Applications of Numerical Boiler Models to Evaluate NO_X Reduction Methods

Presented by:

Roger Ettema
Airflow Sciences Corporation

James C. Paul, P.E.

Airflow Sciences Corporation

Bruce E. Scherer

Consumers Power Company

ABSTRACT

A general purpose numerical modeling method has been developed for application to fossil-fueled boilers. The method utilizes basic physical and chemical relationships and thus avoids the requirement of extensive test data as input. Each simulation provides a full three-dimensional representation of the gas flow field, heat transfer rates and chemical reactions that occur within an operating boiler.

An example application of the numerical boiler modeling method is presented. Conditions within the furnace at Consumers Power Company's J.R. Whiting Plant Unit 3 are simulated for a variety of operating conditions and compared to test data. The simulation results provide a definition of the NO_x *generation process within the boiler and allow comparisons to be made of various combustion system modifications.*

INTRODUCTION

Operators of fossil-fueled boilers have employed a variety of emission reduction methods to attain levels specified by U.S. federal, state and local regulations. Nitric acid (NO) and nitrogen dioxide (NO_2), collectively referred to as NO_x, are specifically regulated by Federal New Source Performance Standards (NSPS) and Title I and Title IV of the 1990 Clean Air Act Amendments. An overview of current regulations and NO_x control techniques is provided in the paper by Reese, et.al [1].

A sample of NO_x reduction strategies, along with typical installation costs, are shown in Figure 1 [2] [3] [4] [5]. With such a variety of approaches to evaluate and with the time constraints imposed by the NO_x emissions regulations, utility operators are not always presented with sufficient information to make effective decisions. The impact on plant efficiency and plant operating costs resulting from incorporation of the various NO_x reduction methods at specific sites is generally based on extrapolation of laboratory experiments and equipment tests at other boilers. Because of the large number of variables affecting performance, approaches that have proven effective in controlled situations do not necessarily perform as expected in others. A need is thus established for an objective method to evaluate the site-specific effectiveness of proposed NO_x reduction schemes.

APPROACH

Several researchers have incorporated empirically based approaches to evaluating the effectiveness of NO_x control strategies [6] [7] [8]. These methods are effective for conditions that can be interpolated within the framework of the available data. However, they cannot accurately represent the effects of changes in geometry, fuel or operational parameters outside of the empirical data base. Since many NO_x reduction schemes involve unique combinations of conditions, it was decided to develop a simulation tool that could accommodate virtually any boiler geometry, fuel composition or combustion process (wall fired, tangentially-fired, cyclone, fluidized bed, etc.).

The goals for the numerical model are listed in Figure 2. To reduce the input requirements needed for each simulation, the model is based on first principles. This allows maximum flexibility for representing any boiler design or operating condition. A schematic of the basic model components is shown in Figure 3. It is noted that the information required for input is generally available from drawings and plant instrumentation.

A detailed description of the theory used for the numerical model is presented in the paper by Nelson, Franklin and Scherer [9]. A summary of the sources for the model components is presented in Figure 4. A primary focus of the model development effort was to incorporate state-of-the-art theory for each portion of the computer code.

To reduce the computer time required for each boiler simulation, simplifying assumptions were made that established the simulation method as primarily an engineering tool rather than a research platform. The model was considered acceptable if it produced results that were within the accuracy of the test data to which the model was being compared.

An expanded list of possible applications for the boiler modeling method is included in Figure 5. In addition to reducing the need for time-consuming trial-and-error testing and field adjustment programs, use of the numerical models provides several other advantages over traditional approaches to boiler performance improvements. These include confirmation of the effects due to design changes prior to fabrication and installation of hardware. Trade-off studies for competing modifications can be completed relatively quickly once the baseline boiler model is developed. In addition, the numerical models generally provide greater insight regarding the source of changes in boiler performance.

APPLICATION TO J.R. WHITING PLANT

The J.R. Whiting Plant (Figure 6) is located in Luna Pier, Michigan. Unit 3 originally entered service in 1953 and was built by Babcock and Wilcox. The unit is presently run at 125 MW net which corresponds to 810,000 lb/hr of feedwater flow. Normal drum pressure is 1550 psia resulting in a saturation temperature in the water wall tubes of 600°F nominal.

The firebox that was modeled is front wall fired and has no division wall. The physical dimensions are 30'6" wide by 22'3" deep with a vertical dimension from the throat of the ash pit to the bullnose of 79'. The water walls consist of 3" diameter, 0.240" wall SA-210 tubing, close spaced. The heating surface of the water walls is 12,200 ft^2. A most interesting aspect of this boiler is the two rows of close coupled burners. The two lower rows of burners and the two upper rows are spaced on 5' centers. The second and third burner rows are separated by 14' and the first (lowest) burner row is located 17' above the ash pit throat. A schematic of the portion of the firebox below the bullnose is shown in

Figure 7. The locations of the boiler centerline plane and a plane through one of the burner columns are indicated. The data plane shown was chosen for displaying simulation results found later in this paper.

One E-70 pulverizer is dedicated to each elevation (row) of 4 burners. The unit, as of this writing, retains the original turbulent burners, designed with a 12" pipe, 11.75" tip (impeller), a 31" throat and a 39" casing. The burners have integral throat brick. A cutaway drawing of one of the burners is shown in Figure 8. The unit can marginally make full load with one mill out of service, assuming quality coal and no other problems. The burners operate with a secondary air differential pressure of approximately 1.5" H_2O and will operate as low as 1". Running the unit's FD fan at capacity results in approximately 4" H_2O differential pressure between the windbox and the furnace.

The burners have an inherent problem with sloppy secondary air linkages that allow one side of the secondary air dampers to hang open while the other side hangs shut. For the final characterization test, each damper on each burner was measured and the total opening for each burner was equalized.

Controls for the unit are the original pneumatics, which presented stability problems during the characterization testing. The most significant problem appears to be the rotating table feeders that control coal flow to the mills by a pneumatically actuated gate instead of a variable speed control. The `hunting' which results from this pneumatic control leads to a varying bed of coal in the mill which, in turn, leads to a varying fuel/air ratio at the burners. This shows up as an unstable excess O_2 trace during testing. This instability is exacerbated by turbulence in the passages between the FD fan and the windbox. Since total air flow is measured as a pressure difference across the tubular air heaters, this turbulence contributes to controls swing.

Because of these problems, the controls were manually operated during the characterization test. This eliminated some, but not all of the swing in excess of O_2. Presently the pneumatics are being replaced with new digital loop controllers prior to low NO_x burner installation.

As tested, the unit burned 100,200 lb/hr of eastern bituminous coal with a composition as follows:

Ash	9.19%	Moisture	4.48%
Hydrogen	4.69%	Carbon	72.19%
Nitrogen	1.60%	Oxygen	6.95%
Sulfur	0.90%		

The secondary air was provided at a temperature of 550°F and a flow rate of 900,000 lb/hr. The primary air temperature was 150°F and its flow rate was 200,400 lb/hr. The primary air tends to dry the coal as it travels from the mill to the burner. Thus, it was assumed that the coal moisture content at the burner was 2%.

The original characterization testing indicated 0.951 lb NO_x/MBTU at 3.2% excess O_2 and 0.853 lb/MBTU at 2.2% excess O_2. The maximum imbalance of coal flow in the unmodified boiler was 5%. Thus, restoring balanced conditions at the burners had a relatively small effect on NO_x levels. Primary air and coal flows were balanced by the installation of coal conduit orifices designed by Airflow Sciences Corporation. After this modification and balancing the secondary air flow through all burners, the full load NO_x production was reduced to 0.930 lb/MBTU at 3.2% excess O_2 and 0.794 lb/MBTU at 2.2% excess O_2. These are 5 minute averages taken at the economizer by a multipoint sampler that extracted a representative sample and corrected it for leakage. These values are in general agreement with the readings from Continuous Emission Monitors which were installed subsequent to the tests.

One goal of the project was to validate the numerical methods by comparison with previously gathered test data. The testing was performed by Fossil Energy Research Company (FERCo) during the summer of 1993.

A zonal approach was taken to modeling the tested configurations. A detailed simulation was made of an individual burner and these results were used as boundary conditions for a model of the boiler as a whole.

SIMULATION RESULTS

Although several low NO_x burners were simulated as part of the Consumers Whiting study, the results cannot be presented because of proprietary constraints imposed by the burner manufacturers. Instead, the results of two models of the existing boiler configuration will be reviewed. These two conditions are 1) full load operation with all mills in service and 2) full load operation with one mill out-of-service. For the second case, the upper row of burners provided an approximation to an over-fire-air system.

The model begins with a simulation of conditions at each burner. Coal particle trajectories and combustion air velocity fields are calculated using the detailed burner models. The results are imposed as boundary conditions at each burner location for the full furnace model. Coal particle trajectories are based on samples taken at the pulverizer outlet. With all four mills in service, the coal particle distribution for Whiting Unit 3 is shown in the table below:

Particle Diameter (Microns)	Mesh Size	% by Weight
40	368	61
110	135	28
200	73	11

Particles of different sizes behave differently as they exit the burner. This can be seen by comparing the trajectories of 40 micron and 200 micron particles (368 and 73 mesh, respectively) as shown in Figure 9.

As the particles enter the furnace, their temperature is modified due to the effects of radiation, convective heating and evaporation (Figure 10). Volatile matter is released by the particles, eventually producing char which is available for oxidation. Trajectories of 40 micron and 200 micron particles (368 and 73 mesh, respectively) within the furnace are shown in Figure 11. For these plots, a coal particle is tracked until all combustibles are consumed or until it exits the top of the furnace. Thus, this simulation methods can be used to calculate loss on ignition (L.O.I.) which represents the amount of combustible matter leaving the boiler.

The fuel particle trajectories can be used to calculate furnace residence time (2.0 seconds for particles from the bottom burner and 1.2 seconds for particles from the top burner) and to evaluate the effects of burner modifications on combustion zone geometry.

A direct correlation can be seen between the furnace temperature distribution and NO_x generation rates. The plots in Figure 12 show the temperature distribution and regions of NO_x generation for the full unit load, all-mills-in-service case.

At present, the model calculates the concentrations of over 126 products of combustion. These can be plotted, as shown for SO_2 and CO in Figure 13, to define areas where burners can be improved, reducing atmospheres could lead to corrosion, or to determine locations for monitor probes.

For the case of the top-row-of-burners-out-of-service, significant changes are predicted (compared to the baseline run) for temperature distribution, particle trajectories, L.O.I. and NO_x levels. Temperature distribution and particle trajectories within one plane are shown in Figure 14. L.O.I., for example, increased from 6% for the case of all four pulverizers in service to 18% when the top row of burners was configured for over fire air. Corresponding average NO_x levels decreased from 678 ppm to 513 ppm.

CORRELATION WITH TEST DATA

The simulation results agree well with test data. In fact, all predicted values are within the measurement accuracy band for the data. Comparisons of furnace exit gas temperatures for the four-mills-in-operation case are shown in Figure 15. Other comparisons for conditions measured at the economizer outlet (also for the four-mills-in-service case) are shown in Figure 16. Corresponding lots for the top-row-of-burners-out-of-service case are shown in Figure 17. An example of the gas velocity field is shown in Figure 18.

SUMMARY AND CONCLUSIONS

The simulation of combustion in a boiler under various conditions can be an important tool in evaluating NO_x reduction strategies. A numerical analysis tool has been developed which allows for both a detailed simulation of flow through individual burners as well as the entire boiler. The procedure includes submodels which predict turbulence, particle trajectories, chemical reactions and radiation effects.

Comparisons were made with test data gathered by Fossil Energy Research Company at the J.R. Whiting plant of Consumers Power Company. A baseline and a top-row-of-burners-out-of-service case were modeled. Strong correlation with experimentally measured NO_x concentrations was established for both cases. The method is currently scheduled for use as a practical aid in comparing NO_x reduction strategies at several electric utilities.

ACKNOWLEDGEMENT

The authors wish to thank Consumers Power Company for their support during this study and for agreeing to release the information contained in this paper.

BIBLIOGRAPHY

1. Reese, J.L., et.al., "State of the Art of NO_x Emission Control Technology", ASME, 94-JPGC-EC-15, Joint International Power Generation Conference, Phoenix, AZ, October 1994.

2. D.J. Smith, "Low NO_x Burners Lead Technologies to Meet CAA's Title IV, "*Power Engineering*, June 1993.

3. "Retrofit NO_x Controls for Utility Boilers, "Electric Power Research Institute, Report TR-102012.

4. N. Kaplan, "NO_x Controls Costs in AIAPSC Model," 1993 Joint Symposium on Stationary Combustion NO_x Control, Electric Power Research Institute and U.S. Environmental Protection Agency, 1993.

5. C. Castaldini, W.J. Neuffer, K.R. Durkee, "NO_x Reductions for Utility Boilers in the NESCAUM Region," 1993 Joint Symposium on Stationary Combustion NO_x Control, Electric Power Research Institute and U.S. Environmental Protection Agency, 1993

6. Squires, R., Stallings, J., "Update on the Development of GNOCIS - a Generic NO_x Control Intelligent System," Entergy 1994 Fossil Operations Technology Transfer Conference, Baton Rouge, Louisiana, June 30, 1994.

7. Bauer, F.W., Mancini, R.A., Kimiecik, D., "Mathematical Modeling Development and Application for Evaluation of Fuels on Chain Grate Stoker Boilers," ASME 91-JPGC-PWR-64, International Power Generation Conference, San Diego, California, October 1991.

8. Bauer, F.W., Petrella, P.A., "Fully Engineered Approach to Acid Rain Controls," Competitive Power Congress, 1994, Philadelphia, Pennsylvania, June, 1994.

9. Nelson, R.K., Franklin, J.D., Scherer, B.E., "Prediction of NO_x Generation in Coal Fired Boilers", Power-Gen Americas '94, Orlando, Florida, December, 1994.

NO_x Reduction Strategies and Costs

Figure 1

Technology	Retrofit Cost ($/kW)	% NOx Reduction
Combustion Modifications	Range: 0-10 Average: 3.2	Range: 10-25 Average: 22.5
Overfire Air	Range: 5-15 Average: 8.2	Range: 10-30 Average: 23
Low NOx Burners	Range: 6-40 Average: 16.1	Range: 20-60 Average: 51
Natural Gas Reburning	Range: 14-50 Average: 32	Range: 40-60 Average: 51
Selective Non-Catalytic Reduction	Range: 5-50 Average 19.6	Range: 20-70 Average 43.1
Selective Catalytic Reduction	Range: 80-180 Average: 123.5	Range: 60-90 Average: 77.5

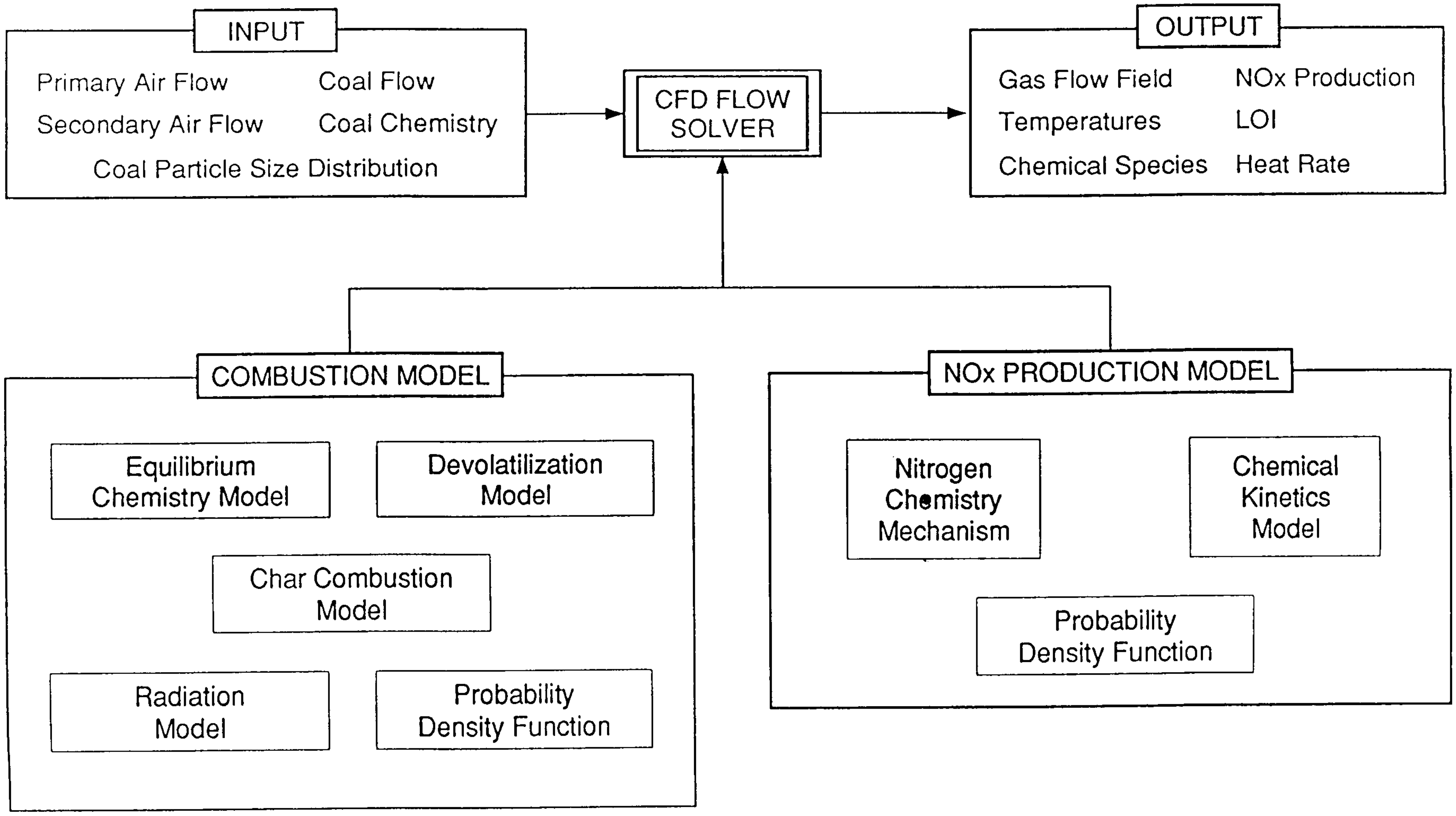
Goals for Boiler Modeling Method

Figure 2

1. Provide a full 3-D representation of conditions within the furnace including the gas flow field, heat transfer, combustion, particle trajectories and gas component concentrations.
2. Method is to be based on first principles. Empirical data needed for the model are to be minimized.
3. The model is to be developed as an engineering tool rather than a research aid. Model accuracy is to match that of test methods used to obtain comparison data.
4. To contain costs, model is to be implemented on engineering workstations rather than supercomputers.
5. The model is to accommodate any boiler or burner geometry.
6. The model is to predict all of the major products of combustion including NO_x.
7. The model is to accommodate any fossil fuel including pulverized coal, oil and gas.
8. The model is to incorporate state-of-the-art theory from premier researchers in the fields of combustion, heat transfer and boiler design.
9. The model is to predict levels of unburned fuel leaving the furnace.
10. The model is to accommodate all possible furnace modifications including over-fire air, gas reburn and flue gas recirculation.
11. The model is to accommodate any changes to the fuel delivery system including burners out-of-service, mills out-of-service, skewed combustion air distributions and fuel particle size changes.
12. The model is to calculate heat rate (BTU/kWh).

Combustion and NOx Production Simulation
Primary Model Components - Input and Output

FIGURE 3



Theory Incorporated Into Boiler Model

Figure 4

Model Section	Researchers	Association
Gas Flow Field	Patankar	Univ. of Minnesota
	Spalding	Imperial College
Coal Particle Simulation	Crowe, Sharma, Stock	Washington State University
Devolitilization and Char Oxidation	Smoot, Smith	ACERC, Bringham Young
	Monroe	Southern Research Institute
Radiation	Lockwood, Shah	Imperial College
Equilibrium Chemistry Combustion	Gordon, McBride	NASA Lewis Research Center
Turbulence Model	Launder	Univ. of Manchester Inst. of Science and Tech.
	Spalding	Imperial College
Probability Density Function: Favre Averaging	Bilger	Univ. of California San Diego
Nitrogen Chemistry	Miller	Sandia National Lab.
	Bowman	Stanford University
NO_x Production Rates	Glarborg	Technical University of Denmark

Boiler Model Applications

Figure 5

Furnace and Back Pass:

1. Evaluation of burner geometries
2. Effects of fuel changes (fuel switching, fuel blending)
3. Calculation of heat transfer to water walls and steam tubes (conductive, convective, radiative); calculation of steam temperatures, pressures
4. Calculation of unburned fuel at boiler exit
5. Determination of effects to combustion system
   A. Over fire air
   B. Under fire air
   C. Flue gas recirculation
   D. Gas reburn
6. Effects of changes in boiler operating conditions
   A. Mill out-of-service
   B. Burner out-of-service
   C. Reduced load
   D. Fuel droplet/particle size distribution
7. Define heat rate for specific operating condition
8. Calculate components of flue gas
   A. Excess O2
   B. Definition of reducing atmospheres
   C. NOx, SOx emissions
9. Determine conditions associated with ash
   A. Slagging
   B. Fouling
   C. Erosion

Boiler Model Applications (Continued)

Figure 5, Continued

Associated Equipment

10. Coal pipe balancing/fuel line balancing

11. Combustion air balancing

12. Alleviation of air pre-heater pluggage/corrosion

13. Gas cleaning equipment performance improvement
    A. Electrostatic precipitators
    B. Baghouses
    C. Mechanical separators (hoppers, cyclones)

14. Air/gas system balancing

15. Stack flows/CEM placement

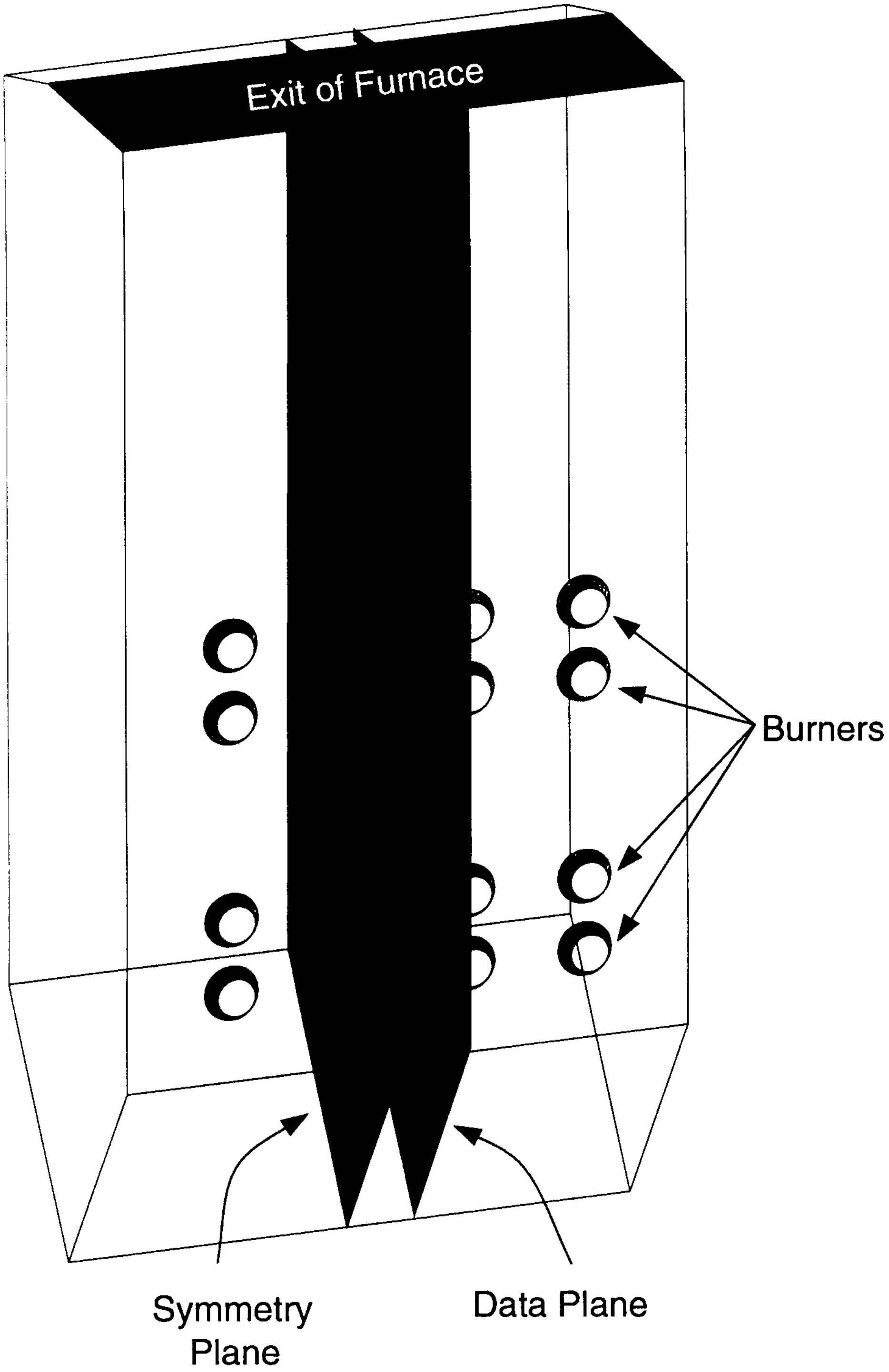
16. Plume dispersion

Figure 6
J.R. WHITING PLANT - CONSUMERS POWER COMPANY

J.R. Whiting Unit 3 Firebox

Below bullnose

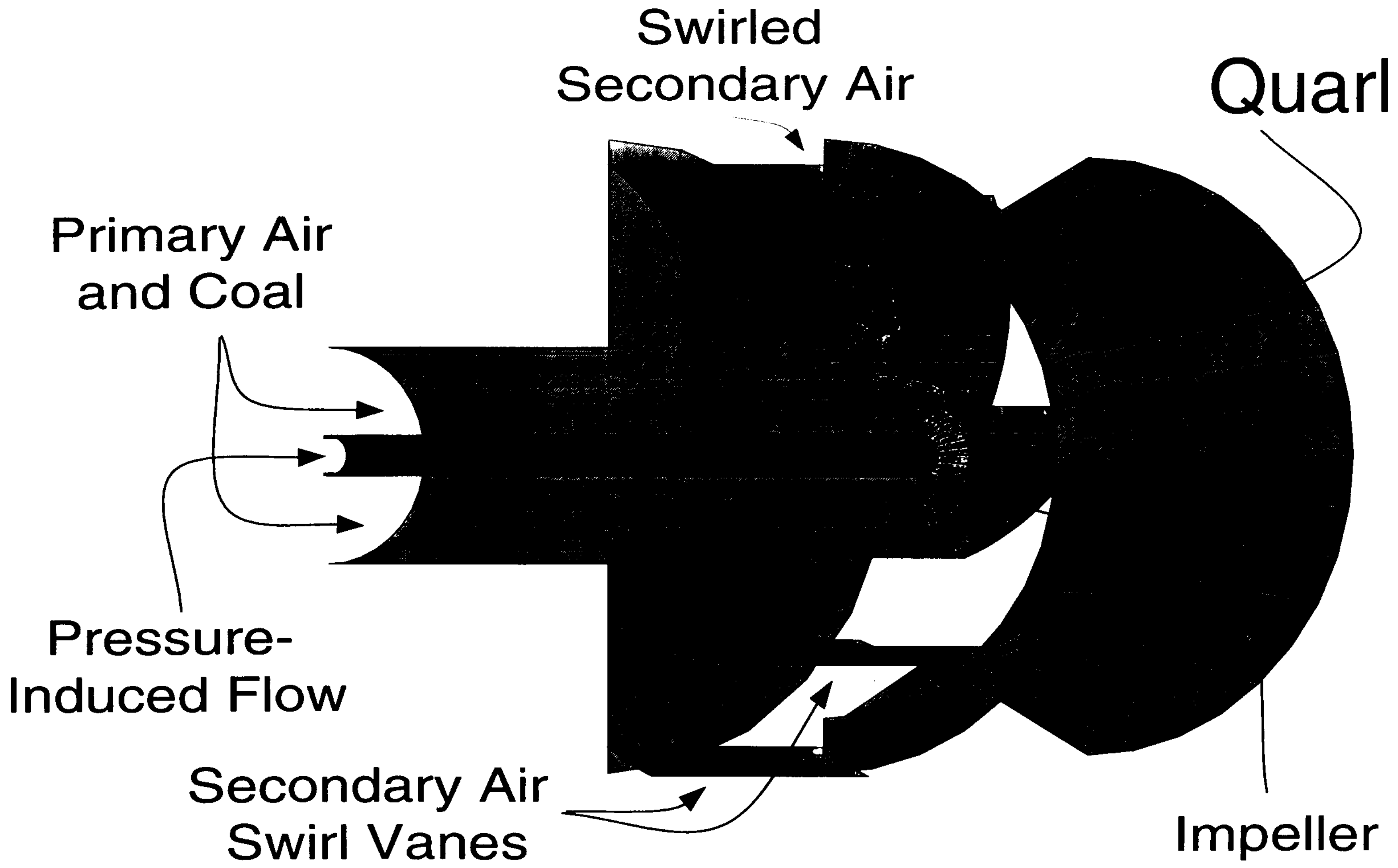
Figure 7



Original Turbulent Burners

As installed at J.R. Whiting Unit 3

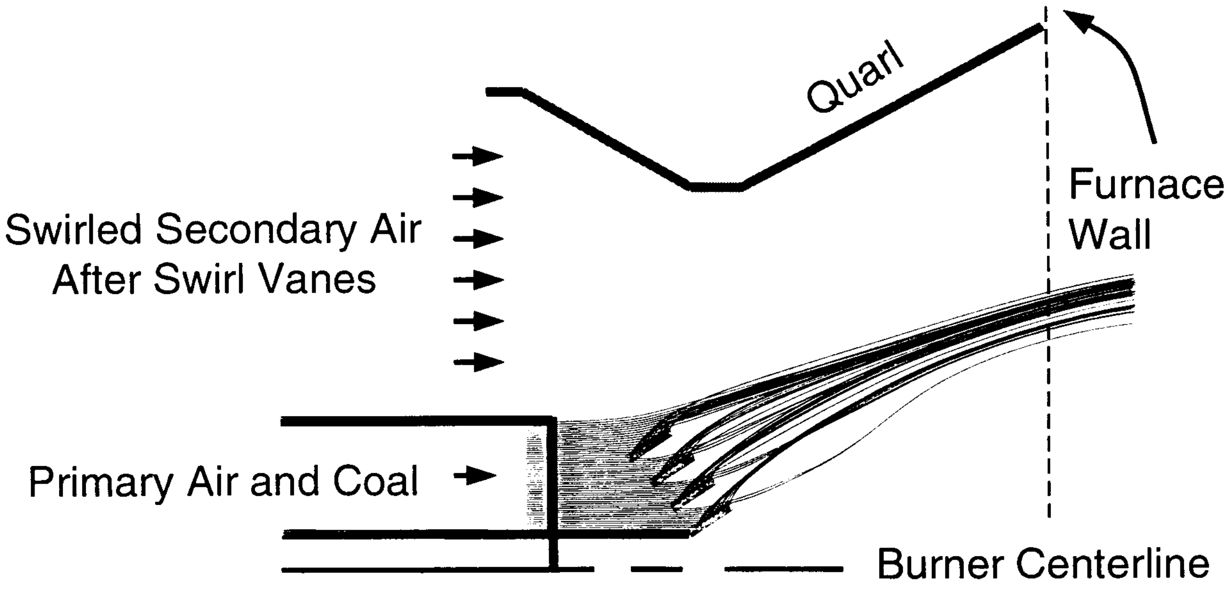
Figure 8



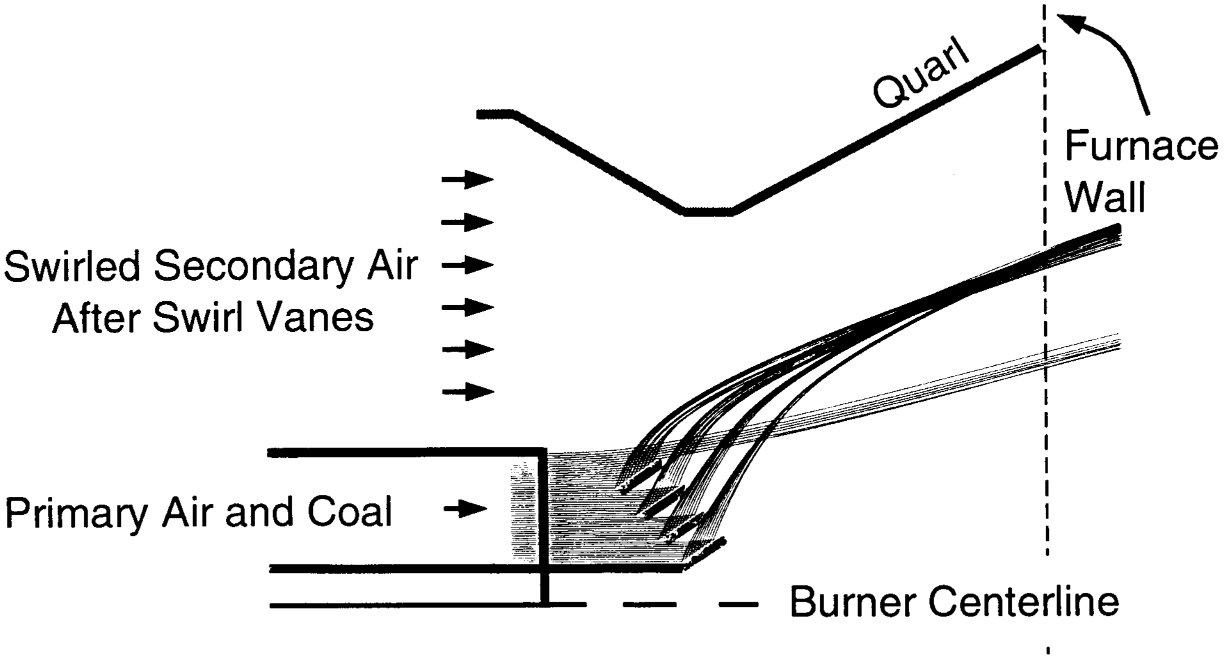
Particle Trajectories Through Burner

Figure 9

40μ Particles (325 Mesh)



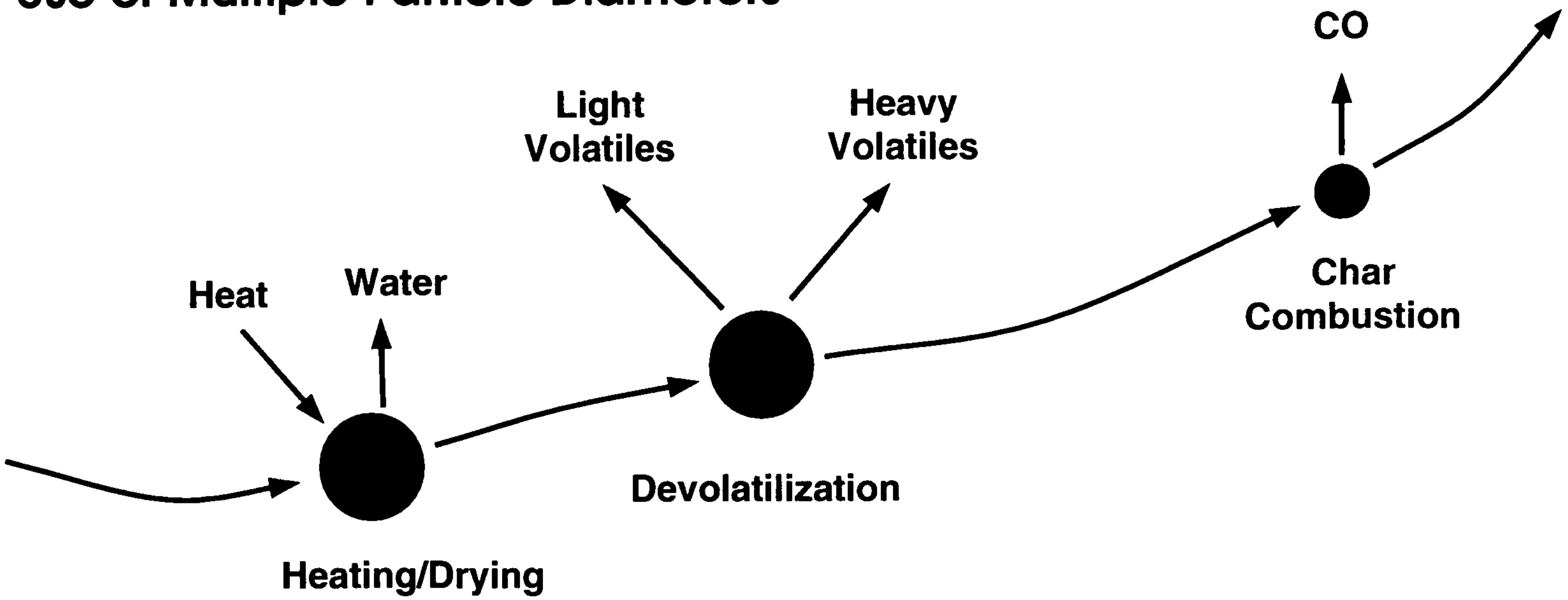
200μ Particles (70 Mesh)



Coal Particle Submodel

Figure 10

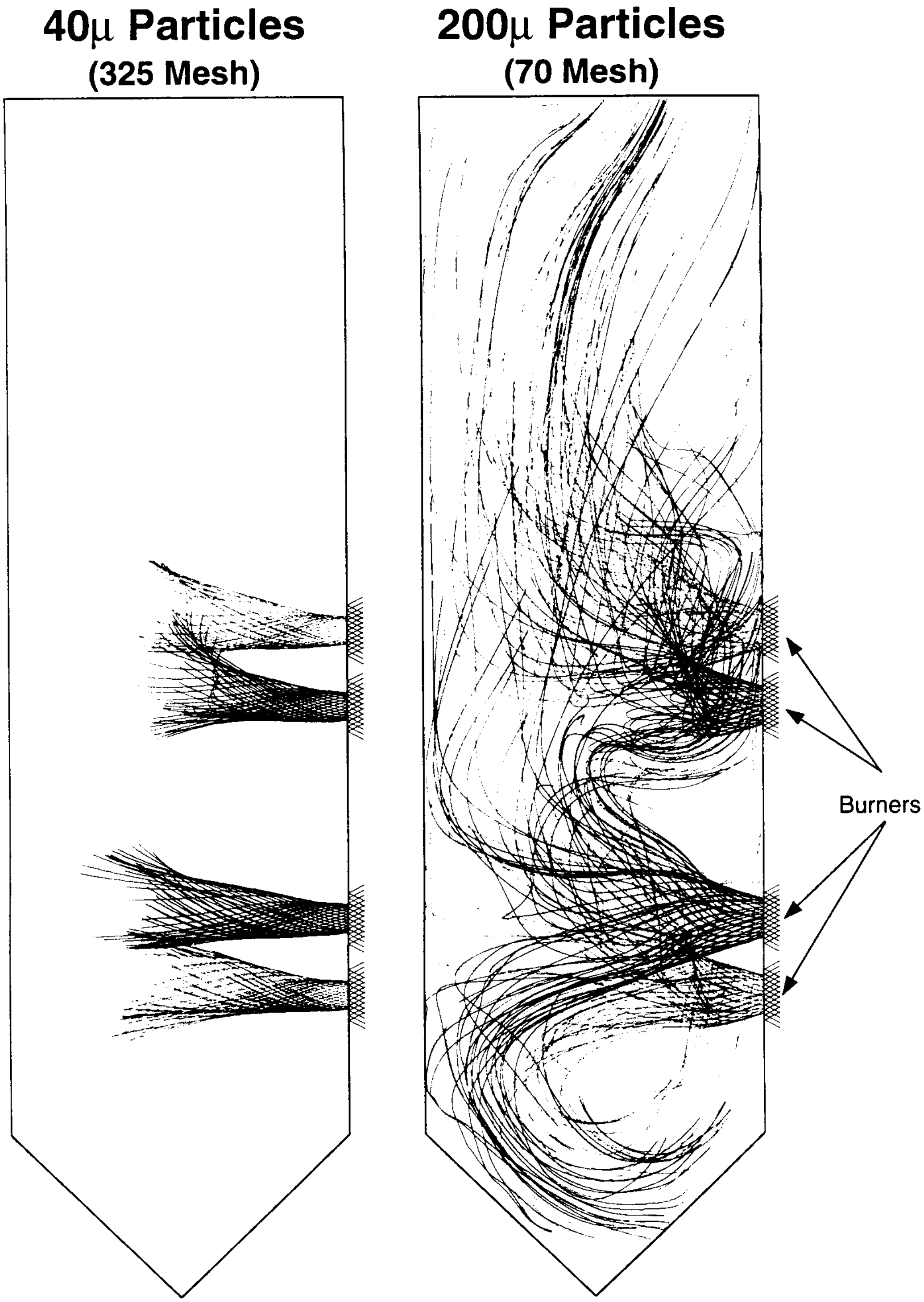
PSI-CELL Lagrangian Method
(Due to Crowe, Sharma and Stock)
Proprietary Rebound Logic
Use of Multiple Particle Diameters



Airflow Sciences
Corporation

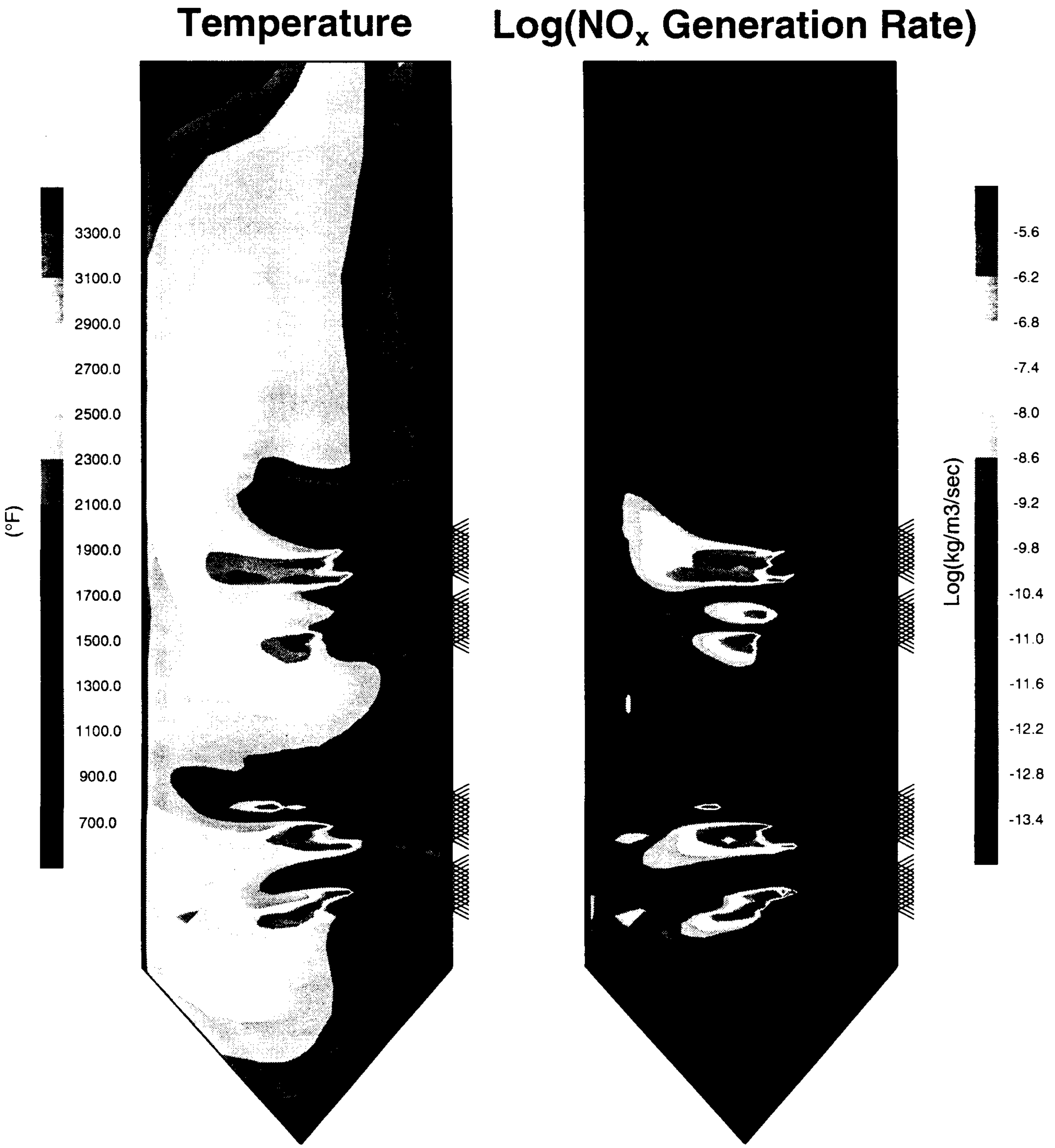
Trajectories of Coal Particles in Baseline Burner Model

Figure 11



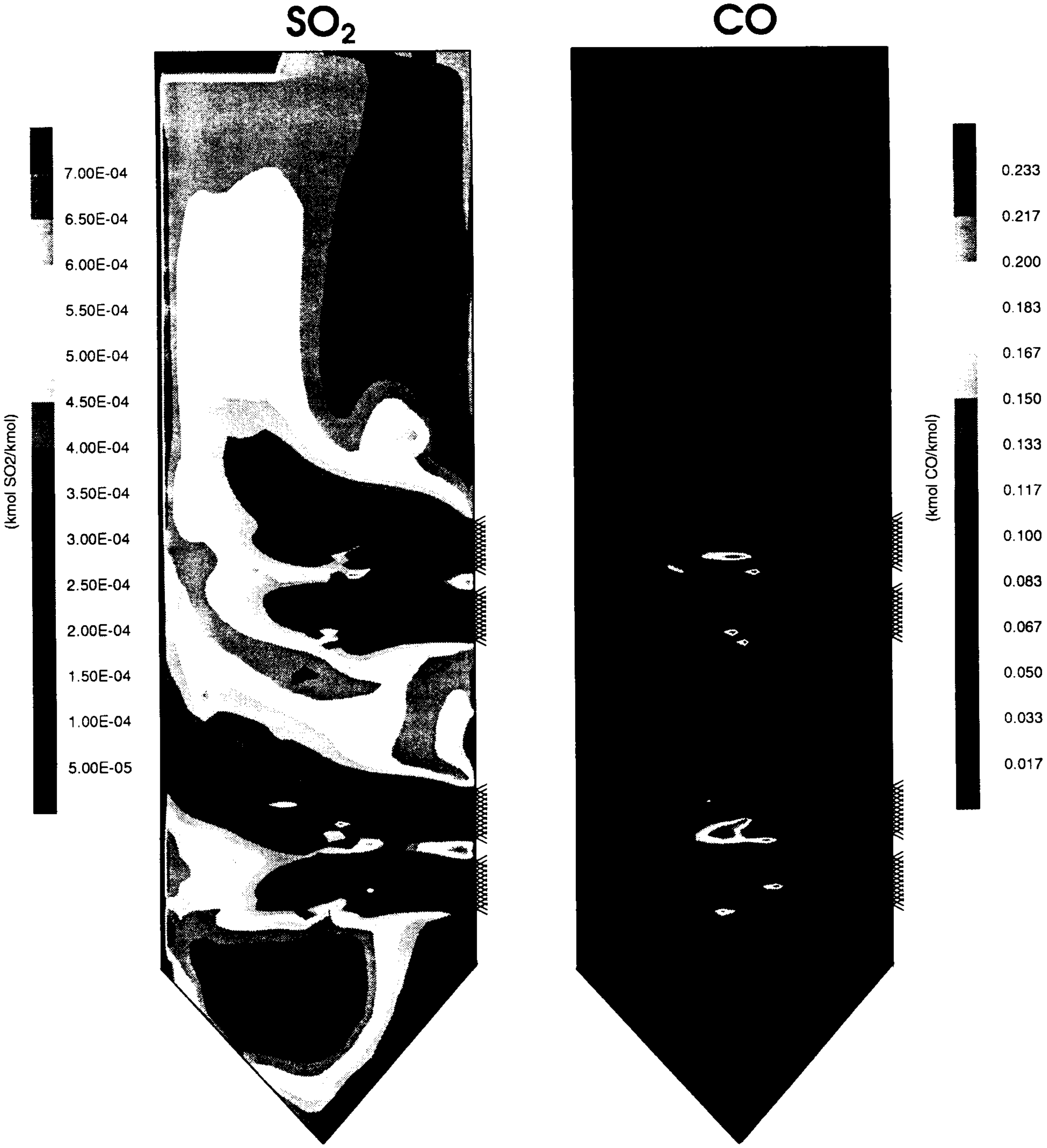
Temperature & NO_x Generation Rate for Baseline Boiler Model

Figure 12



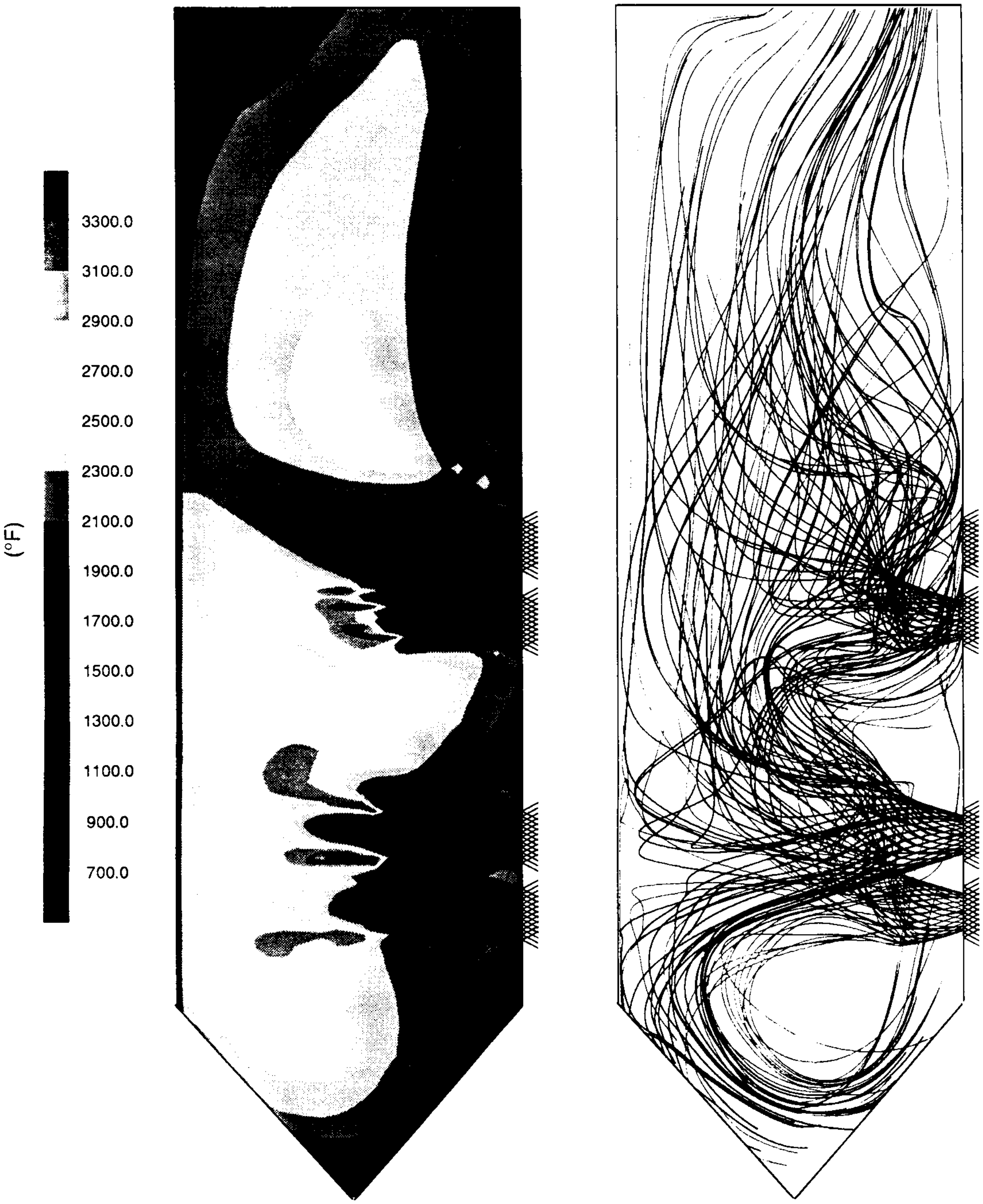
SO_2 and CO Distributions for Baseline Boiler Model

Figure 13



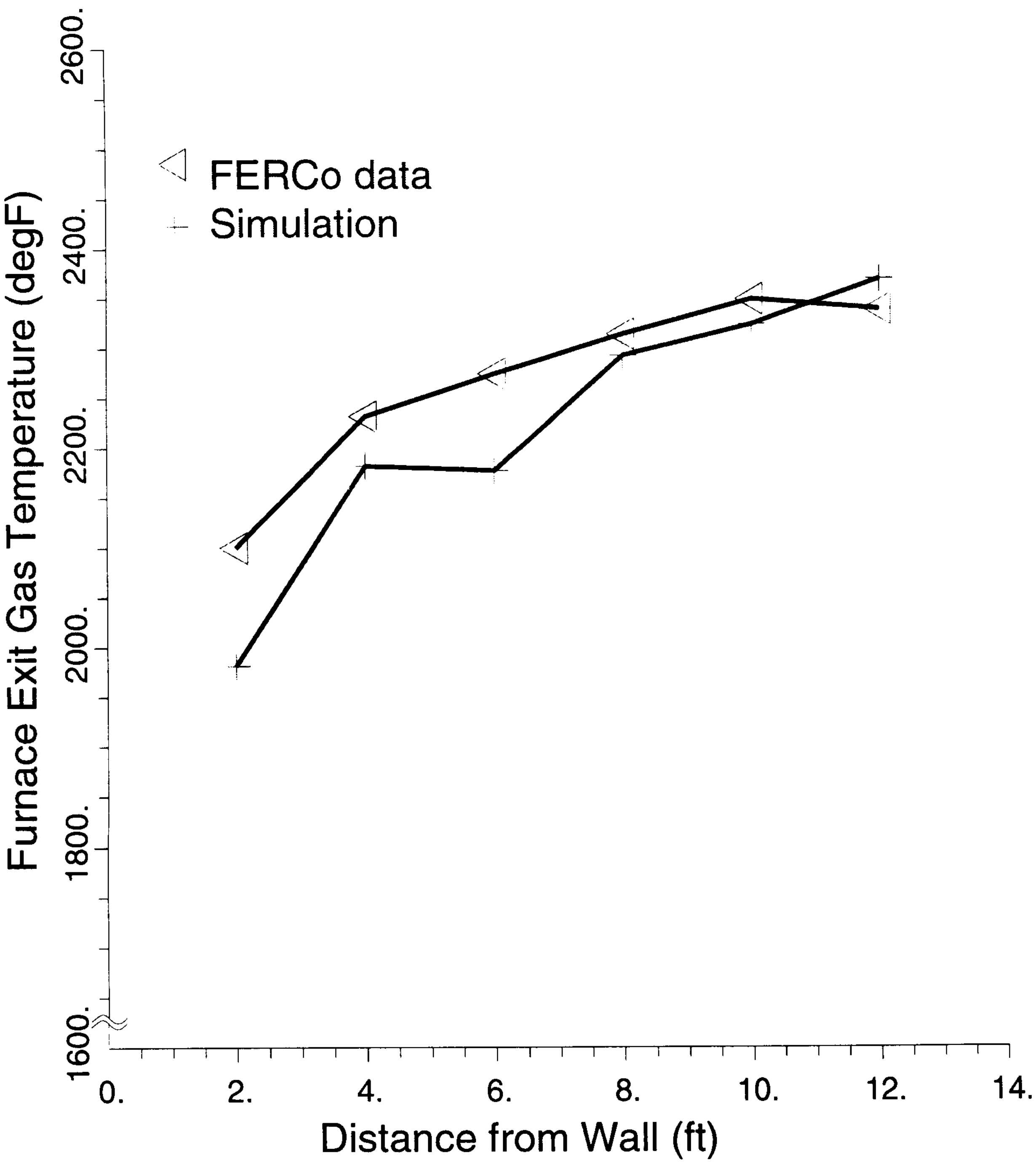
Temperature Distribution and 200μ Particle Trajectories for Top Row of Burners-Out-of-Service Model

Figure 14



Comparison of Simulation Exit Gas Temperatures with Experimental Data

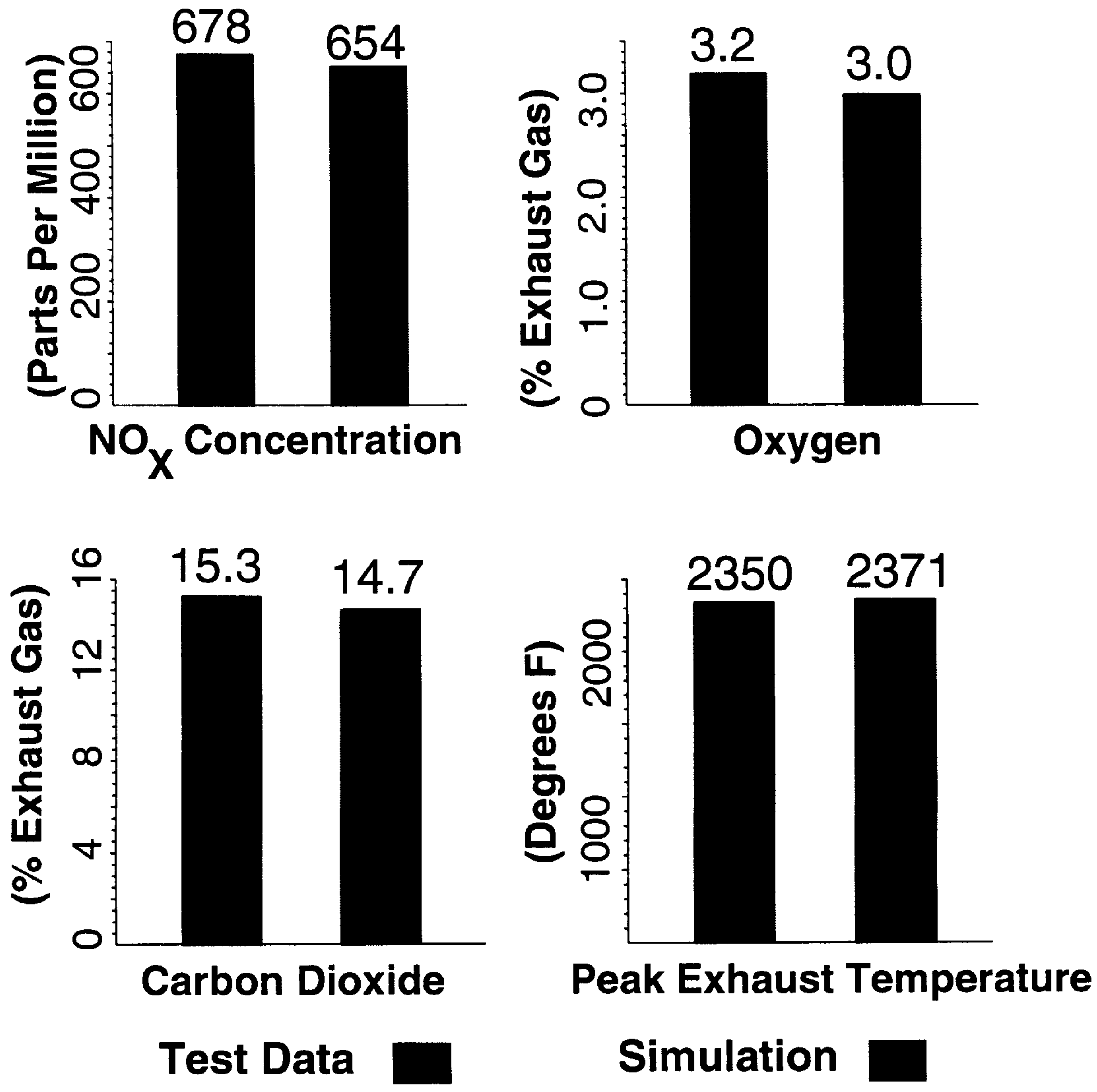
Figure 15



Comparison of Simulation Results with Experimental Data

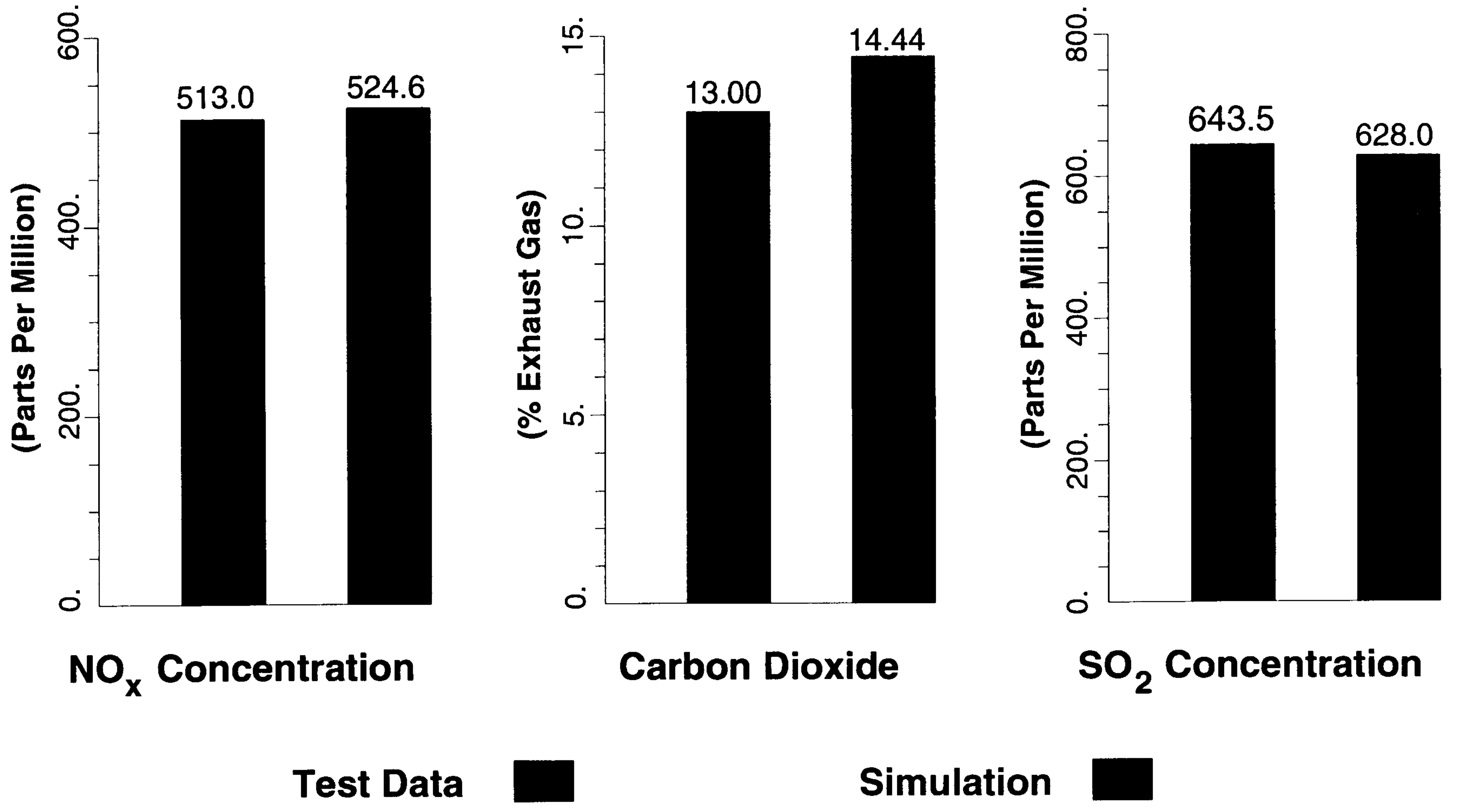
(All four mills in service)

Figure 16



Correlation for Top-Row-of-Burners-Out-of-Service Case

Figure 17



O_2 and peak exit temperature data not available.

Airflow Sciences Corporation

Furnace Velocity Vectors
All Mills in Service

Figure 18