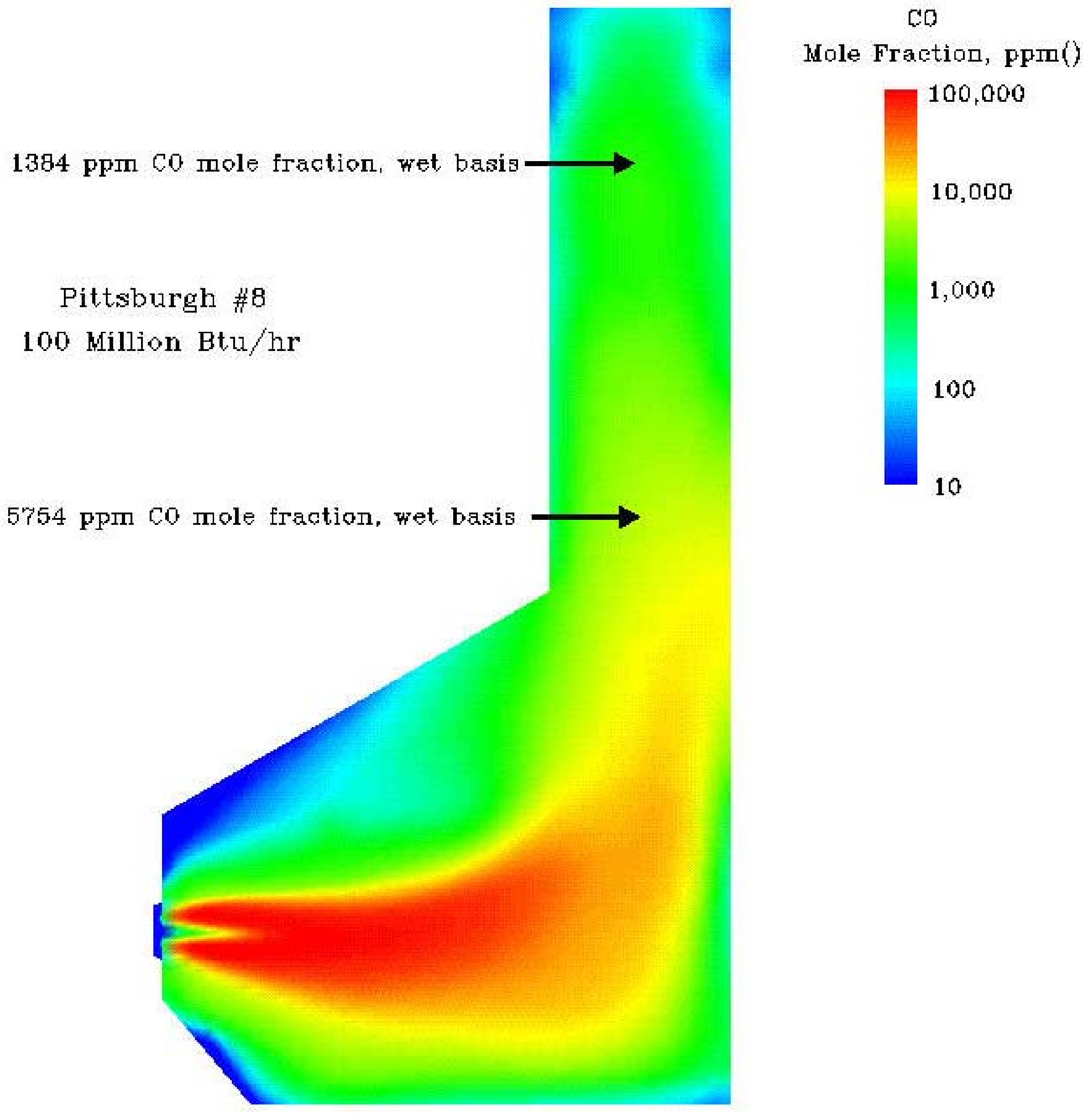


FIGURE 4.8. CEDF CO CONTOURS IN FURNACE CONVECTION PASS WITH PITTSBURGH #8 COAL AT 100 MILLION BTU/HR

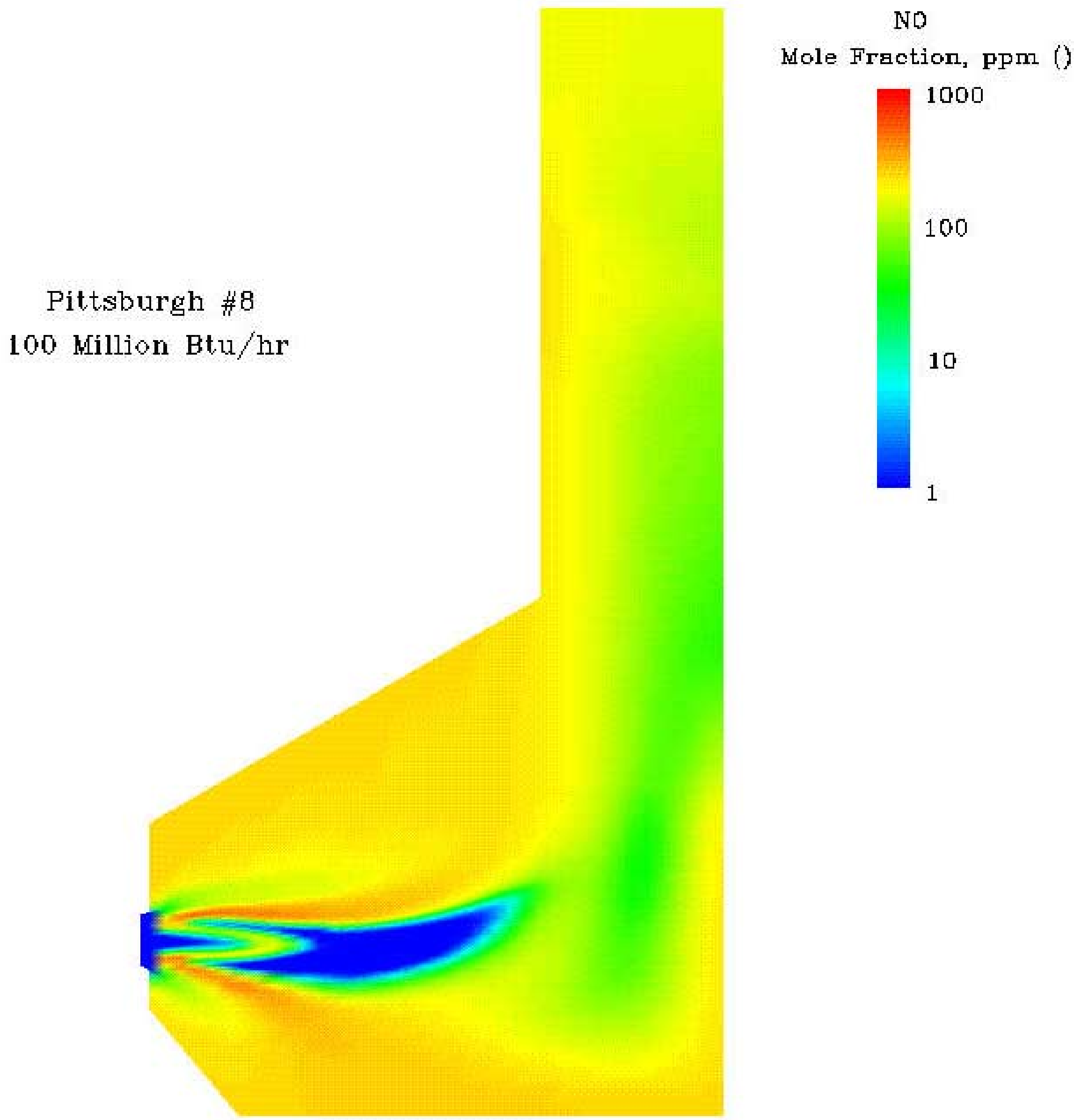


FIGURE 4.9. CEDF NO CONTOURS WITH PITTSBURGH #8 COAL AND AT 100 MILLION BTU/HR

4.1.5 *SUMMARY*

The plug-in DRB-4Z^{TM} burner firing three coals in the CEDF has been modeled at three loads, 40, 60 and 100 million Btu/hr. These cases have been modeled to generate data sets for subsequent post-processing by Fuel Tech, Inc. to determine optimum areas for SNCR urea injection in the convection pass of the CEDF. These data sets were provided to Fuel Tech, Inc. for further analyses.

4.2 ADDITIVE INJECTOR AND SNCR PERFORMANCE SIMULATIONS

4.2.1 *CFD FURNACE MODELS*

The flow pattern, gas velocity, and gas temperatures, were estimated using the CFD furnace model developed by MTI. From these estimates, chemical kinetics model (CKM) results were generated by Fuel Tech which were used to predict the performance of the NO_xOUT® process and identify the optimum temperature ranges in which chemicals should be released. Figures 4.10 through 4.19 are rear and side view plots, through the center of the up-flow section of the furnace, for each fuel. Velocity vectors are superimposed on the contour planes for the rear views.

The three full-load flow fields are significantly different in the region just above the nose. The PRB case, Figure 4.10, describes a large recirculation zone above the "arch", just beyond the nose, that creates a high velocity flow near the top of the convective pass. The medium volatility coal (Middle Kittanning) case at 100 million Btu does not form this recirculation zone at all, Figure 4.16. The main flow remains near the nose with a stagnation zone, and a small back-recirculation, appear near the top of the up-flow section. Finally, the high-volatile bituminous coal full load case reveals high gas velocities along the wall opposite the nose, with a stagnation zone above the arch.

There is no difference in the total gas flow or gas temperatures that would be large enough to justify such variations in the flow field on a steady-state basis. The likely scenario is that the flow filed is unstable in this region and so has many possible solutions. The unsteady nature of the gas circulation in this region of the test facility does not limit the resulting process effectiveness but may introduce additional uncertainty in model predictions.

4.2.1.1 Chemical Kinetics Model

Three operating conditions for each fuel type were considered corresponding to 100%, 60% and 40% load. Temperature-residence time data were computed from the CFD streamlines as input to the chemical kinetics model. Multiple streamlines were generated for each of the three load cases. The streamlines follow the modeled furnace flow beginning at an elevation in the lower furnace. A representative sample of the streamlines was selected and considered to sufficiently describe the temperature distribution within the boiler. CKM modeling was performed on these representative profiles for each of the three load cases.

Several chemical release locations, starting points for the NO_x reduction reactions, were evaluated. The different locations were investigated in order to determine the optimum injection location for each streamline. The results are plotted as a function of chemical release temperature. Initial values of NO_x, CO, and chemical ratio (nitrogen stoichiometric ratio - NSR) were specified at the point of chemical release. The remaining starting species concentrations are the equilibrium concentrations found at the origin of each streamline.

Fuel analysis data were used to generate an expected flue gas composition as required for CKM analysis. Modeling was performed to evaluate the effect of load, chemical injection rate, and chemical location on process effectiveness. The CKM results were obtained under the ideal assumption that there was complete chemical coverage of the flue gas. Chemical coverage is addressed in more detail during injection / injector location analysis.

Achievable NO_x reduction is typically limited at low temperatures by ammonia slip and at high temperatures by a lack of significant NO_x reduction. The identification of temperature limits for desired NO_x control is an important result of CKM analysis.

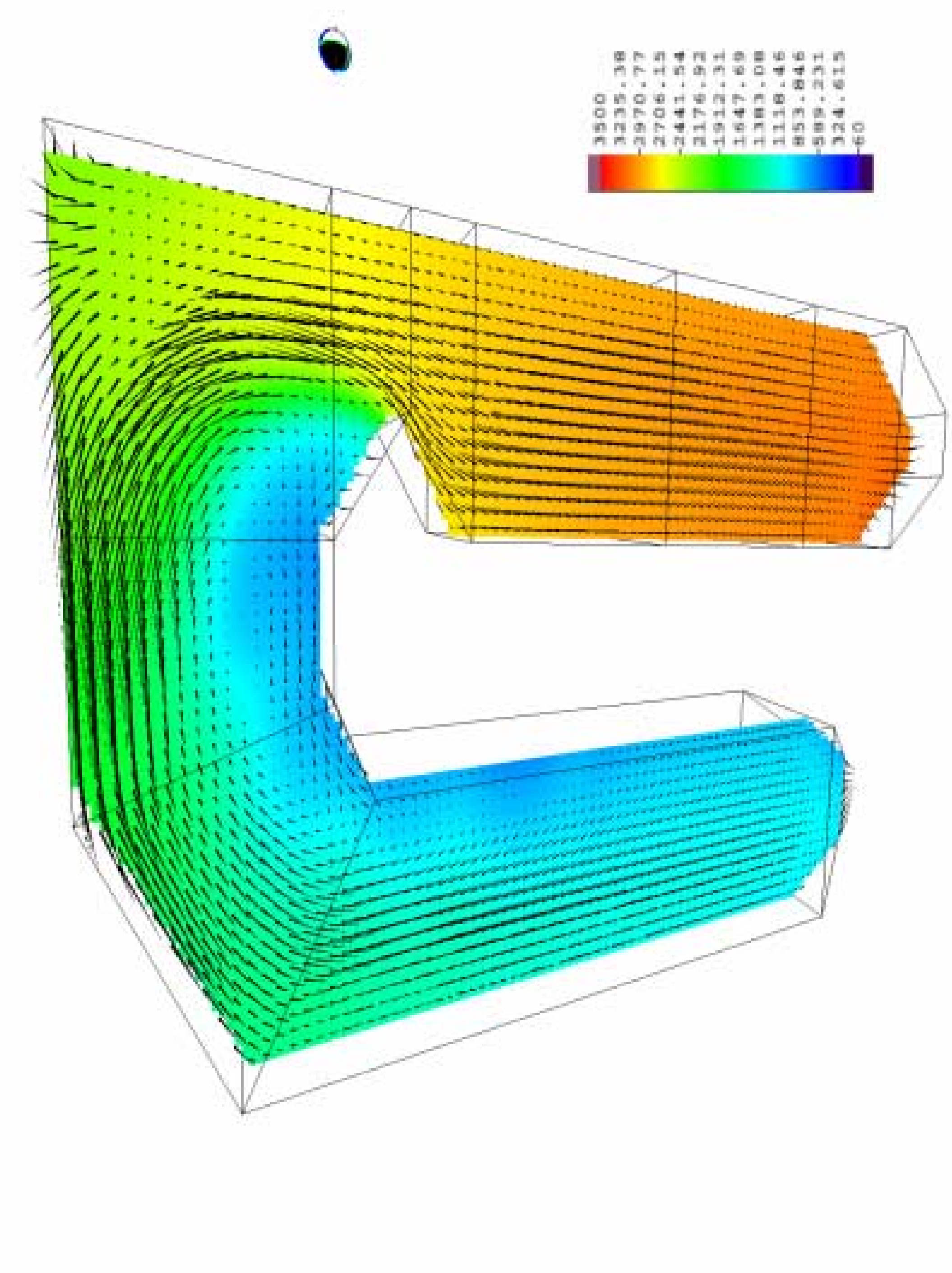


FIGURE 4.10. PRB COAL – 100% LOAD – CFD TEMPERATURE AND VELOCITY RESULTS – REAR VIEW

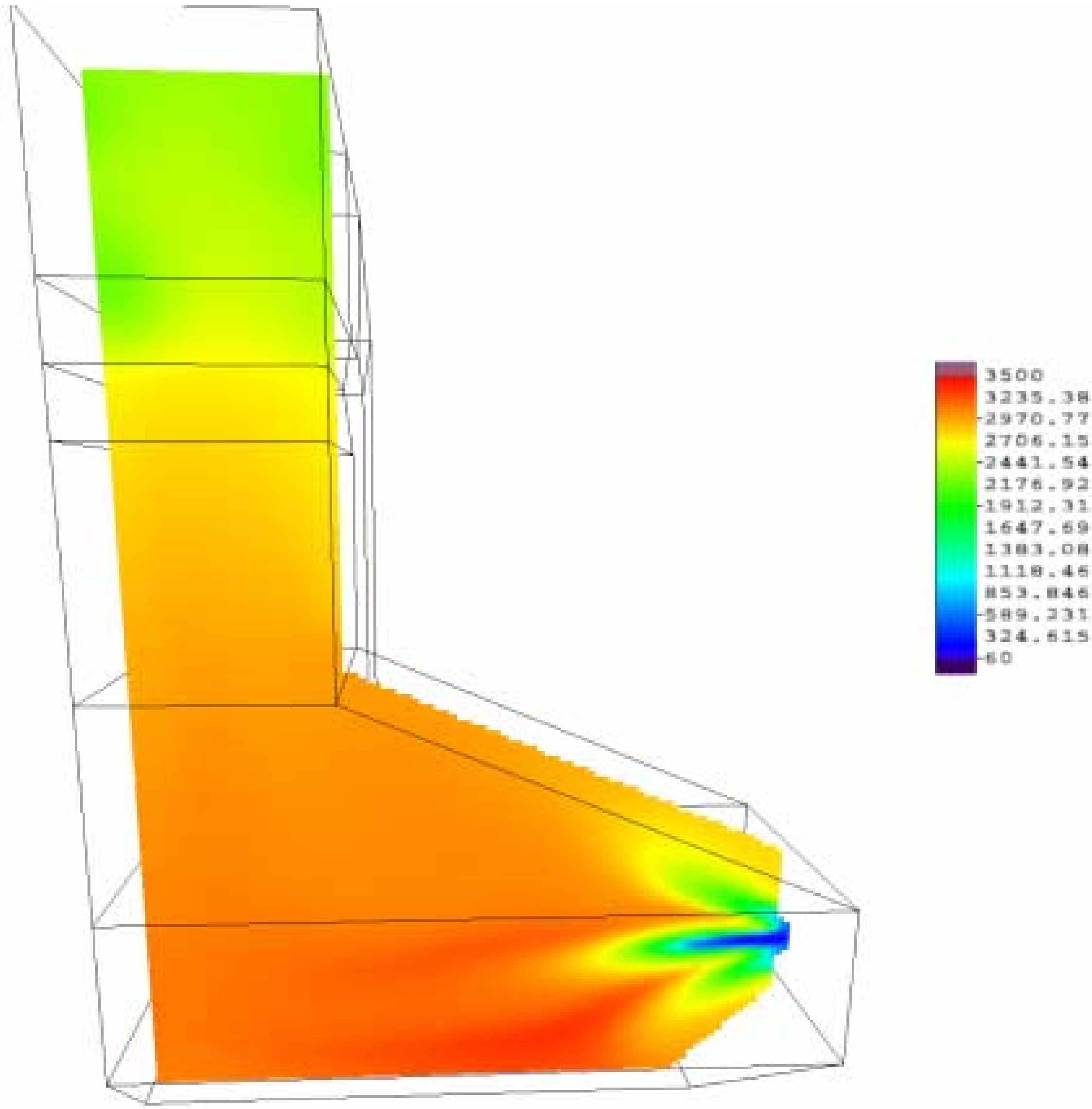


FIGURE 4.11. PRB COAL – 100% LOAD – CFD TEMPERATURE RESULTS – SIDE VIEW

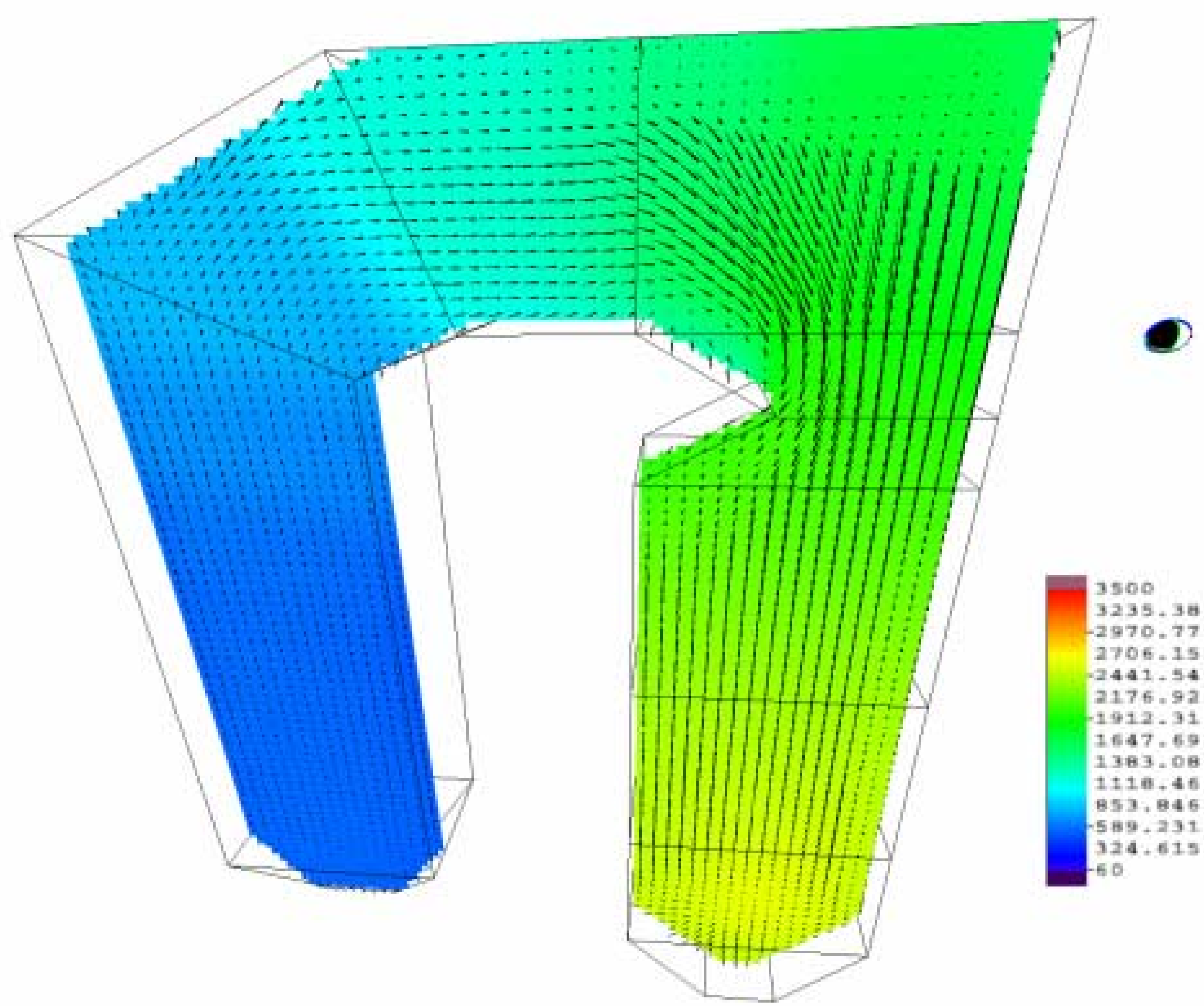


FIGURE 4.12. PRB COAL – 60% LOAD – CFD TEMPERATURE AND VELOCITY RESULTS – REAR VIEW

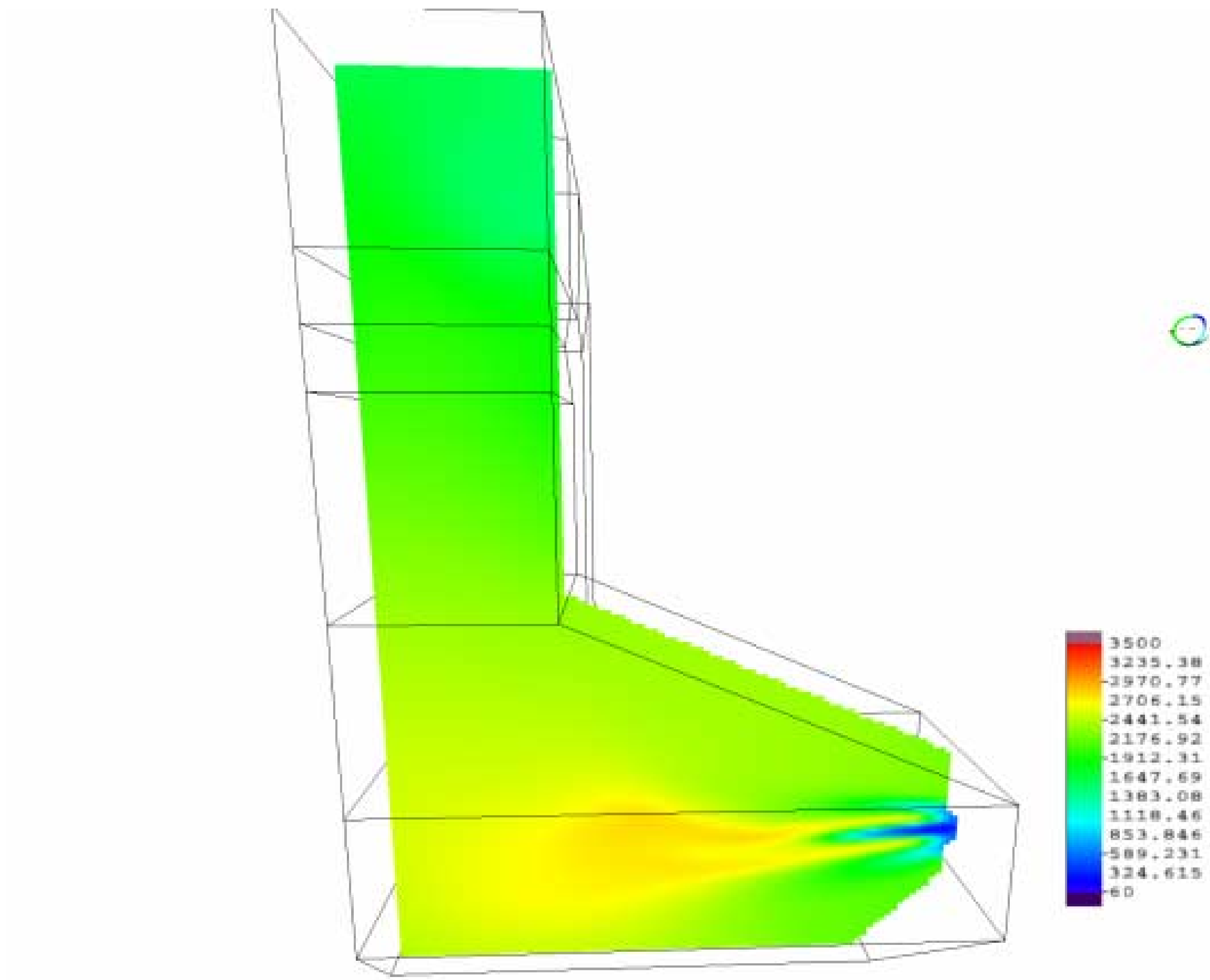


FIGURE 4.13. PRB COAL – 60%LOAD – CFD TEMPERATURE RESULTS – SIDE VIEW

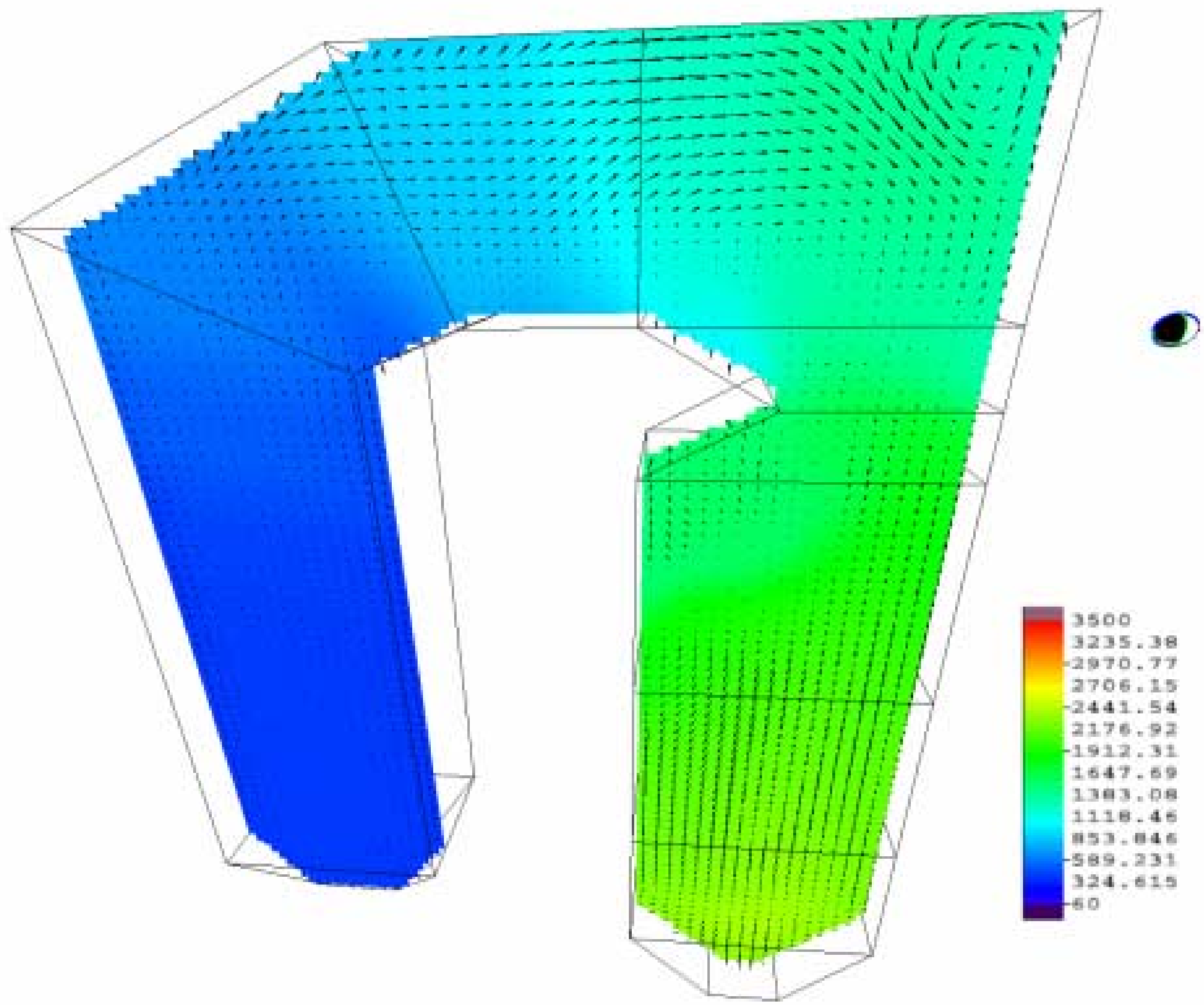


FIGURE 4.14. PRB COAL – 40% LOAD – CFD TEMPERATURE AND VELOCITY RESULTS – REAR VIEW

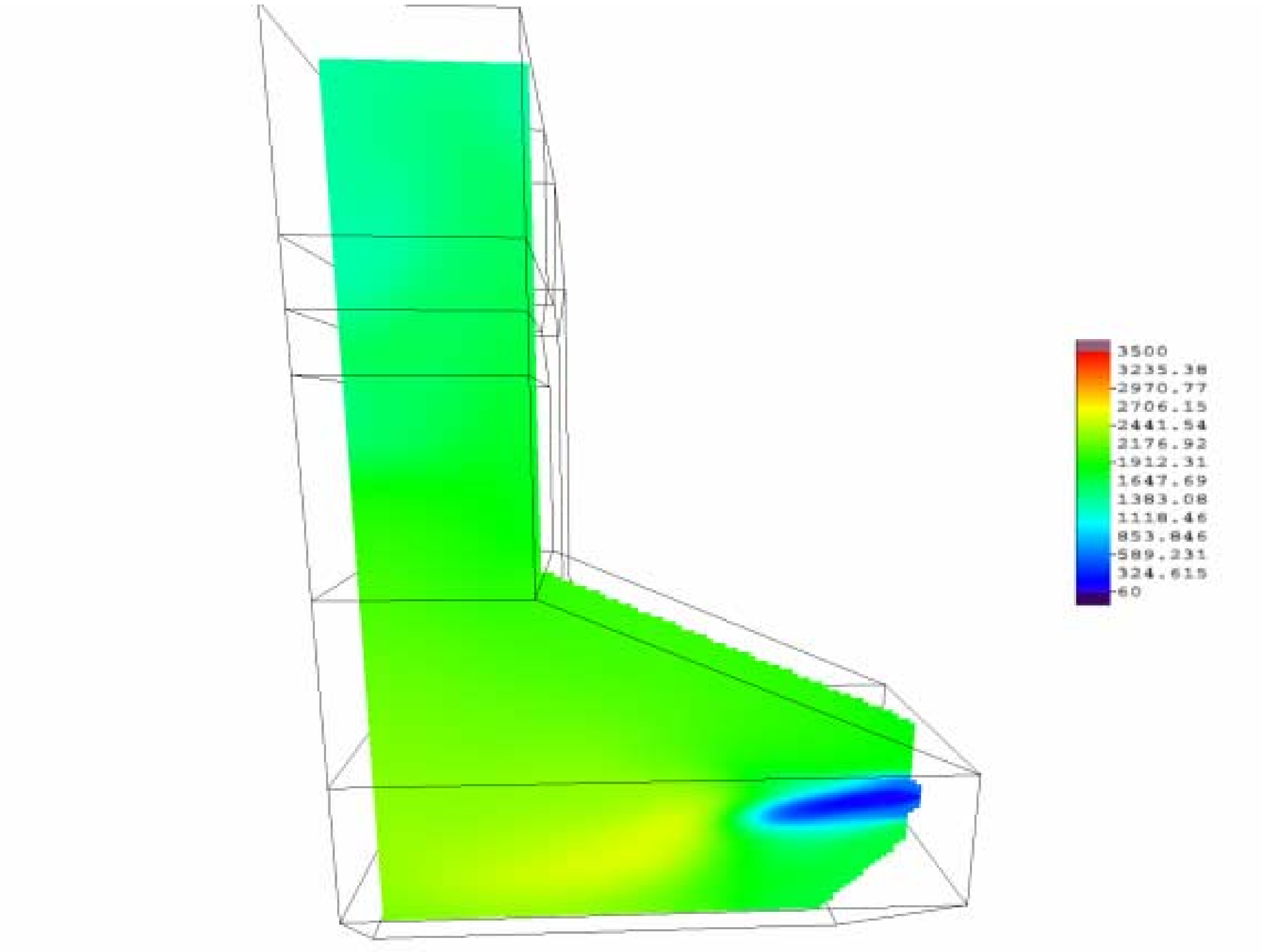


FIGURE 4.15. PRB COAL – 40% LOAD – CFD TEMPERATURE RESULTS – SIDE VIEW

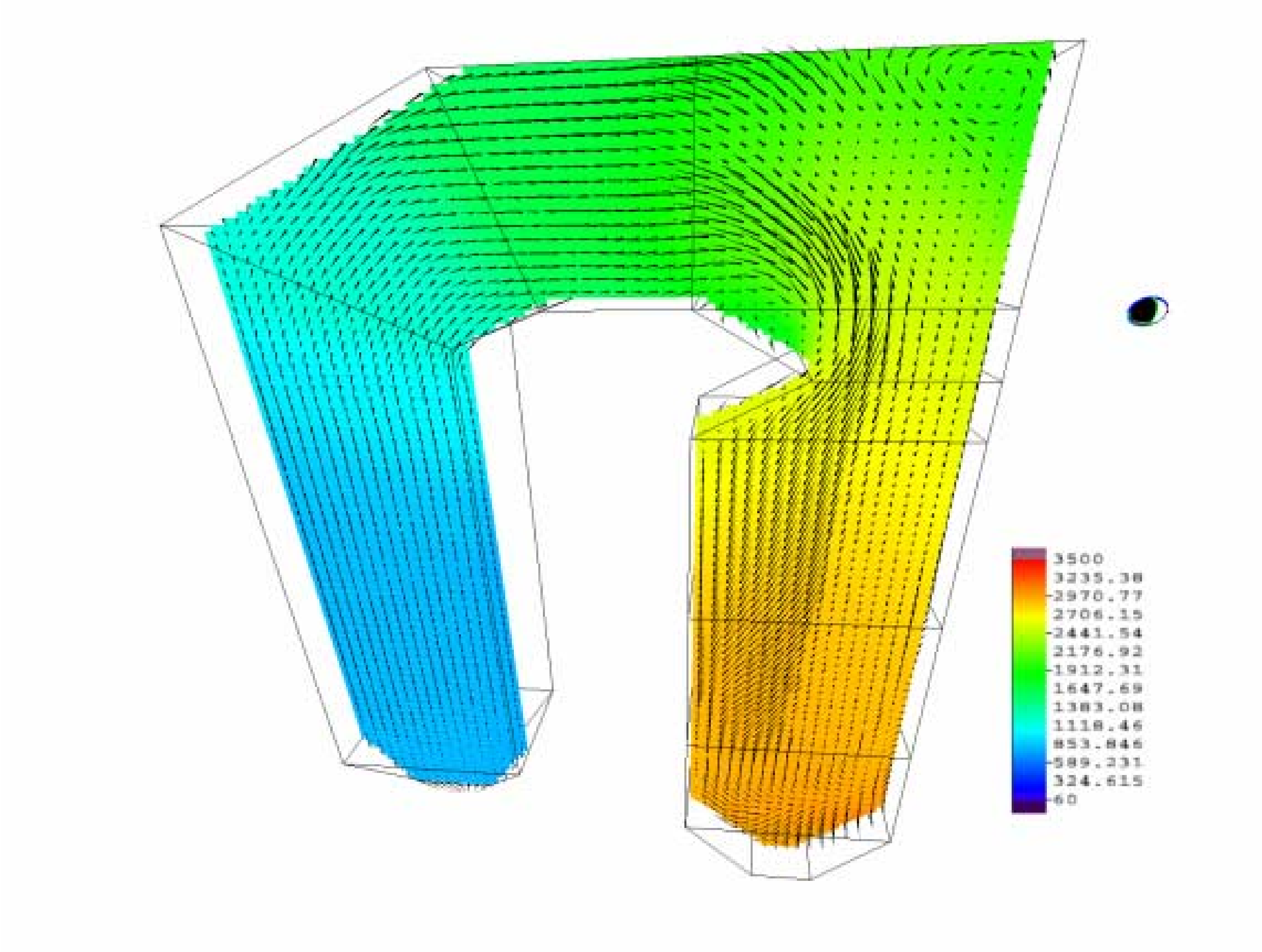


FIGURE 4.16. MK COAL – 100% LOAD – CFD TEMPERATURE AND VELOCITY RESULTS – REAR VIEW

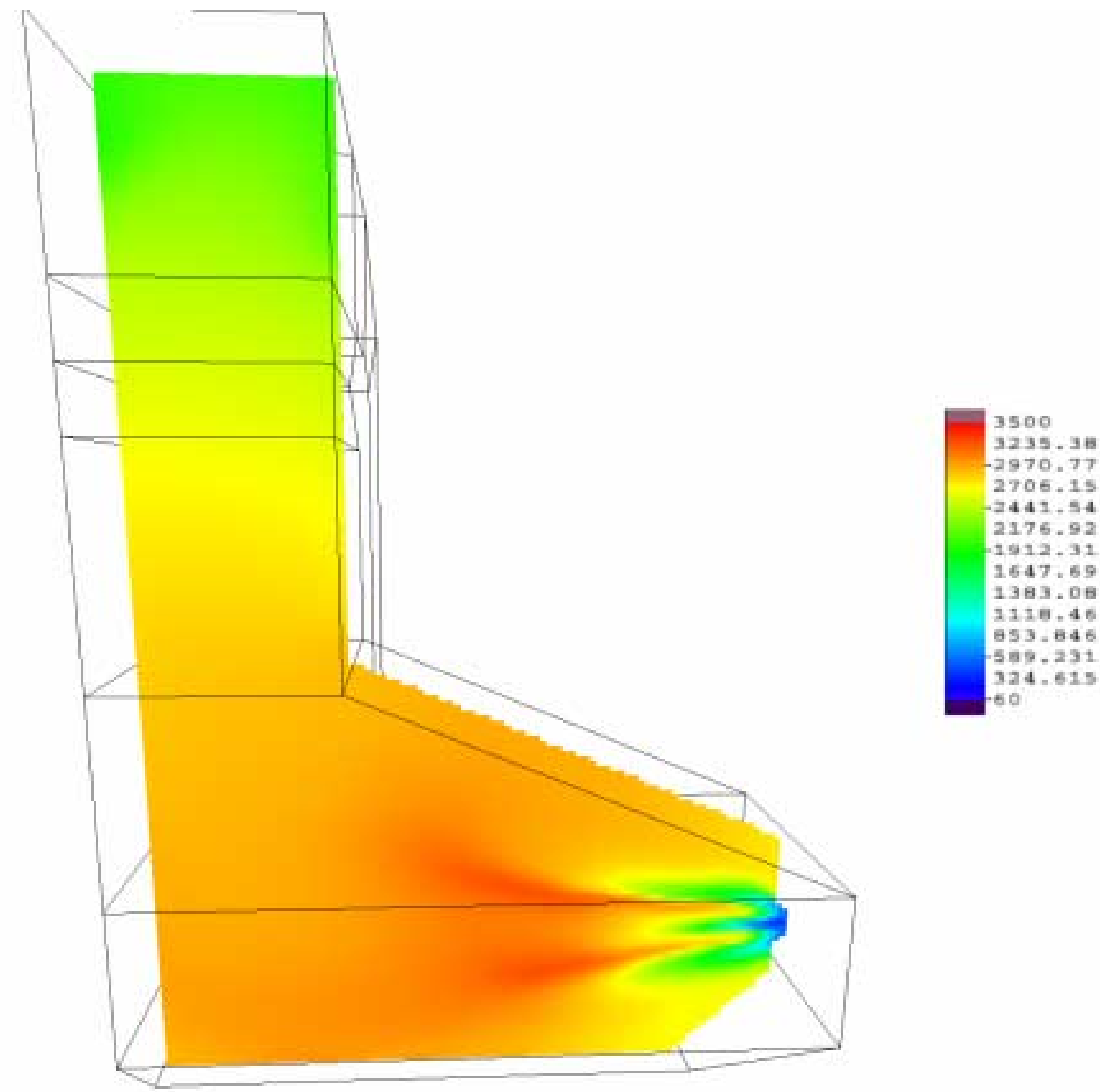


FIGURE 4.17. MK COAL – 100% LOAD – CFD TEMPERATURE RESULTS – SIDE VIEW

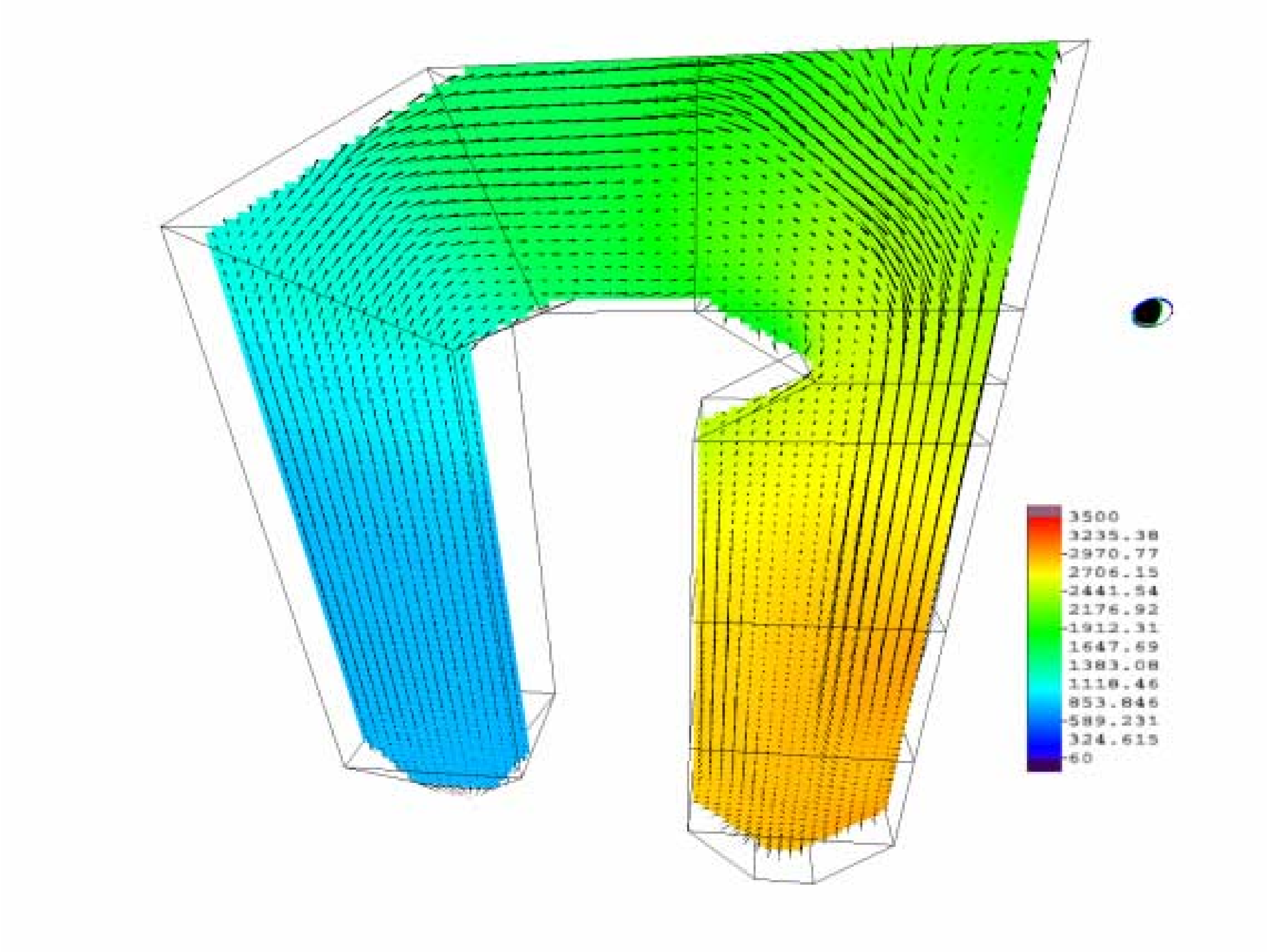


FIGURE 4.18. HVB COAL – 100% LOAD – CFD TEMPERATURE AND VELOCITY RESULTS – REAR VIEW

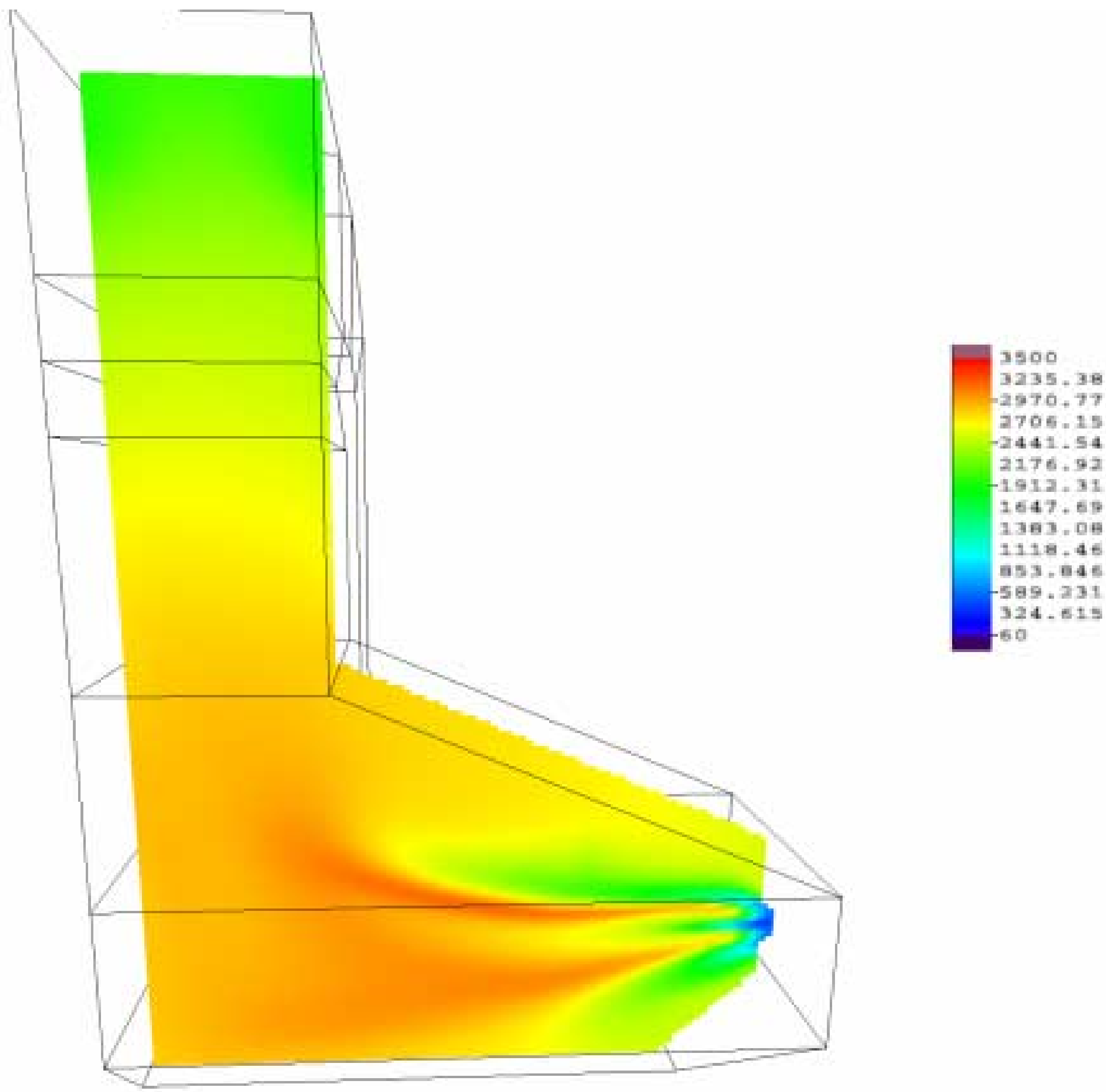


FIGURE 4.19. HVB COAL – 100% LOAD – CFD TEMPERATURE RESULTS – SIDE VIEW

4.2.1.2 PRB COAL CKM

4.2.1.2.1 100% LOAD

For the baseline CKM analysis, an NSR of 1.0 was selected and a CO concentration of 100 ppm at the point of chemical release was assumed. The baseline NO_x level used was 0.27 lb/10^6 Btu. Variation of the CO concentration produces the two CKM cases shown in Figure 4.20. The fraction of NO_x remaining and the NH_3 slip are shown for CO concentrations of 100 ppm, and 300 ppm. For the 100 ppm case, the effective temperature window for NO_x reduction was approximately 1750°F to 2050°F. A maximum reduction of 45% occurred at the minimum release temperature of 1750°F. For the 300 ppm case, the temperature window decreased to between 1650°F and 1950°F.

The model results displayed in Figure 4.21 demonstrate the effect of increasing the NSR from 1.0 to 1.75, using the same CO concentrations as before. The maximum release temperature for the 100 ppm CO case rose to 2125°F from 2050°F, with ammonia slip controllable above 1950°F. A maximum theoretical reduction of 62%, with ammonia slip less than 10 ppm, occurred at the minimum release temperature of 1950°F.

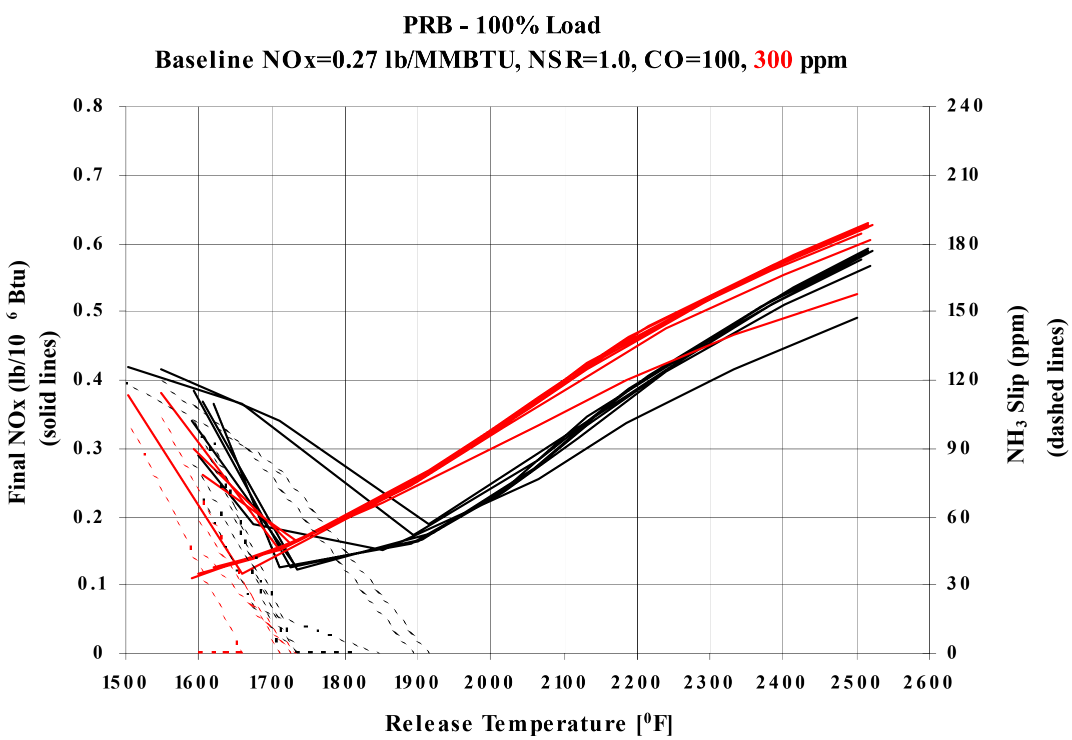


FIGURE 4.20. CEDF MODEL RESULTS WITH A PRB COAL AT 100% LOAD AND A 1.0 NSR

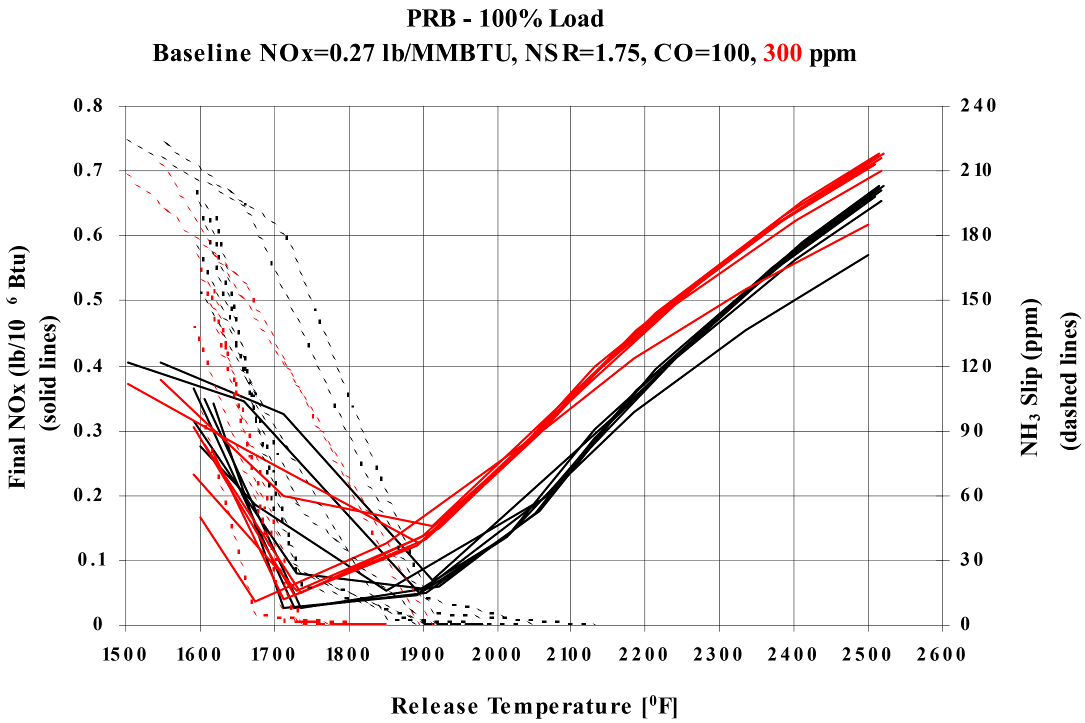


FIGURE 4.21. CEDF MODEL RESULTS WITH A PRB COAL AT 100% LOAD AND A 1.75 NSR

4.2.1.2.2 60% LOAD

This load condition was also modeled using a nominal NSR of 1.0, but a decreased CO concentration of 50 ppm, consistent with measured data, was assumed at the point of chemical release. The baseline NO_x concentration was 0.16 lb/10^6 Btu, and the CO concentration was varied to produce the two CKM cases shown in Figure 4.22. The fraction of NO_x remaining, and the predicted NH_3 slip, is shown for the two CO concentrations of 50 ppm, and 300 ppm. For the 50 ppm case, the effective temperature window for NO_x reduction was approximately 1600°F to 2000°F. A maximum reduction of 50% occurred at the minimum release temperature of 1600°F. For the 300 ppm case, the high temperature limit of the window dropped to 1850°F. The low temperature limit, 1600°F, did not change as this boundary is more dependent on residence time than CO concentration for this case.

The data shown in Figure 4.23 demonstrates the effect of increasing the NSR from 1.0 to 1.75, using the same CO concentrations as before. The maximum release temperature for 50 ppm CO did not change significantly. A maximum theoretical reduction of 65% occurred at the minimum release temperature of 1700°F. For 300 ppm CO, a maximum theoretical reduction of 50%, with ammonia slip of less than 10 ppm, occurred at a release temperature of 1600°F.

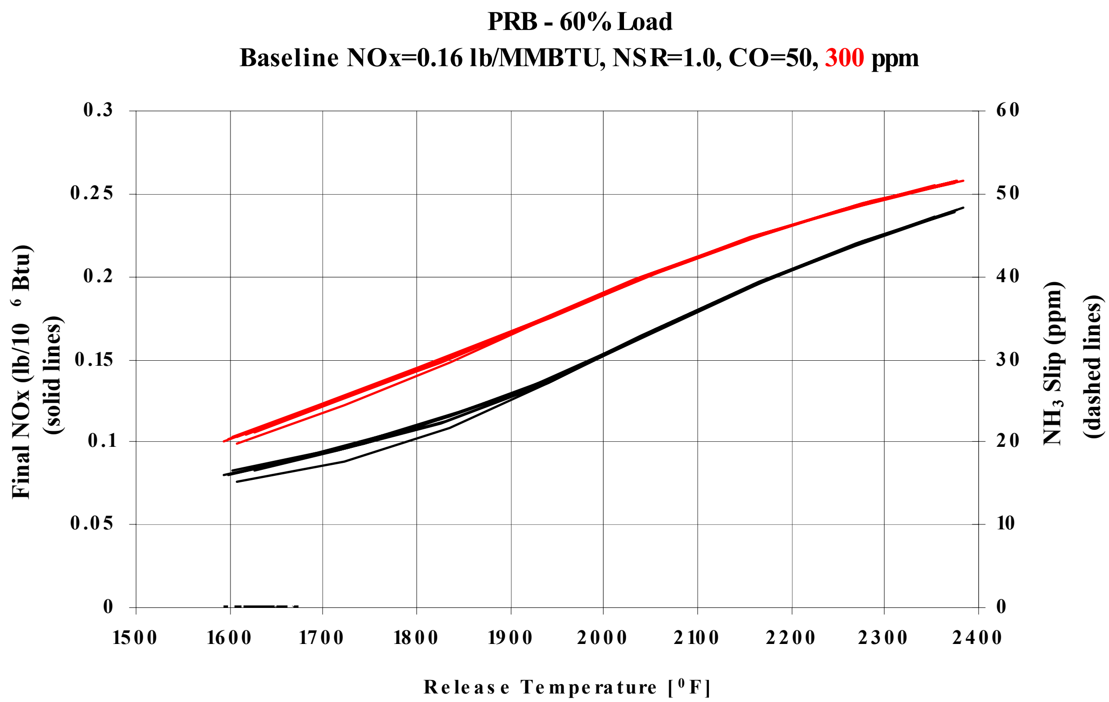


FIGURE 4.22. CEDF MODEL RESULTS WITH A PRB COAL AT 60% LOAD AND A 1.0 NSR

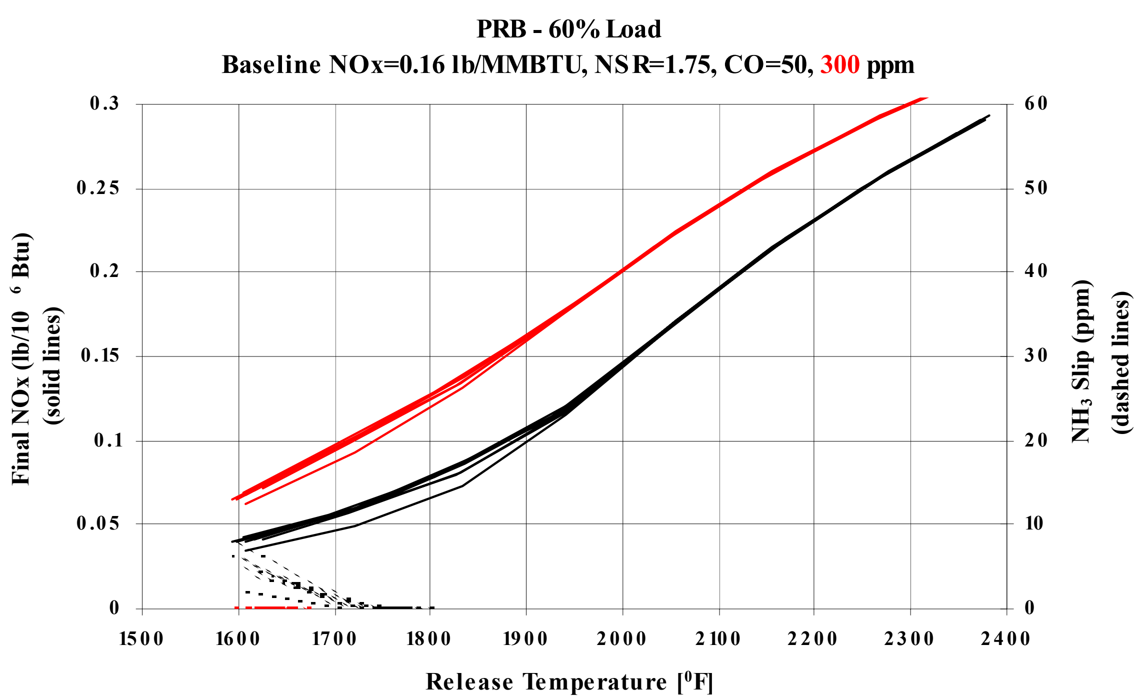


FIGURE 4.23. CEDF MODEL RESULTS WITH A PRB COAL AT 60% LOAD AND A 1.75 NSR

4.2.1.2.3 40% LOAD

The nominal NSR of 1.0 and a CO concentration of 50 ppm were set at the point of chemical release for this analysis. A baseline NO_x concentration of 0.16 lb/10^6 Btu was used to produce the CKM curves shown in Figure 4.24. For this case, the effective temperature window for NO_x reduction was approximately 1600°F to 2075°F. Chemical release at the minimum release temperature produced a 55% NO_x reduction with negligible ammonia slip.

The model results displayed in Figure 4.25 demonstrate the effect of increasing the NSR from 1.0 to 1.75. The maximum release temperature for 50 ppm CO can be extrapolated to approximately 2100°F. A maximum theoretical reduction of 65% occurred at the minimum release temperature of 1700°F. For 300 ppm CO, a maximum theoretical reduction of 50%, with ammonia slip of less than 10 ppm, occurred at a release temperature of 1600°F.

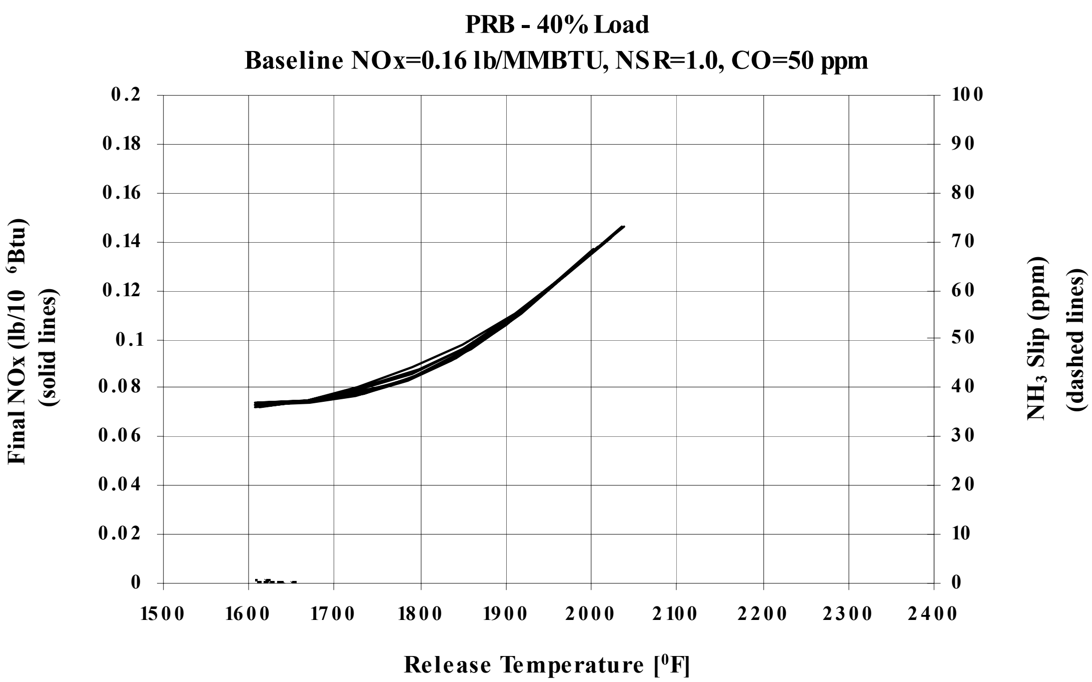


FIGURE 4.24. CEDF MODEL RESULTS WITH A PRB COAL AT 40% LOAD AND A 1.0 NSR

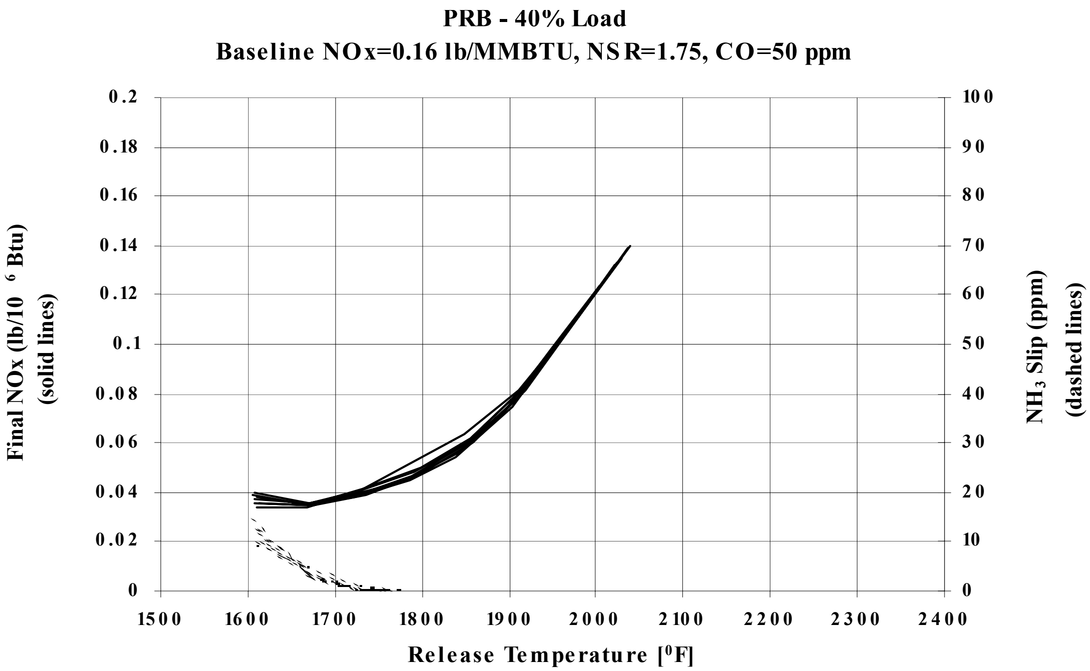


FIGURE 4.25. CEDF MODEL RESULTS WITH A PRB COAL AT 40% LOAD AND A 1.75 NSR

4.2.1.3 <u>*MIDDLE KITTANNING COAL CKM*</u>

All of the CKM cases for this fuel used an NSR of 1.0, and a baseline NO_x concentration of 0.35 $lb/10^6$ Btu for the baseline analysis.

4.2.1.3.1 100% LOAD

For this load, a CO concentration of 100 ppm at the point of chemical release was assumed as shown in Figure 4.26. The fraction of NO_x remaining and the NH_3 slip are shown for CO concentrations of 100 ppm, and 300 ppm. For the 100 ppm case, the effective temperature window for NO_x reduction was approximately 1750°F to 2200°F. A maximum reduction of 70% occurred at the minimum release temperature of 1750°F. For the 300 ppm case, the temperature window sifted to between 1600°F and 2050°F.

The model results, as displayed in Figure 4.27, demonstrate the effect of increasing the NSR from 1.0 to 1.75, using the same CO concentrations of 100 ppm and 300 ppm. The maximum release temperature for 100 ppm CO remained at 2200°F, with ammonia slip becoming excessive below 1800°F. For 100 ppm CO, a maximum theoretical reduction of 85%, with ammonia slip of less than 10 ppm, occurred at a release temperature of 1800°F.

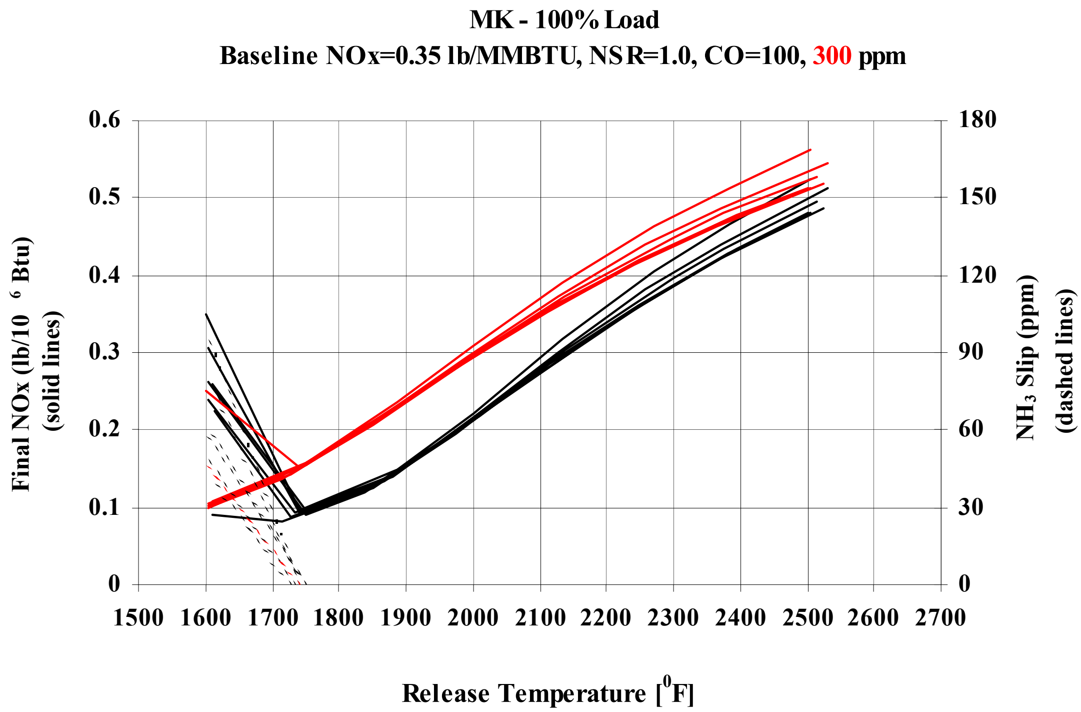


FIGURE 4.26. CEDF MODEL RESULTS WITH MIDDLE KITTANNING COAL AT 100% LOAD AND A 1.0 NSR

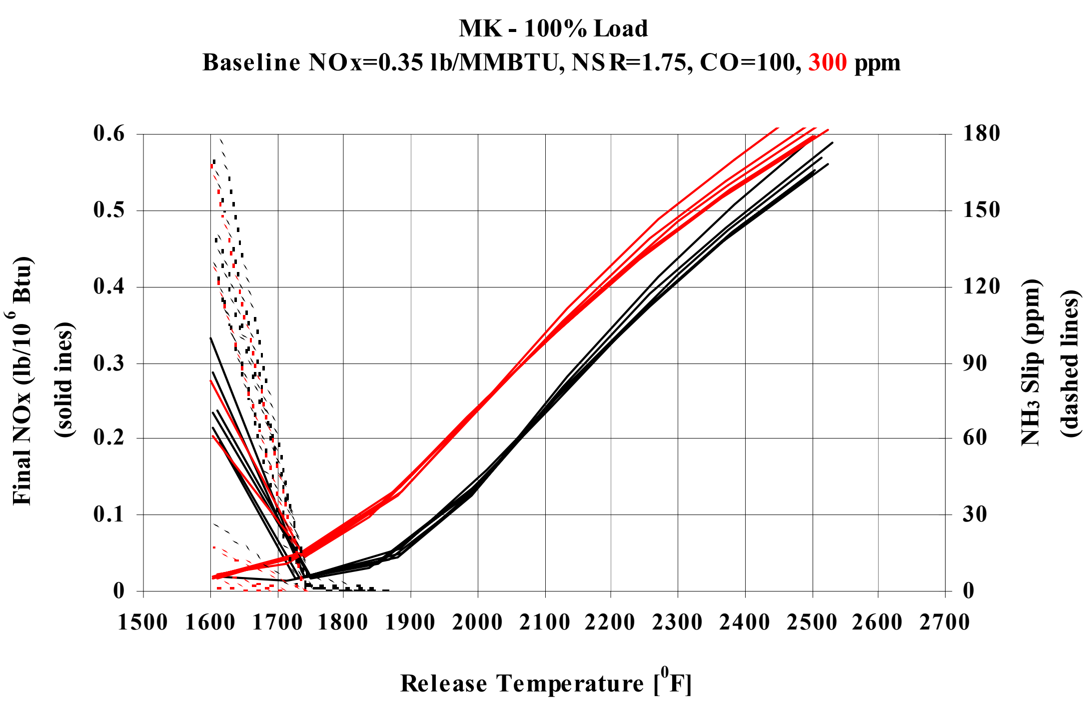


FIGURE 4.27. CEDF MODEL RESULTS WITH MIDDLE KITTANNING COAL AT 100% LOAD AND A 1.75 NSR

4.2.1.3.2 60% LOAD

The results of the CKM are shown in Figure 4.28. A CO concentration of 50 ppm at the point of chemical release was assumed, and the effective temperature window for NO_x reduction was approximately 1750°F to 2350°F. A maximum reduction of 70% occurred at the minimum release temperature of 1750°F.

The effect of increasing the NSR from 1.0 to 1.75, using the same CO concentration as before, is demonstrated by the results in Figure 4.29. The maximum release temperature for 50 ppm CO did not change significantly, and the maximum theoretical reduction of 65% occurred at the minimum release temperature of 1700°F. For 300 ppm CO, a maximum theoretical reduction of 90%, with ammonia slip of less than 10 ppm, occurred at a release temperature of 1750°F.

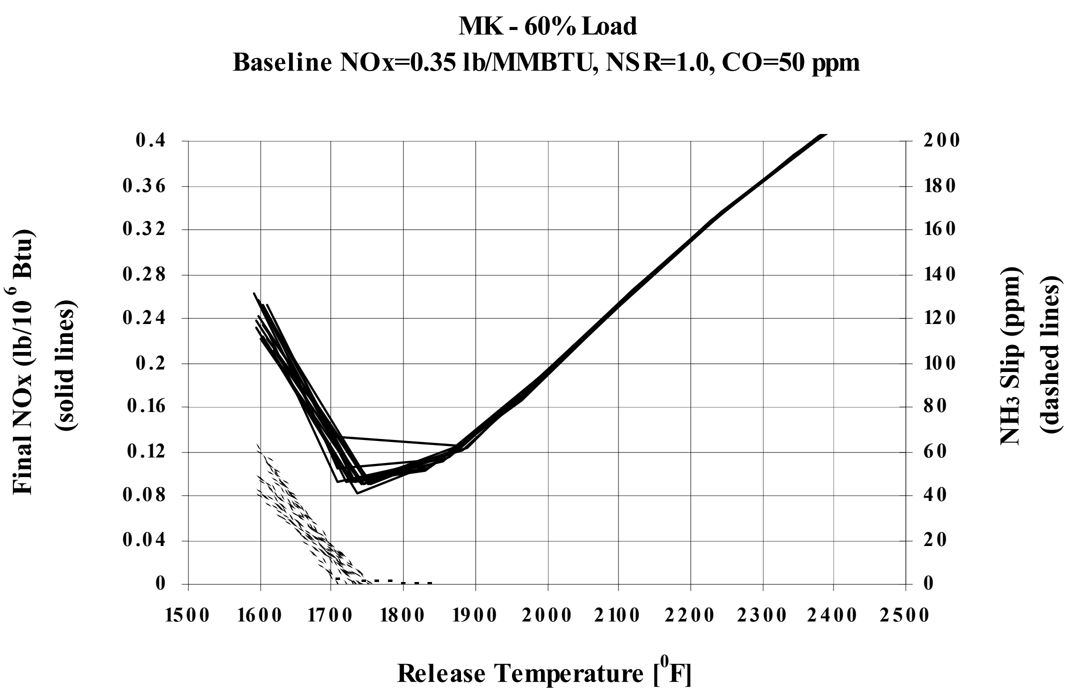


FIGURE 4.28. CEDF MODEL RESULTS WITH MIDDLE KITTANNING COAL AT 60% LOAD AND A 1.0 NSR

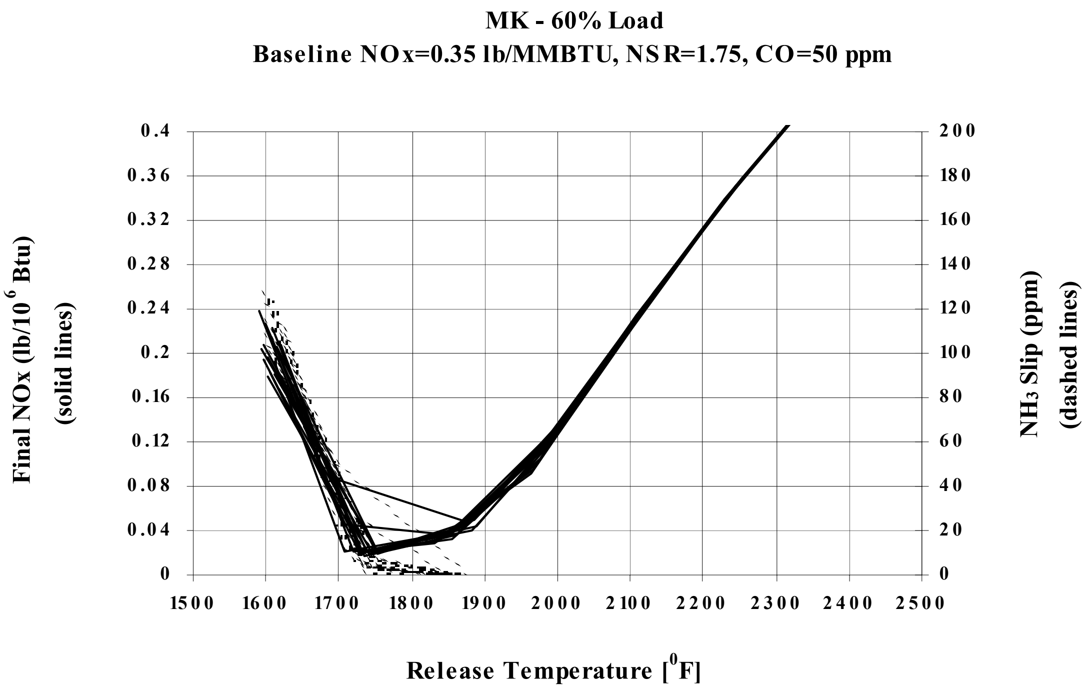


FIGURE 4.29. CEDF MODEL RESULTS WITH MIDDLE KITTANNING COAL AT 60% LOAD AND A 1.75 NSR

4.2.1.3.3 40% LOAD

A CO concentration of 50 ppm at the point of chemical release was assumed for this load, producing the CKM case shown in Figure 4.30. For this case, the effective temperature window for NO_x reduction was approximately 1700°F to 2350°F. A maximum reduction of 75% occurred at the minimum release temperature of 1700°F with negligible ammonia slip.

The model results displayed in Figure 4.31 demonstrate the effect of increasing the NSR from 1.0 to 1.75. The maximum release temperature for 50 ppm CO can be extrapolated to approximately 2300°F and the maximum theoretical reduction of 94% occurred at the minimum release temperature of 1800°F.

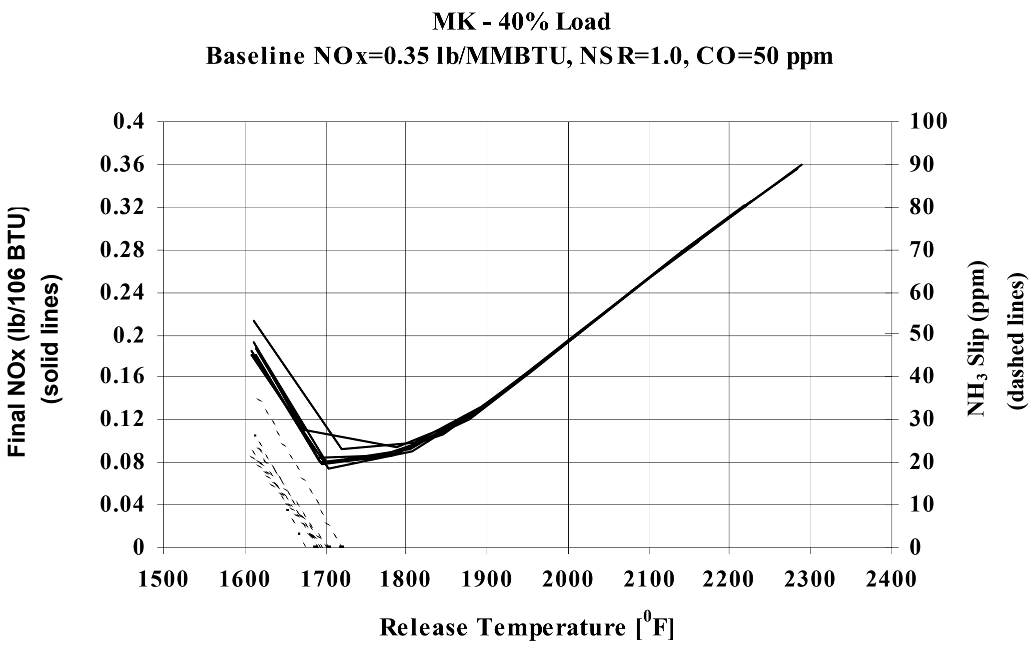


FIGURE 4.30. CEDF MODEL RESULTS WITH MIDDLE KITTANNING COAL AT 40% LOAD AND A 1.0 NSR

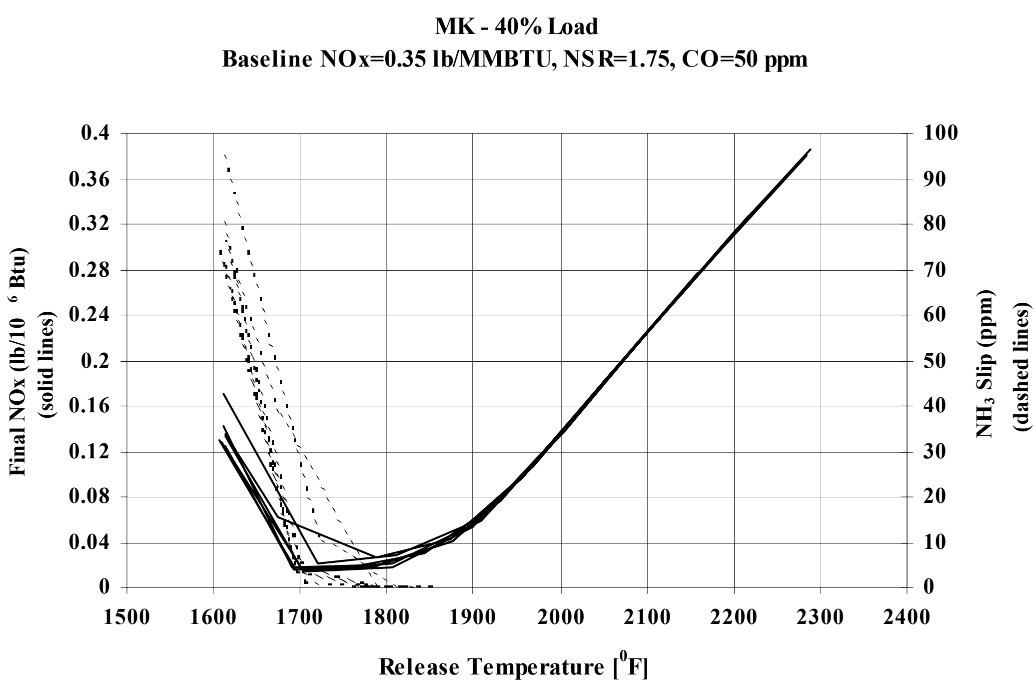


FIGURE 4.31. CEDF MODEL RESULTS WITH MIDDLE KITTANNING COAL AT 40% LOAD AND A 1.75 NSR

4.2.1.4 HIGH-VOLATILE BITUMINOUS COAL CKM

An NSR of 1.0 and a baseline NO_x concentration of 0.19 lb/10^6 Btu were used for the nominal CKM analysis in each of the following cases. Note that the simulations were performed before testing and the measured NO_x Level was higher.

4.2.1.4.1 100% LOAD

For the baseline CKM analysis, a CO concentration of 100 ppm at the point of chemical release was assumed as actual. Variation of the CO concentration produces the two CKM cases shown in Figure 4.32. For the 100 ppm case, the effective temperature window for NO_x reduction was approximately 1600°F to 2050°F. A maximum reduction of 55% occurred at the minimum release temperature of 1600°F. For the 300 ppm case, the temperature window was 1600°F to 1900°F.

The effects of raising the NSR from 1.0 to 1.75, using the same CO concentrations as before, are displayed in Figure 4.33. The maximum release temperature for 100 ppm CO remained at 2050°F, with ammonia slip becoming excessive below 1700°F. For 100 ppm CO, a maximum theoretical reduction of 78%, with ammonia slip of less than 10 ppm, occurred at a release temperature of 1700°F.

4.2.1.4.2 60% LOAD

For this load, a CO concentration of 50 ppm at the point of chemical release was assumed. The results of the CKM analysis for this case are shown in Figure 4.34. The effective temperature window for NO_x reduction was approximately 1750°F to 2250°F, and a maximum reduction of 66% occurred at the minimum release temperature of 1750°F.

The model results displayed in Figure 4.35 demonstrate the effect of increasing the NSR from 1.0 to 1.75, using the same CO concentration as before. The maximum release temperature for 50 ppm CO did not change significantly. A maximum theoretical reduction of 78% occurred at the minimum release temperature of 1850°F.

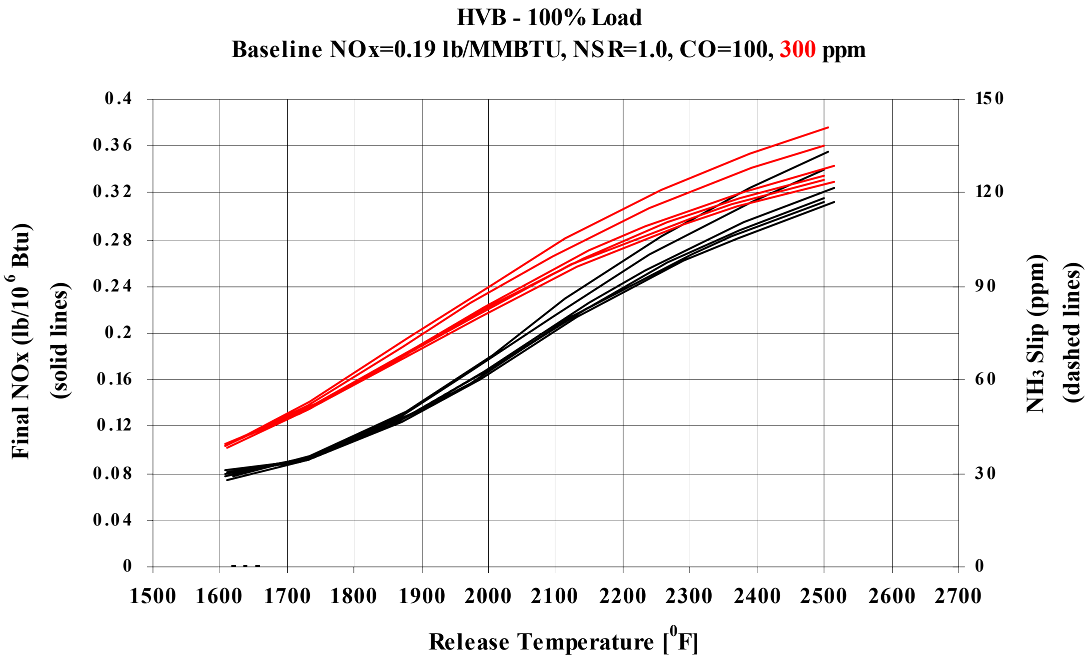


FIGURE 4.32. CEDF MODEL RESULTS WITH A HVB COAL AT 100% LOAD AND A 1.0 NSR

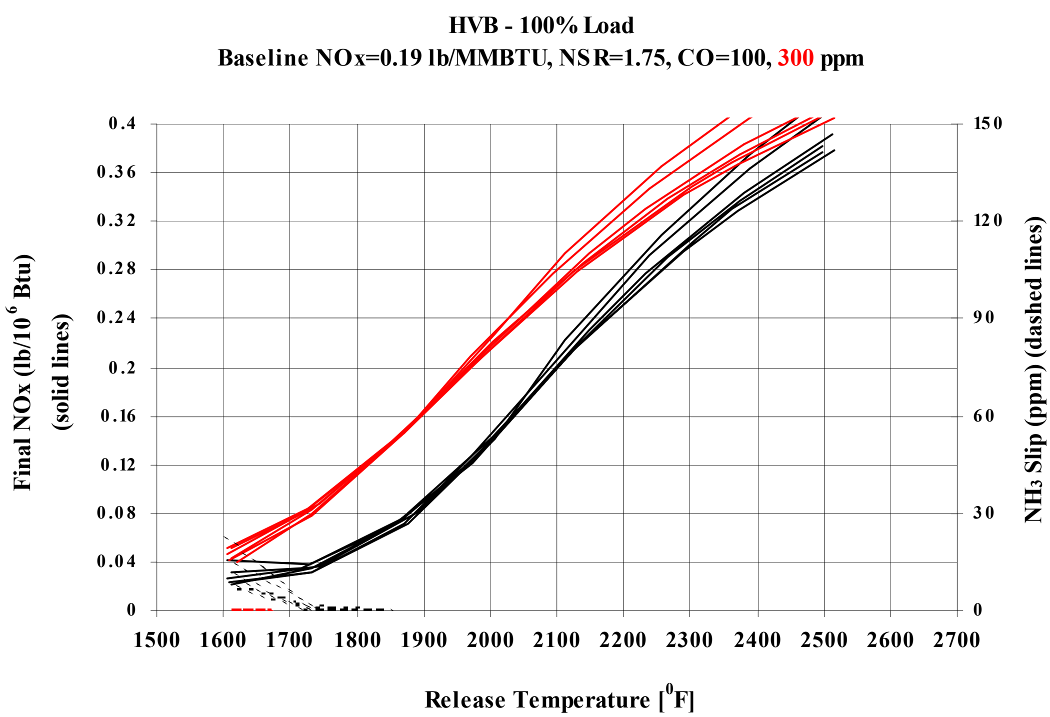


FIGURE 4.33. CEDF MODEL RESULTS WITH A HVB COAL AT 100% LOAD AND A 1.75 NSR

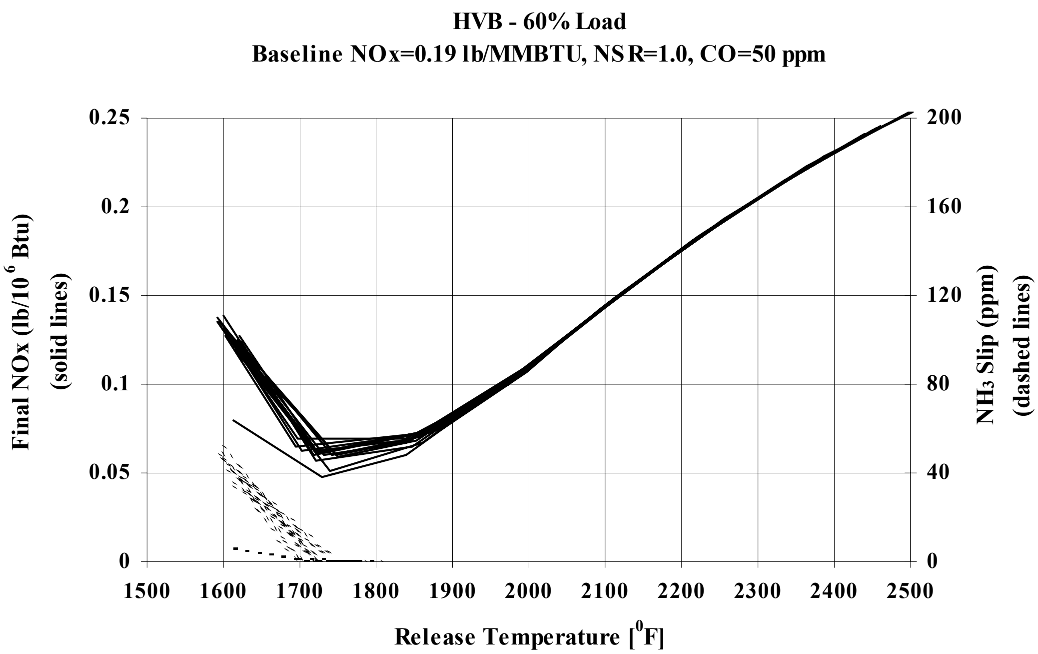


FIGURE 4.34. CEDF MODEL RESULTS WITH A HVB COAL AT 60% LOAD AND A 1.0 NSR

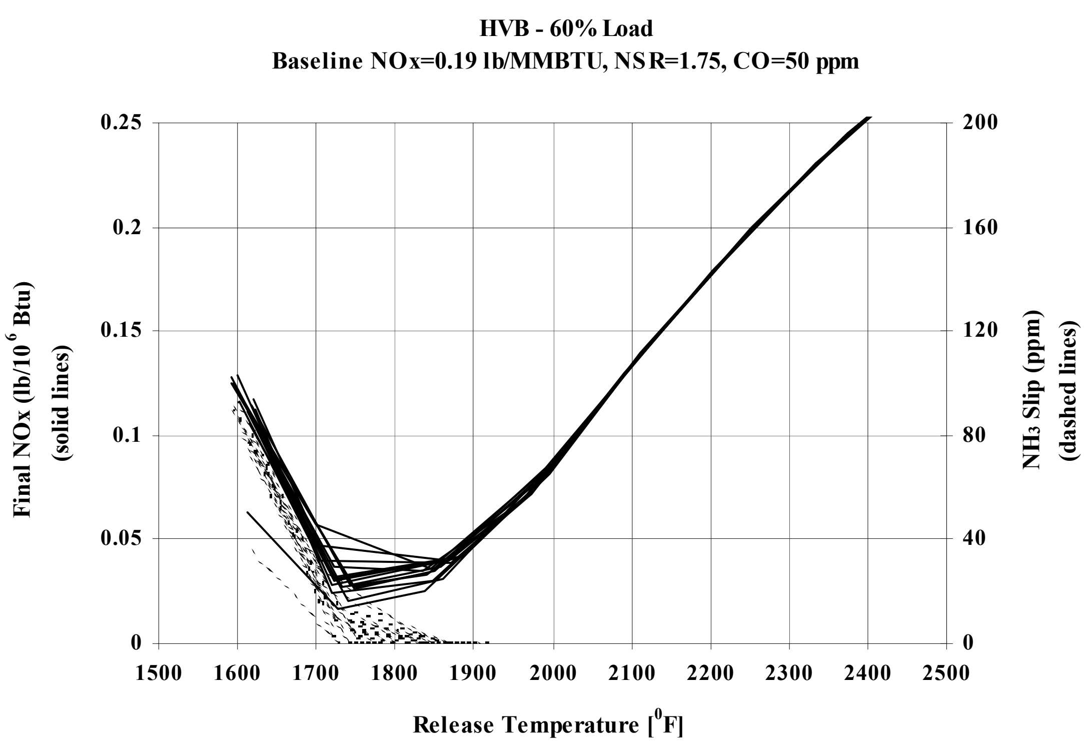


FIGURE 4.35. CEDF MODEL RESULTS WITH A HVB COAL AT 60% LOAD AND A 1.75 NSR

4.2.1.4.3 40% LOAD

As in the 60% load case, a CO concentration of 50 ppm at the point of chemical release was assumed. The CKM results are shown in Figure 4.36. For this case, the effective temperature window for NO_x reduction did not change significantly from the 60% load case and was approximately 1700°F to 2250°F. A maximum reduction of 73% occurred at the minimum release temperature of 1700°F with negligible ammonia slip.

The model results displayed in Figure 4.37 demonstrate the effect of increasing the NSR from 1.0 to 1.75. The maximum release temperature for 50 ppm CO can be extrapolated to approximately 2300°F. A maximum theoretical reduction of 94% occurred at the minimum release temperature of 1800°F.

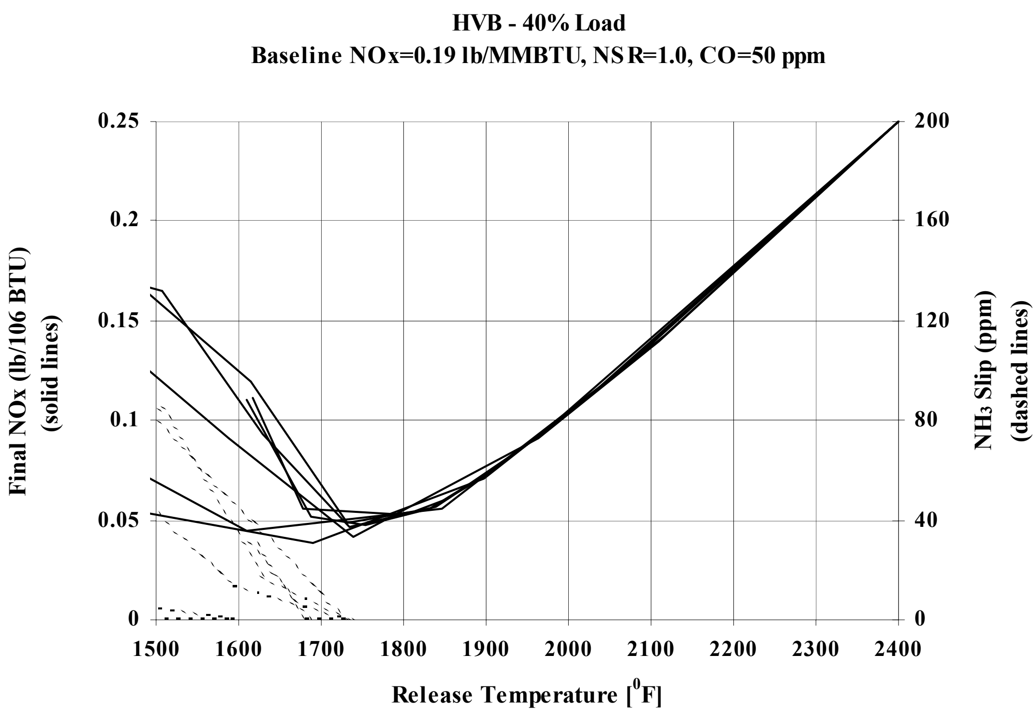


FIGURE 4.36. CEDF MODEL RESULTS WITH A HVB COAL AT 40% LOAD AND A 1.0 NSR

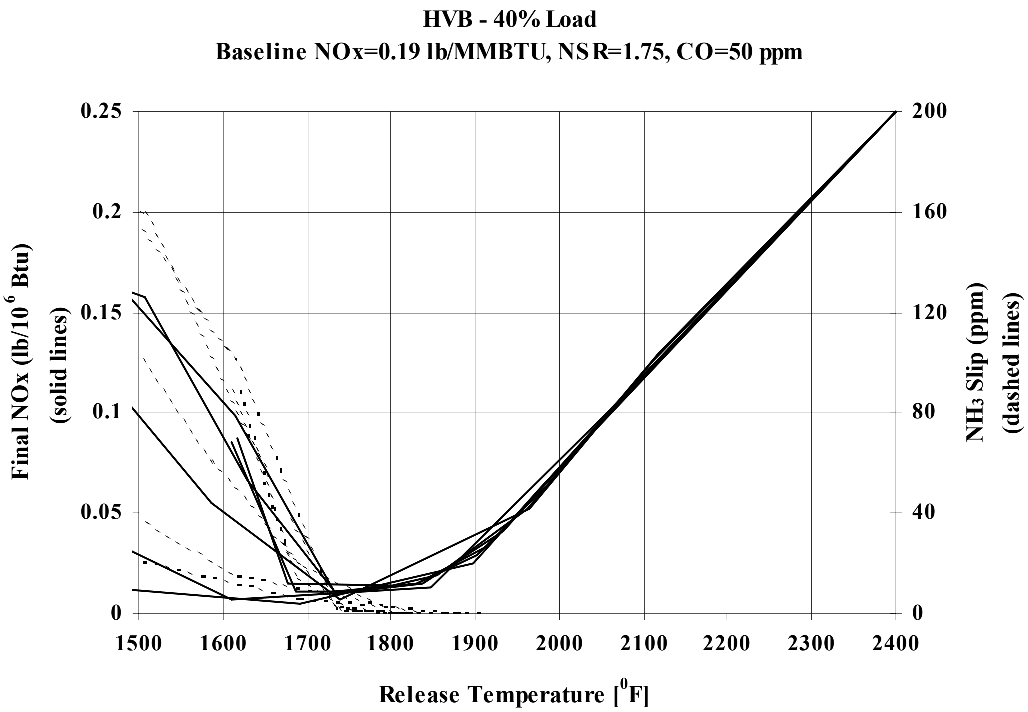


FIGURE 4.37. CEDF MODEL RESULTS WITH A HVB COAL AT 40% LOAD AND A 1.75 NSR

4.2.2 INJECTOR SIMULATION

Five injection zones were modeled. Four of the zones consisted of wall injectors, and the fifth consisted of a multiple nozzle lance (MNL). The MNL zone was simulated for the temporary location used during testing, and also at a proposed location. An overview of the furnace and the injector layout is shown in Figure 4.38. Elevations stated below are taken from a datum of 0" at the burner centerline. Zones 1, 2, 3, and 4 injector locations are illustrated in Figure 4.39 through Figure 4.42.

The five separate injector zones were simulated to determine the ability of the injectors to disperse chemicals as near as possible to the optimal zones for various operating conditions. The results were examined to identify those providing the maximum opportunities for NO_x reduction through good chemical distribution near the optimal temperature range identified by the CKM.

The NO_x reductions predicted by the CKM assumed ideal chemical distributions. Because the chemical distribution, although good, is not complete, the expected NO_x reduction is less than the maximum potential reduction predicted by chemical kinetics. Furthermore, a level of uncertainty exists in the operational parameters of the furnace, which necessitates additional caution in the interpretation of the CKM results.

Zone 1 consisted of five wall-mounted injectors located at elevation 171”. Three injectors were located on the wall opposite the burner and one was located on each sidewall. Zone 2 was located at elevation 219”, with three injectors on both the front and rear wall for a total of six injectors. Zone 3 consisted of six injectors on two different elevations. Four injectors were located at elevation 403”, having two injectors each on the front and rear walls. The other two injectors were located at elevation 470” on the sidewall opposite the furnace exit. Zone 4 was located at elevation 541”. Three injectors were mounted on the sidewall opposite the furnace exit. The MNL temporary location was in the back pass of the convective section. The proposed MNL location is at an elevation just above the furnace nose.

All of the injector model results were obtained using nominal droplet parameters. Therefore the injector model results can be used to compare and estimate zone effectiveness, but may not reflect the best performance possible. The results of the injector model are shown for each fuel, at selected load/zone combinations. The colored lines represent the droplet paths before they evaporate completely. The colors represent the temperature of the fluegas along the droplets path, and can be used to estimate the release temperature of the droplets. The temperature scale is in degrees Fahrenheit, from 1500°F (blue) to 2400°F (red). The light purple color is for temperatures above 2400°F and the dark purple color is for temperatures below 1500°F. Chemical coverage was estimated by inspection of the droplet trajectories.

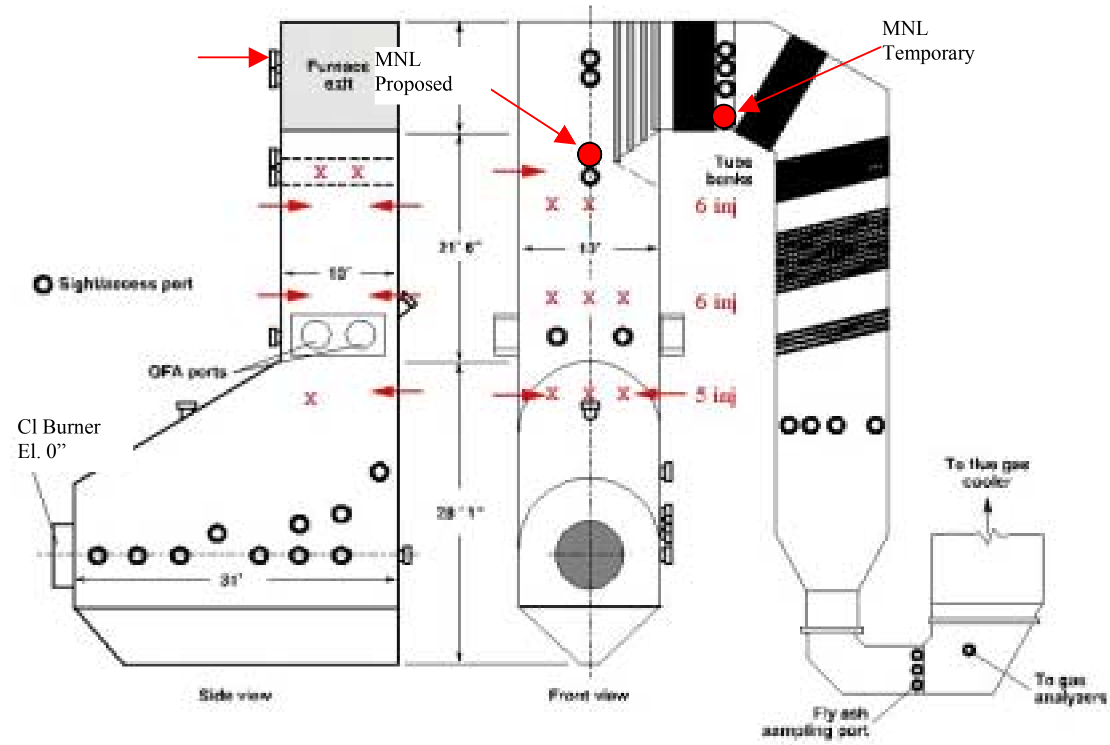


FIGURE 4.38. INJECTOR AND FURNACE LAYOUT

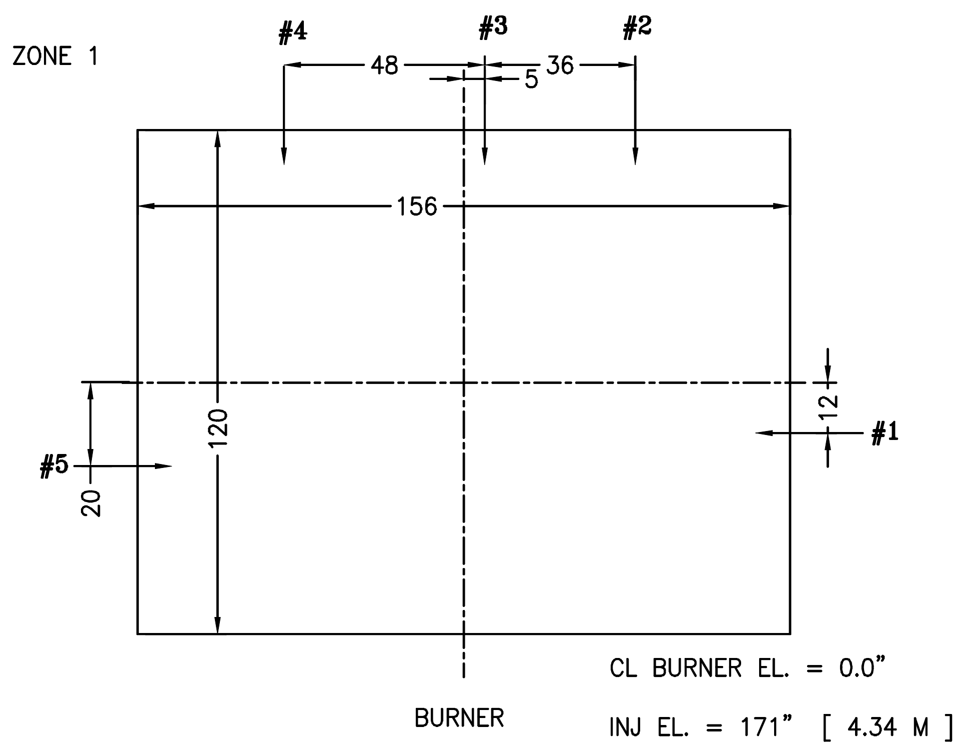


FIGURE 4.39. ZONE 1

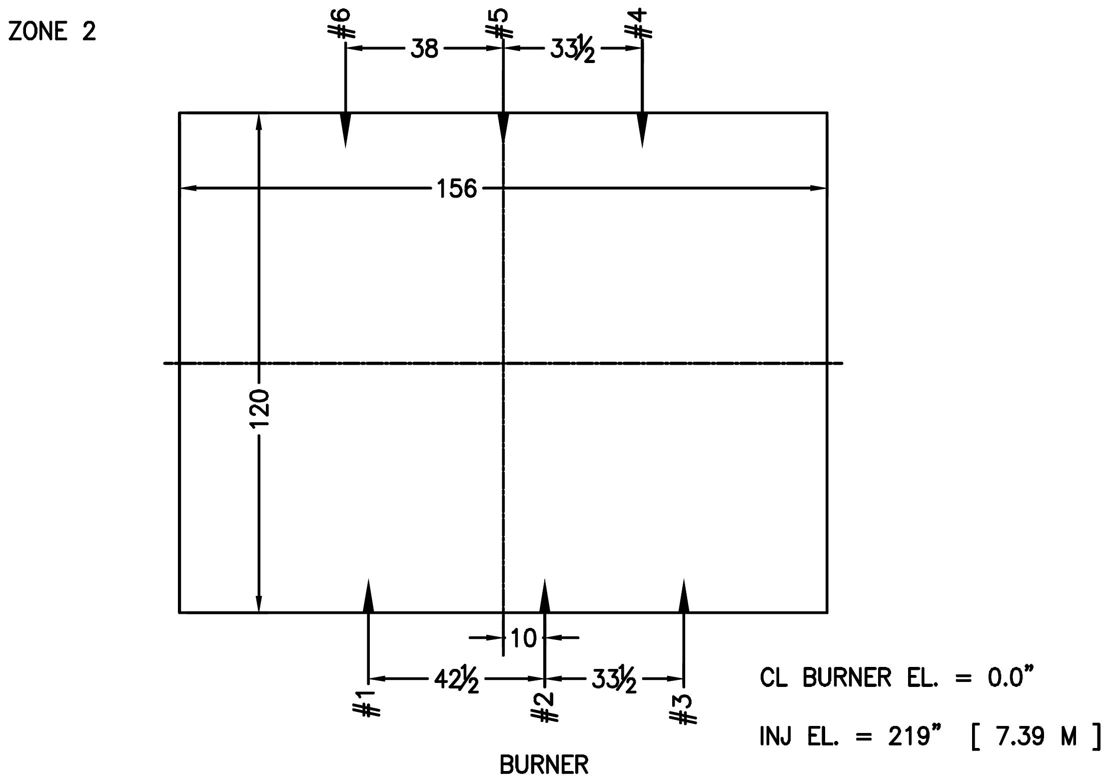


FIGURE 4.40. ZONE 2

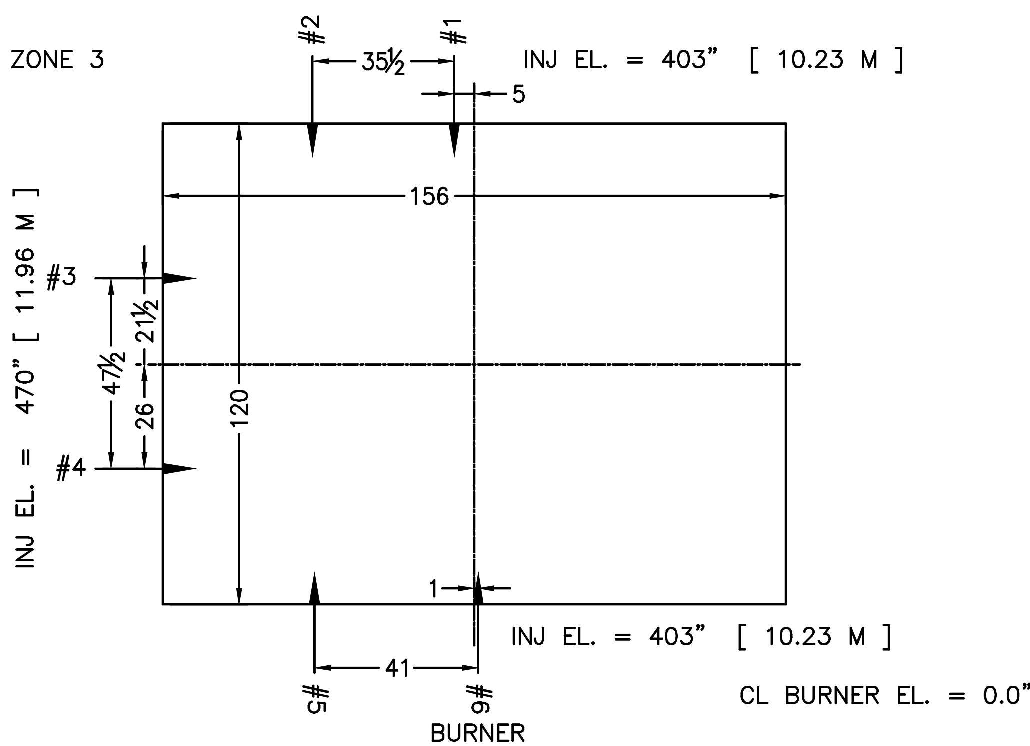


FIGURE 4.41. ZONE 3

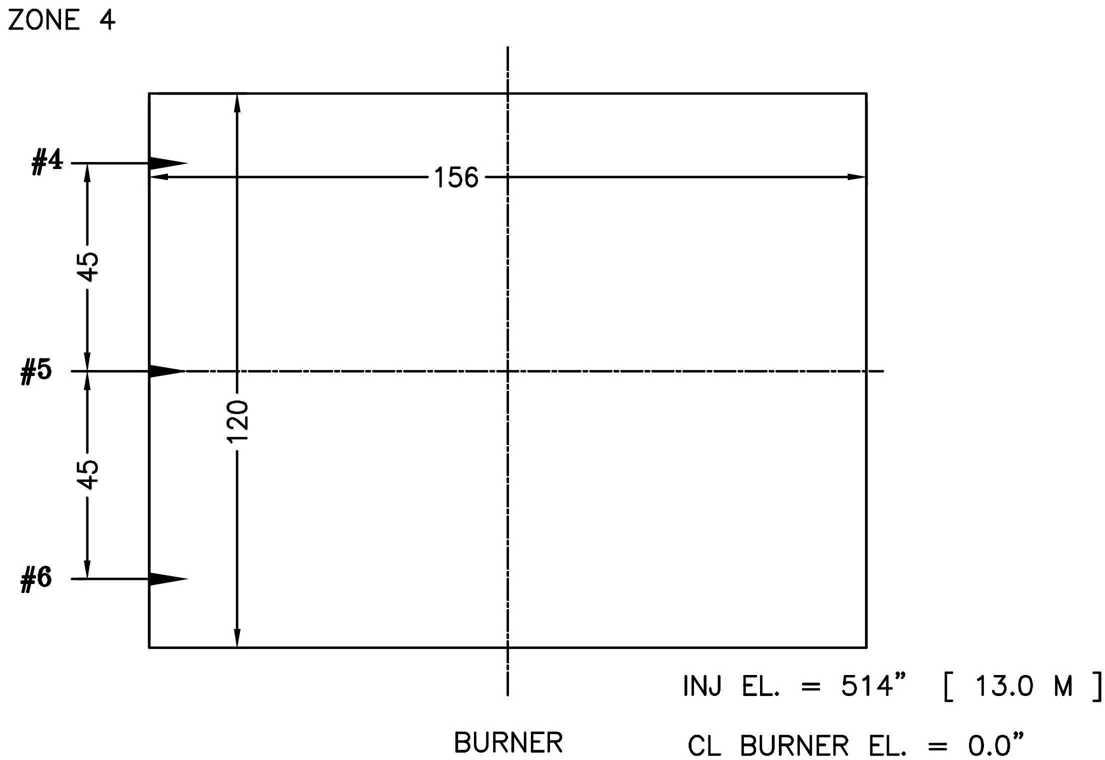


FIGURE 4.42. ZONE 4

4.2.2.1 PRB COAL

4.2.2.1.1 100% LOAD

Figures 4.43, 4.44, and 4.45 are the results of the injector model for PRB coal at 100% load for Zones 2, 3, and 4 respectively. Zone 2 droplet trajectories do not release chemical within the effective window using the nominal droplet distribution. Larger than typical droplets would be required to utilize this zone effectively. One of the Zone 3 trajectories shows that this injection zone may provide effective treatment within the temperature window with somewhat larger than typical droplets. Zone 4 clearly releases chemical within the temperature window. Although much of the spray also produces chemical release outside the apparent temperature window, the CFD model is not coupled to the spray model and as such does not include local cooling due to spray evaporation.

The temporary MNL injectors shown in Figure 4.46 release chemical below the minimum release temperature. However at this location there is a significant recirculation and residence times are longer, which will allow NO_x reduction and limit ammonia slip levels to less than predicted by the CKM. The proposed MNL location would release chemical in the desired temperature window as shown in Figure 4.47.

4.2.2.1.2 60% Load

Lower temperatures at 60% load may allow zone 2 to provide some NO_x reduction, if the injectors were operated to produce larger droplets than modeled. The zone 2 injector model results are shown in Figure 4.48. Zone 3 provided the best opportunity for NO_x reduction at this load, with release temperatures within the effective temperature window, as shown in Figure 4.49. Coverage for both zone 2 and zone 3 was estimated at 80%. The zone 4 results are shown in Figure 4.50. This zone released chemical near the minimum temperature limit, and therefore had the greatest opportunity for both NO_x reduction and ammonia slip.

4.2.2.1.3 40% Load

Zone 1 and 2 results are shown in Figure 4.51 and Figure 4.52, respectively. Both of these zones operated within the desired temperature window. Zone 3 injectors released chemical below the effective minimum temperature, as shown in Figure 4.53. Coverage for the combined zones 1 and 2 was estimated at 80%.

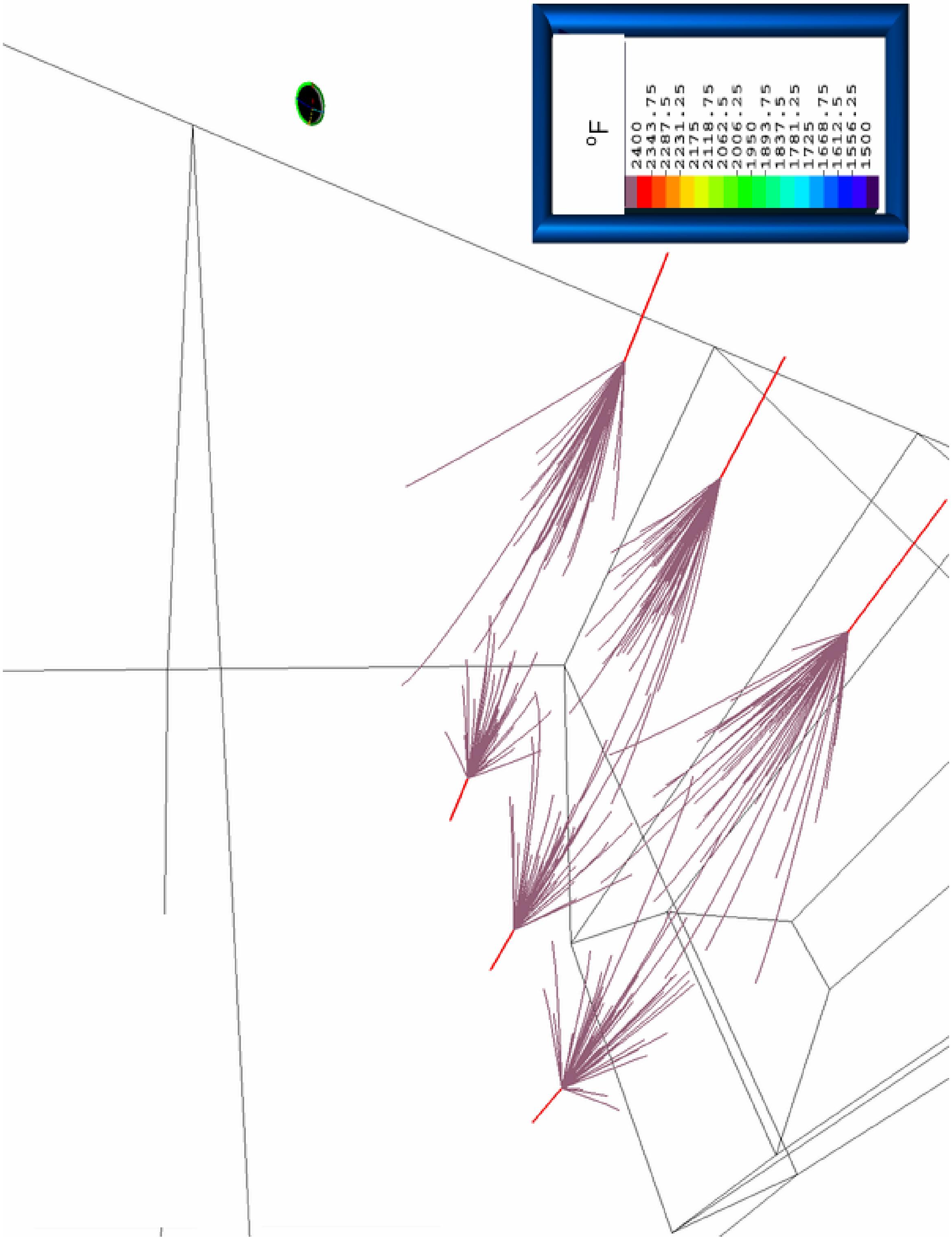


FIGURE 4.43. PRB COAL – 100% LOAD – ZONE 2

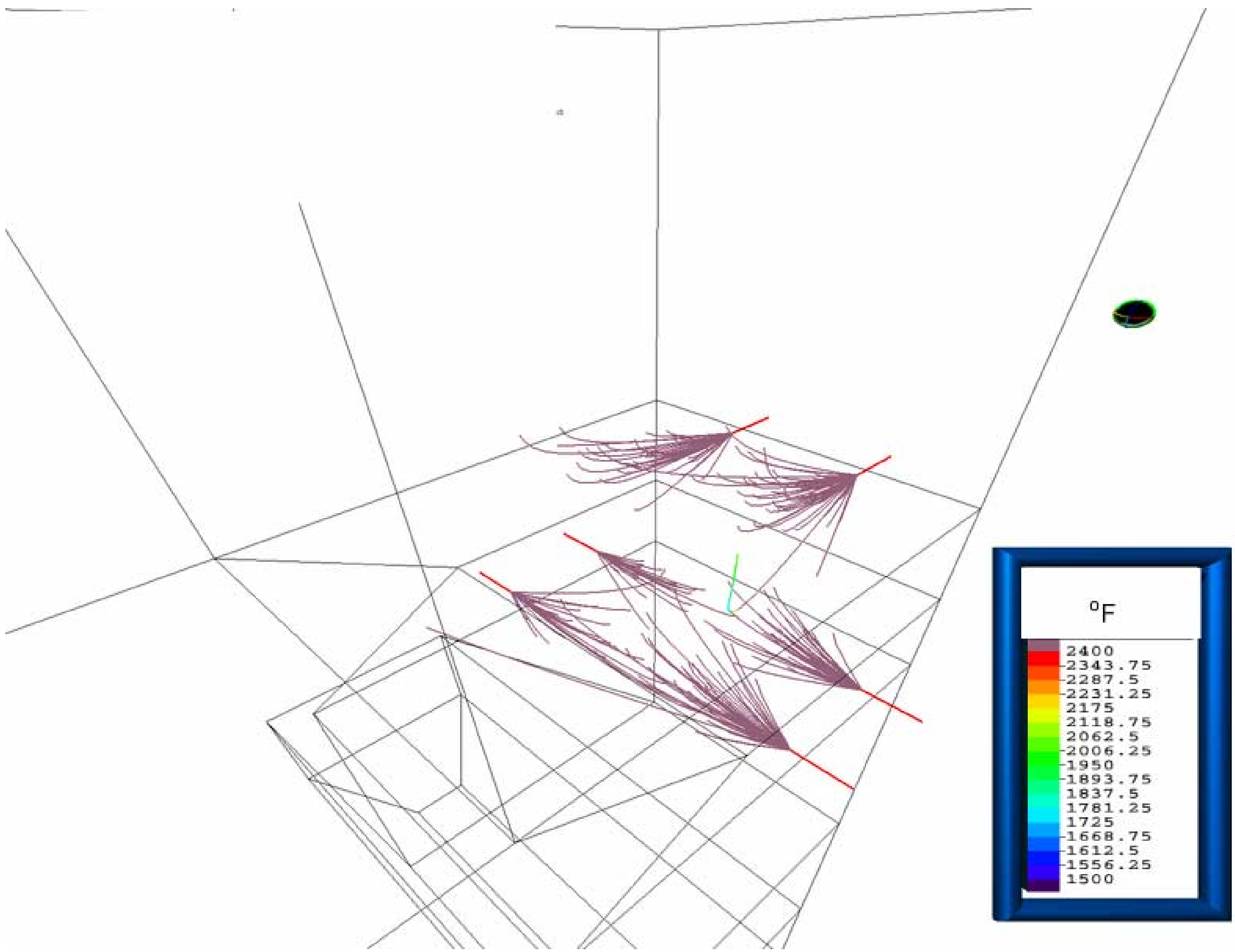


FIGURE 4.44. PRB COAL – 100% LOAD – ZONE 3

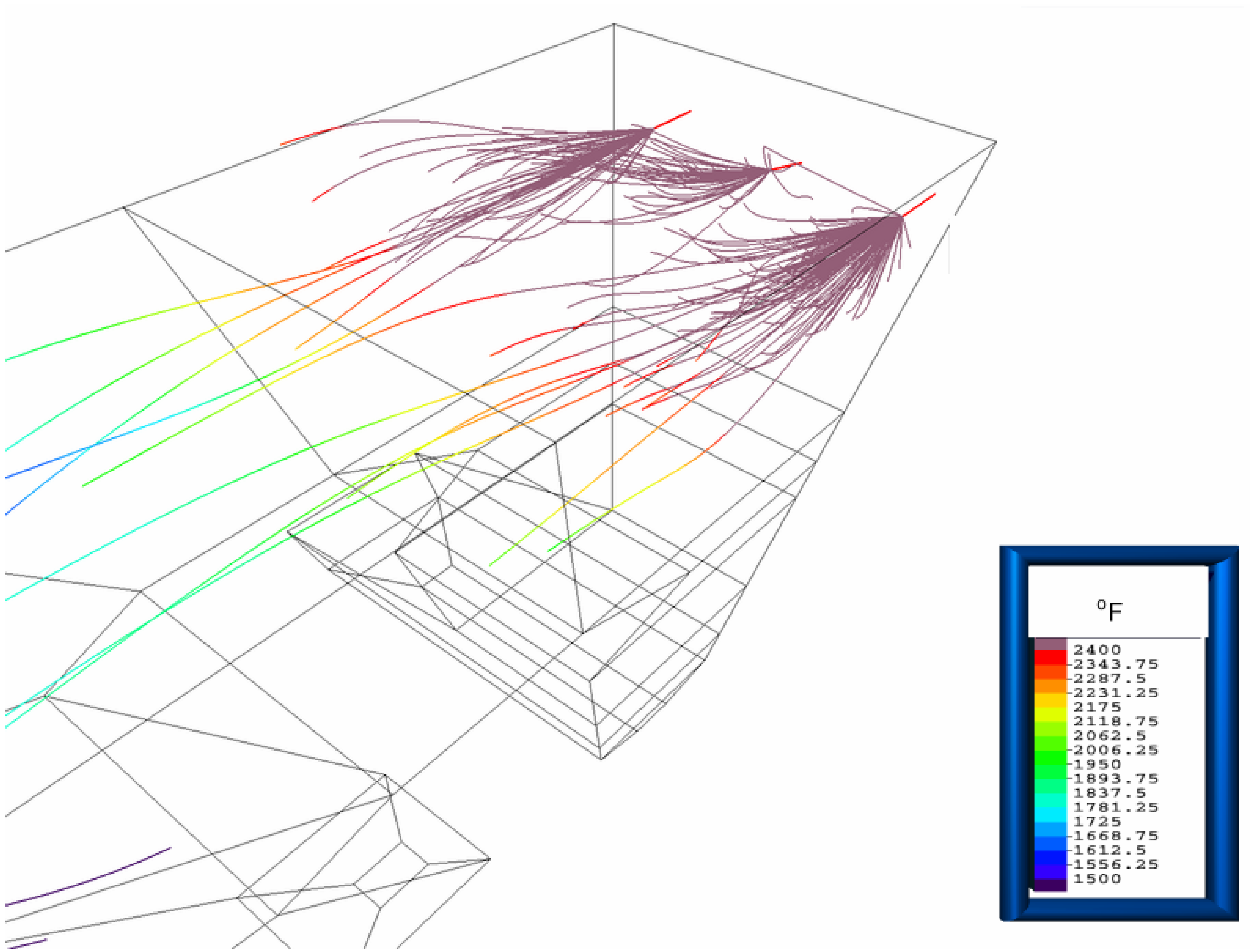


FIGURE 4.45. PRB COAL – 100% LOAD – ZONE 4

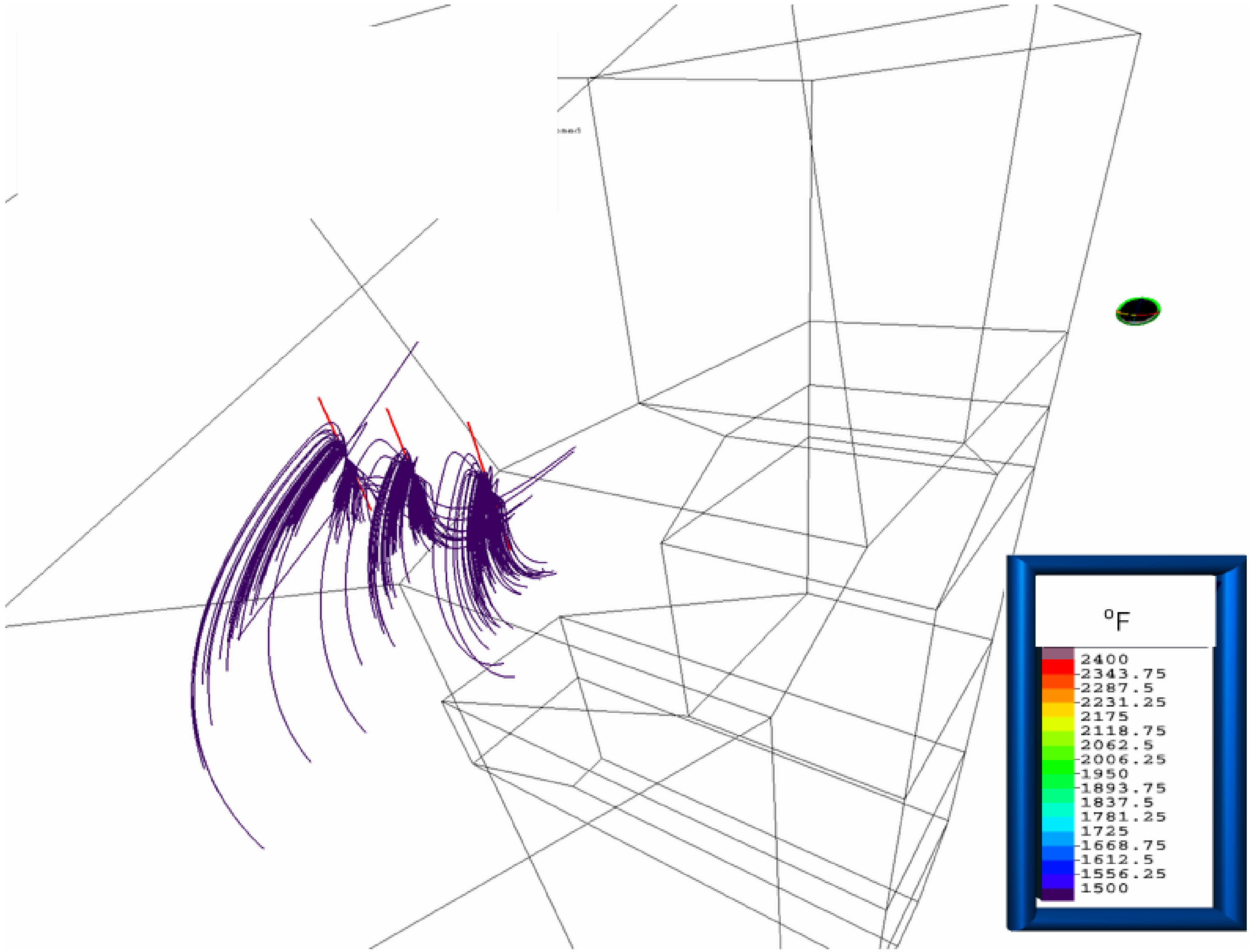


FIGURE 4.46. PRB COAL – 100% LOAD – TEMPORARY MNL LOCATION

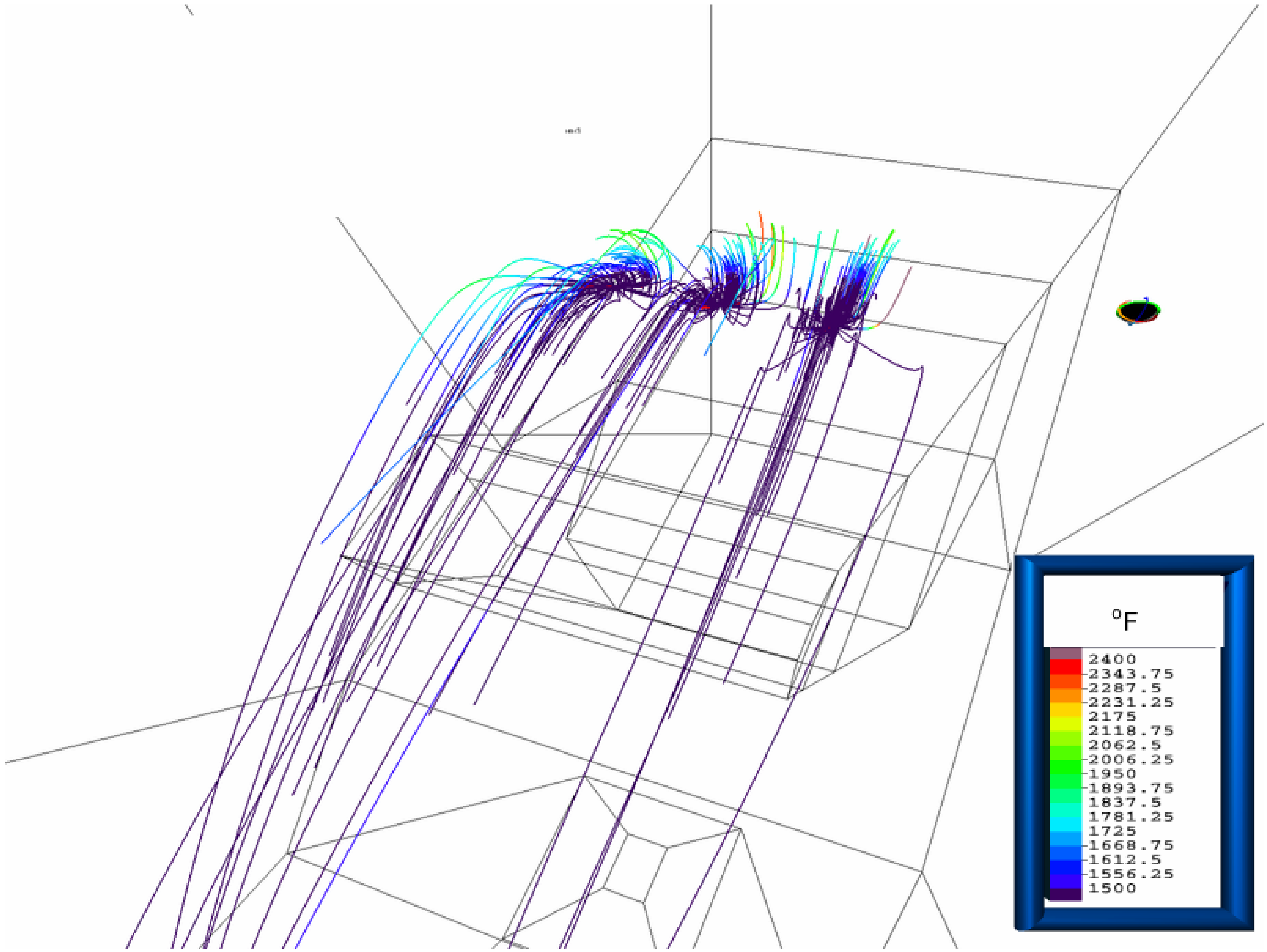


FIGURE 4.47. PRB COAL – 100% LOAD – PROPOSED MNL LOCATION

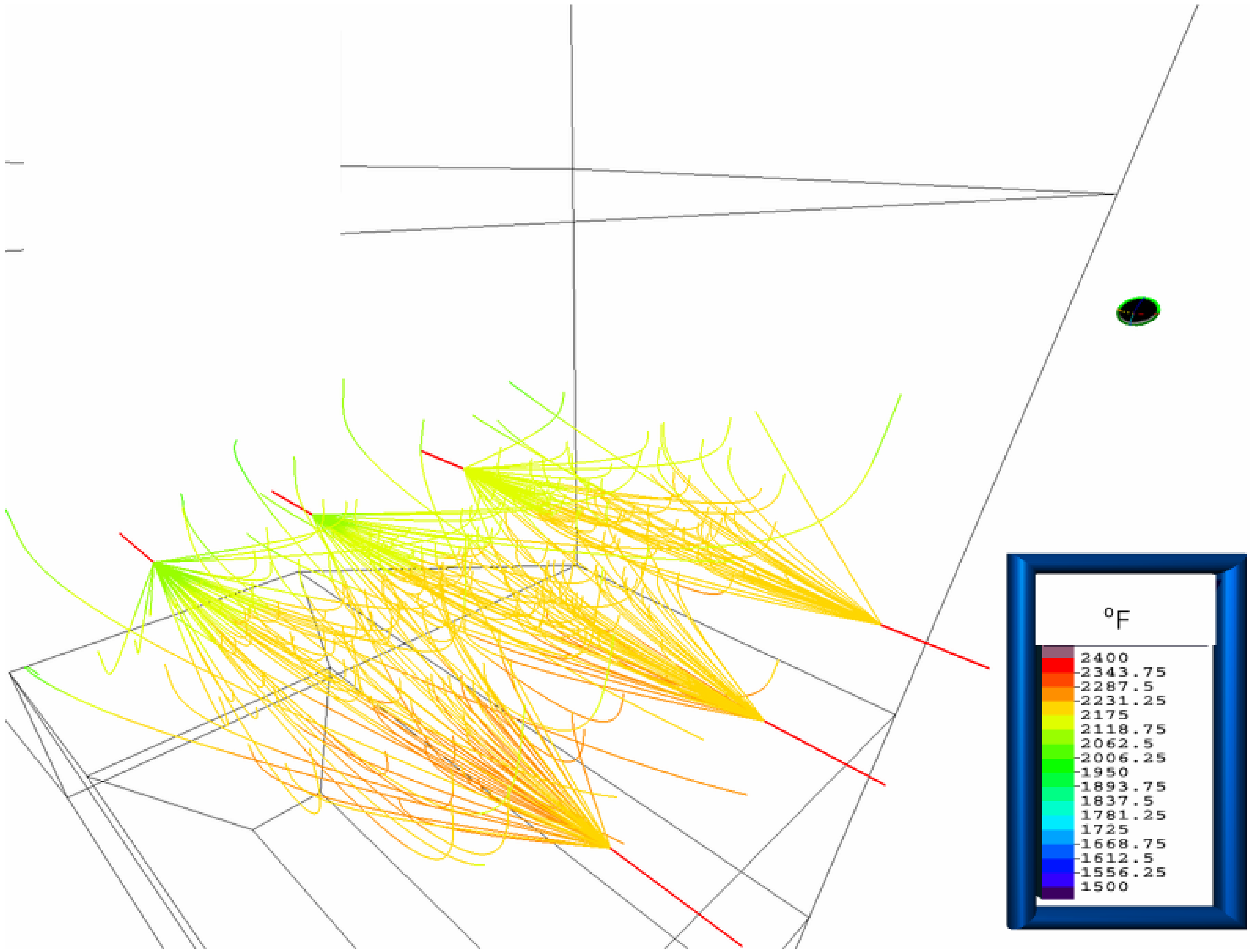


FIGURE 4.48. PRB COAL – 60% LOAD – ZONE 2

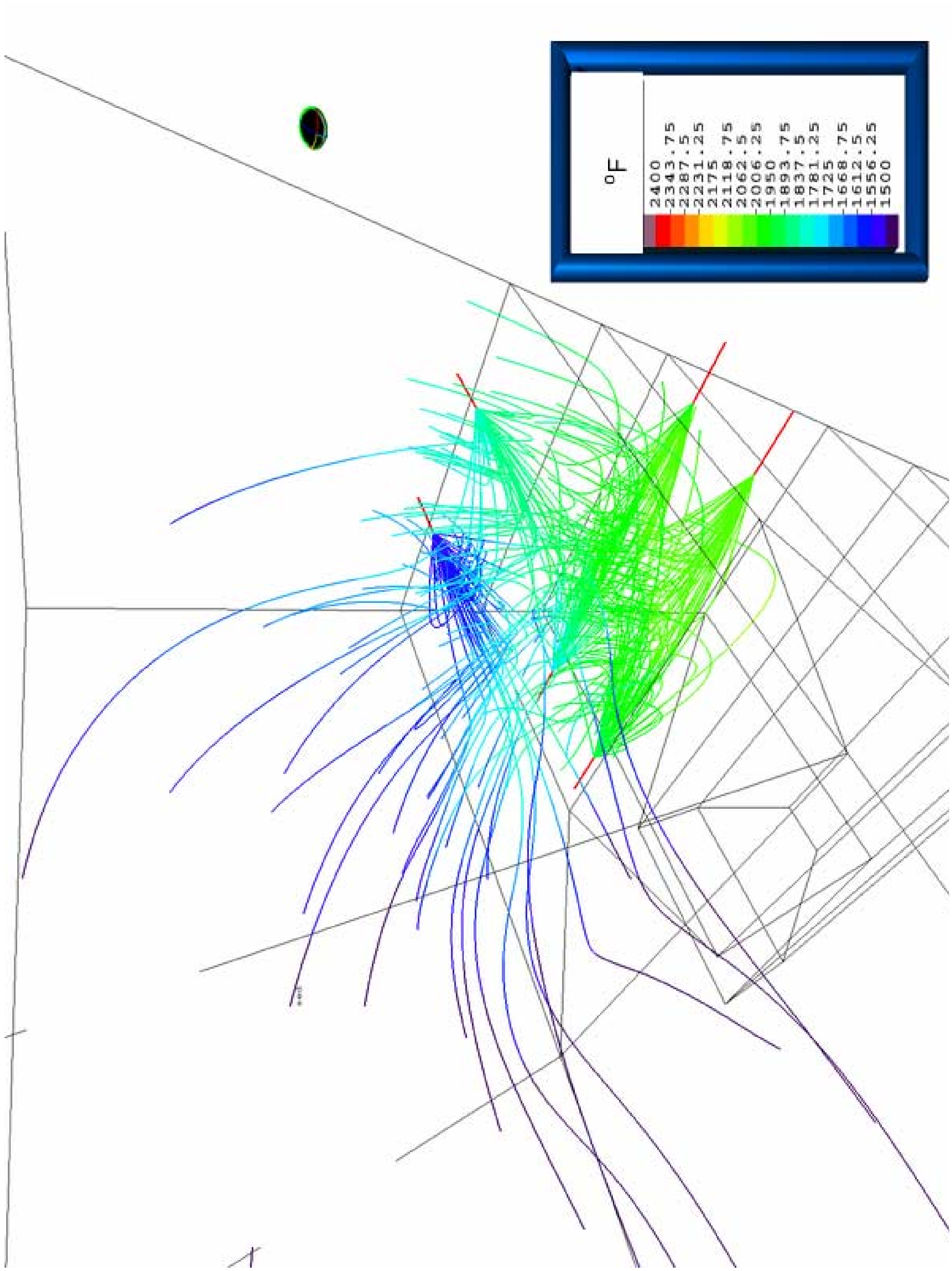


FIGURE 4.49. PRB COAL – 60% LOAD – ZONE 3

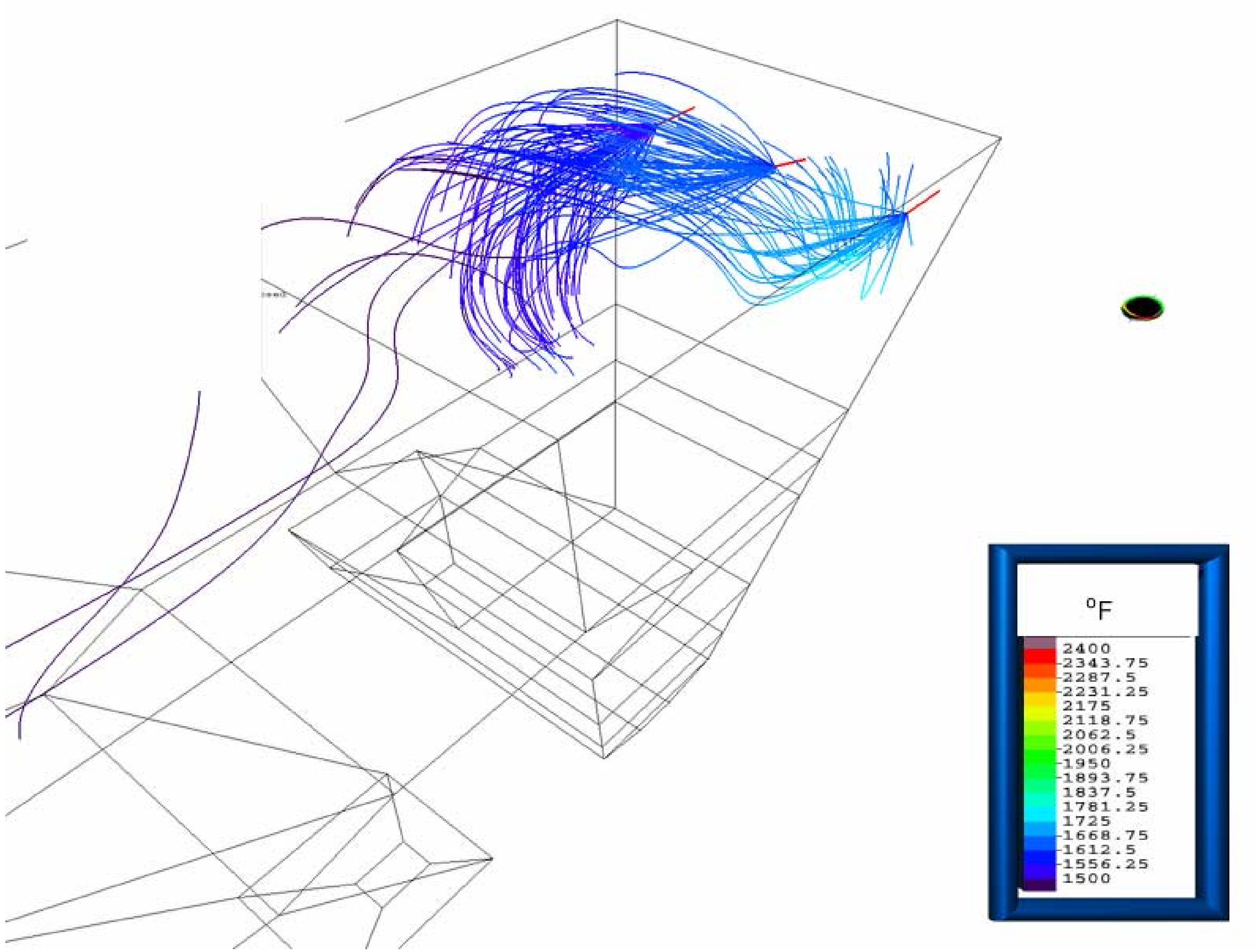


FIGURE 4.50. PRB COAL – 60% LOAD – ZONE 4

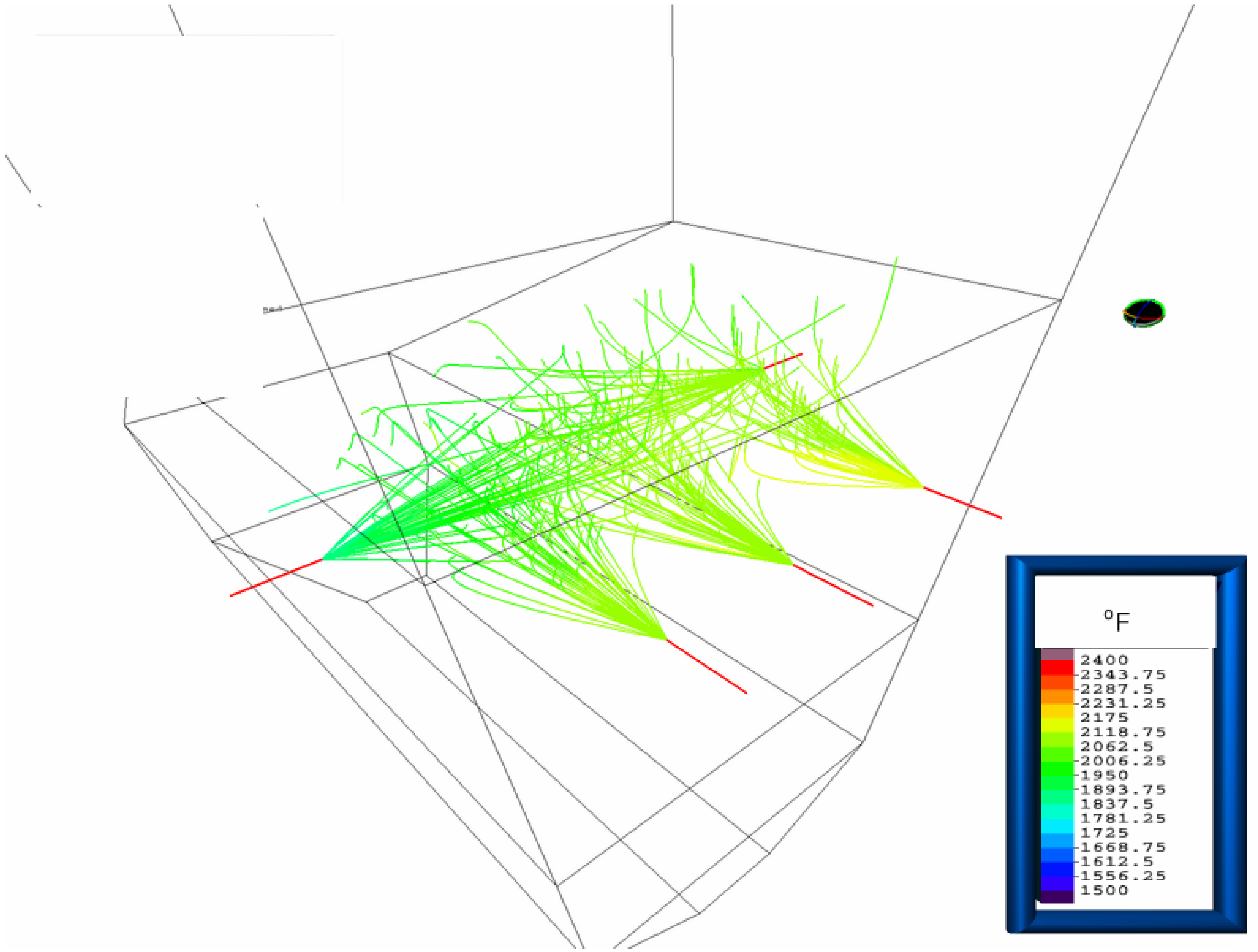


FIGURE 4.51. PRB COAL – 40% LOAD – ZONE 1

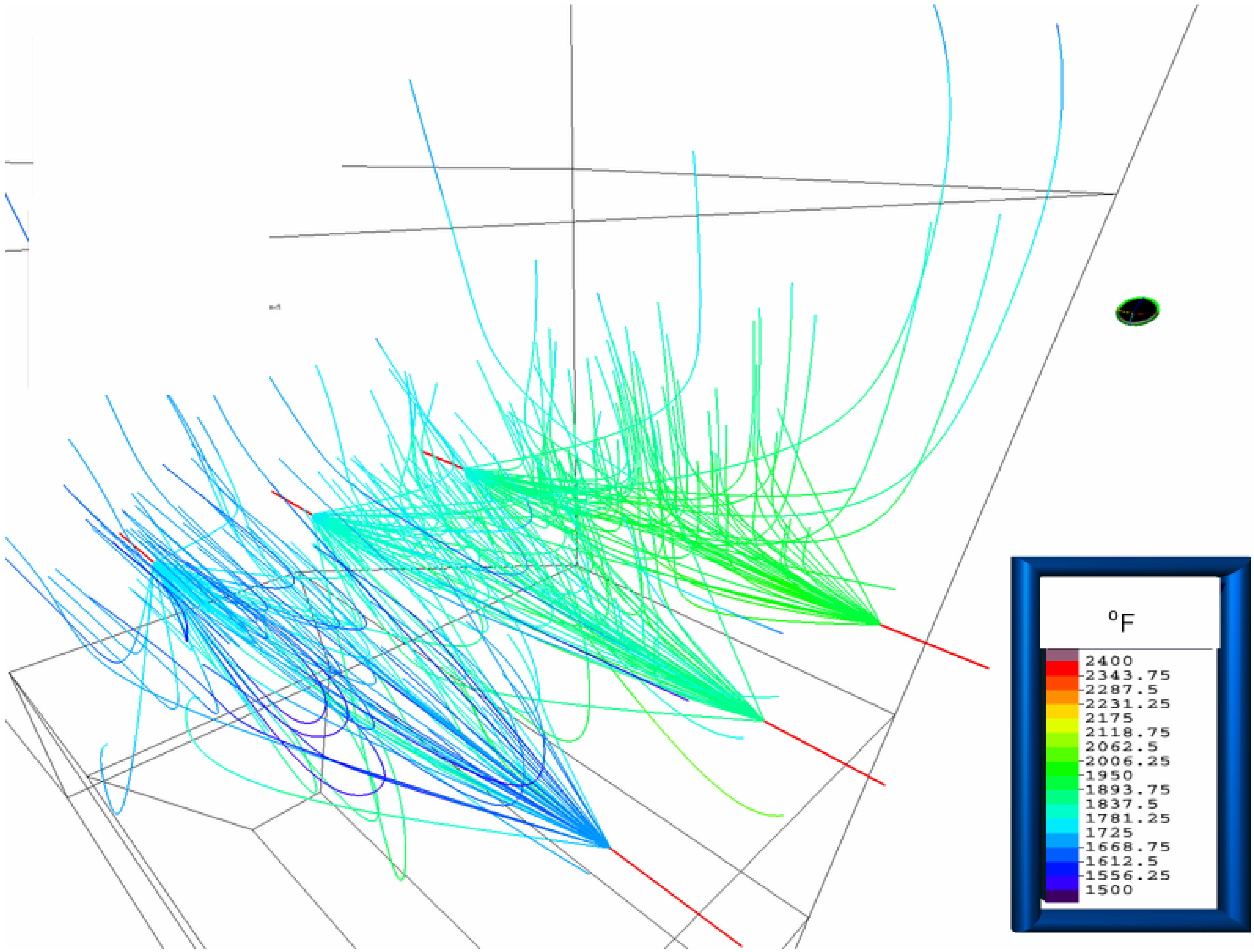


FIGURE 4.52. PRB COAL – 40% LOAD – ZONE 2

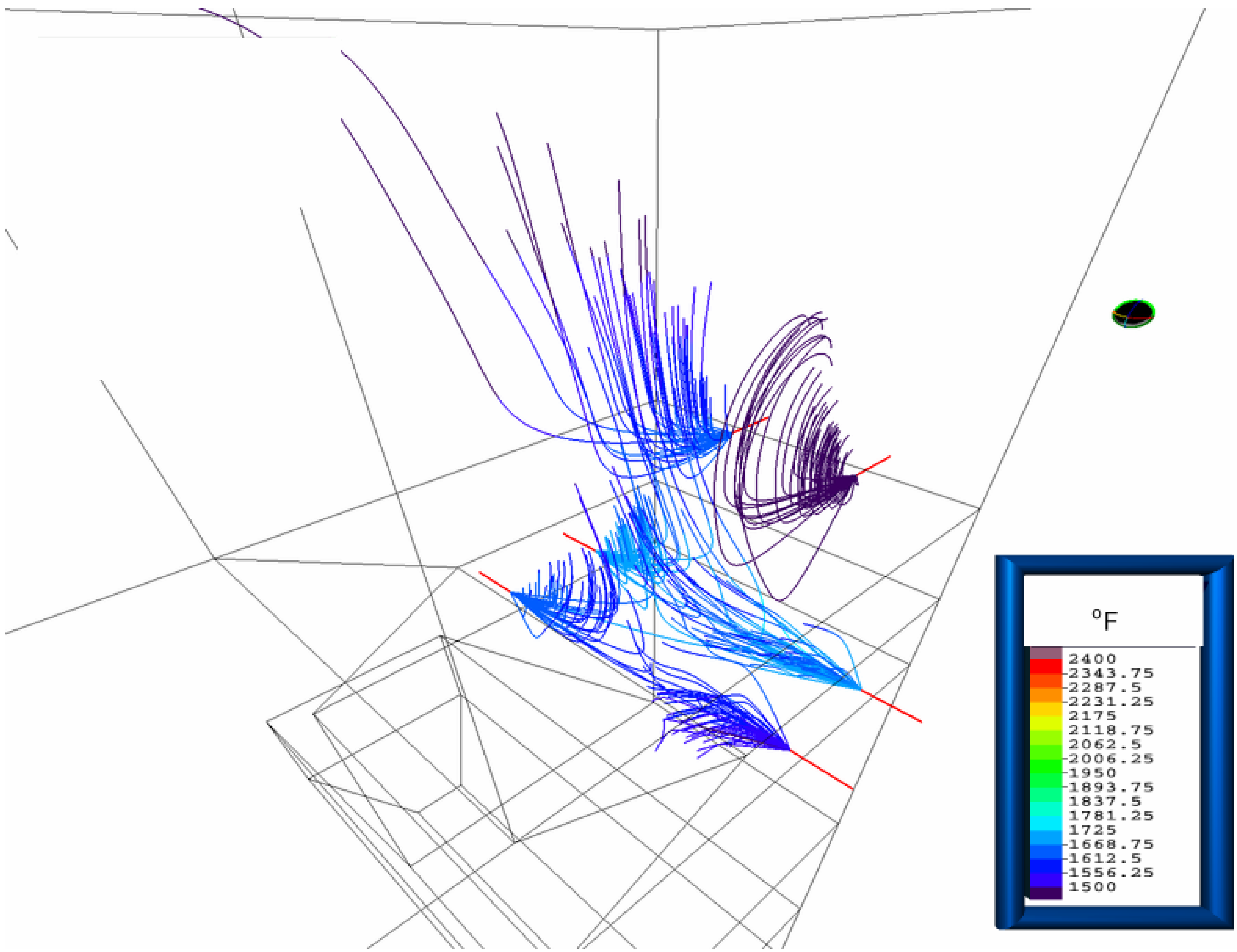


FIGURE 4.53. PRB COAL – 40% LOAD – ZONE 3

4.2.2.2 *Middle Kittanning Coal*

4.2.2.2.1 100% Load

Zone 3 injectors were unable to release significant chemical in the desired temperature window as modeled and shown in Figure 4.54. The best opportunity for NO_x reduction occurred in zone 4, with release temperatures within the effective temperature window as shown in Figure 4.55.

4.2.2.2.2 60% Load

Both zone 2 and zone 3 released chemical within the desired temperature range at this load. The zone 2 results are shown in Figure 4.56, and released chemical near the maximum desired temperature. As shown in Figure 4.57, zone 3 released chemical near the minimum desired temperature providing the best opportunity for NO_x reduction. The estimated coverage for the combined use of zones 2 and 3 was near 80%.

4.2.2.2.3 40% Load

The results of the zone 1 injection model suggested the zone could be used to reduce NO_x. Figure 4.58 shows the release temperatures of the two side wall injectors to be above the effective maximum, but those of the three rear wall injectors to be below the effective maximum. Zone 2 provided the best opportunity to reduce NO_x as shown in Figure 4.59. All zone 2 injectors released chemical near the minimum of the effective temperature window, and covered an estimated 80% of the fluegas.

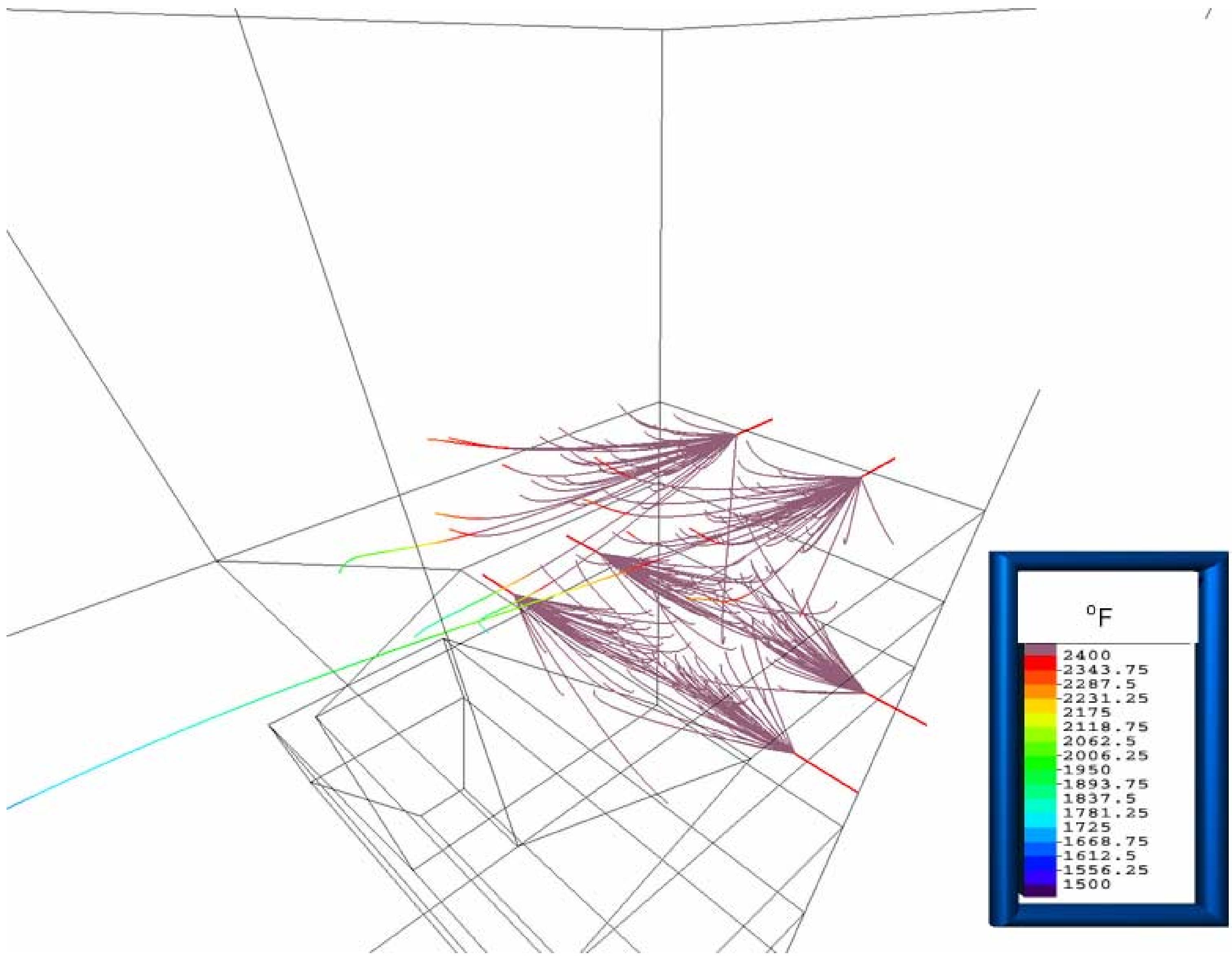


FIGURE 4.54. MIDDLE KITTANNING COAL – 100% LOAD – ZONE 3

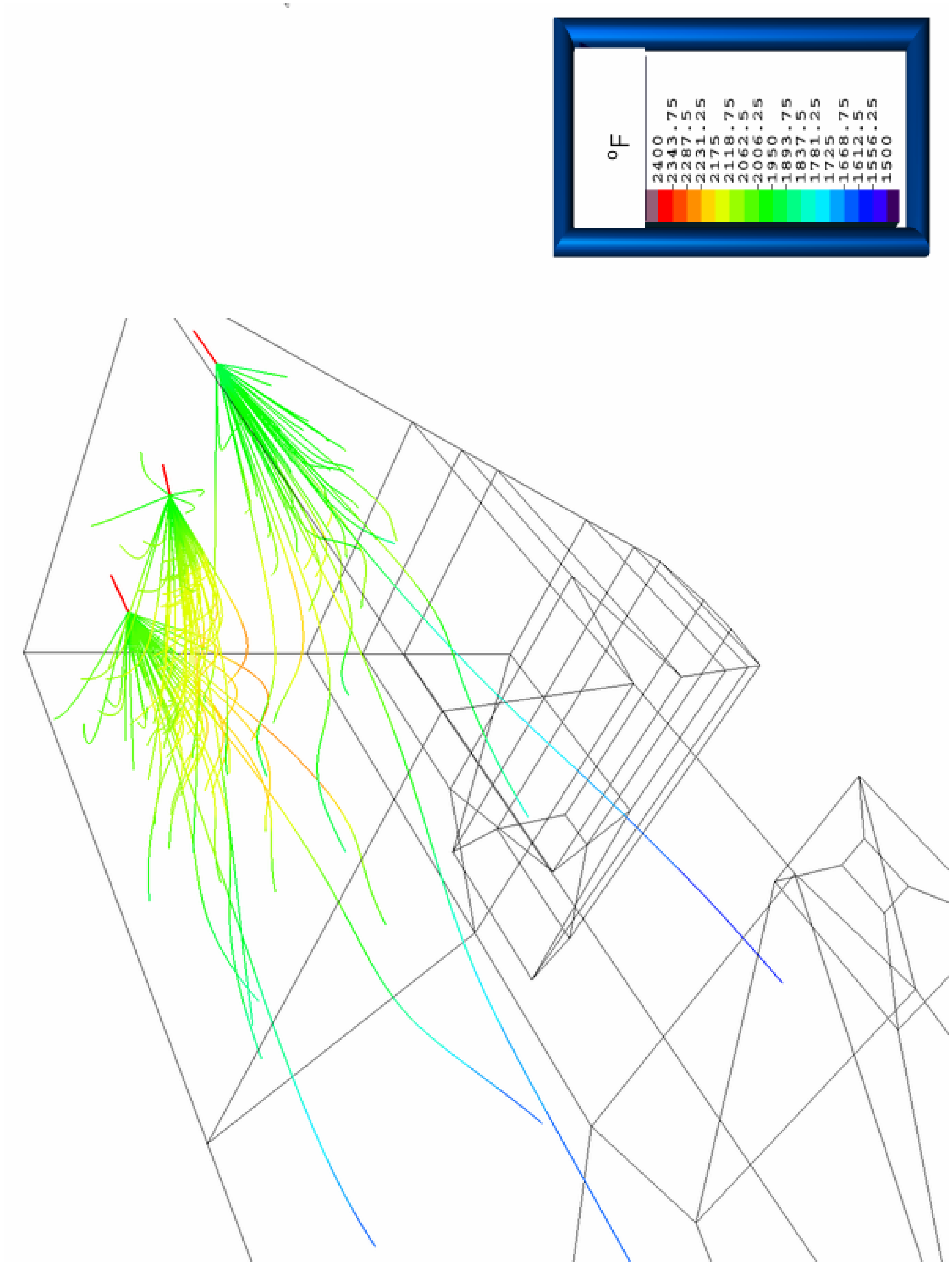


FIGURE 4.55. MIDDLE KITTANNING COAL – 100% LOAD – ZONE 4

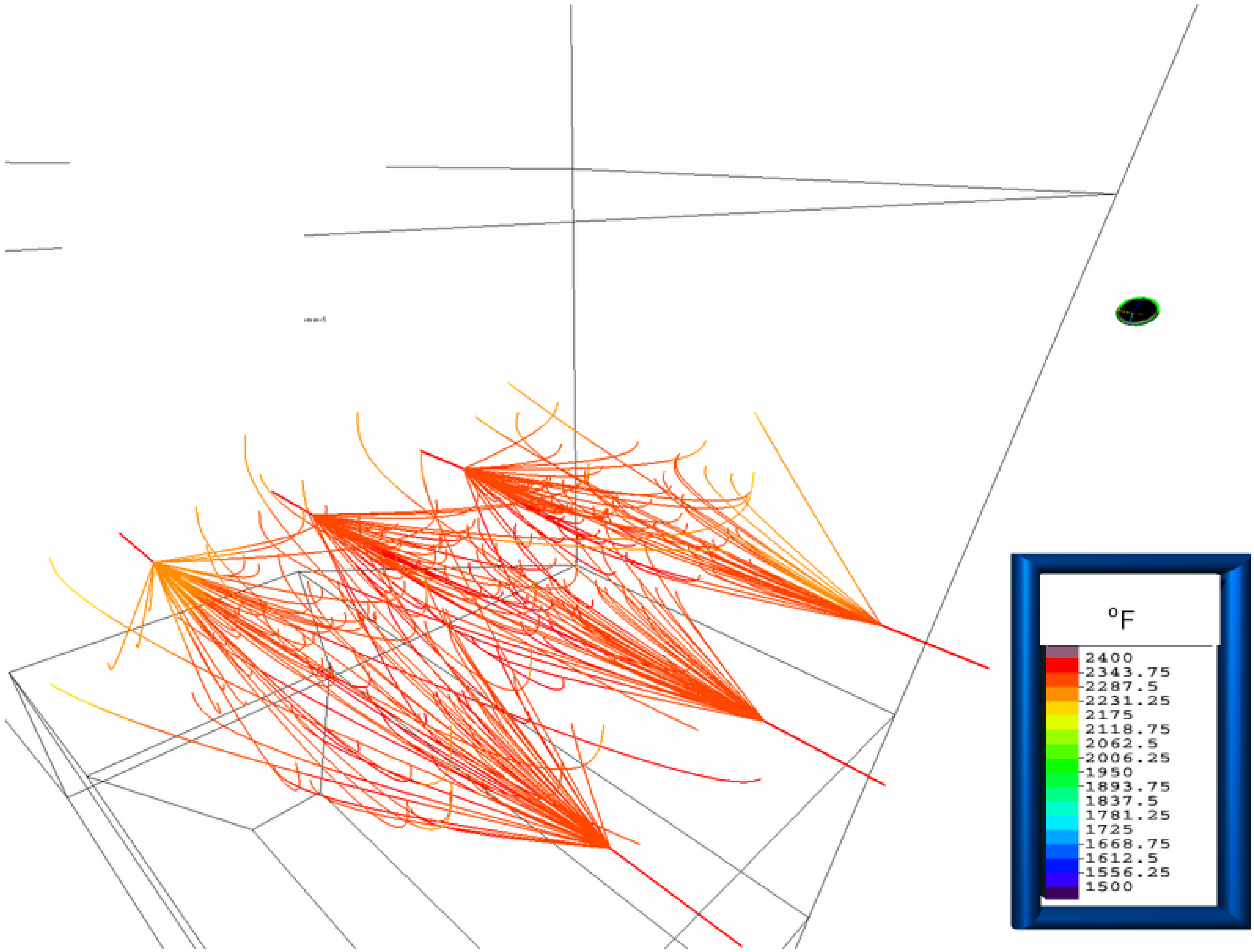


FIGURE 4.56. MIDDLE KITTANNING COAL – 60% LOAD – ZONE 2

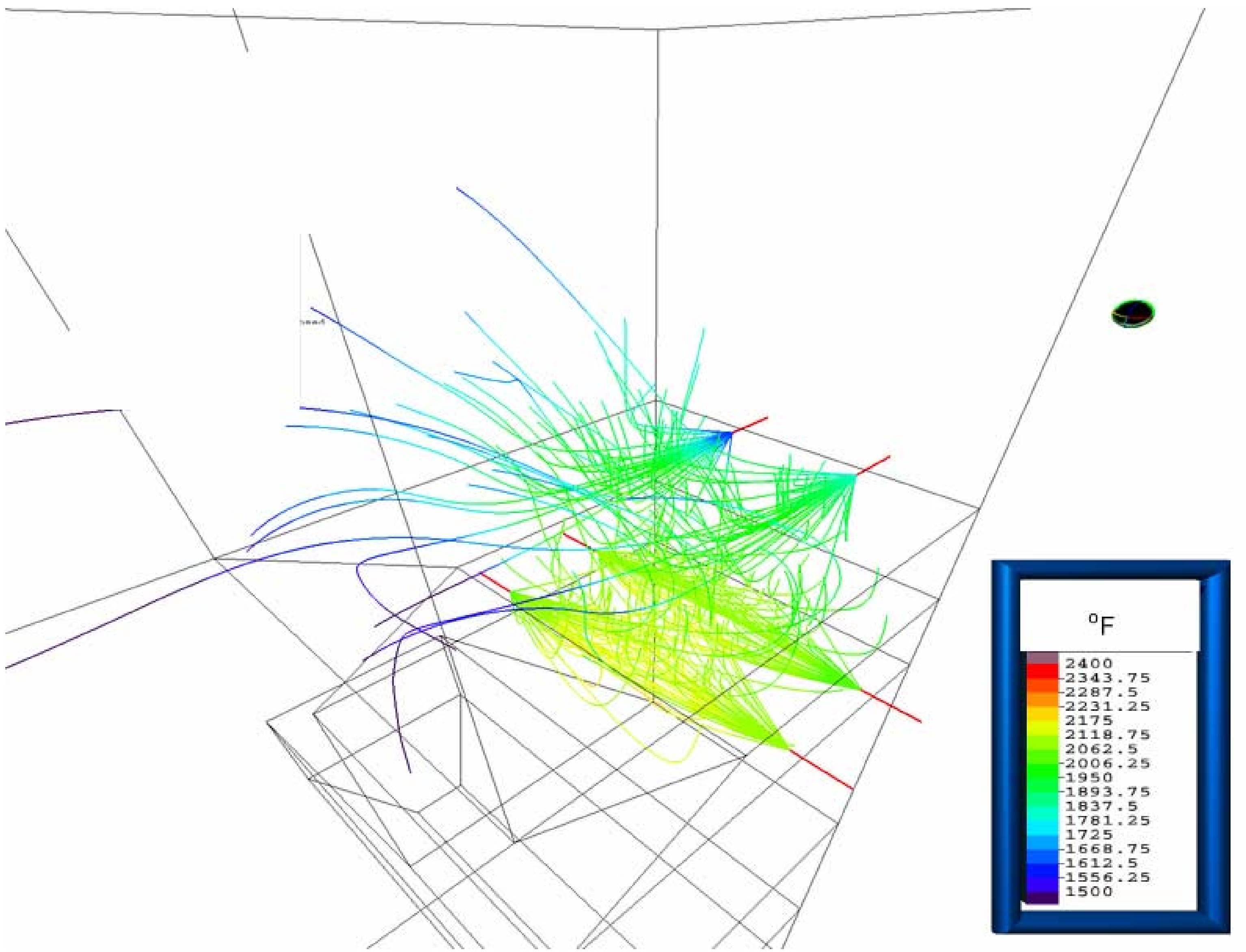


FIGURE 4.57. MIDDLE KITTANNING COAL – 60% LOAD – ZONE 3

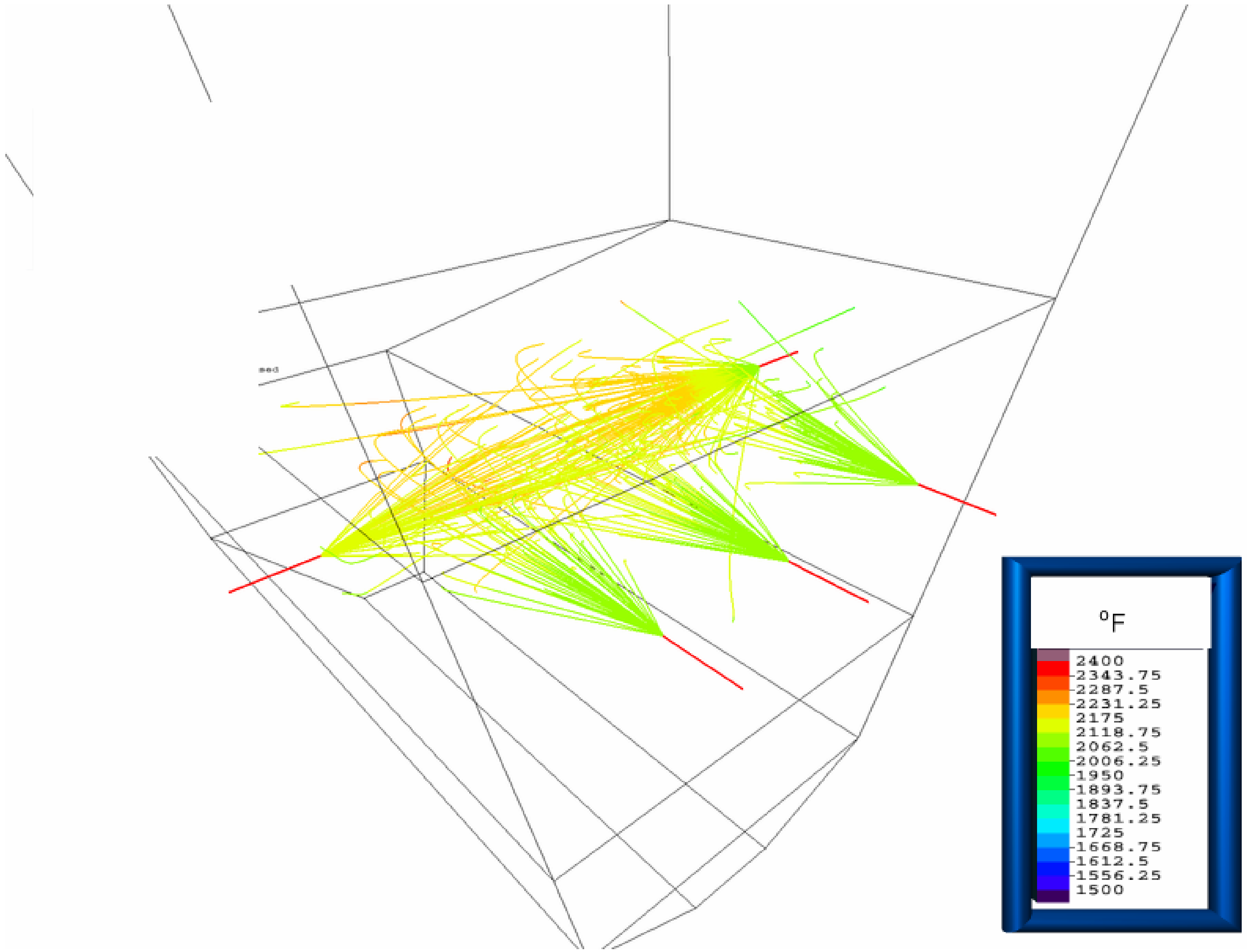


FIGURE 4.58. MIDDLE KITTANNING COAL – 40% LOAD – ZONE 1

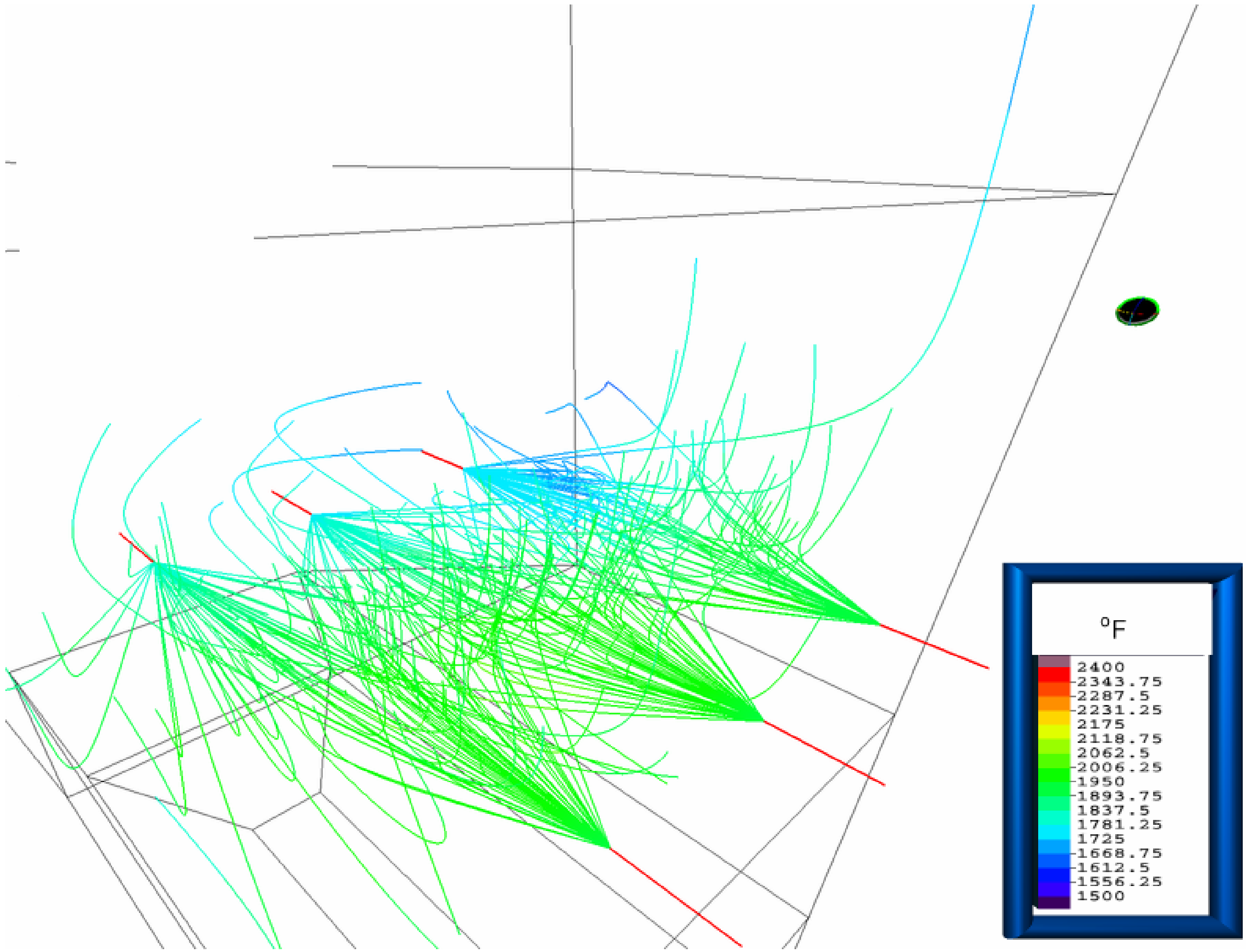


FIGURE 4.59. MIDDLE KITTANNING COAL – 40% LOAD – ZONE 2

4.2.2.3 HIGH-VOLATILE BITUMINOUS COAL

4.2.2.3.1 100% LOAD

At this load and fuel, a typical spray pattern in zone 3 released chemical at temperatures above the desired temperature window, as shown in Figure 4.60. Zone 4 provided the best opportunity for NO_x reduction by releasing chemical within the effective temperature window, but at lower temperatures, as shown in Figure 4.61. The estimated coverage for zone 4 was 50%, and when combined with zone 3 could reach 90%.

4.2.2.3.2 60% LOAD

The injector model for zone 2 at this load predicted that this zone may not be effective in reducing NO_x. This zone released chemical at or above the maximum effective temperature as shown in Figure 4.62. Zone 3 at this load provided the best opportunity for NO_x reduction with release temperatures from the middle to the minimum of the effective temperature window, as shown in Figure 4.63. Coverage for zone 3 was estimated at near 70%

4.2.2.3.3 40% LOAD

Figure 4.64 and Figure 4.65 are plots of the results of zone 1 and zone 2 respectively. Zone 1 released chemical within the upper half of the effective temperature range, limiting possible NO_x reduction. Zone 2 released chemical near the minimum effective temperature, providing the best opportunity for NO_x reduction for this load and fuel.

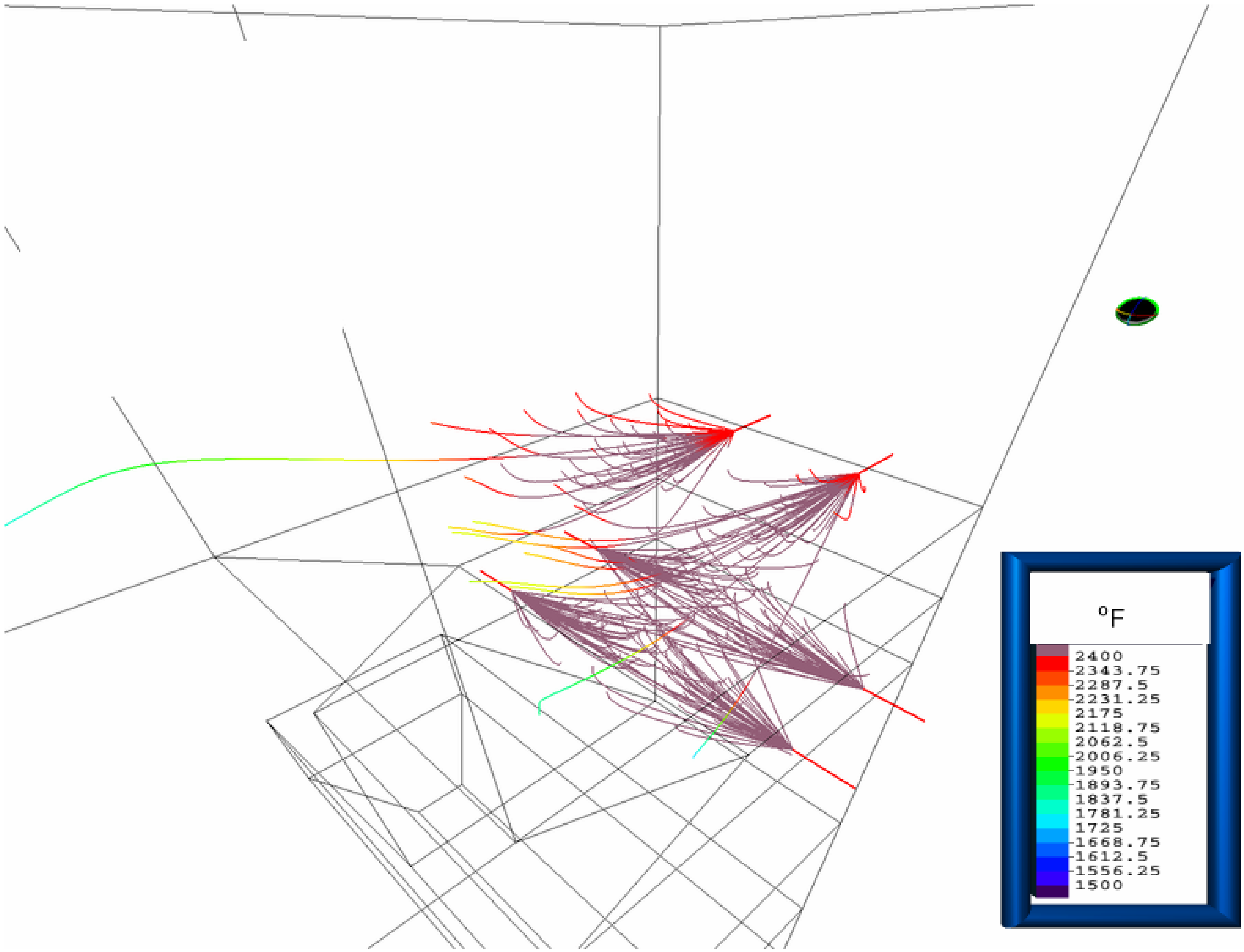


FIGURE 4.60. HVB COAL – 100% LOAD – ZONE 3

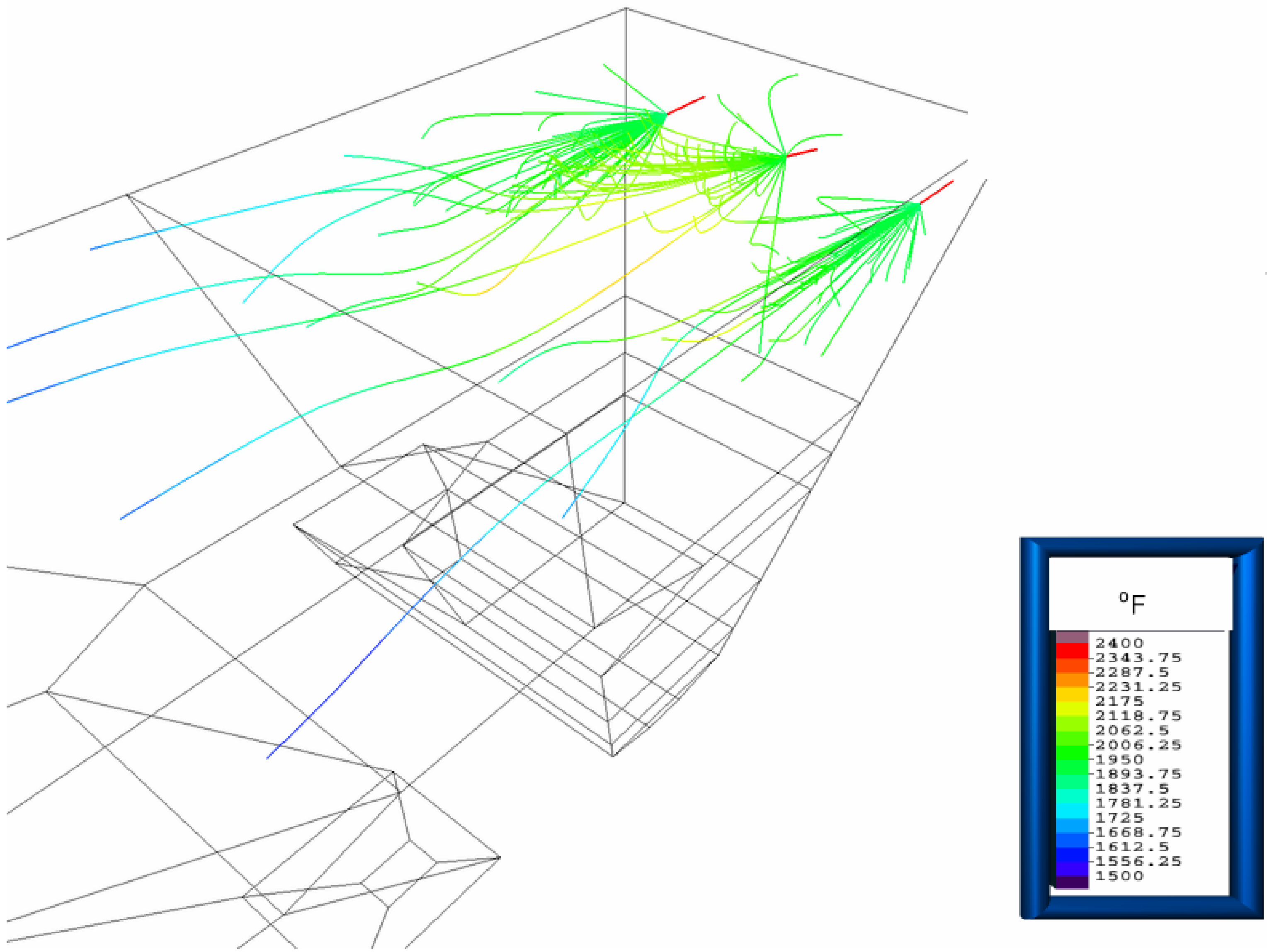


FIGURE 4.61. HVB COAL – 100% LOAD – ZONE 4

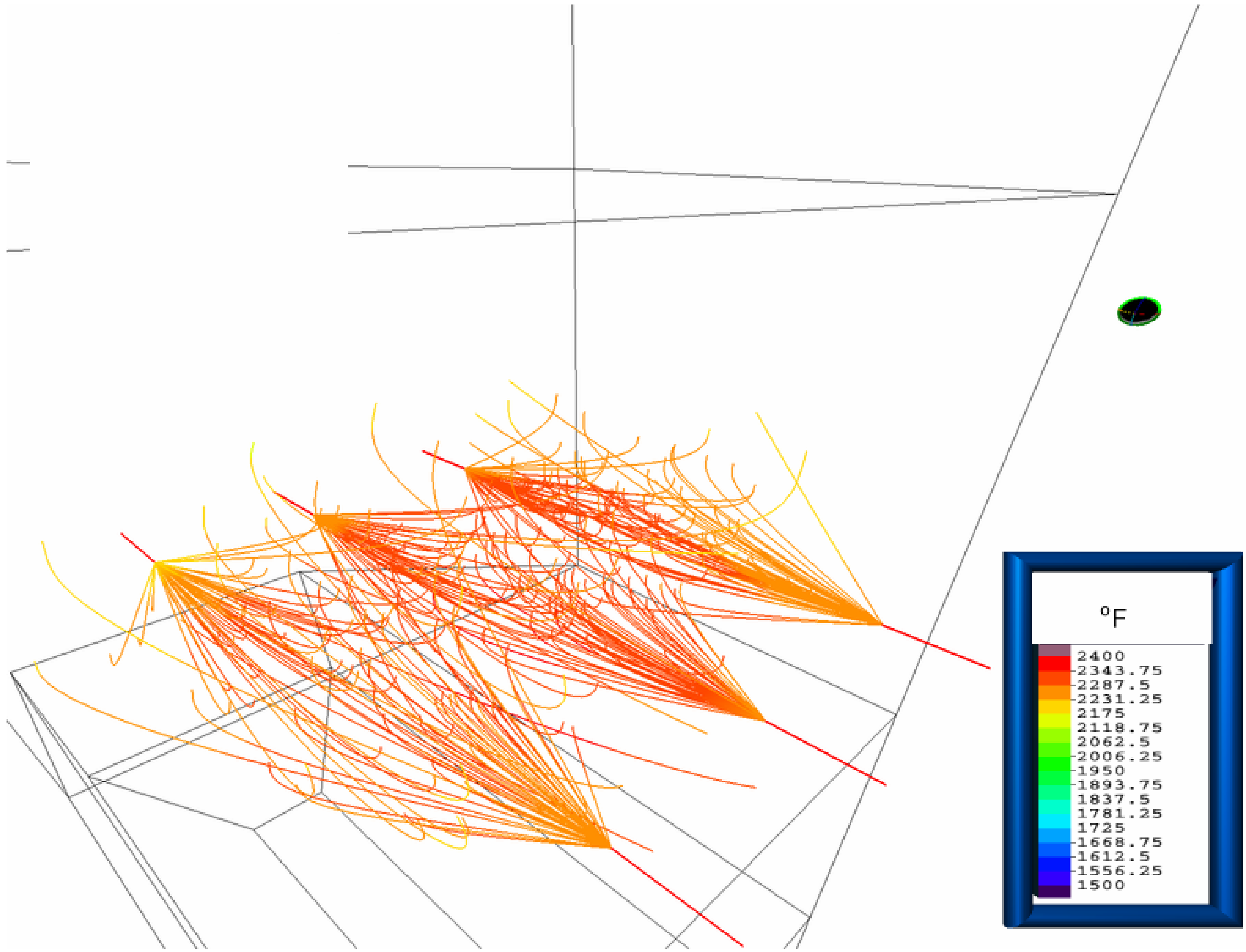


FIGURE 4.62. HVB COAL – 60% LOAD – ZONE 2

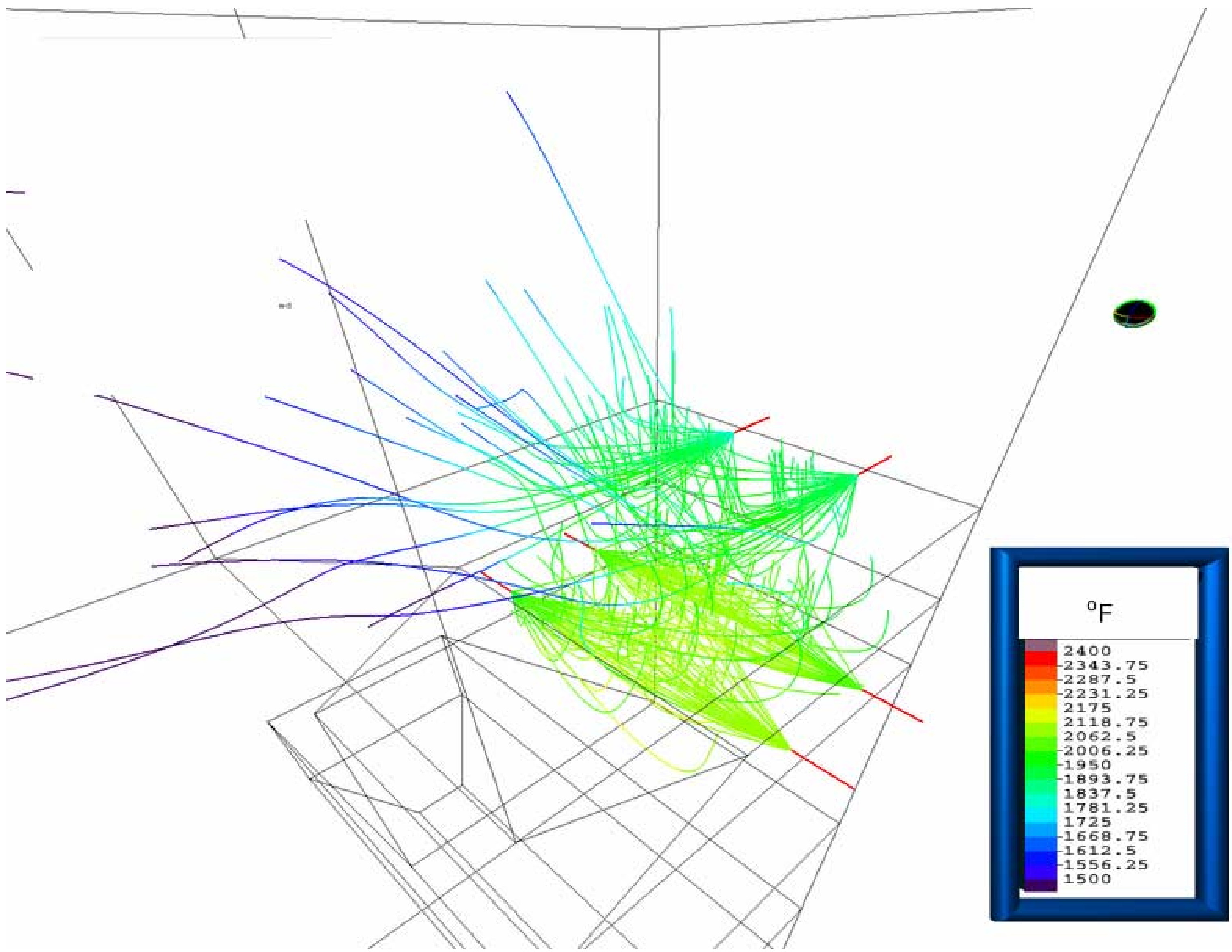


FIGURE 4.63. HVB COAL – 60% LOAD – ZONE 3

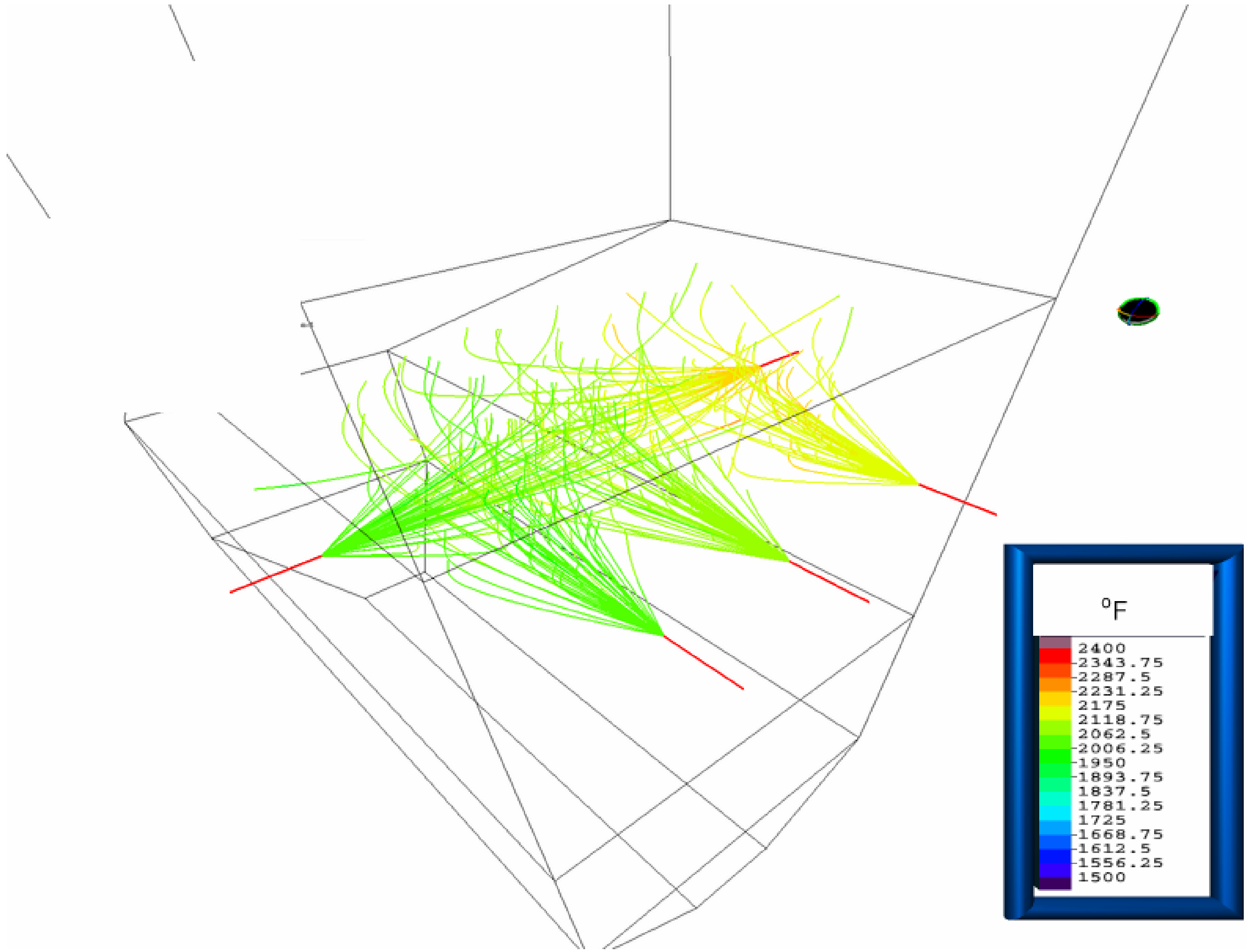


FIGURE 4.64. HVB COAL – 40% LOAD – ZONE 1

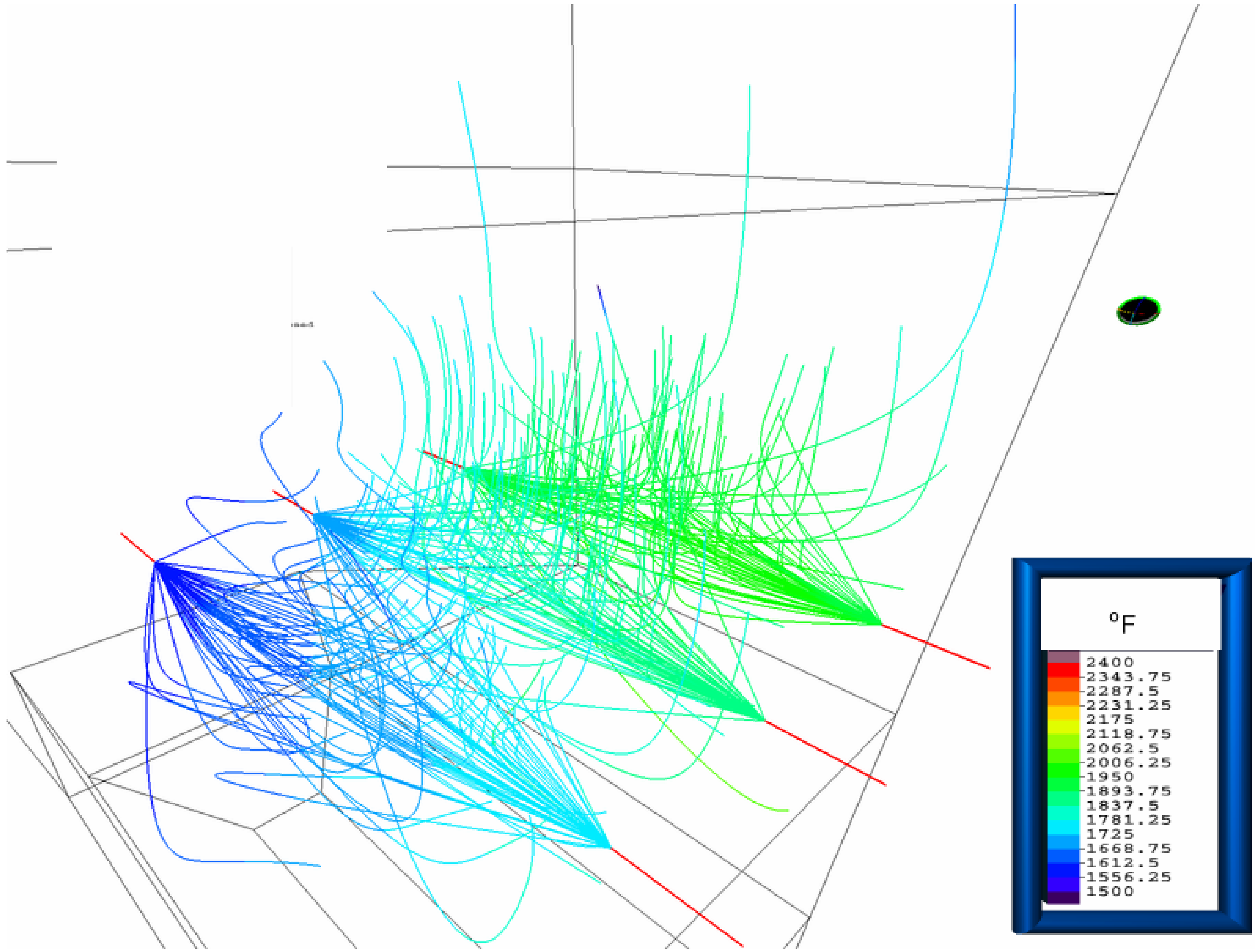


FIGURE 4.65. HVB COAL – 40% LOAD – ZONE 2

5 TEST EQUIPMENT AND PROCEDURES

The Clean Environment Development Facility (CEDF), located at McDermott Technology's Alliance Research Center, was utilized for optimization of the Effective Control of NO_x with Integrated Ultra Low-NO_x PC Burners and SNCR program. This large scale, 100 million Btu/hr, state-of-the-art test facility integrates combustion and post-combustion testing capabilities to provide the products and processes needed to meet or exceed the current air emission requirements. This scale test facility allows for testing equipment with a minimum of scale-up for commercialization.

5.1 TEST FACILITY DESCRIPTION

The CEDF is sized for a fuel heat input of 100 million Btu/hr when burning a wide range of pulverized coals, #2 and #6 oils, and natural gas. In smaller facilities the complex flow and mixing patterns and the pyrolysis and char combustion reactions occurring at the flame front do not always result in predictable geometric scaling. The CEDF has been designed to accommodate either a single burner of 100 million Btu/hr or multiple burners of equivalent total capacity. Baseline and permitting runs have already been performed in the CEDF with a single, 100 million Btu/hr B&W DRB-XCL® commercial burner. A single 100 million Btu/hr DRB-4Z™ ultra low-NO_x burner was utilized for this program. A description of this burner is discussed in section 6.1.

The design of the furnace and convection pass is shown in Figure 5.1. The shape of the furnace results from rotating the firing axis of the large burner 90 degrees from the firing axis of the small burners and furnace exit. The furnace is designed as a water-jacketed box with a refractory lining to maintain the proper combustion zone temperature. The vertical part of the furnace is 13 feet deep by 10 feet wide inside the refractory, and about 44 feet high from the centerline of the large burner to the centerline of the gas exit duct. The furnace tunnel for the single burner is 13 feet wide and extends an additional 20 feet from the furnace shaft to prevent flame impingement on the side of back walls. The furnace extends about 9 feet below the burner centerline and terminates in a hopper. The water jacket extends approximately 4 feet above the top of the

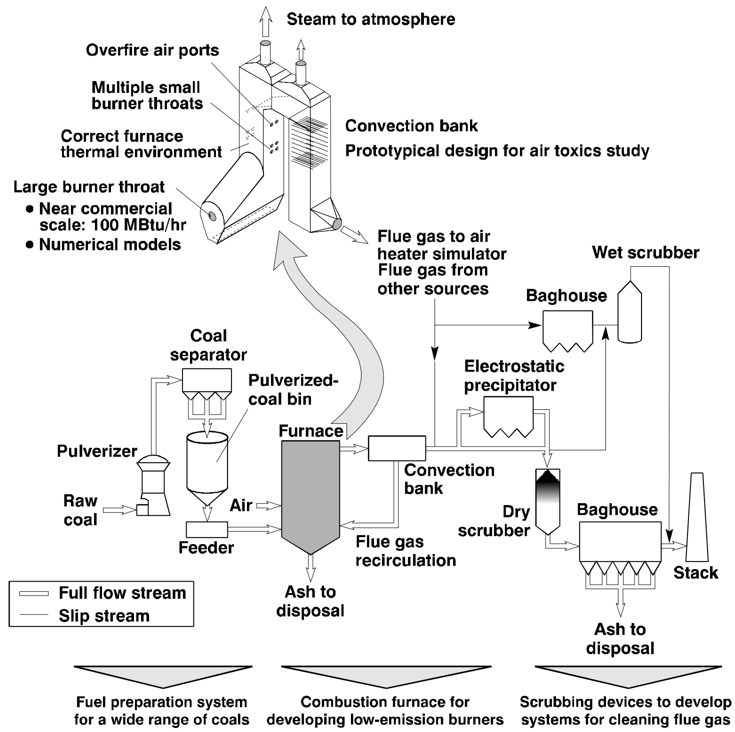


FIGURE 5.1. CLEAN ENVIRONMENT DEVELOPMENT FACILITY FURNACE AND CONVECTION PASS

furnace to provide for steam/water separation in the jacket. Thus the total external height of the furnace from the apex of the hopper to the top of the water jacket is approximately 62 feet.

The single 100 million Btu/hr ultra low-NO_x burner was mounted on the north wall of the lower furnace as an extended zone. This zone is 13 feet wide by about 15 feet high at the burner. The roof of this zone is arch shaped and slopes upward toward the vertical shaft by about 30 degrees. The sloped arch roof is required to provide room for gas recirculation above the burner and to accommodate the natural buoyancy of the flame. Beneath the large burner and furnace shaft there is a hopper and slag tank with a water-impounded drag chain conveyor for removing ash and slag. The windbox, which is about 10 feet square, is not shown but extends out about 6 feet from the front of the furnace.

Overfire air port are located in the furnace side wall at approximately 3 feet above the transition from the burner tunnel to the furnace shaft (OFA was not utilized for the SNCR tests). This location allows for introduction of the overfire air for carbon burnout without interfering with the gas flow patterns in the burner tunnel. The NO_x concentrations can be further reduced by the use of overfire air to create deeper staging of the combustion. The residence time at high temperatures must be kept within critical limits when using overfire air. This residence time may not be easily achieved with the large single burner because of the width and depth established by flame impingement limits with the single burner. In order to optimize the complete overfire air system; the multiple burner system would be required. However, burner performance, stability, and NO_x reduction trends at low stoichiometries can be explored with this OFA port arrangement.

B&W's unique dual-zone overfire air ports provide even distribution of overfire air. The ports are equipped with sliding dampers, spin vanes and air flow measurement devices to enable flow balancing during commissioning of the equipment. The sliding air damper may be automated to control the air through each port. The spin vanes control the swirl or tangential velocity and flare of the air pattern through the OFA port and into the furnace. The air for the OFA ports is taken from the secondary (or combustion) air. Metering devices are installed to control the airflow to the burner and to the OFA ports. The metering devices are connected to the data acquisition system for data collection.

The flue gas from the furnace passes over a nose or arch that protrudes approximately 35% into the furnace. The nose provides sufficient flow resistance to develop the proper gas flow patterns in the vertical shaft and at the entrance of the convection pass for the large single burner. The gas exit is the full width of the furnace (10 feet) by 12 feet high. When the single burner is in use, the evolution of flame-generated volatile organic compounds (VOCs) and air toxics can be followed as the flue gas cools from flame temperature to a typical emission control device temperature. This is accomplished by taking measurements at various points along the flue gas path from the furnace exit to the inlet of the SO_2 emission control device. Careful control of the gas cooling rate is required to provide a gas time-temperature profile that is similar to commercial units. In this way a representative reaction environment is created for the formation and destruction of NO_x-related species and air toxics. A two-stage cooling process is used to achieve the desired time-temperature history. The first stage is simulated convection back while the second stage more closely simulates an air heater.

The convection bank is a 10 x 12-foot water-cooled duct. In order to make the best use of the available space the convection pass has a horizontal section followed by a down flow vertical section. A large number of water-cooled tubes run from the floor to the ceiling of the horizontal section and side to side with an incline of about 15 degrees in the vertical section. The tubes are spaced uniformly across the duct in any given row but the number of tubes per row and the row spacing along the duct is very irregular. This non-uniform tube spacing is designed to simulate the flue gas time-temperature pattern found commercial boilers. Tube spacing is also influenced by the need to accommodate coals with strong fouling tendencies. Sootblowers are installed to keep the convection pass tubes clean. The flue gas cools rapidly in the initial section of the bank but more slowly in the later parts that simulate the economizer. Sufficient heat transfer surface is provided to cool the flue gas from the furnace exit temperature to about 700° at the exit.

Following the convection pass the flue gas enters a combination flue gas cool and air heater. The gas temperature leaving this unit is controlled to a suitable value for the gas clean-up systems. The flue gas is primarily cooled with secondary air through preheating of the air. The outlet temperature is adjusted by independently adjusting the airflow through the upper modules. The simulation of the burner and furnace test zone terminates at the flue gas cooler. Numerous sample connections are located along gas flow path to follow the formation and destruction of VOCs and other air toxics.

Boiler convection pass and air heater simulators maintain representative conditions through the entire boiler system to facilitate studies of air toxics capture in the dry scrubber and baghouse. Representative gas phase time-temperature profiles and surface metal temperatures are maintained throughout the convection pass. Convection pass metal temperatures are maintained in the 600-1000°F range by way of a novel double-walled tube design.

5.1.1 *Air and Coal Supply*

Pulverized coal is supplied to the burner by an indirect or “bin feed” system so that a wide range of air-to-fuel ratios and fuel moistures can be studied. Separating the pulverizer and burner also allows limited periods of independent operation of the coal preparation and burning units. A B&W EL-56 pulverizer is equipped with a dynamically staged, variable speed classifier so that the effects of coal fineness on NO_x production and unburned carbon can be evaluated. Preheated primary air picks up the coal and transfers it to a small baghouse that vents the wet air and drops the coal into a pulverized coal storage bin. The bin is equipped with a nitrogen inerting system to prevent bin fires. The pulverized coal can also be sent directly from the pulverizer to the burner when burning fuels for which the pulverizer output matches the required feed rate and air/fuel ratio.

Pulverized coal is withdrawn from the bottom of the bin by a flow control device and picked up in a transport air stream that carries it to the burner. Spraying water into the transport air upstream of the pick-up point can vary the as-fired moisture level. In order to obtain maximum flexibility and control, separate fans and air preheaters are used for the primary air to the pulverizer, transport air from the pulverizer to the burner, and secondary air to the burner and overfire airports.

5.1.2 *Post-Combustion Emission Control*

From the flue gas cooler the gas enters a dry scrubber to control sulfur dioxide emissions. Although this system can be used to advance dry scrubber technology, its current primary purpose is to allow the facility to meet air emission regulation. The dry scrubber is a vertically oriented, 14-foot diameter by 60-foot tall tower (including inlet and exit transition sections) constructed of carbon steel. Flue gas enters the top through an expansion containing flow straightening devices.

Atomized slurry is introduced through a single B&W DuraJet™ atomizer located to provide uniform spray coverage in the vessel. The B&W DuraJet™ atomizer is used in commercial dry scrubbing and humidification systems. The atomizer not only provides finely atomized slurry, but also acts as a mixer to ensure intimate contact between the hot entering flue gas and slurry, maximizing SO_2 removal and drying. The atomizer is mounted in a shield air tube at the scrubber inlet allowing for naturally aspirated vent airflow. A reagent preparation system is designed to wet hydrated lime and prepare slurry for injection into the dry scrubber. The flue gas, along with the dried particulate, travels down the chamber and turns 180° into an air outlet duct. The outlet duct is fitted with a sloped cone to minimize solids dropout in the duct.

Flue gas exiting the dry scrubber is ducted to a pulse-jet fabric filter baghouse. The baghouse consists of six modules arranged in a three-by-two array. Each of the six modules contains 42 full-size bags for a total of 252 bags in the baghouse. The air-to-cloth ratio is adjustable from 4:1 to 6:1 at full load by blanking off modules. The entering flue gas is distributed to the bottom of each of the six modules through a tapered inlet manifold. Manually operated butterfly dampers are used for module isolation. The clean gas exits each module at the top and is collected in a tapered clean gas manifold. Pneumatically operated poppet values are utilized for module outlet isolation.

The pulse-jet cleaning system is designed to permit either on-line or off-line cleaning in either manual of automatic operating modes. For additional flexibility, in the automatic mode the fully adjustable cleaning cycle may be initiated on either baghouse pressure differential, timed, or combined pressure differential/timed basis. The solid byproduct dislodged from the bags is transferred from the baghouse by a pneumatic conveyor system to an ash silo for disposal.

Existing post combustion emissions control instrumentation includes: dry scrubber and baghouse outlet temperature, dry scrubber skin thermocouples to monitor deposition, atomizer slurry and air pressure gauges, baghouse pressure drop across each of the six baghouse modules, and a continuous emissions monitor at the stack.

5.1.3 INSTRUMENTATION

Calibrated pressure transducers, thermocouples, and flow metering and control devices are integral to the CEDF. Voltage signals from instruments, sensors, and metering devices are collected, converted to a digital signal, and stored by the Data Acquisition System (DAS).

STARS/LabVIEW software is utilized to convert these signals to engineering units for on-line real time display in tabular or graphical form at time intervals specified by the operator. Derived quantities such as fuel input (load) and airflow are calculated utilizing other measured instrument values converted to engineering units. The fuel and combustion flows are measured by the DAS electronically utilizing pressure transducers and thermocouples at the flow orifices. Raw voltages from these devices are converted to static pressure, pressure drop, and flow temperature at the orifice by utilizing calibrations based on reference signals. Engineering units for flow are calculated with a calibrated flow orifice equation expressing flow as a function of the above variables.

Convective pass section outlet gaseous species are sampled continuously through a heated sample line. After filtering and drying, CO, CO_2, O_2, NO_x, and SO_2 concentrations are measured and recorded. All analyzers are calibrated daily with certified gas standards.

5.2 MODIFICATIONS

The CEDF contains the basic equipment needed for the Cost-Effective Control of NO_x with Integrated Ultra Low-NO_x Burners and SNCR program. Only a few modifications were necessary for test evaluation, namely the addition of site ports for the injection of the NO_xOUT®LT solution and the NO_xOUT® process equipment.

5.2.1 SITE PORTS

CEDF boiler high velocity thermocouple (HVT) measurements were taken during burner optimization test campaigns. The temperature measurements were used with numerical modeling to determine the optimum injection port locations. Site ports were added to the CEDF to accommodate the aqueous urea injection. Ports were added at three elevations and on all sides of the furnace to provide adequate penetration and coverage over various temperature ranges. (See discussion in section 4.2.2.)

5.2.2 NO_xOUT® System Description

The NO_xOUT® Process incorporates a trailer-mounted reagent delivery system to inject the NO_xOUT®LT solution into the combustion gases of the boiler.

The purpose of the Circulation Module is to supply the chemical NO_xOUT®LT to the Metering Modules through constant circulation. The Module is skid mounted and fully shop tested. The circulation pump should run at all times during system operation.

The Metering Modules are skid-mounted units in the demonstration trailer used to supply mixed NO_xOUT®LT to each Distribution Module. The trailer is prepackaged and shop tested and includes three sub-modules each with a chemical metering pump and two sub-modules each with a water boost pump. In addition, the trailer contains all necessary valves, check valves, strainers, flow transmitters, in-line mixers and stainless steel piping/tubing to make it a self-contained metering and pumping system. Each chemical metering pump sub-module and water boost sub-module is intended to supply chemical solution to the distribution modules at a given level of injection. The chemical metering pump sub-modules can be routed in varying combinations to increase the available flow of NO_xOUT®LT to any level of injection by the use of manual crossover valves.

NO_x reduction is a function of the chemical feed rate, which is controlled by varying the speed of the metering pumps through a 4-20 mA signal. Control for the Metering Module is provided via local potentiometers on the module control boxes.

Mixed NO_xOUT®LT is transported from the Metering Modules to the Distribution Modules, which channel the NO_xOUT®LT mixture to each injector. Each Distribution Module consists of flow meters, balancing valves and regulators, which accurately control and display the chemical and atomizing air to each injector. Also contained on these modules are the necessary manual ball valves, gauges and stainless steel tubing required to adequately control the NO_xOUT®LT injection process.

The injectors consist of an atomizing chamber in which the air and $NO_xOUT^{®}LT$ mixture first meet. Liquid is sprayed through small orifices forming a jet. The atomizing air shears this jet forming small droplets. The atomized chemical then flows through the injector tube to the nozzle. The nozzle is specially designed and characterized to meet the appropriate plant conditions. This is done by detailed computer analysis of the temperature, combustion and gas velocity profiles in the boiler. The atomized $NO_xOUT^{®}LT$ reagent then enters the boiler and mixes with the boiler flue gas to form nitrogen, carbon dioxide and water. Air is required for cooling at any time the injectors are in operation and not retracted from the boiler. The injectors are equipped with quick disconnects and hydraulic hoses for flexibility and ease of maintenance.

The final addition to the injector is an outer cooling air jacket. This shield is attached to the atomizing chamber via a cooling shield adapter. Plant air is fed into the coolant air jacket at a low volume and pressure. The air acts as a coolant for the nozzle. The jacket minimizes direct contact between the corrosive flue gas and the nozzle. This maximizes the useful life of the nozzle in a hostile environment.

5.2.3 Furnace Refractory

It should be noted that after the first round of burner optimization testing, refractory maintenance activities were performed on the CEDF. The repair and replacement of the refractory caused the furnace environment to be at a higher temperature than during previous operation. Testing showed an increased NO_x level during the optimization testing performed firing the Pittsburgh #8 and Middle Kittanning coals in comparison to previous testing. Furthermore, the temperature mapping obtained during the furnace characterization showed higher temperatures throughout the furnace compared to previous temperature mappings. New baseline values were obtained while firing the Spring Creek coal before the SNCR optimization testing began.

5.3 OPERATION

5.3.1 START-UP

Start-up of the facility begins with a walk down of the unit to ensure components are ready. One operator is in the control room, while another is at each major piece of equipment during start-up of the component. The baghouse compressor is brought on-line first. The water level for the furnace, convection pass, and slag conveyor tank is then checked and adjusted for an adequate level. Next, the I.D. fan is started with minimal flow, and the scanner seal air blower initiated. The secondary air fan is then started at a low rate. The I.D. fan is set at automatic while the secondary air flow rate is increased to approximately 40% of the total airflow. At this time, the burner management system (BMS) begins a purge if all permissives have been met. After the purge is complete, the gas lighter is ignited. The unit heats up with the lighter. The primary air fan can be started only after the gas lighter is in service. After the gas lighter has been in service for a given amount of time, the auxiliary gas spud can be started at a minimum firing rate. The secondary air trim heater is brought into service next. The controller output is slowly brought to the desired temperature required for testing once the unit is near operating conditions. The burner primary air heater is then brought into service and the temperature slowly increased to the testing set point. The gas firing rate is steadily increased to the maximum firing rate. This is maintained until the unit temperature stabilizes at the convection pass inlet and the dry scrubber inlet. The temperatures at the dry scrubber should be over 200°F and at the baghouse over 160°F. The boiler feedwater pumps are started at this point. Three of six baghouse compartments are brought into service after reaching temperature and prior to firing coal. While maintaining adequate primary airflow to the burner, coal firing is initiated. The coal flow rate can is increased while still maintaining maximum gas firing. As the dry scrubber outlet temperature increases to 240 to 250°F, the lime slurry pump is started at a minimum rate. The coal-firing rate is slowly increased while the gas-firing rate is slowly decreased. The lime slurry pump is slowly increased to maintain a SO_2 emission of 1.2 lb SO_2/MBtu and dry scrubber temperatures. Coal firing is brought up to full load, while gas firing is discontinued. Once the furnace reaches equilibrium, the burner optimization or the SNCR injection parametric testing could begin.

Start up of the $NO_xOUT^{®}$ system follows the procedure outlined below:

1. Verify the Circulation Module is operational and NO_xOUT® LT is circulating through the Trailer Chemical Circulation Loop.
2. Verify the plant Dilution Water is aligned to the Trailer.
3. Verify Atomizing/Cooling Air is available to the Distribution Modules before inserting injectors.
4. Determine which Injectors are to be placed in service at this time and verify the corresponding Distribution Panel isolation valves are in the open position.
5. Verify the Water Pump flow path is open for the appropriate Water Pump and desired level of injection.
6. Start the Water Pump and adjust the pressure regulator to obtain the desired water flow rate (as shown on the appropriate Water Flow Meter.)
7. Verify the Chemical Metering Pump flow path(s) is/are open for the appropriate Chemical Metering Pump(s) and desired level of injection.
8. Start the Chemical Metering Pump(s) and adjust the motor speed(s) to obtain the desired chemical flow rate (as shown on the appropriate Chemical Flow Meter.)

Repeat Steps 5 through 8 for the second Water Pump and remaining Chemical Metering Pump(s) to inject to a second level simultaneously.

5.3.2 SHAKEDOWN

Shakedown of all furnace equipment was completed prior to initial start-up. All parts were started and checked to make sure in good working order and any maintenance required was completed.

The shakedown of the SNCR system consists of verification of proper alignment of all Chemical, Dilution Water and Atomizing/Cooling Air lines.

The Chemical Circulation Module is started to ensure proper delivery of $NO_xOUT^{®}LT$ to the Trailer Circulation Loop.

The Water Pumps are started and individually routed to each level of injection to 1) flush all lines and 2) verify proper alignment of all hose runs to the correct level of injection.

The Chemical Metering Pumps are started and the Calibration Column provided on each sub-module is used to compare the actual chemical flow rate to the flow measured by and displayed on the Chemical Flow Meter.

The chemical flow rates, atomizing/cooling air pressures were verified and balanced at each level of injection on the Distribution Modules.

5.3.3 SHUT-DOWN

There are two types of shutdown for the CEDF. The first is a short tem shutdown to keep the unit hot during burner hardware changes. The second type is shutdown for maintenance or when not intending to refire the unit in a short period of time. For both types of shutdown, the coal-firing rate is reduced to 60 MBtu/hr, at which time the gas lighter is placed into service. This level is maintained for approximately one hour. The auxiliary gas burner can be brought into service while the coal burner is further reduced until brought out of service. Once coal firing has stopped, the primary and secondary air heaters are removed from service along with the dry scrubber and baghouse. The auxiliary gas is reduced to 30 MBtu/hr for a time, after which it can be brought out of service. The gas lighter continues firing to bring down the unit temperature slowly. After removal of the gas lighter from service, a five-minute purge of the system is required before the fans can be shutdown. The burner can be removed after shutting down the fans to permit hardware changes. If the unit is being shutdown for a longer period of time, the gas lighter stays on an additional amount of time and then is brought out of service. The fans continue to run at low rate for some time.

The procedure to shutdown the SNCR system is as follows:

1. Turn Metering Pump Disconnect(s) to off position.

2. Turn Water Boost Disconnect(s) to off position.

For long-term shutdown, run Water Boost Pump(s) through each level of injection for additional 1 – 5 minutes to flush chemical out of hose runs before stopping and then perform the following additional steps:

3. Close isolation valves inside trailer for each level of injection.

4. Turn Circulation Pump Disconnect to off position.

5. Close the isolation valve on the NO_xOUT®LT Storage Tank.

6. Turn Trailer Main 480V Power Feed Disconnect to off position.

6 Ultra Low-NO_X DRB-4Z™ PC Burner Performance Evaluation

6.1 Ultra Low-NO_X PC Burner Hardware Selection

The DRB-4Z™ pulverized coal burner, shown in Figure 6.1, is designed to reduce NO_x by diverting air away from the core of the flame, reducing the local stoichiometry during coal devolatilization, and thereby reducing initial NO_x formation. Limited recirculation zones between the primary and secondary stream also act to transport evolved fuel NO_x back toward the oxygen lean devolatilization zone for reduction to molecular nitrogen. The coal stream is transported by air in the central primary zone. The air/coal mixture in this zone is set to create a fuel-rich core region. Encircling the primary zone is the primary and secondary air streams to control near-burner and downstream mixing. Combustion air can be diverted from the secondary air stream to the transition zone, or the zone can operate without combustion air. A sliding damper is located over the openings of the transition zone to regulate the flow of air into this zone. Radial pitot grids in the transition zone can be used for airflow measurements. Fixed or adjustable vanes can be used to impart proper spin to the transition air for flame stability and additional near-burner mixing control. The majority of the combustion air is supplied through the dual inner/outer secondary zones to complete burnout in the downstream fuel-lean zone. The burner is equipped with a set of fixed pre-spin vanes located in the outer air zone to enhance distribution of air around the periphery of the burner. Adjustable vanes are located in both the inner and outer air zones to impart proper spin to the secondary air for flame stability and optimum mixing of fuel and air. Curved adjustable and fixed vanes were added to the inner secondary air zone to lower the pressure drop through the burner. Secondary air to the inner and outer zones is controlled independently of the spin vanes by means of a sliding damper blocking the inner zone. An inner air distribution cone (IADC) device may be added to enhance flame stability. An outer air distribution cone (OADC) can also be used to change the secondary airflow for mixing control. Devices can also be placed in the transition zone to change the air patterns, thus effecting the air/fuel mixing.

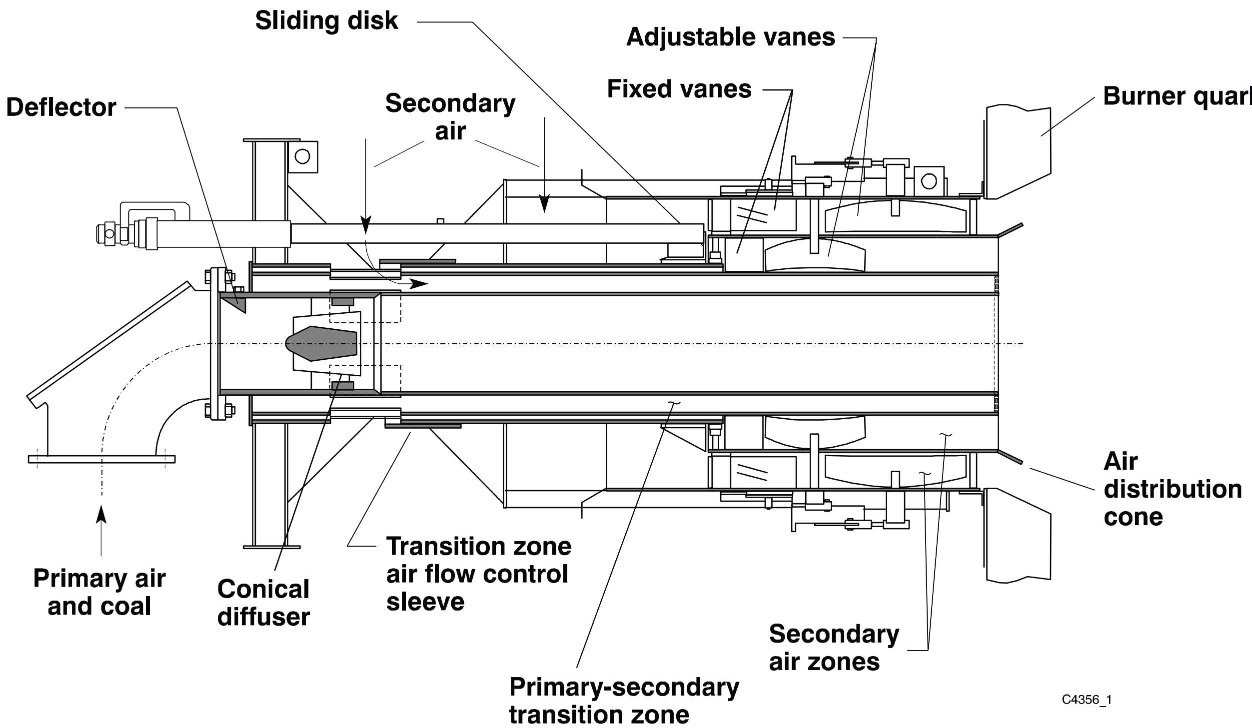


FIGURE 6.1. SCHEMATIC OF PLUG-IN DRB-4Z™ PC BURNER

B&W and MTI, under DOE sponsorship, have further developed and successfully demonstrated two versions of the DRB-4Z™ burner. The first is a full diameter 100 million Btu/hr, unstaged burner developed for new boiler applications. This version, however, is not readily retrofitable to existing boilers since substantial boiler pressure part modifications would be required for installation of this burner. The second version of the DRB-4Z™ burner developed is a plug-in (small throat) burner that would be easily retrofitable to an existing boiler.

The performance of both burners was evaluated to determine which burner should be used for this program. Analysis of the burners showed that both burners achieved similar NO_x emissions, however, new features of the plug-in burner resulted in pressure drop and unburned carbon reductions. Therefore, the plug-in burner was chosen for further evaluation with SNCR injection.

6.2 HARDWARE CONFIGURATIONS

Numerous hardware configurations have been tested with the plug-in DRB-4Z™ burner firing common eastern bituminous coals. The most promising hardware was selected for further evaluation with the three test coals for this program; these are listed in Table 6.1. Testing began with firing the Spring Creek coal since it had not been fired with the plug-in DRB-4Z™ burner previously. Most burner hardware configurations were tested with the Spring Creek coal to make sure the burner was fully optimized.

TABLE 6.1. BURNER HARDWARE CONFIGURATIONS

Test Series	Coal	Mixing Device	Discharge Configuration	Air Distribution Cone
SCPP	Spring Creek	none	straight pipe	yes
SC30SNC	Spring Creek	swirler	straight pipe	yes
SC15SNC	Spring Creek	swirler	straight pipe	yes
SCIPP	Spring Creek	none	pipe insert	yes
SCPPI15C	Spring Creek	none	pipe insert plus protruding flame cone	yes
SCPPI15CR	Spring Creek	none	pipe insert plus retracted flame cone	yes
SCPPINA	Spring Creek	none	pipe insert	no
MK15SASV	Middle Kittanning	swirler	pipe insert	yes
MKCDASV	Middle Kittanning	none	pipe insert	yes
MKCDASVIN	Middle Kittanning	none	straight pipe	yes
MKDASVOPT	Middle Kittanning	none	pipe insert	yes
P8CDASV	Pittsburgh 8	none	pipe insert	yes
P815SASV	Pittsburgh 8	swirler	pipe insert	yes
P8CDASVOPT	Pittsburgh 8	none	pipe insert	yes

6.3 COAL SELECTION

Three coals including a Western subbituminous, a high-volatile bituminous, and a medium-volatile bituminous were procured for testing. Proximate, ultimate, and heating value analyses of the as-received coal were determined by standard ASTM methods. Table 6.2 shows representative analyses of the coals. The purpose of testing these various coals was to show the effect of changing fuel types on burner and SNCR injection performance. These coals ranged in fixed carbon-to-volatile matter ratios (FC/VM) of 1.2 to 2.4. The Western subbituminous coal was a Spring Creek coal from the Powder River Basin. This coal has a very high volatile matter content, therefore a low FC/VM (1.26), subsequently resulting in lower NO_x emissions. This coal was typical to other PRB coals tested in the CEDF and in the field with the DRB-4Z™ burner. A Pittsburgh #8 coal was chosen to represent typical high-volatile bituminous coals. Pittsburgh #8 is one of the most mined coals in Ohio and has been fired many times in the CEDF. It is harder to obtain low NO_x emissions with the high-volatile coals than it is with a Western subbituminous coal. Since high-volatile bituminous coals are typically fired in the northeastern part of the United States, it was a good candidate to showcase the ultra low-NO_x burner with SNCR injection technology. A Middle Kittanning coal was chosen for the middle-volatile bituminous coal. This coal had a FC/VM of approximately 2.4. A middle-volatile coal was chosen to serve as a challenging coal to meet the NO_x emissions goals. The Middle Kittanning coal has also been fired in the CEDF previously, so comparisons could be made to earlier testing.

Pulverizer settings were adjusted for each coal to produce a PC fineness of about 70% through a 200-mesh screen. Pulverized coal samples were extracted from the PC-laden stream after the mill (before the filterhouse) according to the ASME PTC 4.2 procedure. Mass percentage of as-fired PC particles passing through stacked sieves of 200 to 30 mesh screens (74 to 595 μm) were checked each day the coal was pulverized. The particle size distribution can be seen in Table 6.3. Although a 70% through 200 mesh fineness was desired, as shown in Table 6.3, a coarser grind was achieved for the Spring Creek and Pittsburgh #8 coals. This coarser grind size could partially account for increased CO values due to slower fuel oxidation

TABLE 6.2. REPRESENTATIVE COAL ANALYSES

	Subbituminous *Spring Creek*	High-Volatile Bituminous *Pittsburgh #8*	Medium-Volatile Bituminous *Middle Kittanning*
PROXIMATE (as rec'd)			
Fixed Carbon (%)	39.10	44.00	47.31
Volatile Matter (%)	31.05	36.82	19.89
Moisture (%)	26.21	12.87	9.55
Ash (%)	3.64	6.31	23.25
Fixed Carbon/Volatile Matter	1.26	1.20	2.38
ULTIMATE (as rec'd)			
Carbon (%)	53.10	65.45	57.16
Hydrogen (%)	3.78	4.52	3.43
Nitrogen (%)	0.64	1.12	0.96
Sulfur (%)	0.23	3.10	1.20
Oxygen (%)	12.40	6.62	4.44
As-Fired Moisture (%)	13.56	1.95	1.06
Heating Value (Btu/lb) (as rec'd)	9110	11733	10054

TABLE 6.3. PULVERIZED COAL SIZE DISTRIBUTION

Mesh Designation & Size (μm)	(Percent Smaller)		
	Spring Creek	Pittsburgh #8	Middle Kittanning
30 (595)	100.00	100.00	100.00
50 (297)	99.77	99.80	99.89
70 (210)	98.56	98.67	99.13
100 (149)	93.00	93.50	95.16
140 (105)	79.51	80.03	85.37
200 (74)	63.10	63.50	73.08

6.4 BURNER PERFORMANCE OPTIMIZATION

Parametric testing was performed for each burner configuration. Optimum burner settings for each hardware and coal arrangement was established at full load (100 million Btu/hr) and 17% excess air by systematic adjustment of spin vane angles and secondary and transition zone air damper positioning. After the hardware positioning was optimized, furnace variables such as the primary air-to-coal ratio, burner stoichiometry and load were varied.

6.4.1 VANE ANGLE EFFECTS

The adjustable vanes located in the inner and outer secondary air zones were varied to show the effect of the air distribution and the spin placed on the air. These tests led to optimizing the secondary air distribution. The effect of the vane angle on NO_x and LOI with regard to CO emissions for various hardware configurations tested were compiled for comparison. The results showed the general preference of the vanes to be set at 30° for the inner vanes and 60° for the outer vanes. The DRB-4Z^{TM} burner tends to favor a tighter vane setting, producing more swirl on the secondary air and creating a tighter flame boundary. For the most part, the burner behaved as would be expected in terms of the correlation between NO_x, CO, and LOI.

6.4.2 SECONDARY AIR SLIDING DAMPER POSITION EFFECTS

Closing of the secondary air sliding damper (0% is closed, 100% is open) blocked off the inner secondary air zone and directed more air to go through the outer secondary zone. This affects the availability of oxygen at the core of the flame, the air mixing patterns, and the recirculation zone. The position of the sliding damper was measured linearly on the rod connected to the damper and did not necessarily represent the percentage of the area blocked. Typically, as the sliding damper was closed, the CO emissions tended to increase, while either not changing the NO_x emissions or increasing the NO_x slightly. In only one test series, SCPP, did the NO_x emissions decrease, however, the CO emissions increased significantly as the secondary air sliding damper was closed. The same trend was seen for LOI. This is illustrated in Figure 6.2.

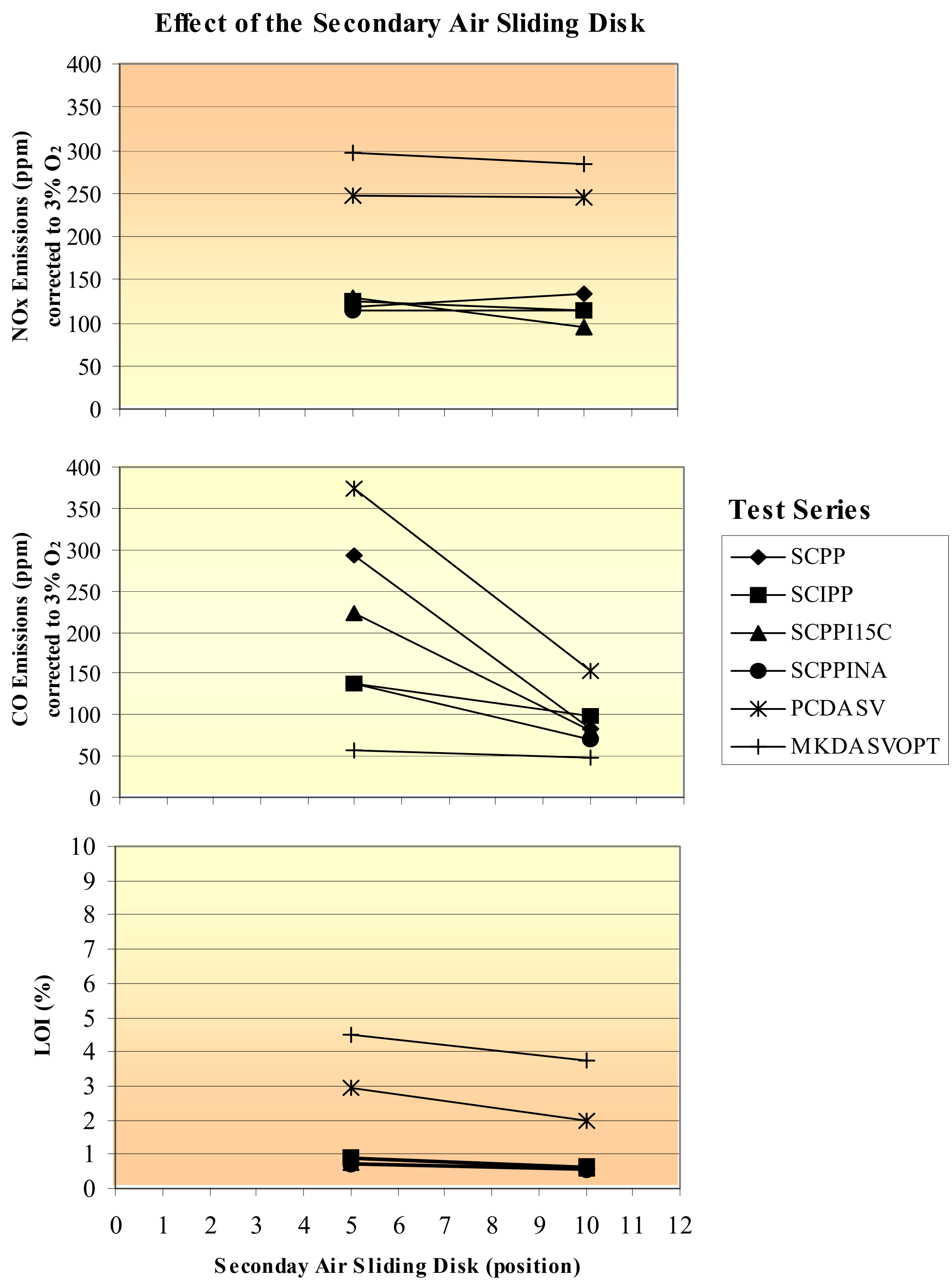


FIGURE 6.2. SECONDARY AIR SLIDING DAMPER EFFECT ON NO_X, CO, AND LOI FOR DIFFERENT CONFIGURATIONS OF THE ULTRA LOW-NO_X PLUG-IN DRB-4Z™ BURNER FIRING PULVERIZED SPRING CREEK (SC), PITTSBURGH #8 (P), AND MIDDLE KITTANNING (MK) COALS AT 100 MILLION BTU/HR AND 17% EXCESS AIR.

6.4.3 *TRANSITION ZONE AIR FLOW DAMPER POSITION EFFECTS*

A sliding sleeve damper allows for control over the amount of air entering the transition zone. This damper can be varied from 0% to 100% open. A minimal amount of air does enter the transition zone in the closed position. Generally the transition zone air damper position preference depends on the transition zone mixing device utilized. For most cases, firing the Spring Creek coal, CO emissions increased as the transition zone sliding air damper was opened. NO_x values stayed relatively the same, except for the SCPP configuration that decreased in NO_x emissions after 50% open on the transition zone sliding damper, however, CO emissions increased dramatically in this case. When firing the Middle Kittanning coal, NO_x values slightly increased as the transition zone damper opened, except for the MKDASVOPT case where NO_x decreased. For most cases firing the Middle Kittanning coal, there was little effect on CO emissions as the transition zone sliding air damper opened. While firing with the Pittsburgh #8 coal, it was noted that if NO_x slightly increased, CO greatly decreased, and if NO_x slightly decreased, CO greatly increased. These patterns are shown in Figure 6.3. For the most part, regardless of which coal fired, NO_x emissions showed little changes due to the position of the transition zone damper. However, CO emissions could be greatly effected depending on transition zone device utilized and position of the transition zone damper.

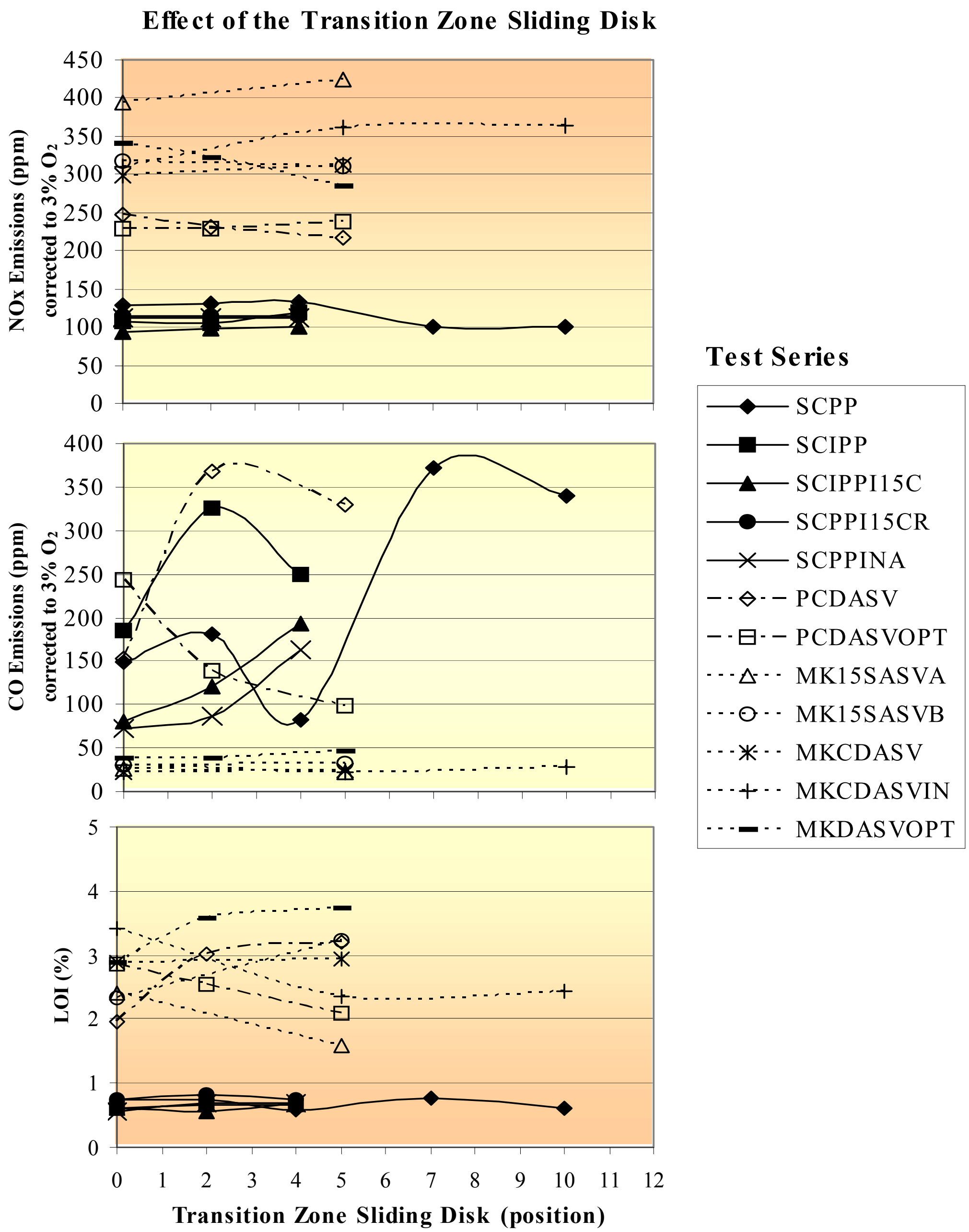


FIGURE 6.3. TRANSITION ZONE DAMPER POSITION EFFECT ON NO_X, CO, AND LOI FOR CONFIGURATIONS OF THE ULTRA LOW-NO_X PLUG-IN DRB-4Z™ PC BURNER FIRING SPRING CREEK, PITTSBURGH #8, AND MIDDLE KITTANNING PULVERIZED COALS AT 100 MILLION BTU/HR AND 17% EXCESS AIR.

6.4.4 *PRIMARY AIR-TO-COAL RATIO EFFECTS*

After variations of the vane angle, secondary air sliding damper, and transition zone sliding damper were tested, an optimum setting was chosen and used for all subsequent tests. The coal nozzle velocity for the DRB-4Z™ burner was sized for transporting a specific fuel at a specific primary air velocity. At this velocity, the nominal primary air-to-coal mass ratio (PA/PC) was 1.8. For selected cases, the primary-air-to-coal ratio was varied from 1.3 to 2.2. The ratio was changed by varying the amount of primary air to the burner to achieve a set ratio and then adjusting the secondary air accordingly to maintain a consistent furnace stoichiometry. Within limits, raising the primary airflow rate increases the flame temperature and luminosity, improves combustion efficiency, and enhances the early release of the NO_x reducing precursors. Higher primary air velocities also preserve the pulverized coal jet from rapid dispersion and mixing with the swirling secondary air streams. Accordingly, raising the PA/PC increased the primary combustion zone stoichiometry and flame temperature. As PA/PC was increased, more O_2 was available causing an increase in the fuel-N oxidation resulting in higher NO_x, while the combustion efficiency was greater (especially with the mid-volatile Middle Kittanning coal) resulting in lower CO emissions and LOI. This is illustrated in Figure 6.4. The optimum primary air-to-coal ratio design point for the Spring Creek coal was 1.8. As shown in the figure, when the PA/PC increased from this value, typically NO_x emissions increased and CO emissions decreased. When the PA/PC was decreased in case SCPPI15C, NO_x increased and CO decreased. However, for case SCPPINA when the PA/PC was decreased, NO_x decreased and CO increased significantly. The optimum primary air-to-pulverized coal ratio design point for the Pittsburgh coal was also 1.8. As the PA/PC increased from this value, NO_x increased and CO decreased. The optimum primary air-to-pulverized coal design point for the Middle Kittanning coal was 1.45. Again, when the PA/PC increased, NO_x increased and CO decreased, whereas when PA/PC decreased, NO_x increased and CO decreased or remained the same

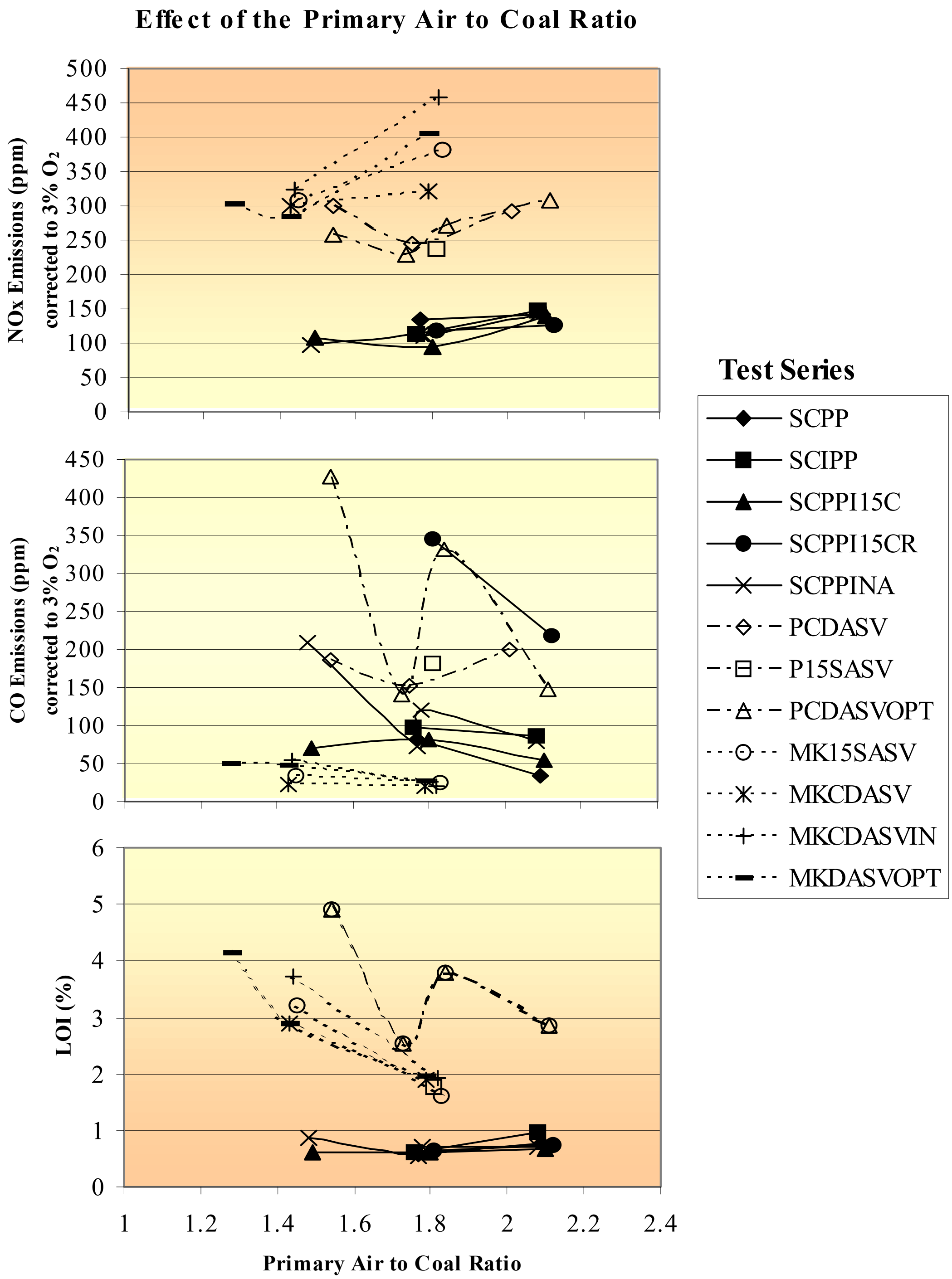


FIGURE 6.4. PRIMARY AIR TO COAL RATIO EFFECT ON NO_X, CO, LOI FOR CONFIGURATIONS OF THE ULTRA LOW-NO_X, PLUG-IN DRB-4Z™ PC BURNER SPRING CREEK, PITTSBURGH #8, AND MIDDLE KITTANNING PULVERIZED COALS AT 100 MILLION BTU/HR AND 17% EXCESS AIR.

6.4.5 *BURNER STOICHIOMETRY*

Changing the amount of excess air to the burner through adjusting the secondary airflow varied the burner stoichiometry. By doing this, more O_2 was available causing more complete combustion resulting in lower CO and LOI values, while increasing the fuel-N transformation to NO_x. When firing the Spring Creek coal, NO_x remained relatively constant despite changes in O_2 level, however CO dramatically increased when excess O_2 levels were brought below 3%. When firing both the Pittsburgh #8 and Middle Kittanning coals, NO_x increased significantly when O_2 increased and slightly when O_2 decreased from nominal operating conditions. However, CO emissions followed as would be expected for both coals with CO increasing as O_2 decreased and CO decreasing as O_2 increased. LOI results followed similarly to CO trends. These results are shown in Figure 6.5.

6.4.6 *THERMAL LOAD EFFECTS*

Figure 6.6 shows the thermal load effect on NO_x and LOI while firing the test coals. Figure 6.7 shows the effect of the burner stoichiometry, with respect to load, on NO_x, CO, and LOI values with the plug-in DRB-4Z™ burner. Part load (~60 x 10^6 Btu/hr) and minimum load (~40 x 10^6 Btu/hr) operations at a fixed stoichiometry resulted in little to no change in LOI due to the cooler furnace environment. NO_x values increased for the plug-in burner at the lower loads. This is typically seen with the plug-in burner while firing in the CEDF. Non-optimum (off-design) burner aerodynamics at lower loads is likely to have influenced the emissions results. Also, burner stoichiometry was increased to simulate full-scale conditions. All flames were well attached, even at minimum load. The Pittsburgh #8 coal experienced higher CO values at the full case load and dropped significantly when going to lower load due to higher residence time and the higher O_2 values obtained because of fan turndown limitations. Figure 6.7 shows that all cases followed basically the same trend as load was varied over a range of burner stoichiometries.

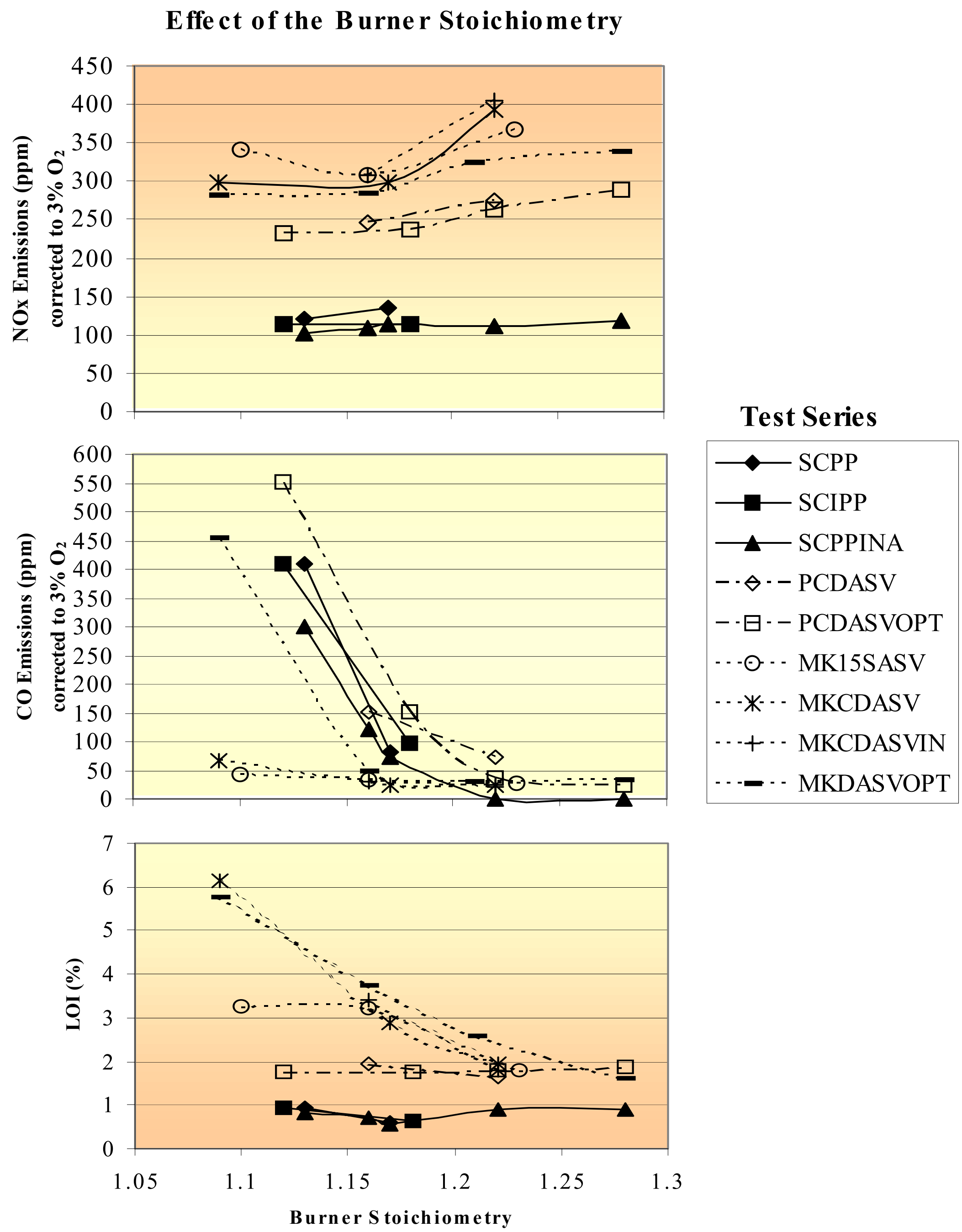


FIGURE 6.5. BURNER STOICHIOMETRY EFFECT ON NO_X, CO, AND LOI FOR CONFIGURATIONS OF THE ULTRA LOW-NO_X PLUG-IN DRB-4Z^{TM} BURNER FIRING SPRING CREEK, PITTSBURGH #8 AND MIDDLE KITTANNING PULVERIZED COALS AT 100 MILLION BTU/HR.

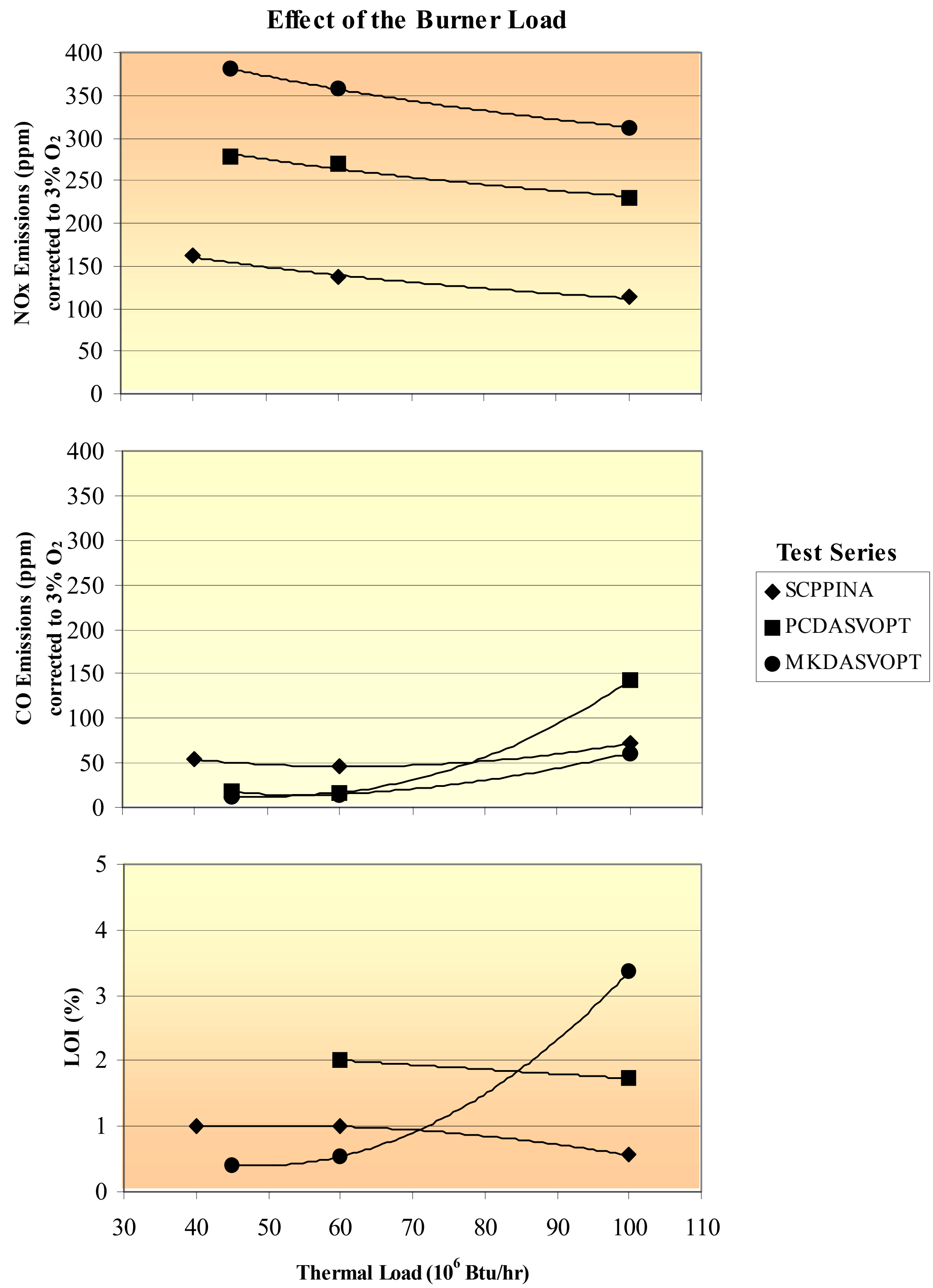


FIGURE 6.6. THERMAL LOAD EFFECT ON NO_X, CO, AND LOI FOR THE ULTRA LOW-NO_X PC BURNER FIRING SPRING CREEK, PITTSBURGH #8, AND MIDDLE KITTANNING PULVERIZED COALS.

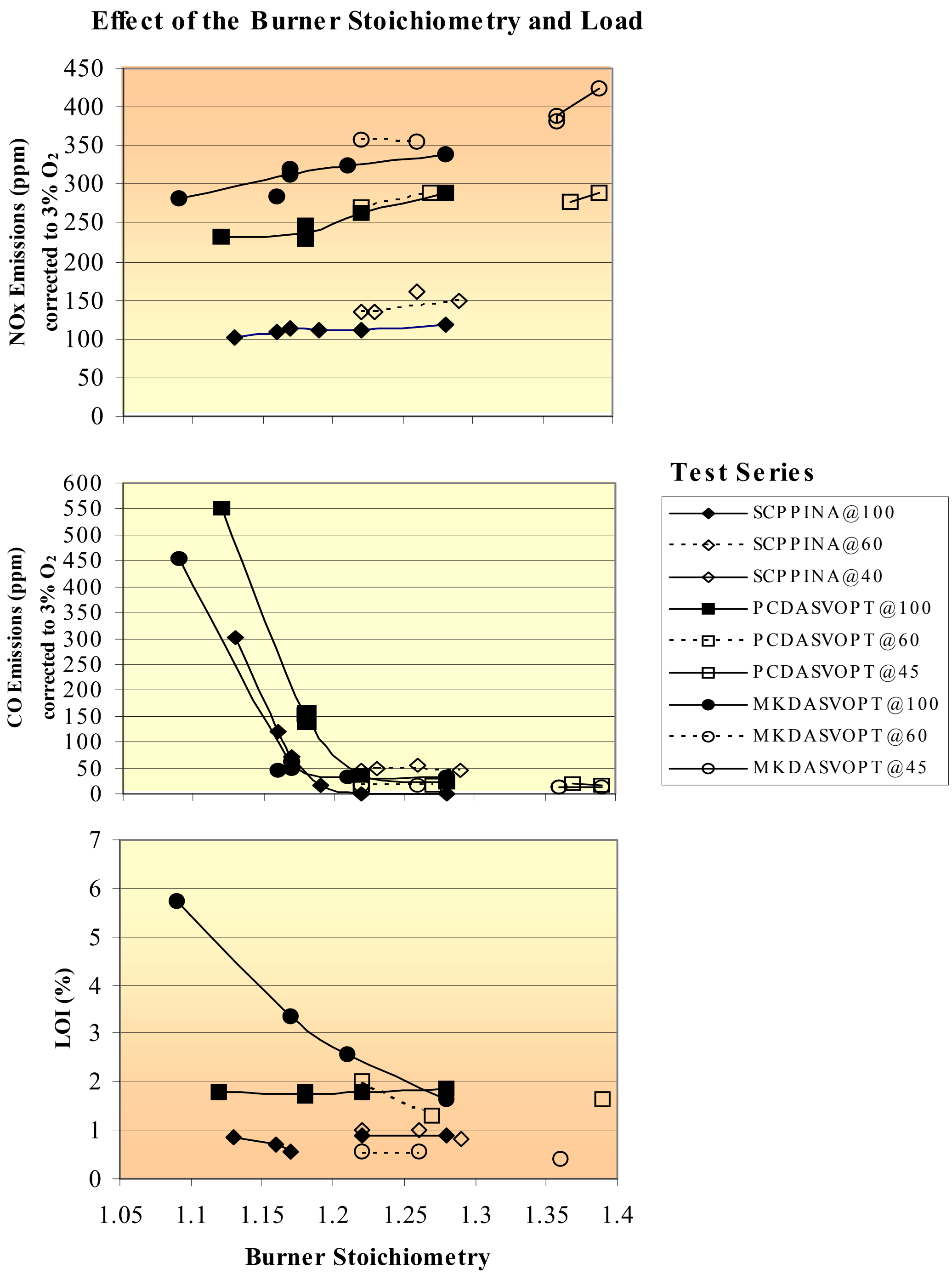


FIGURE 6.7. EFFECT OF BURNER STOICHIOMETRY WITH RESPECT TO LOAD ON NO_X, CO AND LOI FOR THE ULTRA LOW-NO_X PC BURNER FIRING SPRING CREEK, PITTSBURGH #8, AND MIDDLE KITTANNING PULVERIZED COALS.

6.4.7 *HARDWARE COMPARISON*

Figure 6.8 summaries the performance of various configurations tested during this program. A description of the burner hardware was given in Table 6.1. All configurations were tested at normal operating conditions of 100 million Btu/hr and 17% excess air. Figure 6.8 shows each configuration at the optimum burner setting. High combustion efficiency, short flame length, low NO_x and CO emissions, low burner pressure drop, flame stability at minimum load, and the amount of carbon in the flyash were all taken into consideration to determine the optimum hardware configuration. The optimum burner hardware configuration proved to be relatively independent of the three coals fired. The optimum burner configuration for the plug-in DRB-4Z™ burner was with a perforated plate in the transition zone and a coal nozzle insert (size based on coal to obtain an optimum velocity). For firing both the Middle Kittanning and Pittsburgh #8 coals, an air separation vane was also utilized.

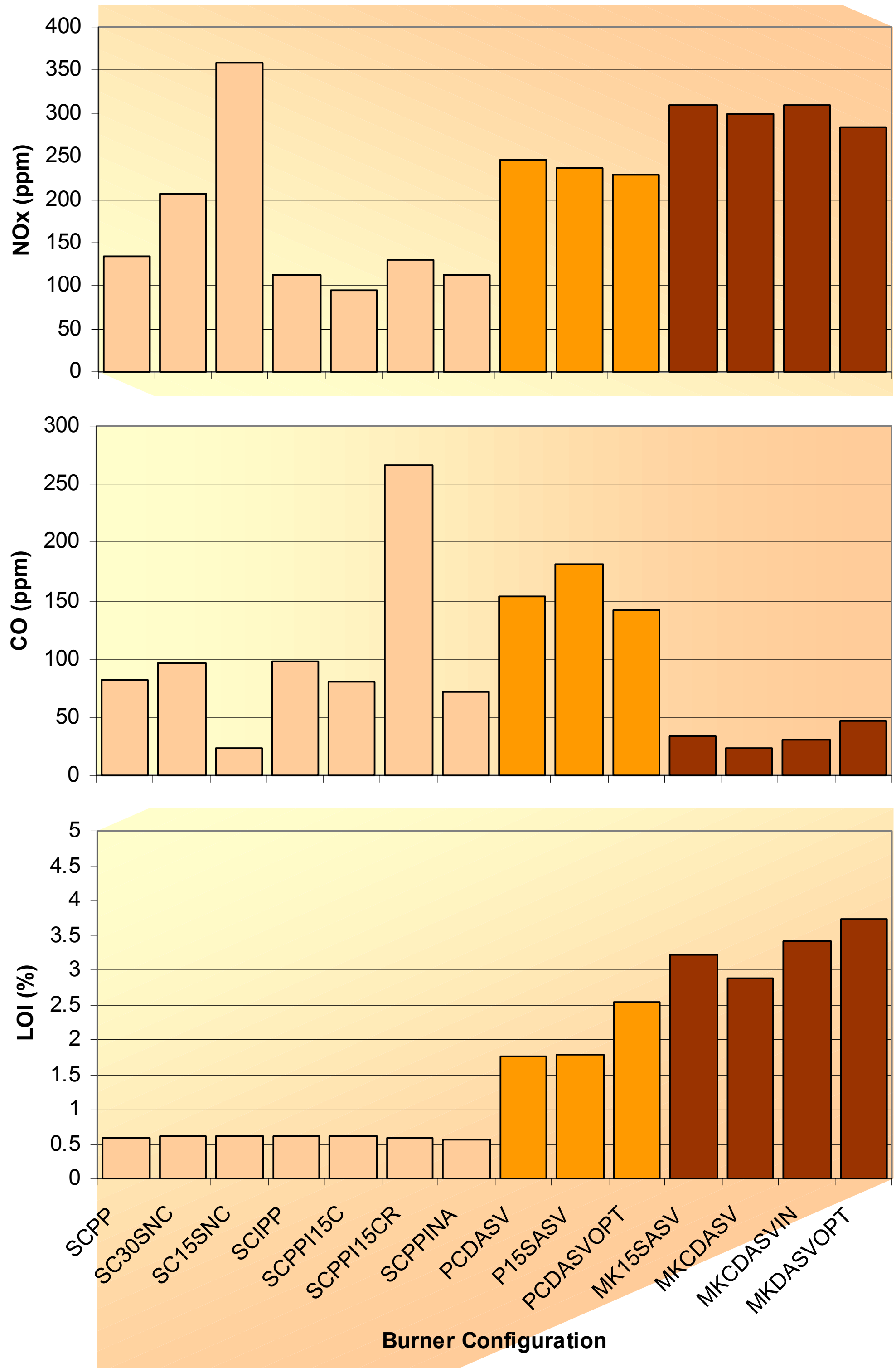


FIGURE 6.8. PERFORMANCE DATA AT OPTIMUM BURNER SETTINGS FOR VARIOUS CONFIGURATIONS OF THE PLUG-IN DRB-4Z^{TM} PC BURNER WHEN FIRING PULVERIZED SPRING CREEK, PITTSBURGH #8, AND MIDDLE KITTANNING COALS AT 100 MILLION BTU/HR.

6.4.8 *COAL VARIATION EFFECTS*

As previous discussed, three coals were utilized during testing, a subbituminous Powder River Basin, a high-volatile bituminous, and a medium-volatile bituminous. These coals covered a range of NO_x reduction expectations due to the fixed carbon-to-volatile matter ratios. NO_x values trended as would be expected. The lowest NO_x emissions were achieved with the Spring Creek coal followed by the Pittsburgh #8 coal and then the Middle Kittanning coal.

6.4.9 *COAL FINENESS EFFECTS*

Although coal fineness variations were not examined during the burner optimization tests, it should be noted that there were differences in the coal fineness for the coals and burner configurations tested. The fineness of the Spring Creek coal utilized with the DRB-4Z^{TM} burner averaged 63.10% less than 200 mesh. The fineness of the Pittsburgh #8 coal averaged 63.50% less than 200 mesh. The average fineness of the Middle Kittanning coal was 73.08% less than 200 mesh. The detailed fineness evaluation is given in Table 6.3.

6.5 FURNACE CHARACTERIZATION

Gas species and temperature mappings were performed after the burner was optimized for each coal. Figures 6.9 through 6.11 show the average (across the boiler width) temperature readings (in degrees F) for each coal throughout the furnace. This information was used as input to the urea injection modeling and to locate the optimum, injection locations. The temperature readings show how the fluegas temperature increases as the three coals are compared, with the Spring Creek coal firing at the lowest temperature and the Middle Kittanning firing at the highest temperatures. The furnace exit gas temperatures while firing the Spring Creek coal and the Pittsburgh #8 coal were both around 2100°F which is close to design temperature at full load conditions. The furnace exit gas temperature was approximately 2300°F while firing with the Middle Kittanning coal due to its low volatile matter and low moisture content. Temperature variations are important to note as coals are switched and loads are changed for proper injection location for the SNCR process.

The second series of burner optimization tests firing the Pittsburgh #8 and Middle Kittanning coals showed that after refractory maintenance was performed in the CEDF, the tunnel furnace became very hot, and resulted in higher NO_x emissions. When comparing results while firing at full load with the Spring Creek coal, NO_x emissions increased from the initial baseline value of 0.19 lbs/MBtu to a value of 0.26 lbs/MBtu after the refractory repairs. This was further confirmed by comparison of temperature measurements taken previously in the CEDF firing the Pittsburgh #8 coal with the new data obtain during the second test series. To re-confirm this occurrence and to determine initial NO_x values, baseline testing was performed with the various coals at the start of each SNCR injection test series. The baseline values obtained corresponded to the burner optimization tests performed after the refractory maintenance. Baseline conditions were also repeated throughout the test series to check for any system variances.

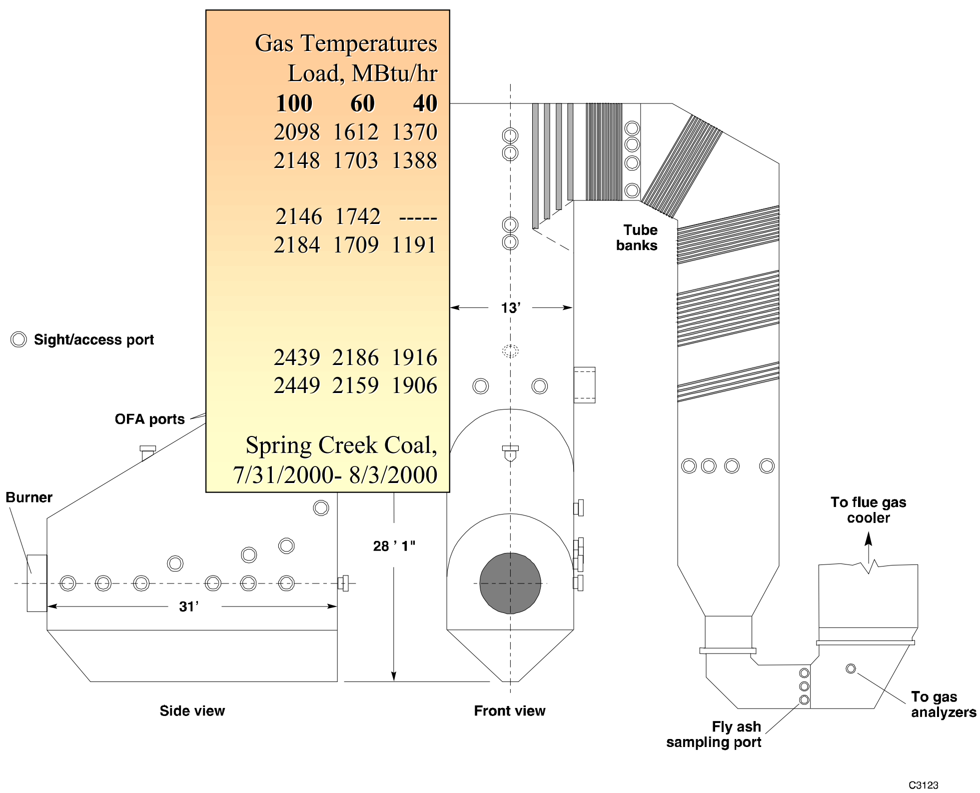


FIGURE 6.9. GAS TEMPERATURE (°F) MAPPING OF CEDF FURNACE FIRING SPRING CREEK PULVERIZED COAL WITH THE ULTRA LOW-NO_x DRB-4Z™ BURNER.

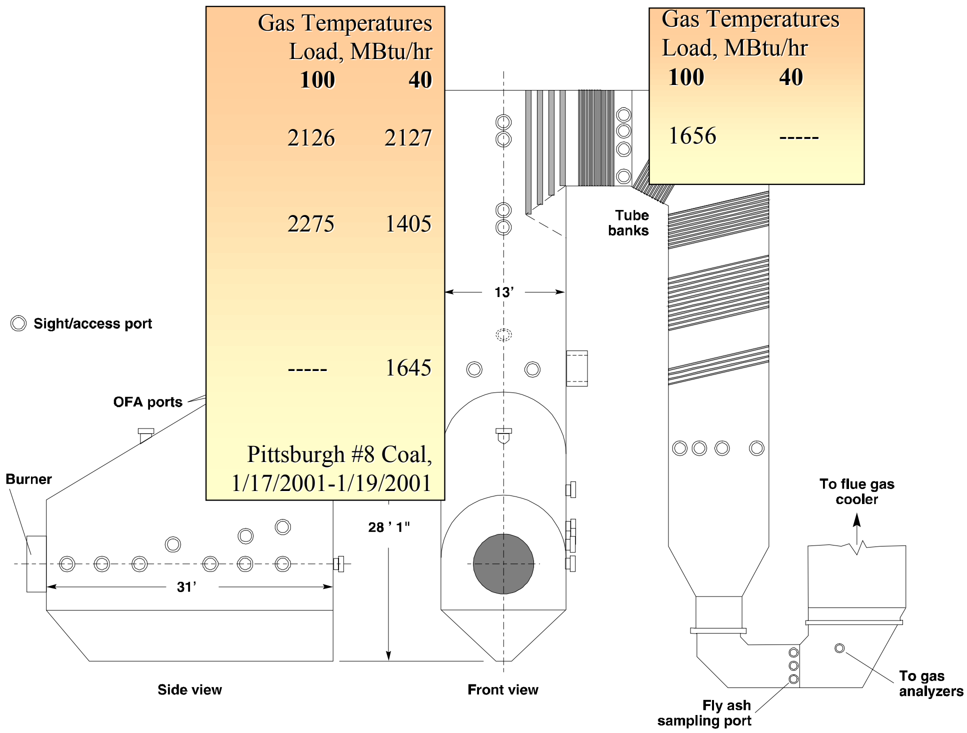


FIGURE 6.10. GAS TEMPERATURE (°F) MAPPING OF CEDF FURNACE FIRING PITTSBURGH #8 PULVERIZED COAL WITH THE ULTRA LOW-NO_X DRB-4Z™ BURNER.

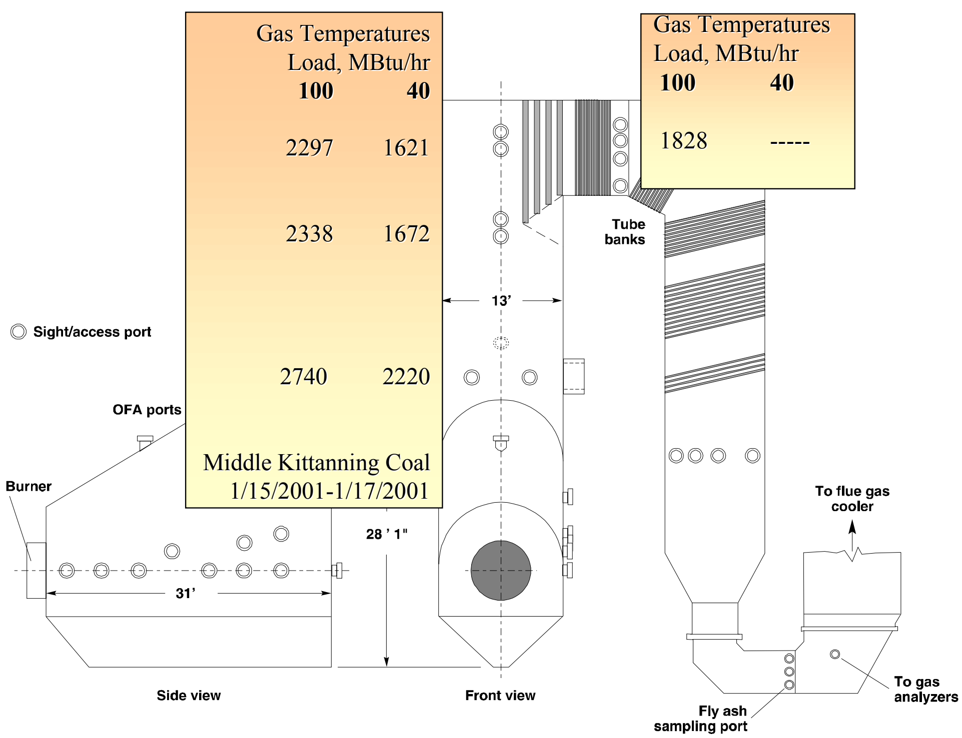


FIGURE 6.11. GAS TEMPERATURE (°F) MAPPING OF CEDF FURNACE FIRING MIDDLE KITTANNING PULVERIZED COAL WITH THE ULTRA LOW-NO_X BURNER

7 INTEGRATED NO_XOUT® AND ULTRA LOW-NO_X PC BURNER PERFORMANCE EVALUATION

7.1 SNCR OPTIMIZATION

SNCR optimization tests took place in the CEDF during the weeks of June 3 and June 17, 2001. To allow sufficient time for facility warm up and shut down, the SNCR testing was conducted between noon on Monday and noon on Friday, for a total ninety-six hours each week. The focus of the testing was full load firing of Western subbituminous Spring Creek coal. The first 60 hours of the first week and the final 48 hours of the second week, approximately 56% of the total test hours, were dedicated to investigation of SNCR with the western coal. Testing of the Pittsburgh #8 high-volatile bituminous coal took place during the final 36 hours of the first week and the Middle Kittanning medium-volatile bituminous coal test were performed during the first 48 hours of the second week. This scheduled break between initial and final Spring Creek testing provided an opportunity to make adjustments in the burner and SNCR configurations.

As has been previously discussed, the SNCR system was designed to operate in three distinct injection zones. The three zones differed primarily in their relative elevation with zone 1 as the lowest and nearest the burner, zone 2 located in the vertical section midway between the burner chamber and the convective pass and zone 3 placed just below the nose (see Figure 4-38). Generally, the higher elevations are expected to provide the most effective injection at high heat input with the lower elevations being used at mid and low loads.

The system was optimized at each firing condition for two modes of operation: NO_xOUT and NO_xOUT CASCADE. The NO_xOUT mode was defined, for this investigation, to be the most productive NO_x reduction achievable with less than 5 ppm ammonia slip. The CASCADE mode permits the SNCR system to provide additional reduction by easing the ammonia slip limit. A small SCR reactor while simultaneously providing additional reduction would theoretically remove this additional ammonia slip, between 10 and 30 ppm. No catalyst was used in the CEDF tests. Specific data points are referenced in the discussion below. These data are presented in Table 7.1 and are sorted between NO_xOUT and CASCADE data points in Table 7.2. Baseline values are listed as BL.

TABLE 7.1. DRB-4Z^{TM} AND NO_xOUT TEST SUMMARY

Test No.	Load (10^6Btu/hr)	NO_x (ppm)	Calc. NO_x (lb /10^6Btu)	BL NO_x (lb /10^6Btu)	Reduction (%)	NH_3 (ppm)
7.1.1 - 100 % Western subbituminous						
1.27	100.5	204	0.277	0.271	-2.0%	--
1.33	100.0	166	0.225	0.271	17.0%	--
1.15	100.3	179	0.243	0.273	11.0%	3.3
2.38	100.5	144	0.195	0.259	24.8%	4.2
2.48	100.6	139	0.189	0.251	24.6%	5.5
2.44	100.3	151	0.205	0.242	15.1%	4.8
2.49	101.2	115	0.157	0.251	37.5%	11.4
2.43	100.9	127	0.172	0.242	28.9%	9.4
2.52	99.7	127	0.172	0.241	28.6%	10.9
2.56	92.2	86	0.117	0.219	46.8%	19.1
7.1.2 - Western subbituminous, 10% Natural gas						
8.192	98.8	144	0.196	0.196	0.0%	
8.193	100.5	126	0.171	0.196	12.7%	4.9
8.183	101.6	121	0.164	0.191	14.1%	20.9
9.205	100.5	117	0.158	0.191	16.9%	3.7
7.1.3 - 100% Western subbituminous						
3.63	61.3	102	0.138	0.170	18.6%	4.4
3.66	61.3	97	0.132	0.170	22.1%	5.2
3.67	61.1	91	0.124	0.170	27.1%	10.0
7.1.4 - 100% Western subbituminous						
3.72	42.5	97	0.131	0.168	21.9%	0.5
9.211	41.2	63	0.085	0.192	55.8%	5.0
9.212	40.9	69	0.093	0.192	51.3%	3.0
7.2.1 - Pitts #8						
4.90	100.3	163	0.225	0.304	26.2%	5.3
4.96	100.5	169	0.232	0.313	26.0%	3.8
4.89	100.1	153	0.211	0.304	30.8%	6.6
4.88	100.5	134	0.185	0.304	39.3%	12.4
7.2.2 - Pitts #8						
5.118	60.8	144	0.198	0.289	31.6%	1.9
4.113	40.6	76	0.105	0.309	66.1%	3.4
4.111	40.2	67	0.092	0.309	70.1%	10.8
7.2.3 - Mid Kittanning						
6.138	99.9	243	0.333	0.404	17.6%	5.8
6.128	99.9	232	0.317	0.366	13.3%	4.3
7.153	100.9	216	0.296	0.405	26.9%	15.1
7.2.4 - Mid Kittanning						
7.169	43.1	202	0.276	0.484	42.9%	0.3

TABLE 7.2. SORTED NO_XOUT AND CASCADE DATA POINTS

Test No.	Load (10^6Btu/hr)	NO_x (ppm)	Calc. NO_x (lb/10^6Btu)	BL NO_x (lb/10^6Btu)	Reduction (%)	NH_3 (ppm)
NO_xOUT Data						
7.1.1 - 100 % Western subbituminous						
2.38	100.5	144	0.195	0.259	24.8%	4.2
7.1.2 - Western subbituminous, 10% Natural gas						
9.205	100.5	117	0.158	0.191	16.9%	3.7
7.1.3 - 100% Western subbituminous						
3.66	61.3	97	0.132	0.170	22.1%	5.2
7.1.4 - 100% Western subbituminous						
9.211	41.2	63	0.085	0.192	55.8%	5.0
7.2.1 - Pitts #8						
4.96	100.5	169	0.232	0.313	26.0%	3.8
7.2.2 - Pitts #8						
5.118	60.8	144	0.198	0.289	31.6%	1.9
4.113	40.6	76	0.105	0.309	66.1%	3.4
7.2.3 - Mid Kittanning						
6.138	99.9	243	0.333	0.404	17.6%	5.8
7.2.4 - Mid Kittanning						
7.169	43.1	202	0.276	0.484	42.9%	0.3
NO_xOUT CASCADE Data (no catalyst was used in CEDF tests)						
7.1.1 - 100 % Western subbituminous						
2.49	101.2	115	0.157	0.251	37.5%	11.4
7.1.3 - 100% Western subbituminous						
3.67	61.1	91	0.124	0.170	27.1%	10.0
7.2.1 - Pitts #8						
4.88	100.5	134	0.185	0.304	39.3%	12.4
7.2.2 - Pitts #8						
4.111	40.2	67	0.092	0.309	70.1%	10.8
7.2.3 - Mid Kittanning						
7.153	100.9	216	0.296	0.405	26.9%	15.1

7.1.1 Western Subbituminous Coal - 100 million Btu/hr

The first round of tests was conducted at 100 million Btu/hr, firing PRB coal. The baseline NO_x at this load varied between 0.24 and 0.29 lb/10^6 Btu but was generally between 0.25 and 0.27 lb/10^6 Btu (with no OFA). The first phase of optimization was a survey procedure to determine the relative effectiveness of each of the designed injection zones. Due to changes in the refractory of the CEDF burner region, somewhat higher than originally designed temperatures were expected.

Testing of zone 2 injection revealed that this elevation would be of limited use at this high load (#1.27). When used in combination with zone 3, as much as 17% reduction was achieved (#1.33). Although this was an improvement from the use of zone 3 alone, providing only 11% reduction (#1.15), the target reductions require a more effective alternative.

Three injectors from zone 2 were moved to the top of the vertical section, to existing ports on the front wall above the nose, to become zone 4. This injection zone would provide perhaps somewhat limited coverage of the combustion gases, but at a more desirable and effective chemical release temperature. Combined with zone 3, complete coverage of the gases could still be achieved.

Multiple combinations of zone 3 and zone 4 were tested to determine the most effective NO_xOUT and CASCADE reductions. As stated earlier, no catalysts were used for the CEDF testing. It is assumed if catalysts would have been used that the NO_x reduction would have been even greater. 25% NO_xOUT reduction (#2.38), to 0.195 lb/10^6 Btu, was achieved at less than 5 ppm ammonia slip with chemical evenly divided between the two zones. Although similar performance was achieved when the chemical was shifted towards zone 4 (#2.48), removal of zone 3 altogether caused a drop in both NO_x reduction and chemical utilization (#2.44).

Larger droplets and a simple shifting of chemical from zone 3 to zone 4 released the SNCR system to provide approximately 38% reduction from 0.251 to 0.157 lb/10^6 Btu (#2.49) while producing only 11.4 ppm ammonia slip. This test was conducted for a burner oxygen level of approximately 2.5%. Similar CASCADE tests at 3.3% and 4.5% produced 29% reduction with ammonia slips of 9.4 (#2.43) and 10.9 (#2.52), respectively. In all cases, the achievable reductions were substantially improved when the allowable ammonia slip was increased beyond 5 ppm.

Approximately one hour of testing was conducted at 92 million Btu/hr thermal input. The baseline NO_x dropped to 0.219 lb/10^6 Btu and the achievable CASCADE NO_x reduction increased to 47% (#2.56), or 0.117 lb/10^6 Btu NO_x, with an ammonia slip of 19.1 ppm.

7.1.2 Western Subbituminous Coal - 100 million Btu/hr, 10% Natural Gas

Testing with Spring Creek coal was continued during the last two days of the second week. Natural gas was used to replace 10% (by heat input) of the coal in order to reduce the NO_x baseline to the original target level of 0.2 lb/10^6 Btu. The new baseline was generally between 0.19 and 0.20 lb/10^6 Btu (#8.192).

Beginning with the previous SNCR configurations, changes were made to the chemical distribution and injector spray patterns to fine-tune the system for the new conditions. Using zones 3 and 4, it was possible to achieve NO_xOUT reduction from 0.196 to 0.171 lb/ 10^6 Btu with 4.9 ppm ammonia slip (#8.193). The attempt to provide CASCADE reduction (with no catalyst) led to somewhat improved performance at these conditions with NO_x reduction from 0.191 to 0.164 lb/10^6 Btu, with 20.9 ppm ammonia slip (#8.183). This small increase in performance between 5 ppm and 21 ppm ammonia was an indication that the change in spray pattern, and subsequent NH_3 slip, led to only a small change in the average chemical release temperature. Chemical release, therefore, must be controlled within a narrower temperature window at a lower average temperature through injection in the convective pass.

A small multiple nozzle lance (MNL) was constructed for injection in the back pass of the convective section. The temperature in this cavity is approximately 1650 – 1700°F. This is somewhat cooler than is typically utilized for convective pass injection. This location was selected because there were available ports that could be modified to receive the MNL. In addition, the lower gas temperatures permitted the use of a relatively simple, air-cooled lance.

In limited testing, the back-pass MNL provided NO_xOUT NO_x reduction from 0.191 to 0.158 lb/10^6 Btu with 3.7 ppm ammonia slip (#9.205). The controlled NO_x value is an average across a gradually increasing controlled NO_x concentration. As the temperature exiting the furnace increased slightly, the very fine spray being produced by the MNL at the edge of the temperature window varied in effectiveness. Chemical utilizations in excess of 70% were seen. As the temperature increased slightly, it would have been necessary to gradually increase the chemical flow rate to account for gradually dropping utilization. Although this is routinely done in practice, it is difficult to simulate in manual operation.

7.1.3 Western Subbituminous Coal - 60 million Btu/hr

This mid-load condition was investigated in both the first and second week of testing. The NO_x baseline varied between 0.16 and 0.18 lb/10^6 Btu. It was possible to achieve significant NO_xOUT NO_x reduction using both zones 2 and 3 at this load. Reduction from 0.170 to 0.138 lb/10^6 Btu was seen with less than 5 ppm ammonia slip (#3.63). Subsequent testing, however, showed that zone 3 provided somewhat better chemical utilization than zone 2 and in fact the optimized NO_xOUT condition utilized only zone 3 for a NO_x reduction from 0.170 to 0.132 lb/10^6 Btu with 5.2 ppm ammonia slip (#3.66).

NO_xOUT CASCADE was not optimized at this condition but a quick test was performed which demonstrated reduction from the 0.170 baseline to 0.124 lb/10^6 Btu with 10.0 ppm ammonia slip (#3.67).

7.1.4 Western Subbituminous Coal - 40 million Btu/hr

Low-load testing was performed for approximately six hours during each week of testing. The NO_x baseline during the first set of tests was only 0.168 lb/10^6 Btu. Zone 2 was used to achieve a NO_xOUT reduction to 0.131 lb/10^6 Btu with less than 1 ppm ammonia slip (#3.72).

The addition of zone 3, and the subsequent tuning during the second week, led to a dramatic NO_xOUT NO_x reduction of 56% from the baseline level of 0.192 to 0.085 lb/10^6 Btu with 5.0 ppm ammonia slip (#9.211). This controlled NO_x concentration is approximately 52 ppm at actual flue gas conditions. A decrease in the chemical flow rate led to increased utilization and lower ammonia slip with a small decrease in NO_x reduction. 51% reduction, to 0.093 lb/10^6 Btu from the same baseline was achieved with only 3 ppm ammonia slip (#9.212).

Figure 7.1 shows a summary of the results from SNCR injection when firing the Western subbituminous coal.

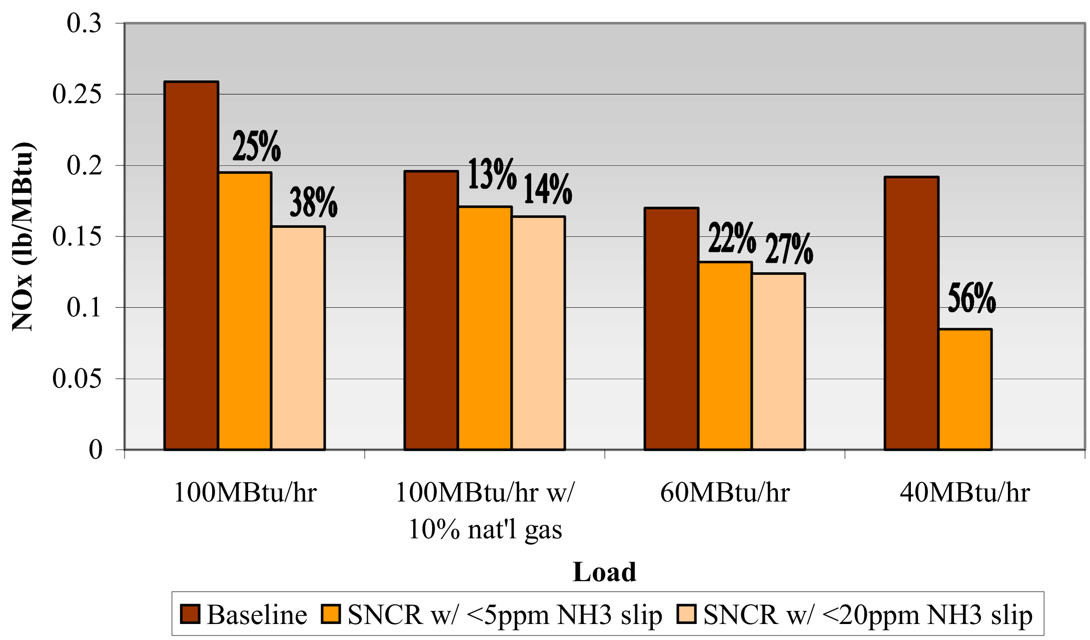


FIGURE 7.1. EFFECT OF SNCR INJECTION ON WESTERN SUBBITUMINOUS COAL OPERATION

7.1.5 WESTERN SUBBITUMINOUS COAL – PROPOSED MNL LOCATION

The CKM analysis was revisited to assess the full load reduction expected with the addition of a multiple nozzle lance at the entrance of the convective pass. CKM results were generated at an assumed baseline of 0.23 lb/10^6 Btu, between the two full load Western subbituminous cases, at a CO concentration of 100 ppm and an NSR of 1.75. The results, shown in Figure 7.2, include a number of colored boxes that indicate the range of chemical distribution and effective NO_x reduction.

The actual NO_x reductions at 100 million Btu/hr were approximately 25% and 29% for the NO_xOUT and CASCADE systems, respectively. The green box in Figure 7.2 shows this average performance, as obtained with wall injectors. The complete reduction range, however, likely spans the significantly larger red box. As was seen in the initial injector modeling, it is likely that some of the chemical is released above the maximum temperature where NO_x production occurs. This is shown in the figure above 2125° F where the fraction of initial NO_x is greater than 1.0. In addition, in order to achieve the 25% NO_x reduction average, chemical is released at lower temperatures where some ammonia slip is evident.

A convective pass MNL will be placed near the effective temperature region at the entrance to the convective pass. A narrower distribution of droplet sizes will be designed to release chemical as shown in the magenta box, between 1940°F and 2110°F. This more precise method of injection will provide treatment at an average temperature as much as 40 degrees cooler than was achievable with wall injectors. This small change in the effective reaction temperature increases the reduction from between 20 and 30% to between 30 and 40%.

NO_x reduction is also dependent on coverage of the NO_x-laden flue gases. To the extent that wall injectors will still be necessary to achieve the most complete treatment, the actual performance improvements may not be so dramatic.

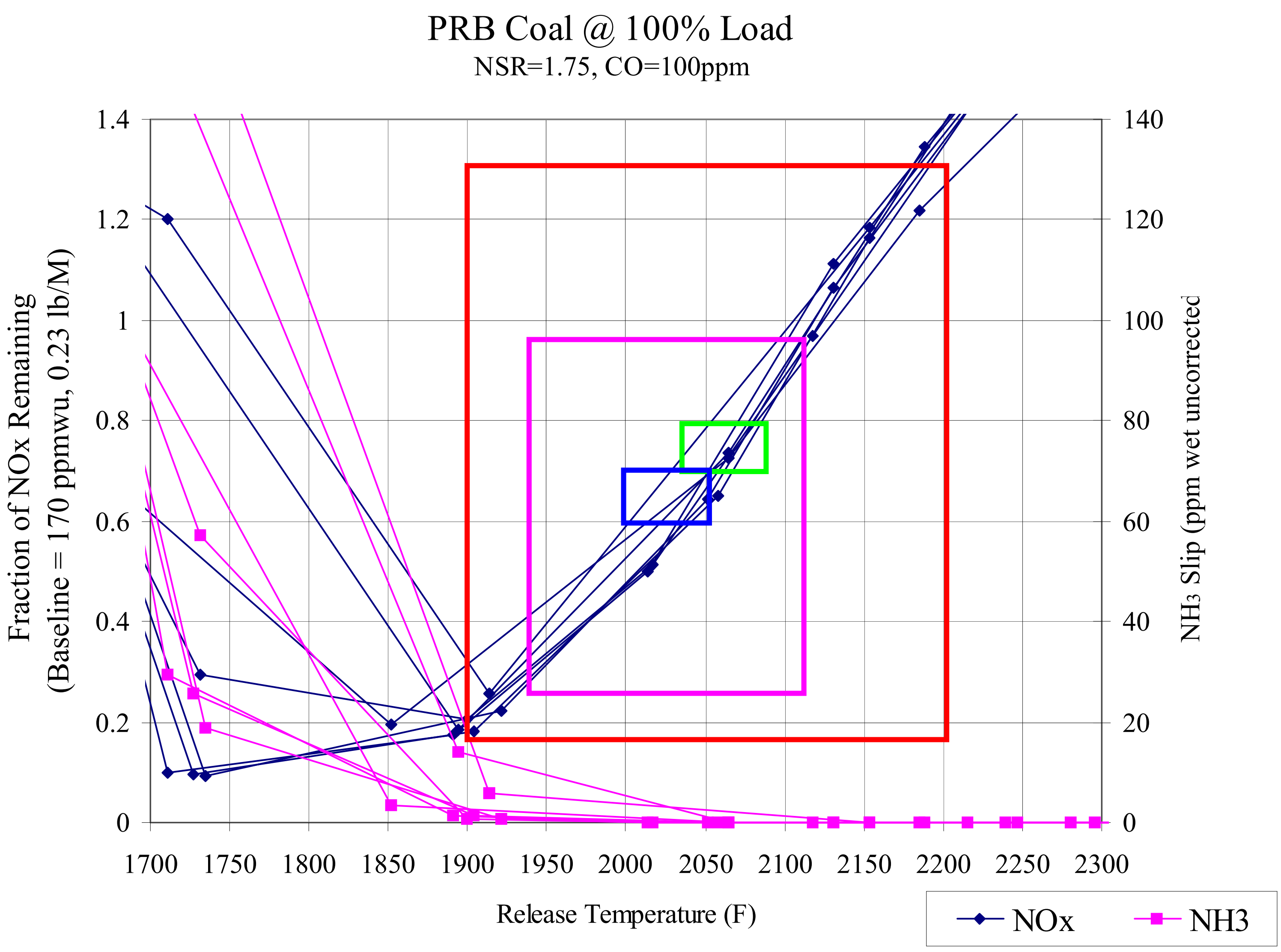


Figure 7.2. Western Subbituminous Coal with a Multiple Nozzle Lance

7.2 EFFECT OF COAL RANK VARIATIONS ON COMBINED PERFORMANCE

Two additional sets of tests were conducted to assess the effectiveness of the NO_xOUT and NO_xOUT CASCADE processes on the flue gas from the DRB-4Z^{TM} low-NO_x burner firing Pittsburgh #8 and Middle Kittanning coals. As has been previously discussed, Pittsburgh #8 is a high volatile bituminous coal with more than 3% sulfur and Middle Kittanning is a medium volatile bituminous coal with 23% ash. The Middle Kittanning coal has shown somewhat higher temperature profiles.

7.2.1 PITTSBURGH #8 - 100 MILLION BTU/HR

The baseline NO_x, firing Pittsburgh #8 bituminous coal at this rate, varied between 0.300 and 0.313 lb/10^6 Btu. Zones 3 and 4 of the SNCR system were used for both the NO_xOUT and CASCADE optimizations. This testing was performed during the first week and so the temporary air-cooled multiple nozzle lance, developed for the PRB condition, was not yet available.

The NO_xOUT NO_x reduction of 26% was achieved from a baseline of 0.304 lb/10^6 Btu, with 5.3 ppm slip, to a controlled NO_x emission of 0.225 lb/10^6 Btu (#4.90). The ammonia slip was subsequently reduced to 3.8 ppm by fine-tuning the injector sprays while achieving the same 26% reduction from a slightly higher baseline (#4.96).

A small increase in the water flow, and hence the evaporation location and chemical release temperature, increases the NO_x reduction to 31%, or 0.211 lb/10^6 Btu (#4.89). The ammonia slip increased slightly to 6.6 ppm for this condition. Increased chemical flow provided the maximum CASCADE NO_x reduction of 39%, to a controlled NO_x concentration of 0.185 lb/10^6 Btu with 12.4 ppm ammonia slip (#4.88). These results are shown in Figure 7.3.

7.2.2 *PITTSBURGH #8 – PARTIAL LOAD*

A short series of tests was completed at each of the two partial load conditions of 60 million Btu/hr and 40 million Btu/hr. Each series was approximately 5 hours long and should not be considered optimized. They do, however, provide a preliminary idea of the expected performance for full-scale comparison.

At 60 million Btu/hr, the NO_x baseline was 0.289 lb/10^6 Btu. A NO_xOUT NO_x reduction of 32%, to a controlled emission of 0.198 lb/10^6 Btu was achieved with 1.9 ppm ammonia slip (#5.118). More NO_x reduction may well be possible at somewhat increased ammonia slip levels, as was evident in Spring Creek testing at this load.

Testing at the lowest firing rate of 40 million Btu/hr yielded extremely high NO_x reductions. The NO_xOUT system decreased emissions from the baseline of 0.309 lb/10^6 Btu to a controlled concentration of 0.105 lb/10^6 Btu (#4.113). This 66% reduction was achieved with only 3.4 ppm ammonia slip. This level of reduction is not unusual given the higher baseline and the longer residence time at this low load. In CASCADE mode, the NO_x reduction increased to 70%, or 0.092 lb/10^6 Btu, with 10.8 ppm ammonia (#4.111).

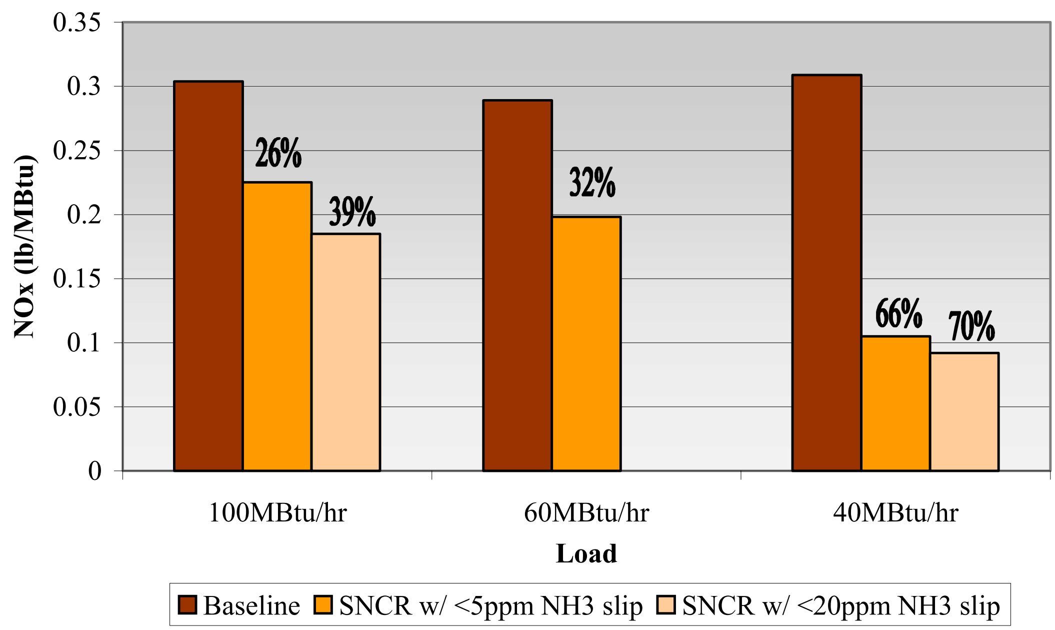


FIGURE 7.3. EFFECT OF SNCR INJECTION ON PITTSBURGH #8 COAL OPERATION

7.2.3 Middle Kittanning - 100 million Btu/hr

Testing of the Middle Kittanning coal was performed during the second week of testing. The NO_x baseline varied between 0.37 and 0.42 lb/10^6 Btu at this maximum firing condition. Previous temperature mapping of the CEDF firing this coal indicated somewhat elevated temperatures, presumably due to lower volatile content of this coal.

Tuning of the SNCR system was more difficult than anticipated, given the increased NO_x baseline. The highest NO_xOUT NO_x reduction achieved was 18%, from a baseline of 0.404 to a controlled emission of 0.333 lb/10^6 Btu (#6.138). The corresponding ammonia slip was 5.8 ppm. The lowest NO_xOUT NO_x emission was 0.317 lb/10^6, with 4.3 ppm ammonia slip, from a somewhat lower baseline of 0.366 lb/10^6 Btu (#6.128). This decrease in SNCR effectiveness can only be attributed to an increase in the temperature entering the convective pass (see Figure 6.11) and/or a locally high CO concentration in the injection region. Species mapping results, performed earlier by MTI, indicated very high CO concentrations at the nose but relatively low CO at the furnace exit.

Increasing the water flow to zone 3 and the overall chemical flow provided a CASCADE NO_x reduction of 27% from a baseline of 0.405 to 0.296 lb/10^6 Btu with 15.1 ppm ammonia slip (#7.153). Further optimization of this hot condition will require the addition of convective pass injection at the furnace exit. Figure 7.4 summarizes these results.

7.2.4 Middle Kittanning – Partial Load

Low load testing on Middle Kittanning coal was performed only at the 40 million Btu/hr firing rate. The data indicate that the unit is still hotter than was seen for the other fuels. The baseline increased, as compared to the higher firing rate, to between 0.43 and 0.48 lb/10^6 Btu. It was not possible, in the available time, to find a condition that generated significant ammonia slip.

The final test point showed a 43% reduction from the baseline of 0.484 to 0.276 lb/10^6 Btu with no significant ammonia slip (#7.169). A subsequent baseline indicates that the uncontrolled NO_x may have dropped to 0.442 lb/10^6. The resulting NO_x reduction, therefore, is between 38% and 43%.

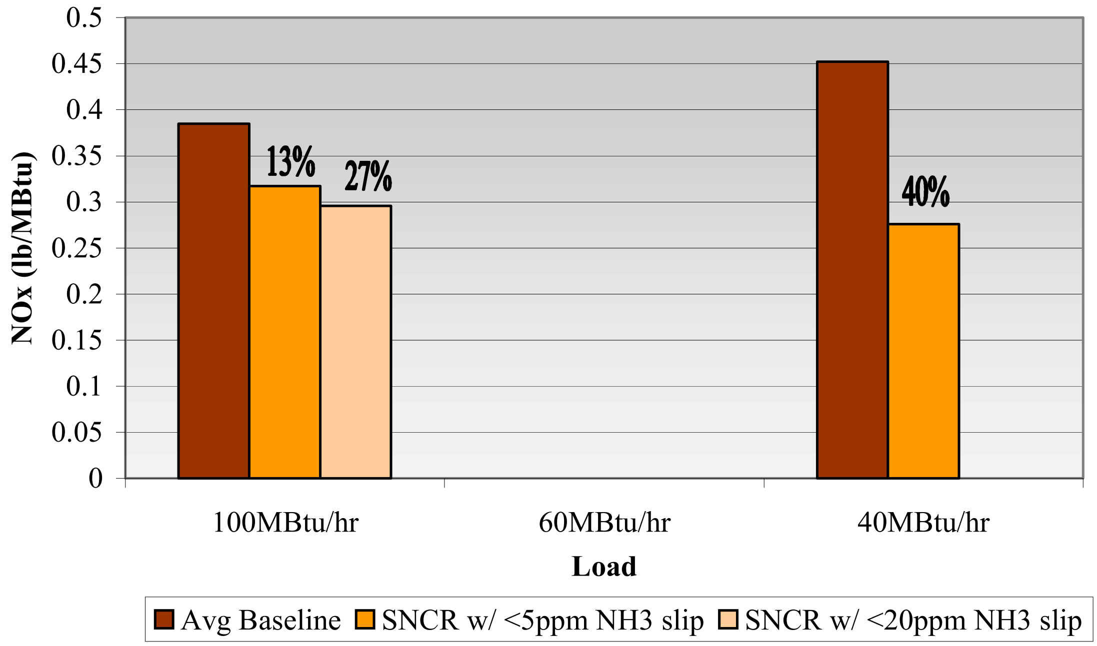


FIGURE 7.4. EFFECT OF SNCR INJECTION ON MIDDLE KITTANNING COAL OPERATION

7.3 N_2O MEASUREMENTS

N_2O measurements were taken to determine the composition of NO_x species. Table 7.3 shows the amount of N_2O found during certain tests as compared to the total amount of NO_x present. As can be seen, the amount of N_2O is negligible in all cases.

TABLE 7.3. N_2O MEASUREMENTS

Spring Creek Coal @ 100 MBtu/hr		Spring Creek Coal @ 60 MBtu/hr		Middle Kittanning Coal @ 100 MBtu/hr	
NOx, ppmV	*N_2O, ppmV*	*NOx, ppmV*	*N_2O, ppmV*	*NOx, ppmV*	*N_2O, ppmV*
129	1.19	111	0.99	263	1.38
	1.79		1.62		0.67
	2.05		1.97		1.33
131	0.82			234	6.27
	0.79				10.38

8 HG RECOVERY

A limited mercury measurement campaign was performed to provide data on western sub-bituminous coals that is representative of utility combustion. Testing provided a baseline mercury measurement for Powder River Basin coal combustion with an Ultra-Low NO_x burner and then investigated if the mercury speciation could be significantly modified by effectively increasing the chloride content of the coal.

8.1 TEST PROCEDURE

Combustion of the Western subbituminous coal using B&W's DRB-4Z™ low-NO_x burner was optimized before the start of the mercury speciation tests. Two mercury tests were conducted over a twenty-four hour test period. A baseline test was performed to determine the normal gas phase mercury speciation of the flue gas from the combustion of the Western subbituminous coal using the DRB-4Z™ burner. Calcium chloride was then injected into the combustion zone to increase the chlorine content of the flue gas and to determine the resultant effect on mercury speciation.

The planned furnace load for the mercury speciation tests was the 100 million Btu/hr capacity of the facility. However, early in testing it was discovered that at full load soot blowing was required on a frequent basis to maintain the flue gas temperature at the outlet from the convection pass at a reasonable value (~820°F). After the first Ontario Hydro sample was completed for the baseline test, the furnace load was reduced to 75 million Btu/hr. This permitted operation of the facility for about 12 hours between soot blowing cycles, which was the length of time required to complete the triplicate measurements for each test.

The flue gas was sampled at the inlet to the Electrostatic Precipitator (ESP). At this location, the flue diameter was 4 feet and the flue gas temperature averaged 320°F. Flue gas was sampled for one hour along each of two orthogonal directions for a total sample time of 2 hours. A triplicate set of Ontario-Hydro measurements were conducted for each test condition; baseline, and with

$CaCl_2$ injection. Additionally, EPA Method 26A sampling was performed for each test condition to quantify the total chlorine concentration in the flue gas.

Chlorine was added to the flue gas as a 30% aqueous $CaCl_2$ solution. To ensure that the chlorine was adequately mixed and volatilized, the $CaCl_2$ solution was sprayed with an atomizer co-axially with the coal in the centerline of the coal pipe. The atomizer was positioned just upstream of the flame front inside the coal pipe. Injecting $CaCl_2$ at the burner also ensured that the chlorine was adequately mixed with the coal, which is source of the mercury in the flue gas. A positive displacement, variable stroke pump provided a constant flow of the solution over an extended time. At temperatures typical of flames, the $CaCl_2$ decomposes providing chlorine for reaction with mercury as well as other flue gas constituents.

8.2 RESULTS

The Western subbituminous coal used for the tests was from the Spring Creek mine. The ultimate and proximate analyses of the as fired coal were given in Table 6.2. The chlorine concentration in the Spring Creek coal was measured at 60 ppm, which is low compared to the 600 to 2000 ppm range of chlorine concentrations typical of Eastern bituminous coal.

Table 8.1 shows the chlorine content of the coal, the chlorine added to the combustion zone, and the results of the Method 26 sampling used to determine the chorine concentration in the flue gas. As shown, the calculated chlorine concentration based on coal analysis and flow rate of $CaCl_2$ is greater than the measured chlorine concentration in the flue gas, but the difference is relatively small.

The CEDF operating conditions for the baseline and calcium chloride addition tests are presented in Table 8.2. The first of the three baseline triplicate tests is listed separately because of the higher furnace firing rate for that one test. The furnace firing rate was reduced to extend the sootblowing cycle to about 12 hours.

TABLE 8.1. MEASURED FLOW RATES OF CHLORINE

Test	Coal Chlorine		Chlorine Injection Rate	Total Chlorine Added[2]	Measured Flue Gas Chlorine
	(ppm)	(lb/hr)[1]	(lb/hr)	(lb/hr)	(lb/hr)
Baseline	64.5	0.53	0.00	0.53	0.27
$CaCl_2$ Injection	69.1	0.56	5.06	5.62	5.01

1 - Based on a coal flow rate of 8150 lb/hr
2 - Sum of the coal chlorine and injected chlorine flow rates

Table 8.2 shows that the NO_x, CO and SO_2 for this Western subbituminous coal are all quite low compared to an Eastern Bituminous coal. The effect of reduced load on flue gas temperature for the baseline test is evident by the decrease in ESP inlet temperature.

TABLE 8.2. CEDF OPERATING CONDITIONS DURING THE HG SPECIATION TESTS

Test Parameter	Baseline		$CaCl_2$ Addition
	Full Load	Reduced Load	Reduced Load
Total Load (10^6 Btu/hr)	100.1	85.1	83.2
Wet Flue Gas Flow (lb/hr)	102,448	85,690	83,841
Coal Flow (lb/hr)	9715	8259	8068
Convection Pass O_2 (%)	3.66	3.35	3.38
Convection Pass NO_x (ppm Dry)	112.5	99.5	117.8
Convection Pass SO_2 (ppm Dry)	170.6	148.7	126.1
Convection Pass CO (ppm Dry)	99.2	180	125.3
ESP Inlet Temperature (°F)	361	318	323

Figure 8.1 shows the average gas phase ionic and elemental mercury concentration and the particulate mercury for the Baseline and Calcium Chloride Addition tests. The total mercury concentration for the two tests (baseline and chloride addition) is nearly the same, while the fractional components of the total mercury for each test are different. The elemental mercury in

the flue gas decreases with the addition of calcium chloride, while the ionic gas phase mercury increases. The particulate mercury shows a small increase with calcium chloride addition. The fractional split in gas phase mercury for the baseline tests is 70% elemental and 30% oxidized. For the calcium chloride addition the fractional split changes to 40% elemental and 60% oxidized. The shift toward ionic mercury represents the conversion of 2 ug/dscm of elemental mercury to ionic mercury.

For the low chlorine Western subbituminous coal, the data show that the addition of chlorine to the combustion zone enhances the formation of ionic mercury. The amount of chlorine added in this test was relatively modest, equivalent to a coal chlorine content of about 630 ppm. It is anticipated that additional increases in chlorine would promote more conversion to ionic mercury. The relationship is likely to be non-linear, however, and would require additional testing.

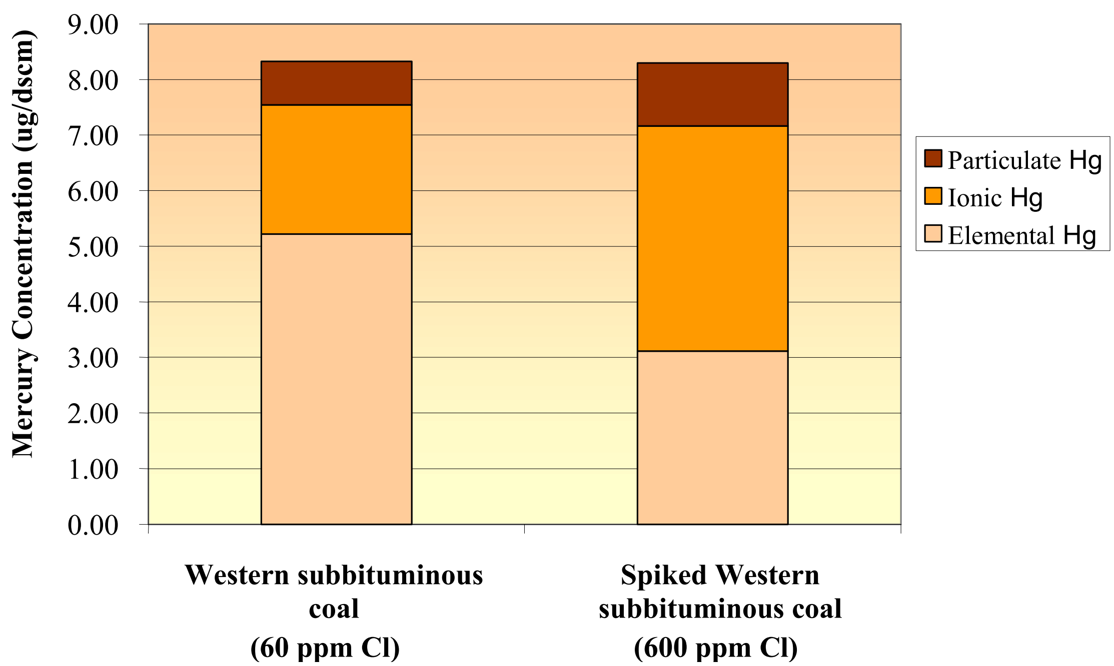


FIGURE 8.1. SPECIATED AND PARTITIONED MERCURY CONCENTRATIONS FOR A PRB COAL AND THE CHLORINE SPIKED PRB COAL

9 COMMERCIAL ASSESSMENT

9.1 COMPARISON WITH EXISTING TECHNOLOGIES

This project was aimed at providing NO_x control options for existing power plants to keep coal both economically and environmentally competitive as a boiler fuel. By integrating the individually demonstrated low NO_x burner (LNB) and Selective non-Catalytic Reduction (SNCR) systems as proposed here, coal-fired electric utilities will have a cost-effective solution to address the EPA SIP call for achieving the 0.15 lb NO_x /10^6Btu limit.

Achieving the target NO_x emission level of 0.15 lb/10^6Btu presents a challenge to pulverized coal (PC) fired utilities. Presently, combustion modification techniques alone cannot achieve this target emission level in most PC boilers. Low-cost NO_x control modification techniques such as low-NO_x burners in combination with over fire air (OFA) ports have shown NO_x emission level approaching the 0.15 lb/10^6Btu with PRB coal and with continuing research may prove to be a viable option. However, a combination of the combustion modification and post-combustion NO_x removal systems is necessary for boilers firing high volatile and medium volatile bituminous coals. Selective catalytic reduction (SCR) of NO_x is a commercially available technology that can be installed as a stand-alone system or in combination with other technologies such as low-NO_x burners. Alternatively, the 0.15 lb NO_x/10^6Btu can be achieved by combining advanced ultra low-NO_x burners with SNCR or SNCR/catalyst hybrid systems. For this reason, B&W is considering its DRB-4Z™ low-NO_x PC burner as the prime candidate in addressing NO_x emissions control. Fuel Tech offers NO_xOUT® (SNCR) and NO_xOUT Cascade® (SNCR/SCR) processes that can further reduce the NO_x emissions. When these technologies are combined, significant NO_x reductions can be attained for boilers in the 19 States that are affected by Title I compliance.

Economic Evaluations - To demonstrate the application and benefits of various NO_x control options, their cost-effectiveness was calculated for a reference 500 MWe wall-fired, coal-burning boiler. Four integrated NO_x control options were considered in this evaluation with the goal of reducing the baseline emissions from 0.5 to 0.15 lb NO_x/10^6 Btu. The options included: 1- LNB with OFA, 2- LNB with OFA plus $NO_XOUT^®$, 3- SCR-only systems, and 4- NO_xOUT Cascade®. A fifth case could have been the use of LNB with OFA and a smaller SCR but this scenario was outside of the scope of this project. The SCR-only scenario as specified in the DOE's program solicitation represents the base case for comparing with the costs of other cases. The low-NO_x burner in combination with OFA was considered a potential technology for boilers using PRB coal. The LNB/OFA plus $NO_xOUT^®$ was considered when burner NO_x level is 0.2 lb/10^6 Btu. Also, Fuel Tech investigated the NO_xOUT Cascade® for cases with high reagent injection rates (burner $NO_x \geq 0.3$ lb/10^6 Btu) where ammonia slip can be reduced with a catalyst (see Table 9.2). In some of the CEDF tests, the SNCR system was forced to slip 10-20 ppm ammonia. There was no catalyst available in the CEDF to promote reaction between ammonia and NO_x which is the basis for NO_xOUT Cascade® technology. For the purpose of this economic analysis, the NO_xOUT Cascade® NO_x reduction was estimated based on the Fuel Tech's experience.

Table 9.1 compares the capital costs of different options. These costs include purchase and installation of hardware (e.g., LNB, or urea or ammonia delivery systems, catalyst), controls, and interest. The costs are based on 2002 dollars, 500 MW_e boiler, and 66.67% capacity factor. For the SCR, a 15-day ammonia storage, inlet NO_x level of 0.5 lb/10^6Btu and outlet NO_x level of 0.15 lb/10^6Btu was assumed. The SCR capital cost is a strong function of retrofit difficulties such as availability of space for SCR reactor, and the need for fan modification or new forced draft fan since SCR may increase the pressure drop beyond the capability of the existing fan. Low-NO_x burner cost is also very site specific and depends on many factors such as adequacy of air and coal measurements in the boiler, pulverizer performance and boiler control. Although, the DRB-4Z™ low-NO_x PC burner has been specifically developed for retrofit applications with potentially high throat velocity, the potential need for pressure part modifications impacts the cost of equipment. For these reasons a range of capital costs reported here which is according to multiple commercial installations of low-NO_x burners and SCR systems. The SNCR capital and operating costs were based on commercial experience of Fuel Tech. Our study demonstrated that the estimated capital costs of the LNB with OFA and LNB with OFA plus $NO_xOUT^®$ options were substantially 71 to 93% and 60 to 87% lower than the SCR-only case, respectively. The NO_xOUT Cascade® capital cost is lower than SCR. If NOxOUT Cascade® is installed in a reactor outside of boiler flue and ducts, the cost should be close to SCR. It would be a little smaller since Cascade utilizes less catalyst but the other costs are similar. The cost of NO_xOUT Cascade® is lower because it is assumed that the NO_xOUT Cascade® will be an in-duct system and therefore cost saving over a standard SCR system can be realized.

TABLE 9.1. INTEGRATED SYSTEM ECONOMICS FOR A 500 MW BOILER

	Capital Cost (million $)	Operation Cost ($/year)	Levelized Cost ($/ton of NO_x Removed)
LNB+OFA	5 to 10 (10 to 20 $/kW)	166,000 *UBC + pressure loss*	139 to 247
LNB+OFA+SNCR	9 to 14 *4 SNCR* *5-10 LNB+OFA*	761,447 *595,447 urea cost* *166,000 LNB+OFA*	293 to 444
SCR	35 to 70 (70 to 140 $/kW)	760,000 *500,000 ammonia* *260,000 other*	897 to 1652
NO_xOUT Cascade®	15.7 (33 $/kW)	2,157,493 *Urea*	740

Table 9.1 also compares the operating costs and the corresponding annual levelized costs in $/ton of NO_x removed (including capital and operating expenses) for the same options. Operating cost of LNB plus OFA is minimal. Low NO_x burners could increase the unburned combustibles and the pressure drop across the burner. Although DRB-4Z™ low-NO_x burner was designed to maintain an acceptable pressure drop and has shown very low unburned combustibles, for the purpose of this analysis an extra operating cost of $166,000 was added. SNCR operating cost $595,447 for urea usage and no additional operating cost was considered. SCR operating cost was $760,000 from which $500,000 was for ammonia usage. NO_xOUT Cascade® system operating costs of $ 2,157,493 higher than SCR.

The annual levelized cost was calculated over a project life cycle of 20 years and a capital levelization factor of 0.1158. If the project life cycle was 15 years and an 8% interest rate was used, capital levelization would be 0.1147 which is close to our assumptions. Our analysis shows that the DRB-4Z™ low-NO_x burner in combination with OFA has the lowest annual levelized cost (72 to 91% less than SCR). Since low-NO_x burners are more cost-effective on a $/ton of NO_x basis than SNCR or SCR technologies in general, there is a great incentive in using them in combination with post-combustion NO_x control methods. LNB/OFA plus the NO_xOUT® combination cost is $ 293 to $ 444 per ton of NO_x removed when the low-NO_x burner emissions are 0.20 lb/10^6Btu which is 50% to 82% lower than the SCR cost ($897 to $1,652 per ton of NO_x). NO_xOUT Cascade® annual levelized cost is close to the lower range of SCR due its lower capital cost. As stated earlier, it has been assumed that the catalyst can be placed in-duct and a separate reactor is not necessary. It should be mentioned that these costs are site specific and the results may change from unit to unit. Table 9.2 shows the assumptions.

TABLE 9.2. FUEL TECH COST ESTIMATE

NOxOUT® System					
NOx After NOxOUT®	[ppmvdc]	107	128	156	195
	[lb/10^6Btu]	0.150	0.180	0.220	0.275
NOxOUT® Reduction	[%]	25.0%	40.0%	45.0%	45.0%
Chemical Utilization	[%] (30-45)	30%	40%	45%	45%
NSR		0.83	1.00	1.00	1.00
NOxOUT Flow (50%)	[gph]	114.2	205.6	274.2	342.7
"Reagent" Selling Price	[$/gal] or [$/ton]	$ 0.85	$ 0.85	$ 0.85	$ 0.85
Annual SNCR Chemical Cost	[$ / yr]	$ 595,447	$ 1,071,628	$ 1,429,072	$ 1,786,340
NOxOUT® Capital	[$8/kW]	$ 4,000,000	$ 4,000,000	$ 4,000,000	$ 4,000,000
Annual NOxOUT® Cost	[$ / yr]	$ 1,058,647	$ 1,534,828	$ 1,892,272	$ 2,249,540
SCR System					
Final NOx Desired	[ppmvdc]	107	107	107	107
Overall Reduction Required	[%]	25.0%	50.0%	62.5%	70.0%
Necessary SCR Reduction	[%]	0.0%	16.7%	31.8%	45.5%
delta NOx	[ppmvdc]	0.0	21.3	49.7	88.8
Ammonia Slip Requirement	5 or 10 ppm	N/A	5	5	5
slip from NOxOUT	[ppmvdc]		20	20	20
SCR NSR		0	0.049	0.222	0.378
SCR Urea Flow	[gph]	0	6.10	33.51	71.21
Annual SCR Chemical Cost	[$ / yr]	$ -	$ 31,819	$ 174,656	$ 371,153
Catalyst Volume Required	[ft3]	N/A	2898.1	4296.6	5553.3
Necessary Cascade Depth	[ft]	N/A	1.45	2.15	2.78
Cost of Catalyst	$300/ft^3	$ -	$ 869,418	$ 1,288,974	$ 1,665,989
# of times replaced	($10,600/m^3)		4	4	4
$10/kW expanded	[$/kW]	$ -	$ 10.00	$ 10.00	$ 10.00
so...Reactor Cost	[$]	$ -	$ 5,000,000	$ 5,000,000	$ 5,000,000
Total SCR Capital (inc. Cat)	[$]	$ -	$ 8,477,672	$ 10,155,895	$ 11,663,956
Total SCR Capital (inc. Cat)	[$/kW]	$ -	$ 16.96	$ 20.31	$ 23.33
Annual SCR Cost	[$ / yr]	$ -	$ 1,013,533	$ 1,350,709	$ 1,721,839
CASCADE Summary		bl=0.2	bl=0.3	bl=0.4	bl=0.5
Overall Reduction	[%]	25.0%	50.0%	62.5%	70.0%
Final NOx	[lb/10^6Btu]	0.15	0.15	0.15	0.15
Overall Utilization	[%]	30.0%	48.6%	55.7%	58.0%
Total Chemical	[gph]	114.2	211.7	307.7	413.9
Total Capital (inc. Cat)	[$/kW]	$ 8.00	$ 24.96	$ 28.31	$ 31.33

TABLE 9.2. FUEL TECH COST ESTIMATE (CONT'D)

CASCADE Summary	Case =>	bl =0.2	bl =0.3	bl =0.4	bl =0.5
Overall Reduction	[%]	25.0%	50.0%	62.5%	70.0%
Final NOx	[lb/10^6Btu]	0.15	0.15	0.15	0.15
Overall Utilization	[%]	30.0%	48.6%	55.7%	58.0%
Total Chemical	[gph]	114.2	211.7	307.7	413.9
Total Capital (inc. Cat)	[$/kW]	$ 8.00	$ 24.96	$ 28.31	$ 31.33
Total of the two Annual costs	[$/yr]	$ 1,058,647	$ 2,548,361	$ 3,242,981	$ 3,971,380
NOx Reduced	[tons/year]	766.5	2299.5	3832.5	5365.5
Cost per ton	$ / ton	$ 1,381	$ 1,108	$ 846	$ 740
Total Lifecycle Cost	[$ / 20 yrs]	$ 21,172,935	$ 50,967,229	$ 64,859,613	$ 79,427,592

** Urea cost can vary between 0.70 and 0.85 $/gal.*

9.2 MARKET POTENTIAL

Market Niche - Results from successful evaluation of the DRB-4Z™ low-NO_x PC burner/NO_xOUT® Process under this project are directly applicable to front and opposed wall-fired pulverized coal boilers within the 19 states that are facing strict NO_x emissions regulations. A portion of the affected utilities can reduce their emissions substantially by retrofitting their pre-NSPS and post-NSPS units that generate 0.5 lb/10^6Btu of NO_x or higher with the DRB-4Z™ ultra low-NO_x PC burners plus the NO_xOUT® Process. Cell-fired, roof-fired, and arch-fired boilers are also among potential candidates for employing LNB/NO_xOUT® technology. Tangential-fired and cyclone-fired boilers cannot use the LNB technology but they can benefit from the NO_xOUT® technology.

Market Potential - Cost-effectiveness calculations have shown that the LNB/NO_xOUT® system is economically attractive when the low-NO_x burner NO_x emissions are less than or equal to 0.25 lb/10^6Btu. Burner NO_x emissions is a function of the boiler design, fuel type, and other site-specific variables such as boiler heat release rate. Fuel rank in particular is an important parameter. Our near full-scale low-NO_x performance data from CEDF, as well as several commercial unit, indicate that utilities that burn high-volatile bituminous and subbituminous (e.g., PRB) coals would emit low NO_x levels and thus can greatly benefit from utilizing the LNB/NO_xOUT® technology. For boilers with very high heat release and elevated NO_x levels, the combined LNB/NO_xOUT® systems may not be the most economical option to meet the required

NO_x limit. For these and other units that burn medium volatile coals and generate more than 0.20 lb $NO_x/10^6$ Btu, the LNB/SCR system is the best option.

Market Size - Total coal-fired power plant population in U.S. is 332,600 MWe including approximately 200,000 MWe pre-NSPS units [10, 11]. Coal-burning, wall-fired boilers represent 140,000 MWe capacity. Figure 9.1 shows the total installed MW for the Pre-NSPS units. As discussed before, the LNB technology is applicable to all wall-fired and roof-fired boilers. Tangential-fired and cyclone boilers can benefit from NO_xOUT® or NO_xOUT Cascade® technologies alone. Title IV affects about 37,300 MW capacity of wall-fired PC boilers that are not currently in compliance. Title I could impact a much larger population of boilers if the proposed rules are enforced. For example, the Ozone Transport Rule could affect most of the 115,000 MW_e wall-fired, PC boilers within 19 states. The LNB/SNCR combination will be the least cost option for a majority of these boilers. Boilers that burn medium volatile bituminous coals can choose other technologies such as SCR or may opt to change coal (if possible) to minimize their NO_x removal costs. This coal-switching trend has been seen recently in the utility market. Many utilities have switched to PRB coal mainly for SO_X compliance, and the PRB usage is on the rise due to its low-sulfur content and low cost including transportation. Therefore, we estimate the market size for the LNB/SNCR technology to be approximately 86,000 MWe. This is 75% of the 115,000 MWe wall-fired PC boilers within the 19 states.

Commercial Deployment Timeline - A key advantage of this technology is its near-term commercial readiness. Performance evaluation of the integrated LNB and SNCR system carried out at the near full-scale level in B&W's 100 million Btu/hr test facility. Past experience has shown that a large prototype, 100 million Btu/hr burner design, can be readily scaled with minimal risk for commercial retrofit where a typical burner size is about 150 to 200 million Btu/hr. A scale-up concern is varying flow patterns and temperature profiles in the urea injection zone of CEDF and commercial boilers. CEDF was fired with one burner versus the commercial units are fired by multiple burners and with front-wall and opposed-wall firing configurations. The application of SNCR to commercial boilers could result in different flow patterns than CEDF and SNCR system design has to be on a site-specific basis. Commercial offers can be made around the 2003-2004 timeframe.

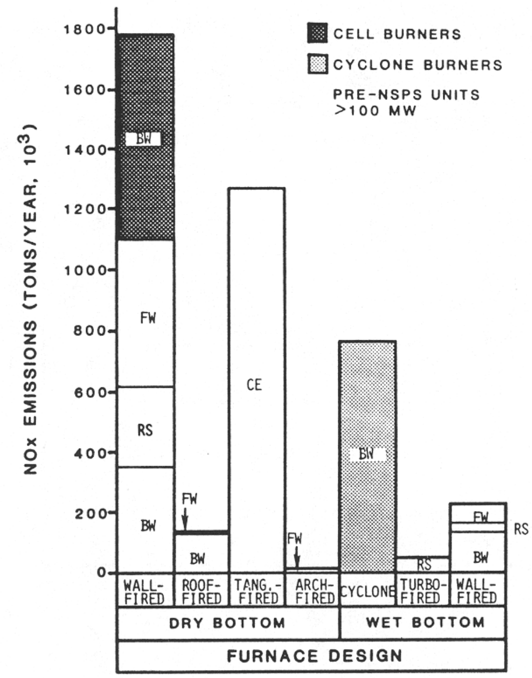


FIGURE 9.1. PRE-NSPS BOILER TYPES AND POPULATION IN U.S.[11]

10 CONCLUSIONS & RECOMMENDATIONS

1. Substantial NO_x reductions were achieved with an unstaged DRB-4Z^{TM} low-NO_x burner and SNCR; however, they fell somewhat short of the OTR limit at the CEDF.

2. At the full load conditions using the SNCR and firing Western subbituminous coal, NO_x reduction of 25% was achieved from a baseline of 0.26 lb/10^6 Btu.

3. Additional NO_x reduction could be achieved through the use of air staging with the ultra low-NO_x DRB-4Z^{TM} burner and SNCR. Based on three large-scale commercial installations of the DRB-4Z^{TM} burners in combination with OFA ports, using PRB coal, the NO_x emissions ranged from 0.16 to 0.18 lb/10^6 Btu. It is expected that OTR NO_x emission level of 0.15 lb/10^6 Btu can be met with DRB-4Z^{TM} burners plus OFA and SNCR using PRB coal.

4. The side effects from the use of the ultra low-NO_x DRB-4Z^{TM} burner and the NO_xOUT system seem to be manageable during the test period, but ammonia slippage of even 5 ppm poses some risk for air heater pluggage etc. in commercial operation.

5. Additional work should be performed to look at the effect of a water-cooled lance in front of the superheater tubes. This arrangement has been commercially tested; it produces very fine urea particles released at more favorable temperatures, and provides better mixing between urea and flue gas, which offer better distribution and potential for reduced ammonia slip.

11 ACKNOWLEDGEMENTS

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