APPLICATION OF NUMERICAL MODELING IN A CLEAN-COAL DEMONSTRATION PROJECT

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ABSTRACT

Currently, utility boilers equipped with cell burners comprise 13% of pre-NSPS coal-fired generating capacity. The cell burner rapidly mixes the pulverized coal and combustion air resulting in rapid combustion and high NO_x generation. A U.S. Department of Energy (DOE) Clean-Coal Technology Demonstration project is underway at Dayton Power & Light's J. M. Stuart Station to demonstrate the Low-NO_x Cell™ burner (LNCB™) on a 605-MWe utility boiler originally equipped with cell burners. The LNCB™ is designed to reduce NO_x emissions by delaying the mixing of the coal and the combustion air without boiler pressure part modifications.

Preliminary post-retrofit testing results showed unexpectedly high carbon monoxide (CO) and hydrogen sulfide (H_2S) concentrations below the lowest burner row. The substoichiometric operation of the lowest burner row caused the relatively high concentrations in the lower furnace.

Babcock & Wilcox's flow, combustion, and heat transfer models were used to predict the CO concentrations in the lower furnace. The predictions were compared to field measurements for three different operating conditions. Based on this validation, the models were used to evaluate several methods for mitigating the CO concentrations. The results of this analysis are presented and discussed. The most attractive alternative was selected and will be implemented during the spring of 1992. The effectiveness of the new alternative will be available when the installation is complete and testing resumes.

INTRODUCTION AND BACKGROUND

One of the Clean-Coal Technology (CCT) Demonstration Program projects is the "Full-Scale Demonstration of Low-NO_x Cell™ Burner Retrofit" (Project DE-FC22-P0P90545). The objective of the LNCB™ demonstration is to evaluate the applicability of this technology for reducing NO_x emissions in full-scale, cell-burner-equipped boilers. The program objectives are:

1. Achieve at least a 50% reduction in NO_x emissions.
2. Reduce NO_x with no degradation to boiler performance or life.
3. Demonstrate a technically and economically feasible retrofit technology

Dayton Power & Light Co. (DP&L) agreed to be the host utility for the full-scale demonstration of the LNCB™, offering the use of J. M. Stuart Station Unit No. 4 as the host site. Unit No. 4 is a 605-MWe universal pressure (UP) boiler originally equipped with 24, two-nozzle cell burners arranged in an opposed wall configuration.

Currently, there are 34 operating units with cell burners. They generate 23,639 MW and represent 13% of pre-NSPS coal-fired generating capacity. Of these 34 units, 29 are opposed wall-fired with two rows of two-nozzle cells and have an average size of 766-MWe. Five units are opposed wall-fired with two rows of three-nozzle cells and have an average size of 285-MWe. The LNCB™ was developed as a low-cost, plug-in burner for the two-nozzle cell burner retrofit market. Applicability to the three-nozzle cell burner market is still under investigation.

To reduce NO_x emissions, the LNCB™ has been designed to stage the mixing of the fuel and combustion air. A key design criterion for the LNCB™ was accomplishing delayed fuel-air mixing with no pres-

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sure part modifications. The traditional approach to cell burner modification was to increase the burner-to-burner spacing with pressure part modifications in addition to installing conventional, two-stage low NO_x burners. Pressure part modifications to rearrange the burners can be much more expensive. Material costs may more than double, and outage duration may double or triple.

Many other aspects of boiler operation may be effected by a low-NO_x combustion system including combustion efficiency, heat transfer, and corrosion potential. Combustion efficiency benefits from rapid, complete mixing of fuel and air. Limiting the rate at which the fuel and air mix — particularly during early stages of combustion — can effectively control NO_x formation, but these measures for coal-fired units have a tendency to reduce combustion efficiency. The delayed combustion often alters the heat release rate which affects the heat absorption patterns and may increase the furnace exit gas temperature (FEGT). The limited mixing between the air and coal can cause some or even all of the lower furnace volume to contain a substoichiometric mixture of combustion products. When fuels containing sulfur are fired, corrosive chemical species, like H_2S, can exist in the oxygen-lean environment, leading to accelerated wall tube corrosion rates. Consequently, one aspect can be controlled fairly easily, but controlling all can prove difficult and trade-offs are necessary.

With the development of high-speed engineering workstations, numerical simulation of combustion systems is now feasible and provides a new engineering tool that is ideal for evaluating applications of new technology. Since the mid-1970s, Babcock & Wilcox (B&W) has been developing flow, combustion, and heat transfer models that can be used together with conventional methods to optimize system performance. The objective of B&W's combustion model development program has been to produce computational models that are applicable to a wide variety of coal-fired furnaces. The models are based on a fundamental description of the various interacting processes that occur during flow, combustion, and heat transfer, and contain a minimum of empiricism. The models have been used extensively in the development of the LNCB™ and are currently being used to assist the full-scale demonstration.

BURNER DEVELOPMENT

Cell Burners

Economic considerations which dominated boiler design during the 1960s led to the development of the standard cell burner for very compact, low-initial-cost boiler designs. Each cell burner consists of two or three coal feed nozzles mounted in the lower furnace. A two-nozzle cell burner is shown in Figure 1. Cell burners were designed for rapid mixing of the fuel and oxidant. The tight burner spacing and rapid mixing minimize the flame size while maximizing the heat release rate and unit efficiency. Consequently, the combustion efficiency is good, but the rapid heat release produces large quantities of NO_x. Typically, NO_x levels associated with cell burners will range from 1.0 to 1.8 lb NO_x as NO_2 per million Btu input (430-770 ng/J).

Low-NO_x Cell™ Burner (LNCB™)

The two-nozzle LNCB™, shown in Figure 2, was developed by B&W in association with the Electric Power Research Institute (EPRI). The features of the LNCB™ were designed to restrict the formation of thermal and fuel NO_x. The original two coal nozzles in a cell burner are replaced with a single coal injection nozzle and a special secondary air injection port (or dedicated overfire air port). The flame shape is controlled using an impeller at the exit of the fuel nozzle and adjustable spin vanes in the secondary air zone. The air port louver dampers provide additional control over the mixing between the fuel and air streams. During operation, the lower fuel nozzle operates at a low stoichiometry, typically 0.6, with the balance of air entering through the upper port. The controlled mixing of the fuel and air delays the combustion, producing a longer flame that limits the production of NO_x.

The LNCB™ is designed to be directly installed into the existing cell burner furnace wall openings (no pressure part changes), without effecting requirements for coal storage, handling, or preparation. Only minor changes in coal piping near the burner will be needed to combine the two coal streams, leaving most of the pulverized coal transport piping intact. Secondary airflow is balanced burner-to-burner using sliding dampers in the air ports and burners. This arrangement typically increases the pressure loss on the secondary air flow system somewhat (1 to 2 inches wg). Since all units equipped with cell burners do not have the same design, a pre-installation engineering evaluation of the secondary air forced draft fans and combustion controls is recommended to determine if sufficient capacity exists to handle the flow resistance increase. In most cases, the existing controls will be sufficient.

The novel design of the burner necessitated characterizing the burner at several scales showing feasibility at each scale to settle concerns about maintaining combustion performance. An integrated numerical and experimental program was designed (LaRue and Rodgers, 1985) to fully characterize the burner at several scales: 1.75-MW, 30-MW, and utility-scale. Several aspects of the LNCB™ performance were investigated in the pilot scale studies. NO_x reductions greater than 50% were achieved. NO_x reductions as high as 75% were obtained with a shallower angle coal impeller, but the carbon losses were somewhat higher. CO emissions were very low (less than 50 ppm) and comparable to cell burner field performance. Unburned carbon losses were low (less than 0.2%) for the standard cell and the LNCB™. No changes in FEGT were measured. The LNCB™ flames were stable at lower loads but were about twice as long as the standard cell flames at full load.

Numerical modeling was done before the pilot-scale testing to project burner performance and locate instrumentation. After the tests, predictions were compared to data, models were refined when required, and performance was scaled to the next level. In general, the pilot-scale numerical modeling agreed well with the data (Fiveland and Wessel, 1991). Consequently, the models were used as a tool to assess the performance of the LNCB™ in a full-scale utility boiler.

In 1985, one full-scale two-nozzle cell burner was replaced with an LNCB™ at DP&L's Stuart Station Unit No. 3 to test the mechanical reliability. Unit Nos. 3 and 4 have identical designs. Since the installation, all of the mechanical components of the burner have operated properly and stayed within material temperature limits.

The feasibility of the burner was demonstrated at two pilot scales, and the mechanical reliability was established at full-scale. The ongoing CCT Demonstration was designed to demonstrate the technical performance at full-scale.

DEMONSTRATION BOILER

DP&L's J.M. Stuart Station Unit No. 4 is a B&W once-through supercritical pressure boiler with a single reheat. A schematic of Unit No. 4 is shown in Figure 3. The 605-MWe boiler is fired by 12 two-nozzle cell burners on each of the front and rear walls, arranged two rows high and six columns wide. Six MPS pulverizers supply pulverized coal to the 24 LNCB™ nozzles. The burner throat diameter is 0.9652 m (38 inches). Unit No. 4 burns Kentucky, Ohio, and West Virginia high-volatile bituminous coals. At full load, the boiler produces 554 kg/s (4.4×10^9 lbm/hr) of main steam at 814 K (1005°F) and 26.34 MPa (3805 psia). The heat input per LNCB™ at full load is 64.3 MW (219.4×10^6 Btu/hr). A typical set of operating conditions are listed in Table 1.

Since the original flue gas tempering system has been removed, the FEGT at full load is approximately 111 K (200°F) above the original design temperature. Operation at these high temperatures has caused slagging and overheating problems in the secondary superheater. Consequently, further increases in FEGT would be unacceptable to DP&L. Unit No. 4 has a history of tube wastage in the furnace, especially along the side walls. The low pressure drop of the standard cell burners and the windbox design cause the burners near the side walls to receive less than their share of the combustion air, resulting in reducing zones near the side walls. With the LNCBs™, the higher flow resistance and individual sliding damper controls are expected to improve the air distribution.

PRELIMINARY TESTING

Baseline and preliminary post-retrofit testing have been completed. NO_x reductions of 35% were achieved with the LNCBs™, but different coals were fired during the two test periods. Projections that account for the differences would give a NO_x reduction of 40%, which is still less than the 50% goal. DP&L reports that the slagging observed with the cell burners has not been observed with the LNCBs™. Higher-than-expected flue gas CO and H_2S concentrations were measured inside the lower furnace/ash hopper zone, below the lowest burner row. The sub-stoichiometric operation of the lowest burner row caused the high CO and H_2S concentrations. Although the LNCBs™ were not detrimental to the performance of Unit No. 4, two design changes were necessary to improve the NO_x reductions and mitigate the high CO concentrations prior to resumption of testing.

The NO_x reduction goal does not appear to be attainable with the current coal impeller design. The first change will be the replacement of the 24 coal impellers. A shallower angle impeller will be used, since pilot-scale testing indicated that greater than NO_x 50% reduction was achievable. The second design change is to mitigate the high CO and H_2S concentrations in the hopper. B&W's numerical models were used to simulate furnace conditions with the current LNCB™ configuration and to evaluate potential solutions. These two changes were implemented in late April 1992 with resumption of testing in May 1992.

NUMERICAL MODELING

Modeling Approach

Computational techniques have been developed to solve the governing, partial-differential equations for turbulent flow, combustion and heat transfer. In general, the models solve the fully elliptic, three-dimensional, finite-difference approximations of the conservation equations for mass, momentum, turbulence, gas and particle species, and energy. The details of the models are documented in Fiveland and Wessel (1988a), and they are similar in many respects to models developed by Lockwood, et al. (1980) and Smith and Smoot (1989). The furnace geometry is divided into control volumes (52000 active) as shown in Figure 4, depicting the grid layout used to analyze Unit No. 4. All features of the furnace are simulated such as the burners, air ports, hopper, arch, and pendant surfaces.

The governing equations are integrated over each control volume and discretized using finite-difference techniques described by Patankar (1980). The modeled equations for flow, combustion, and heat transfer are solved for each control volume shown in Figure 4. Detailed information for each control volume is produced for the flow characteristics, major chemical species (CH_4, C, CO_2, CO, SO_2, H_2O, N_2, and O_2), temperature, and heat flux distributions throughout the boiler — information which is difficult or impractical to obtain experimentally. Combustion of the fuel is characterized by a two-step process: In the first step, fuel is assumed to react with oxygen to form carbon monoxide and products; in the second step, there is a kinetic reduction of the carbon monoxide to carbon dioxide (Fiveland and Wessel, 1988b). The models are sufficiently complex to describe flow, combustion, and heat transfer, and yet simple enough for application to practical systems.

Model Validation

The objective of modeling task of this project is to provide a validated tool that could be used to assist the commercialization of the new technology. To validate the models, the predictions with the original cell burners and the LNCBs™ would be compared with measurements taken during the baseline and post-retrofit tests.

Initially, flow and combustion modeling were performed before the retrofit to determine the impact of the LNCBs™ on performance. Lower combustion temperatures were found implying lower thermal NO; insignificant increases in unburned carbon were predicted; and a more uniform distribution of furnace exit temperature was predicted, leading to less chance of overheating the pendant surfaces. Although the predicted average FEGT increased 4 K (7°F) with the LNCBs™, the temperature predictions show less side-to-side variation and have lower peak-to-minimum values. The flow distribution is also more uniform in the upper furnace and at the secondary superheater inlet plane. The models indicated no *obvious* flow, combustion, or heat transfer problems with the LNCB™ retrofit.

The model predictions did indicate that high CO concentrations existed below the burners. However, the predicted concentrations above the burners and at the furnace exit were similar to the pre-retrofit predictions and measurements. In the pilot-scale studies, the few CO measurements that were made below the burners indicated concentrations that were much lower than the pilot- or full-scale predictions. No full-scale data existed to either confirm or deny the unexpectedly high CO concentrations below the burners.

During baseline testing, extensive probing was conducted at the furnace exit and a plane 12.19 m (40 feet) above burners. Measurements of gas velocity, gas temperature, and chemical species were made at full (605-MWe) and intermediate (458-MWe) loads. The operating conditions during baseline testing were extremely well defined and controlled. The baseline test data were well suited for comparison with three-dimensional flow and combustion model predictions. The gas velocity, temperature, and oxygen concentration predictions were compared with the extensive baseline test data. The agreement between the predictions and the data is qualitatively very good (Fiveland and Latham 1991). The predictions and the data show the same trends about the operation of Unit No. 4 during baseline testing.

CO Mitigation

Preliminary post-retrofit testing results show unexpectedly high CO and H_2S concentrations below the lowest burner row. The substoichiometric operation of the lowest burner row causes the relatively high concentrations in the lower furnace. The objective of the numerical modeling was to evaluate strategies for reducing the CO concentrations and to assess their impact on furnace performance. To mitigate the CO, a strategy was needed that injected more air into the hopper without requiring pressure part modifications, increasing costs or reducing unit efficiency. CO mitigation strategies included modifying burner and air port flow control settings with the existing installation and inverting selected lower row cells.

The CO mitigation strategies were evaluated at full and reduced load and with various mills-out-of-service. All of the modeling results presented are for full-load operation with all mills in service. The following conditions were used to model "normal operation" with the LNCBs™. Any variation in these operating conditions will be noted. The burner stoichiometry was 0.6, and the total excess air was 22% at the economizer outlet. The vanes in the secondary air zone of the burner were set 60° from fully closed. The air port louver dampers angled the flow 7° up. The locations of the burners and air ports are shown in the schematic of the lower furnace and hopper in Figure 5.

The high CO concentrations were measured shortly after startup with the LNCBs™. Figure 6 shows the predicted CO levels near the right side wall of Unit No. 4. The shading indicates the CO concentrations with black indicating 120,000 ppmV (12%) or higher and the cross-hatching indicating concentrations less than 10,000 ppmV (1%). The contour interval is 10,000 ppmV. With normal operation, the CO concentrations along the right side wall below the hopper work point are all higher than 100,000 ppmV. This plane is representative of the entire width of the boiler. CO measurements were made at an elevation approximately halfway between the hopper throat and the hopper work point at the centerline of the furnace. The measured concentrations at this location were between 100,000 and 120,000 ppmV for normal operation.

The air port louver dampers in the lower row of cells were adjusted to turn the flow 20° down to introduce more air into the hopper. The predicted CO concentrations in the hopper actually increased with this change (140,000 to 150,000 ppmV). The results indicate that turning the air port flow 20° down actually forces more substoichiometric combustion products into the oxygen-deficient hopper. Later measurements taken during operation with similar air port louver damper settings showed 130,000 ppmV. The predictions and data both indicated an increase in the CO concentrations.

The stoichiometry of the burners in the lower row of cells was increased from 0.6 to 0.8 and the louver dampers were set to turn the flow 7° up. The total excess air to the unit was not increased. The CO concentrations decreased as expected with the increased burner stoichiometry, but only to about 60,000 ppmV. Later measurements revealed CO concentrations of 50,000 to 60,000 ppmV. Variations in the burner and air port flow control settings were not effective for reducing the CO to acceptable levels. The excellent agreement between the predictions and the data demonstrated the reliability of the CO predictions. Consequently, the models were used to evaluate the CO concentrations with selected lower row cells inverted.

Inverting the outer cells (four total) reduces the CO along the side walls, but the concentrations are above 120,000 ppmV in the remainder of the hopper, as shown in Figure 7. Inverting the outer two cells near each side wall (eight total) gives similar results. Inverting the entire lower row of cells on the front and rear walls reduced the CO concentrations to a few hundred ppmV, but the furnace heat absorption patterns changed dramatically and the FEGT increased by approximately 50 K (90°F). As shown in Figure 8, alternating the inversion of lower row of cells was effective at mitigating the high hopper CO concentrations. Figure 8 also shows that the CO concentrations along the right side wall and in the entire hopper are less than 10,000 ppmV. In fact, the CO levels are under 1000 ppmV, which are comparable to pre-retrofit levels. The alternating lower cell inversion was evaluated at reduced loads and with various mills out of service. Regardless of the load or mills out-of-service, the CO levels were comparable to pre-retrofit operation throughout the hopper. No changes in the furnace heat absorption patterns were predicted with the alternating cell inversion, but the FEGT increased by 3 K (5°F) relative to normal operation with the LNCBs™ at full load.

Modeling results indicated that burner and air port flow control could not lower CO concentrations in the hopper to acceptable levels. Inverting all or alternating the lower row of LNCB™ burners will reduce the CO concentration in the hopper to levels comparable to the pre-retrofit operation, while requiring no changes to boiler pressure parts. Inverting alternating cells on the lower row of burners, however, was the only inversion strategy that did not significantly alter the FEGT or furnace heat absorption patterns. Inverting alternating lower row cells satisfies the need to mitigate the hopper CO concentrations without affecting the furnace heat transfer, reducing the unit efficiency or requiring additional equipment, controls or pressure part modifications.

CONCLUSION

Alternating lower row cells will be inverted, and the shallower angle coal impellers will be installed in all 24 coal nozzles during a 1992 spring outage. Based on results of pilot-scale studies with the shallower angle impellers, B&W expects that the NO_x reduction goals of the project will be met. The impact of the cell inversion on NO_x will be established when the modifications have been completed and testing resumes. The effectiveness of the design changes will be discussed when this paper is presented.

B&W's numerical flow, combustion, and heat transfer models were instrumental for evaluating potential solutions that would mitigate the high hopper CO concentrations. The models have proven to be an invaluable tools for evaluating furnace performance and should be used more extensively during the design phase of future projects. As experience is gained with the models and validation efforts continue, the role of models will play a important role in the commercialization of the LNCB™.

ACKNOWLEDGMENT

Other CCT Demonstration Program project participants include the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), the Ohio Development Office (OCDO), Allegheny Power System, Centerior Energy, Duke Power Company, New England Power Company, and the Tennessee Valley Authority (TVA).

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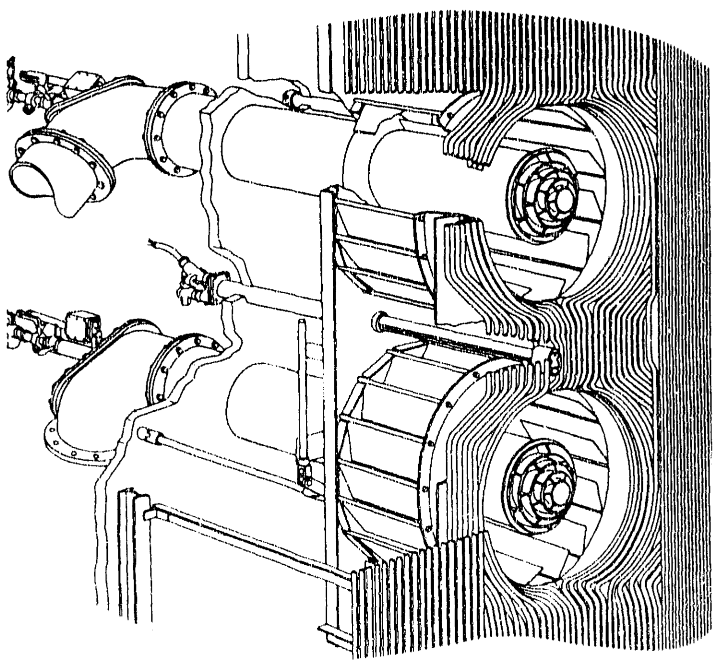

Figure 1. Standard two-nozzle cell burner

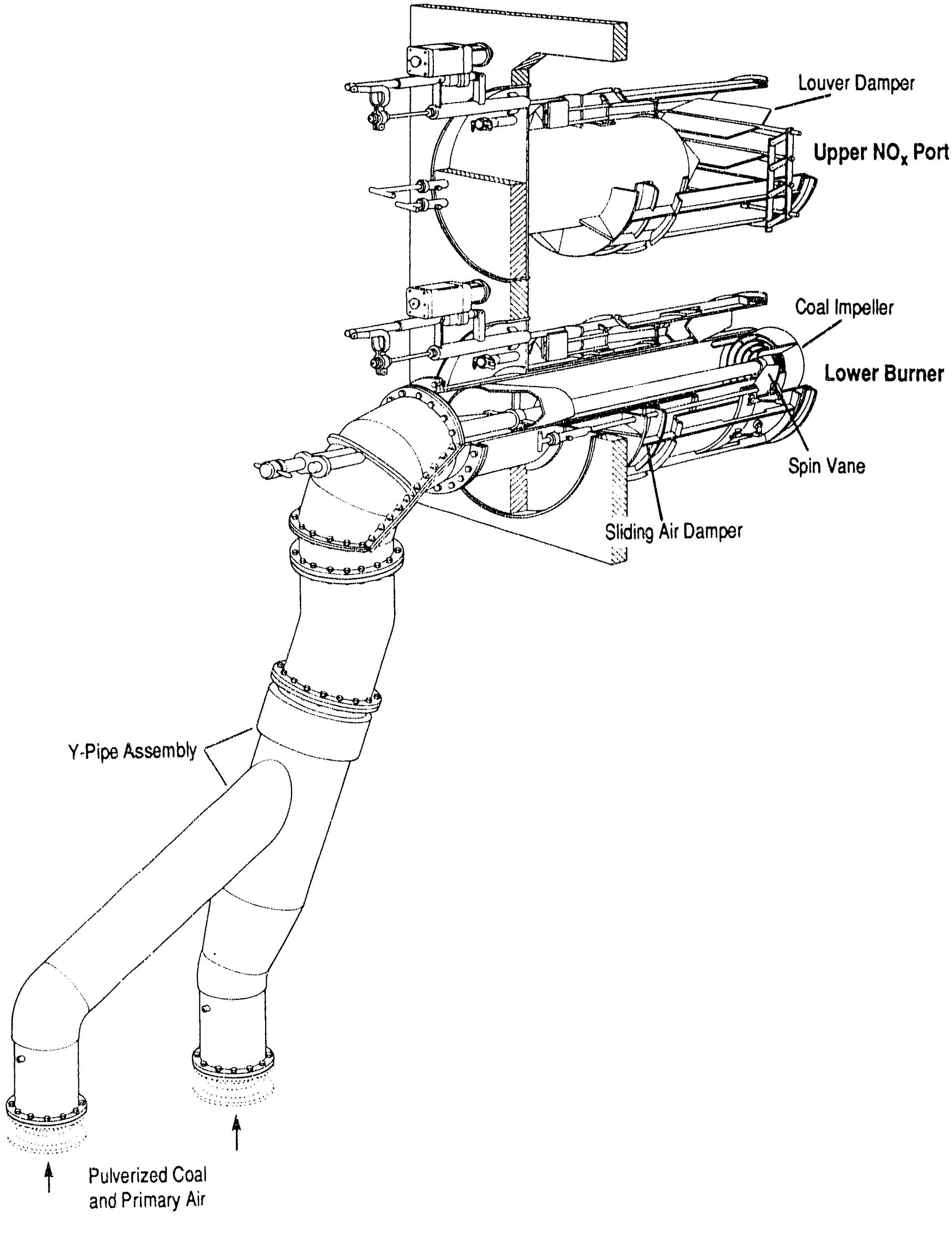

Figure 2. Low-NO_x cell™ burner (LNCB™)

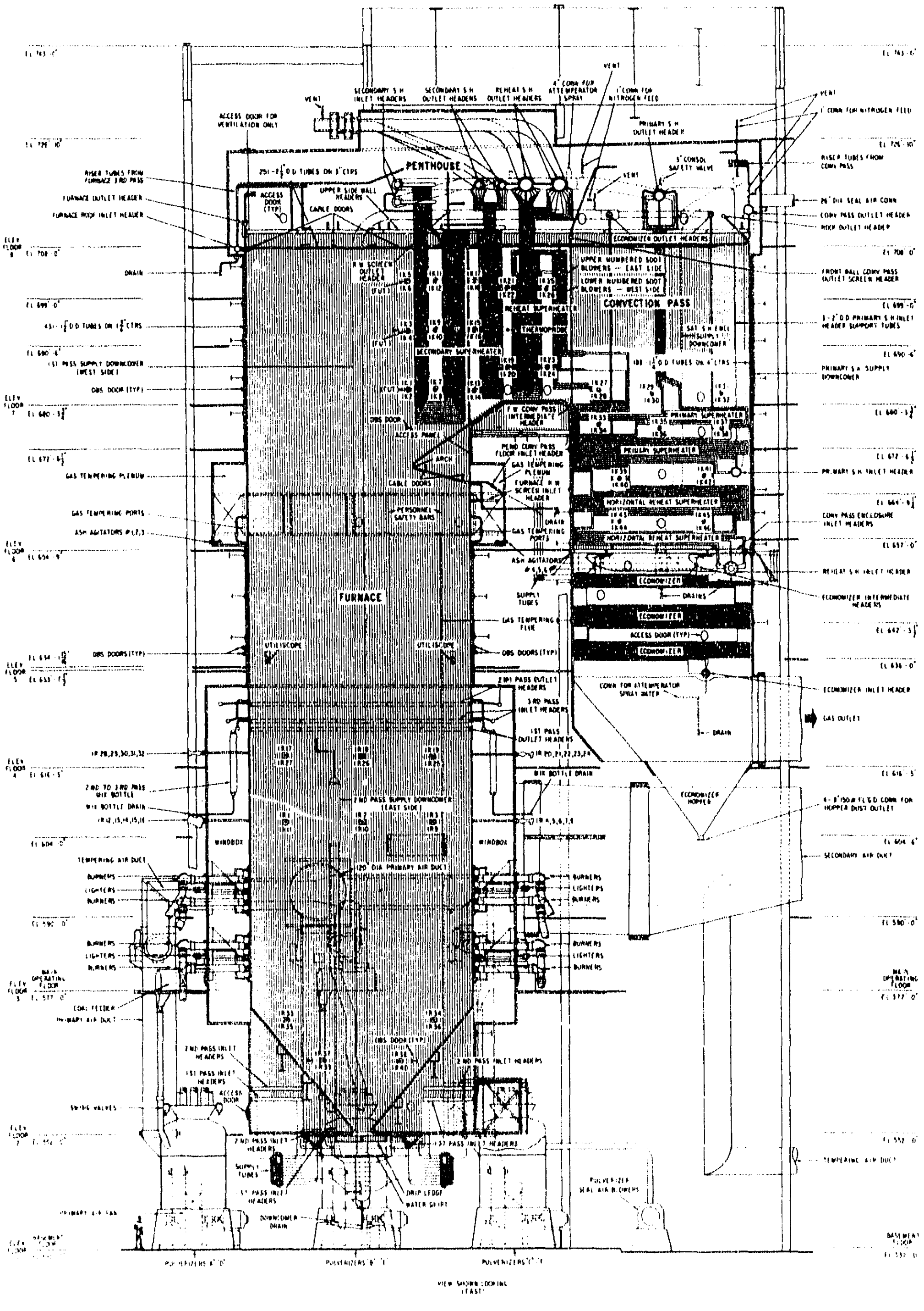

Figure 3. DP&L J. M. Stuart Unit No. 4

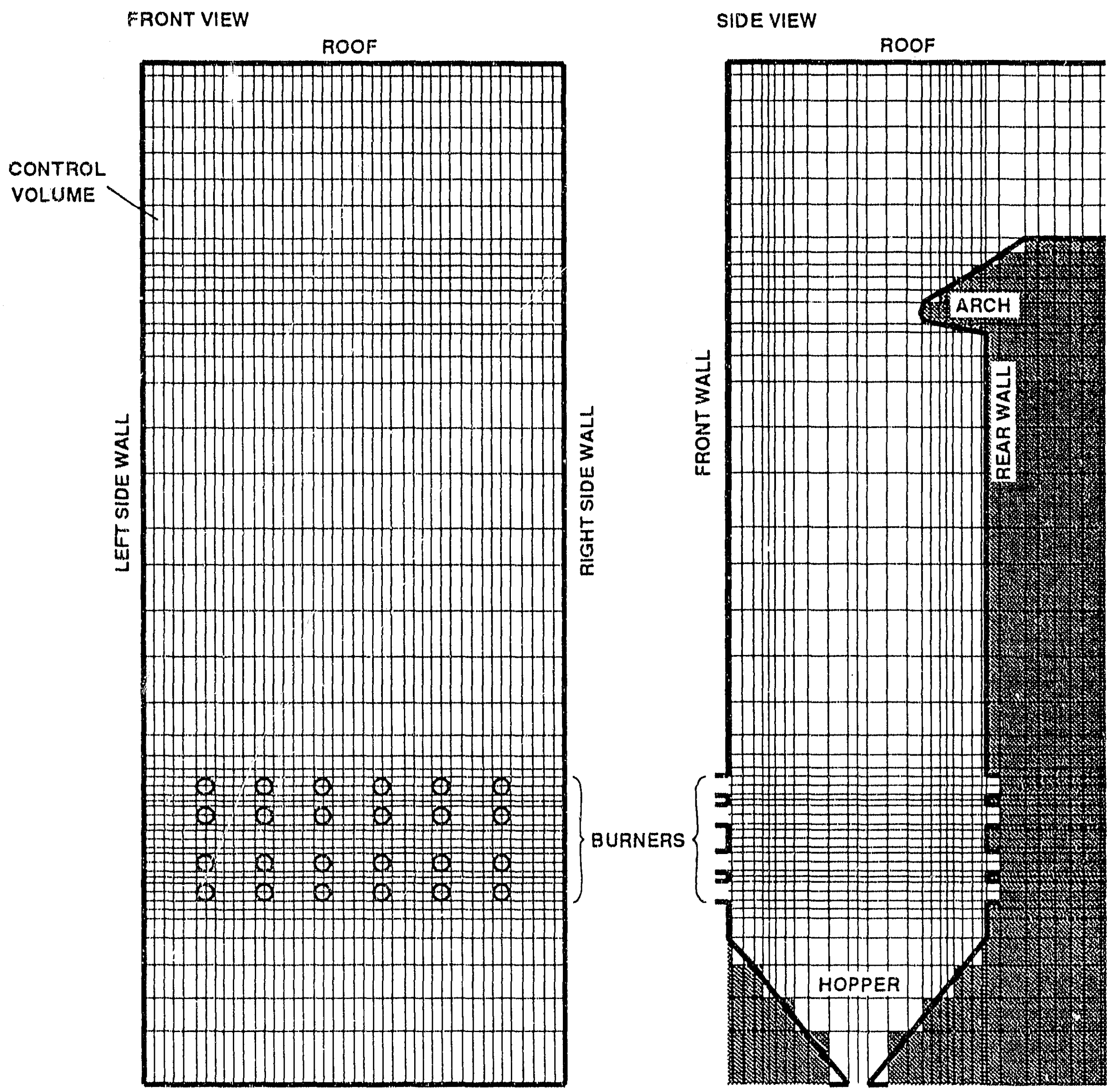

Figure 4. Control volume layout

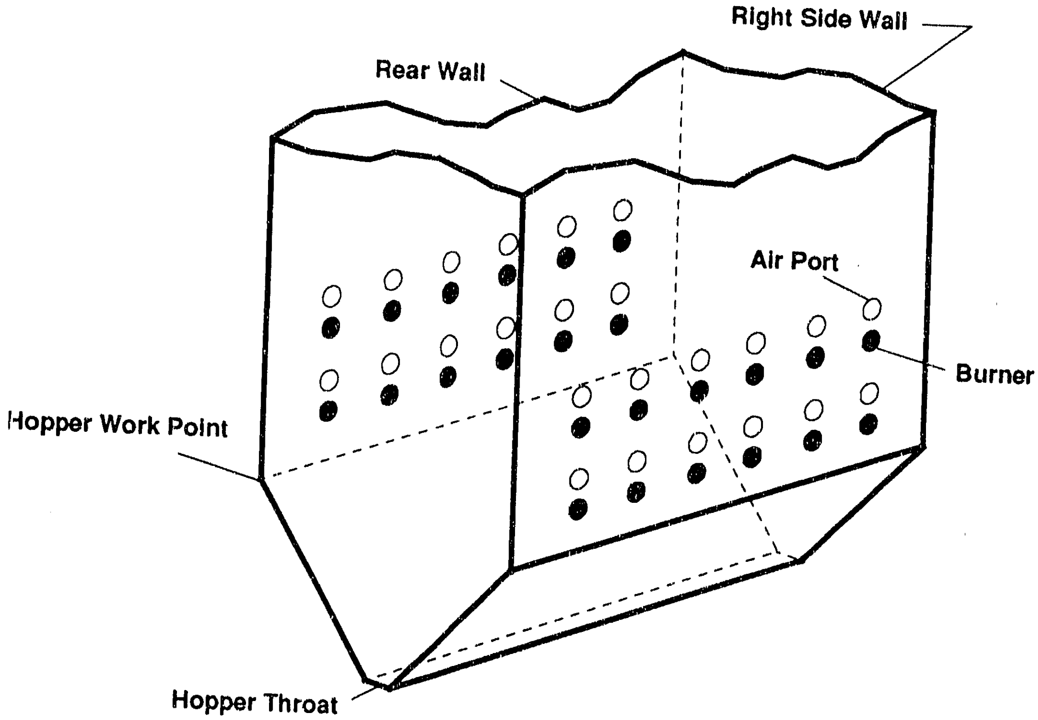

Figure 5. Locations of burners and air ports

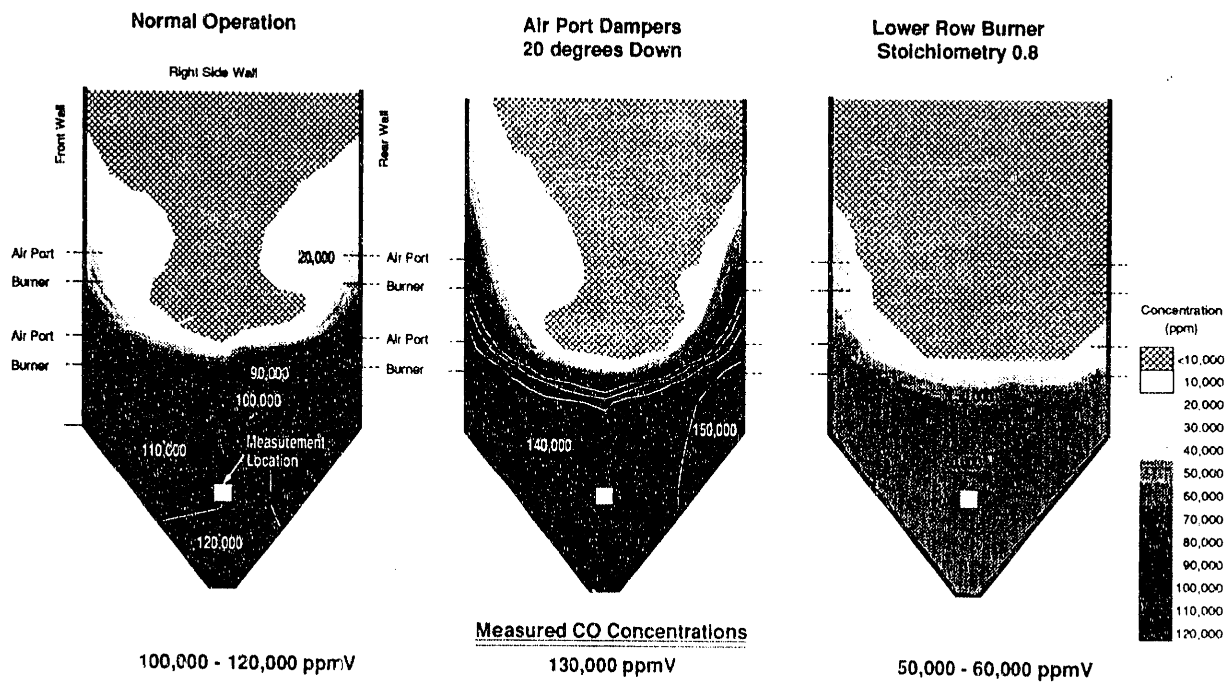

Figure 6. Predicted CO concentrations near the right-side wall of Unit No. 4

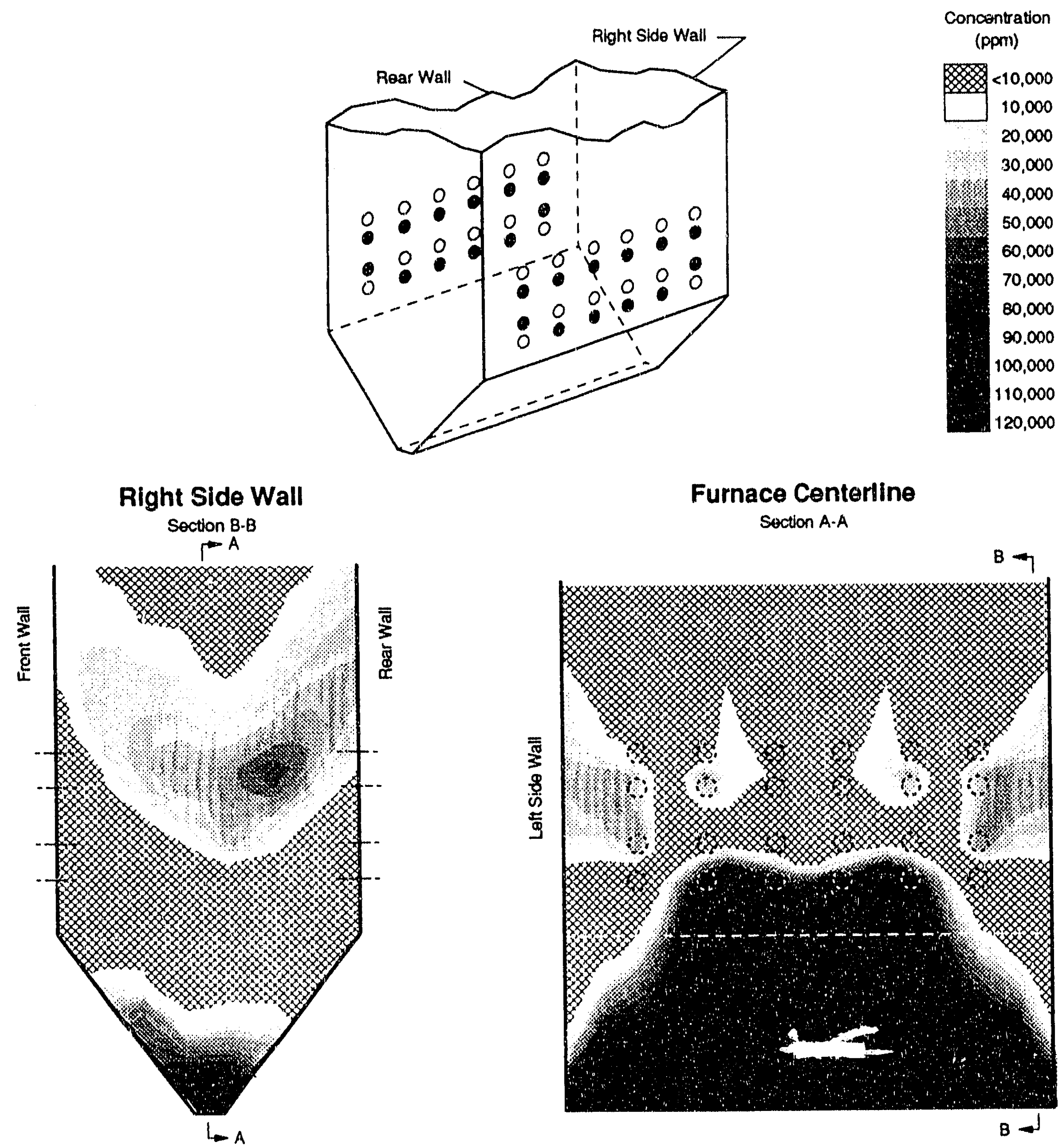

Figure 7. Predicted CO concentrations with the outer lower row cells inverted

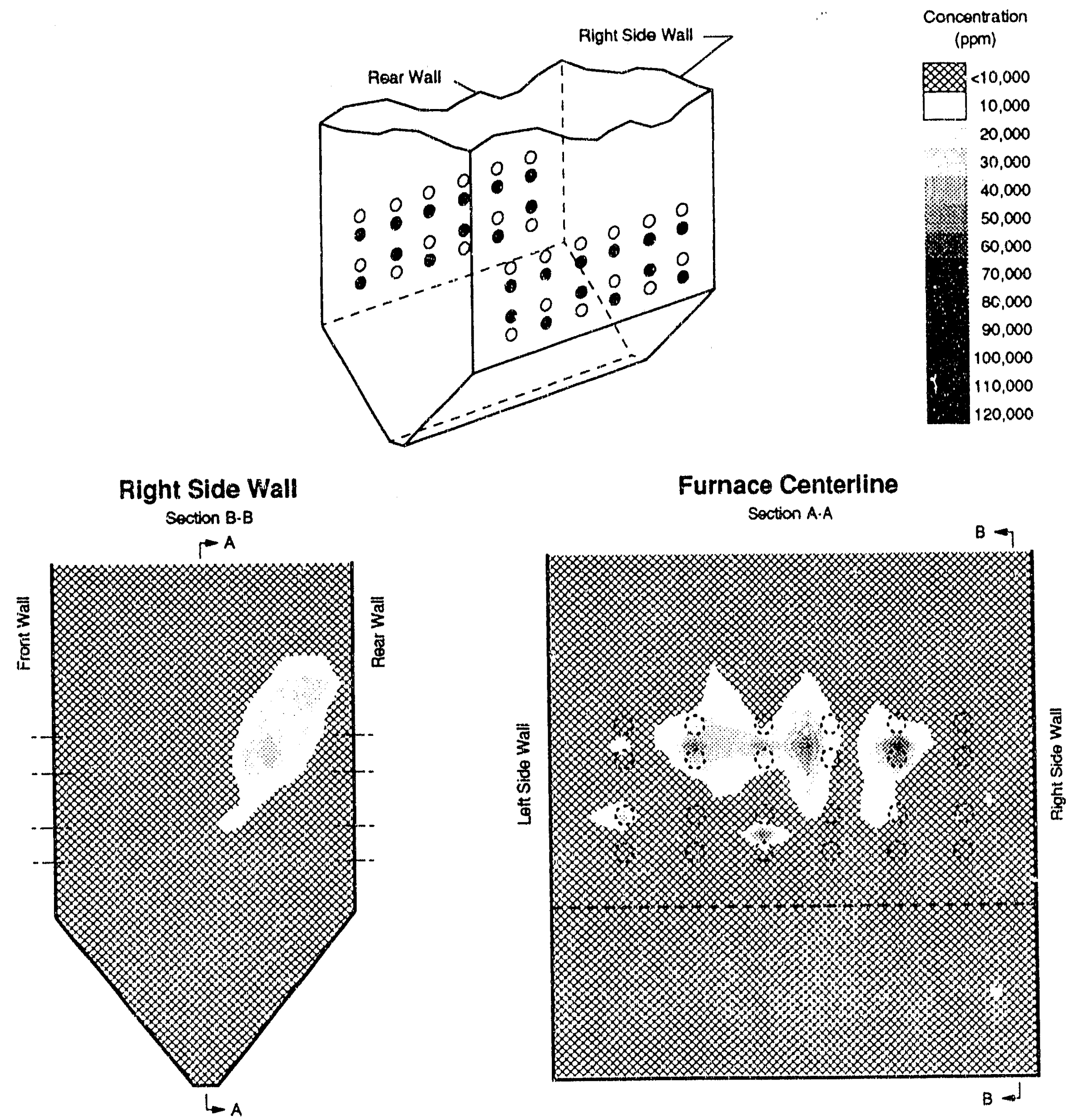

Figure 8. Predicted CO concentrations with alternating lower cells inverted

Table 1

TYPICAL OPERATING CONDITIONS FOR THE DEMONSTRATION BOILER AT FULL AND INTERMEDIATE LOADS

Parameter	Units	Load	
		Full	Intermediate
Output	MWe	605	458
Excess O2 at Economizer Outlet	%	3.739	5.348
Excess Air Leaving Economizer	%	21.2	33.3
Temperatures			
Windbox	K	599	583
Pulverizer Outlet	K	338	338
Pressures			
Windbox	Pa	5960	3334
Furnace	Pa	5462	3160
Atmospheric	Pa	99903	100343
Moisture in air	kg/kg-dry air	0.0073	0.0038
Coal Flow Rate	kg/sec	57.2	44.2
Burners Out of Service		None	B
Ultimate Analysis			
Carbon	%	66.52	65.95
Hydrogen	%	4.49	4.48
Oxygen	%	7.51	7.91
Nitrogen	%	1.23	1.16
Sulfur	%	1.00	1.12
Moisture	%	5.55	5.39
Ash	%	13.70	13.99
		100.00	100.00
Proximate Analysis			
Moisture	%	5.55	5.39
Fixed carbon	%	47.61	47.24
Volatile matter	%	33.14	33.38
Ash	%	13.70	13.99
		100.00	100.00
Higher Heating Value (HHV)	J/kg	2.7654E+07	2.7559E+07

END

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