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Development of Overfire Air Design Guidelines for Front-Fired Boilers

by

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INTRODUCTION

Overfire air (OFA) is one commercial application of two staged combustion. It involves the diversion of combustion air to separate injection ports above the uppermost burners in the furnace. The effectiveness of OFA as a NO_x control technique on utility boilers is strongly dependent on the penetration and mixing of the second stage air with the primary combustion zone products. The Electric Power Research Institute is supporting a program to develop design and operating guidelines for retrofit and new unit overfire air systems. The goal of the first phase of this program is to develop practical guidelines for front-fired (or single wall-fired) utility boiler designs.

The performance of overfire air systems is driven by several factors. Adequate separation must be maintained between the primary and secondary combustion zones for NO_x control. This motivates the designer to locate the OFA ports as far above the burners as practical. However, efficient boiler operation requires maximizing the residence time available for carbon burnout between the OFA ports and the furnace exit. This dictates locating the OFA ports as close to the burners as practical. These conflicting constraints illustrate why a thorough understanding of OFA mixing is required to both reduce NO_x emissions and maintain combustion efficiency.

This study is based on flow modeling results and on a feasibility analysis of overfire air systems on a full scale (400 MWe) front-fired utility boiler. A 1/12th scale laboratory flow model, shown in Figure 1, was used to: 1) assess OFA mixing in a well-controlled test environment; 2) quantitatively compare the mixing achieved among various overfire air port design variations; 3) evaluate design arrangements and concepts that may be expensive or difficult to install in the field. The feasibility studies were used to introduce the realistic constraints encountered in actual retrofits into the guideline development process.

Overfire air is not a new NO_x control process. Successful field installations exist. In other cases, the NO_x reductions or carbon burnout achieved has been disappointing. This project builds upon this field experience and adds data from well-controlled studies to provide a sound technical basis for evaluating OFA mixing. Since other boiler emission control strategies such as reburning and sorbent injection are controlled by similar mixing processes, this understanding is critical to successful field demonstrations of these technologies.

FLOW MODEL

The performance of overfire air systems is dependent on both combustion and fluid dynamics. Successfully mixing overfire air with the combustion products is directly related to boiler performance parameters such as excess air requirements, carbon burnout, and NO_x formation. In the design of an overfire air system, fluid dynamic considerations are often overlooked. As a result the performance of overfire air systems on operating boilers is inconsistent. The following flow-related parameters were evaluated in the test program:

- OFA jet velocity
- OFA port size, number and location
- OFA jet swirl
- OFA velocity and flow bias between ports

Some of these parameters are not independent. For example, OFA port size and number will determine OFA jet velocity for a given degree of staging. The optimization of each is required for achieving ideal mixing performance. Moreover, the complexity of the design process does not end with the theoretical design of the OFA jets. The trajectories, decay, and overall mixing of overfire jets within the furnace are also influenced by the flow of primary combustion products. Front-fired boilers in particular, exhibit non-uniform velocity profiles at the OFA port elevation. A typical flow model velocity profile is shown in Figure 2. The furnace flow field is characterized by a high velocity region along the rear wall, and a low level recirculation area near the burner wall. This flow non-uniformity requires different OFA jet design criteria than classical jet theory based on uniform cross-flows. The experimental flow modeling approach used in this program is designed to properly simulate OFA jet trajectories and mixing in realistic furnace flow fields.

Modeling Criteria

A detailed discussion of overfire air flow modeling criteria used in this program was described by Thompson et al. (1). A brief review of the important criteria is repeated here for completeness.

As with any scaled experimental modeling program, the use of a non-combustion model to investigate the performance of OFA systems is a viable tool only when the important parameters of the mixing process in the furnace are properly duplicated (2). In this case, there are two primary regions of interest, each requiring its own similarity criteria: 1) the burner region extending to the OFA port elevation;

and 2) the region of injection and mixing, typically the region from the OFA ports to the furnace nose arch. The important features of each of these regions can be summarized as follows.

Burner Region - It is important to model the burner or flame zone, since this flow defines the inlet conditions for the overfire air mixing region. The effect of the momentum loss at the burner must be considered to achieve similarity with field boilers. Applying the Thring-Newby method (3) to the model burners allows for the conservation of burner jet momentum by geometrically distorting the burner diameter in the following manner:

$$\frac{d_m}{d_f} = \frac{1}{S} \left(\frac{\rho_a}{\rho_c}\right)^{1/2},$$

where S is the geometric scale factor, ρ is density, and d is the burner diameter. The density subscripts a and c refer to burner secondary air and furnace combustion product temperatures, respectively. The subscripts m and f denote model and field conditions.

Upper Furnace Region - The furnace section comprising the region between the OFA ports and the nose arch defines the mixing section in the furnace. Overfire air mixing is influenced by the characteristics of the cross flowing furnace gases, as well as nozzle injection parameters. Jet trajectories are simulated by maintaining the momentum flux ratio $(\rho_o V_o^2/\rho_f V_f^2)$ where ρ is the gas density, V is velocity. The subscripts o and f denote OFA flow and total furnace gas flow, respectively. To a lesser extent, the effect of buoyancy can also influence the jet trajectory. The density-modified Froude number is used to account for this effect:

$$Fr = \left(\frac{\rho_o}{\rho_o - \rho_f}\right) \frac{V_o^2}{d_o\, g},$$

where d_o is the OFA port diameter and g is the gravitational force.

The furnace flow model is constructed to 1/12th scale and includes the furnace region from the hopper to the nose arch. The pressure loss of the convective pass is also incorporated to simulate its effect on the furnace flow patterns. The model represents a single-wall fired unit with a 4 x 4 burner matrix configuration. Overfire air ports are located one burner spacing above the top row of burners. Figure 3 is a schematic of the front-fired furnace flow model.

The penetration and mixing of the OFA jets with the bulk furnace flow in the model is determined by measuring the resulting local temperature when the two flows of different temperatures are mixed. In the test program, the burner flow is heated to approximately 180°F, while the overfire air flow is kept at ambient temperature. This ensures a ΔT of approximately $100^{\circ}F$ for all test conditions. Local temperature variations within the model are used to evaluate mixing. The test model incorporates a fully automated thermocouple grid, which moves vertically to allow measurements at several elevations in the furnace. The equivalent field spacing between thermocouple grid nodes within the measurement plane is approximately 3 to 4 feet. Local temperatures are converted to OFA concentration values C_i by using the following equation.

$$C_i = \frac{m_o}{m_t} = \frac{T_f - T_i}{T_f \quad T_o} ,$$

where m_o/m_t represents the local mass flow ratio of OFA to total system mass flow. Temperature subscripts f and o denote main burner zone flow and OFA flow. T_i is the local measured mixed temperature.

A computerized data acquisition system allows for virtually instantaneous measurement and recording of all local furnace temperatures. The combination of careful flow rate calibrations and test model insulation translates into a flow balance accuracy of ±1.5% for burners and OFA ports, as well as temperature uniformity among burners of ±1°F. No measurable heat loss (<1°F) occurred in the model between the burner level and arch. In addition to detailed temperature measurements, velocity profiles are also measured to identify the prevailing flow profile. These profiles are taken at an elevation in the furnace just below the nose arch.

Data Analysis

No combustion tests were conducted to quantify the effect of jet mixing on NO_x reductions, or combustion efficiency. However, the overfire air must mix with combustion products across the entire furnace cross-section to achieve good carbon burnout. Several performance criteria and data analysis techniques were used to compare the various OFA design configurations in the flow model. Model test data consisted primarily of temperature and velocity profiles. The velocity profile indicates the general flow distribution in the furnace. Temperature profiles were used to calculate the OFA concentration at each grid point. In addition, two and three-dimensional surface contour plots of OFA concentration, as well as flow visualization techniques (smoke, helium bubbles, video) were used to further enhance our ability to quickly and accurately compare test configurations. Videotapes of several operating conditions were recorded throughout the program to document key test results.

In order to evaluate and compare the mixing patterns among the various test configurations, an overfire air mixing index was established. Uniform mixing should produce a constant OFA concentration level, equal to the theoretical ratio of OFA to total mass flow ($C_i = m_o/m_t$).

For conventional systems, in which 20% of total air flow is diverted to the OFA ports, an ideal mixing profile would show a consistent C_i of 0.2 everywhere at a given cross-sectional elevation. To compare data from various configurations, a range of concentration values around the theoretical mean was selected. For 20% overfire air addition, C_i values from 0.15 to 0.25 was chosen. More severe maldistribution of OFA concentration can result in poor overall combustion efficiency.

This analysis was used to arrive at a single index, N/N_T, to quantify and compare the degree of mixing achieved by different OFA systems. N/N_T is defined as the fraction of furnace cross-sectional area where the local OFA concentration, C_i, falls within a selected range. In our analysis of conventional OFA systems this range was 0.15 to 0.25. For advanced OFA systems with 45% OFA, a range of 0.40 to 0.50 was used. Unlike the local concentration C_i, values of N/N_T range from 0 to 1 with uniform mixing represented by a value of unity.

A further refinement to this mixing index can be made by accounting for the overall furnace mass flow distribution. Velocity profile measurements are required to determine the fraction of furnace mass flow within the selected concentration range. Both methods of analyses were used in this test program. However, the same conclusions were reached using either method.

<u>OFA Configurations</u>

The results of the test program can be divided into four major categories: 1) traditional designs with one OFA port above each burner column; 2) multiple wall designs with OFA ports located on up to four furnace walls; 3) alternate front wall designs with OFA ports serving specific regions of the furnace; and 4) advanced staging.

Initial testing focused on traditional OFA port designs typified by one port above each burner column and injection velocity ratios (V_O/V_F) ranging from 2 to 6. The results of this test series are summarized in Table 1. Mixing indexes, N/N_T, are presented for two of the four upper furnace elevations at which mixing was evaluated. Velocity ratios of 4 and 6 produced the best overall mixing. Contour maps of OFA concentration profiles for each of the three velocity ratios are presented in Figure 4. These concentrations were measured at a furnace elevation, Z_2, slightly below the nose arch. Figure 4 demonstrates why it is very difficult to achieve a good mixing distribution throughout the furnace cross-section with conventional designs. High OFA injection velocity (V_O/V_F=6) results in deep penetration and impingement of the OFA jets on the far wall, and subsequent mixing with the furnace flow primarily near the rear and side walls of the furnace. The mixing near the side wall regions actually occurs due to the impingement of the jets on the far wall. This creates a back mixing effect which, in turn, fills the side wall channels. Similar overall mixing effectiveness can be achieved at $V_O/V_F=4$ without this rear wall back mixing. In the case of $V_O/V_F=4$, the OFA jets turn upward prior to impingement on the far wall, resulting in the mixing region being slightly closer to the burner wall. The lack of rear wall impingement results in lower coverage of the side wall regions. In both velocity cases, the burner wall area exhibits very low concentrations of overfire air due to the deep jet penetration.

The case of a low OFA jet velocity ($V_O/V_F=2$) suggests a different mixing profile due to the rapid jet deflection by the furnace bulk flow. Individual OFA jet profiles are still somewhat evident in the mixing contour map. This produces a mixing profile with high OFA concentrations in the center of the furnace and very low levels in the side wall channels.

These initial tests demonstrated that traditional OFA designs did not distribute air to all regions of the furnace. As a result of this performance, alternate OFA geometries were considered. Incorporating ports on alternate or multiple furnace walls was our first attempt at providing OFA ports for specific regions of the furnace. The results of this test series are summarized in Table 2. Test No. 6 with ports on all four walls showed a substantial improvement over traditional designs. A mixing index, N/N_T, of 0.89 corresponds to a near uniform OFA concentration profile across the furnace. This is achieved by the relatively rapid deflection and mixing of 12 low velocity ($V_O/V_F=2$) OFA jets. In comparison the best N/N_T value obtained for conventional systems was 0.48. However, OFA ports on all four furnace wall are impractical due to cost and potential limitations resulting from interferences and structural design considerations. The importance of this test series was to provide a mixing standard for evaluating the performance of other design concepts. Therefore, no attempt was made to optimize the alternate furnace wall designs summarized in Table 2.

Limited Japanese field experience with various firing wall OFA designs served as the basis for selecting the next set of candidate OFA configurations (4). These configurations and selected operating conditions are summarized in Table 3. The main parameters evaluated in these tests were swirl, additional ports on the burner wall, and OFA flow and velocity bias. This test series demonstrated that good mixing can be achieved with single wall OFA designs. Swirl enhanced mixing near the burner wall. However, swirl did not produce added benefits when wing ports were added, as demonstrated by Test Nos. 9 and 11. An N/N_T mixing index of 1.0 was achieved in Test No. 12 by adding wing overfire air ports and establishing the proper flow and velocity bias. Figure 5 compares concentration profiles for Test Nos. 11 and 12 with a traditional design, (Test No. 2), and OFA ports on four walls, (Test No. 6).

The contour plots in Figure 5c (Test No. 11) and 5d (Test No. 12) illustrate the sensitivity of mixing to OFA flow bias and injection velocities. As shown in Figure 5d biasing both velocity and flow bias between the center and wing ports results in improved penetration and mixing along the furnace side walls. The two cases represent operating conditions with a flow bias of 60% to 40% between the center ports above each burner and wing OFA ports. However, the velocity ratio of the wing jets in Figure 5d was increased from 3.0 to 4.5. The contour plots reveal well mixed profiles in both cases with approximately 80% and 100% coverage for each case. The higher wing jet velocity in Figure 5d provides the added penetration required to achieve the desired mixing levels near the side walls and far corners.

The results presented in Figures 4 and 5 describe mixing just below the furnace arch. Improved mixing at lower furnace elevations may be required in cases where upper furnace residence time for carbon burnout is limited. Therefore, the benefits of adding auxiliary OFA ports between burner columns were evaluated. In Figure 6, profiles at two furnace elevations are presented for Test Nos. 12 and 14. Auxiliary ports were added in Test No. 14 specifically to enhance mixing along the front firing wall. Earlier tests had shown that low OFA injection velocities were effective in achieving this effect. In Test No. 14, the flow bias and injection velocities were refined to achieve good OFA mixing at lower furnace elevations. The results are reflected in an OFA mixing index, N/N_T, of 0.76 obtained approximately midway between the OFA ports and furnace arch. A corresponding index of 0.55 was achieved at the same furnace elevation in Test No. 12 without auxiliary ports between burner columns.

Advanced OFA systems using 40% of the total combustion air as overfire air were also tested. These results are summarized in Table 4. Only two configurations were evaluated; a traditional front wall design (Test No. 15) and a system with OFA ports on the side walls (Test No. 16). For advanced staging systems, the same design principles and criteria apply as for conventional staging. However, because of the large quantities of overfire air, rapid mixing for carbon burnout is more critical. Since the emphasis of the test program was on conventional OFA systems, additional testing is required to better understand and evaluate advanced OFA design concepts.

FEASIBILITY STUDIES

The objective of the flow model tests was to improve the mixing of overfire air with the combustion products leaving the burner zone. In an actual boiler retrofit situation, there are many practical mechanical, structural and design limitations that must also be addressed. The structural integrity of the burner wall, interferences with other existing equipment, and economics may be the overriding factors that determine the number and arrangement of OFA penetrations. Although it is theoretically possible to modify boiler structural members to accommodate most proposed OFA designs, the best retrofit will be a design that minimizes NO_x and unburned carbon for reasonable costs.

Technical and economic analyses of retrofitting several OFA systems were performed on a front-fired boiler design case in order to assess these practical design constraints. The case study unit shown in Figure 7, is a representative 400 MWe natural circulation reheat boiler. It is equipped with 24 burners mounted on four rows. One obvious design limit is the relatively short distance between the top row of burners and the bottom of the superheater platens. Overfire air mixing and carbon burnout must be completed within this distance. The overfire air ports must also be located between existing structural members such as buckstays. This wall section could accommodate several OFA system layouts, with varying port numbers, port geometries and design flow rates. Aerodynamic mixing, combustion, heat transfer, and structural analyses must now be employed to assess the technical impact of installing these systems. The final decision would be based on the predicted technical feasibility of each design, as well as the predicted retrofit costs.

The required technical considerations include: aerodynamic mixing; necessary flow controls; NO_x predictions based on degree of staging and furnace heat release parameters; residence times required to complete combustion; impact on furnace heat transfer and furnace exit temperatures, and feasibility of installing the OFA penetrations without major structural modifications to the boiler. Various flow model test configurations were evaluated. Other EPRI NO_x control programs provided the basis for predicting NO_x reductions (5). These pilot scale studies also identified the potential for decreased combustion efficiency under staged combustion conditions.

Retrofit costs were evaluated using the EPRI Economic Premises for Electric Generating Plants, issued in December, 1982 (6). Proposed designs of the required ductwork, flow controls, and boiler structural modifications were generated for each OFA system. Materials and construction costs were estimated using Riley's design data base. All costs were calculated using 1983 construction costs, and escalated to 1986 dollars using published escalation rates (7). The cost estimates use a 20% Class II project contingency and a 20% process contingency.

Table 5 summarizes costs for five overfire air systems. These include four design approaches for conventional systems, plus one advanced OFA case in which 40% of the total combustion is directed to the overfire air system. The estimates show that costs fall into two general categories: 1) Systems that require windbox extensions, but no extensive structural changes or OFA ports on multiple walls, require 1 - 2 $/KW; 2) systems that require a separate OFA windbox, such as advanced staging or designs that require installing ports on walls in addition to the burner wall, require approximately 6 - 7 $/KW. Costs influenced by structural considerations in particular will be site-specific. Therefore, several overfire air options for each candidate retrofit boiler should be evaluated before the final design is specified.

Cases 1 through 4 illustrate that designs with improved OFA mixing characteristics are not necessarily the most expensive design option. Case 1, a conventional design with one OFA port above each burner column, was the least expensive retrofit considered. The OFA designs in Cases 2, 3, and 4 all showed substantial improvements over conventional designs in our flow model studies. The predicted retrofit costs for these systems, however, are significantly different. Installing overfire air ports on all four boiler walls (Case 2) is the most expensive option considered. The costs illustrate that, while this system is effective in promoting overfire air mixing, the retrofit costs make it impractical. The mixing indices obtained from the flow model results show that adding wing ports and biasing flow between the center and wing ports improves OFA mixing substantially. Our economic analysis indicate that these improvements (Case 3) will cost approximately 10% more than conventional systems (Case 1). Adding the auxiliary ports between the burner columns (Case 4) results in approximately a 30% increase in costs. However, in order to install this sytem without making structural changes to the boiler, an engineering evaluation showed that round OFA ports could not be used. The port shape for Case 4 only was changed to elliptical with a 2.5 to 1 aspect ratio. Brief flow model tests indicated that ports with aspect ratios up to 3 to 1 behaved similarly to round ports

Case 5 is an advanced staging system. The cost of this system is significantly higher, since diverting 40% of the combustion air to the staging system requires a separate OFA windbox with additional flow controls. Case 5 also requires a slight modification to the OFA port design. Because higher flow rates require larger port diameters, it was not possible to install the wing OFA ports with the center ports directly above each burner column unless major structural reinforcements were added to the burner wall. Instead, the OFA ports were spaced equally across the burner wall. Provisions to bias OFA flow between center and wing ports are still included. A comparison of Cases 3 and 5 illustrates the estimated cost difference between conventional and advanced OFA systems.

RETROFIT DESIGN GUIDELINES

These guidelines address the design of conventional overfire air systems for front-fired boilers. Conventional systems divert 10 to 30% of the total combustion air to overfire air ports. Since no combustion tests were conducted to quantify the effect of jet mixing on NO_x emissions or carbon burnout, our recommendations are based on the criterion that the OFA must mix with the combustion products across the entire furnace cross-section to achieve good carbon burnout. Both flow model and feasibility study results have shown that a number of parameters must be considered in designing effective overfire air systems. The location and number of OFA ports, the OFA injection velocity, and the flow bias between ports can have significant effects on OFA mixing and retrofit economics.

Flow model studies have also shown that existing jet trajectory correlations alone are not sufficient to design good OFA systems. These empirical correlations do not address several important furnace flow conditions:

- Single wall fired boilers have unique, non-uniform flow patterns with large recirculation zones. Traditional correlations for jet mixing assume uniform crossflows. Mixing in furnaces is also driven by secondary flows generated by recirculation.

- Traditional jet trajectory correlations only predict mixing in one plane. OFA mixing in a boiler is a three-dimensional problem. The lateral coverage of OFA jets is as important as jet penetration across the furnace depth.

Traditional OFA Designs Traditional OFA system designs are defined as systems with one OFA port above each burner and equal air flow to all ports. The best OFA mixing in the flow model occurred at velocity ratios V_O/V_F between 4 and 6. This design is referred to as the base case OFA design in these guidelines. In front-fired units, most of the combustion product mass flow is near the rear wall. V_O/V_F between 4 and 6 achieved good OFA mixing along the rear wall and in the corners near the rear wall. Mixing was not satisfactory, however, along the burner wall and in the corners near the burner wall. Combustion tests are required to quantify the effects of poor OFA mixing in these regions on carbon burnout.

At an OFA injection to furnace velocity ratio, $V_O/V_F=2$, OFA did not penetrate to the rear wall to mix with main combustion product mass flows. For example, the OFA mixing at $V_O/V_F=6$ was twice as good as with $V_O/V_F=2$. OFA injection velocities ratio <2 therefore, appear too low for traditional OFA designs. At $V_O/V_F > 6$, the OFA jets impinged on the rear furnace wall and rolled downward along the wall into the burner region. This downward mixing could have an adverse effect on the degree of NO_x control achieved. OFA injection velocities in this range, therefore, are not recommended.

The preceding test results are all based on circular OFA ports. At V_O/V_F between 4 and 6, the OFA port diameter is reasonable, i.e., less than the burner diameter. Preliminary model test results suggest that rectangular OFA ports with a height to width aspect ratio up to 3:1 can also be used at V_O/V_F between 4 and 6. More model testing is required to verify this. Rectangular or elliptical ports may have an economic advantage over round ports in some retrofit cases, since fewer tube bends would be required to install them. These traditional OFA designs with one OFA port above each burner column were the lowest cost option evaluated. The total capital cost requirement for retrofitting these systems to existing boilers is 1.3$/kW. This cost estimate is based on the following assumptions: 1) the existing windbox would be extended to accommodate the OFA system; 2) a booster fan is not needed; and (3) the OFA control system would include on/off flow controls and adequate dampers to control the amount of air flow, but would not be designed to modulate the OFA flow over a wide range.

OFA on Alternate Boiler Walls OFA mixing can be improved by placing OFA ports on walls other than the burner wall in front-fired boilers. Given the freedom to utilize OFA ports on all four furnace walls, flow models tests showed that this configuration significantly improved mixing across the furnace cross-section. Recommended design parameters for this system are: 1) maintain the same OFA port spacing along the side and rear walls as on the front wall (i.e., OFA spacing equals horizontal burner spacing); and 2) reduce V_O/V_F to 2. OFA injection velocities can be reduced since the jets don't have to penetrate as deeply into furnaces.

The total capital required for a conventional OFA system installed on all four boiler walls is 7.2 $/kW vs. 1.3 $/kW for the traditional base case design. There are practical as well as economic constraints in installing an OFA system on all four burner walls. Potential problems with installing an OFA windbox on the rear wall, in particular, include interferences with downcomers, economizer hoppers, and boiler convective sections that may extend near or below the top burner elevation.

Alternate Front Wall OFA Designs Recommended injection velocity ratios of 4 to 6 are effective in creating a well-mixed zone near the furnace rear wall. However, the front wall above the burners and near the corners remains starved of OFA. Improvements of OFA mixing near the front walls can be achieved by adding wing OFA ports and biasing both OFA mass flow and velocity across the front firing wall. Flow model tests showed that OFA jet swirl was not required under these conditions.

Wing OFA ports are used to promote mixing in the corners and furnace sidewalls. Recommended design conditions for this system are:

- Center ports: V_O/V_F = 3 to 4
  55-65% of the total OFA flow

- Wing ports: V_o/V_F = 4 to 6
  35-45% of the total OFA flow

Further improvements to OFA systems on the firing wall may be made by adding auxiliary ports without swirl between burner columns to improve lateral mixing. The auxiliary OFA ports can be used to promote mixing along the front wall, while other ports are designed to penetrate toward the furnace rear wall. Since this configuration locates OFA ports between burner columns a structural analysis should be performed. Recommended design conditions for this system are:

- Center ports: V_o/V_F = 4
  55-65% of the total OFA flow

- Wing ports: V_o/V_F = 5.5
  25-35% of the total OFA flow

- Auxiliary Ports: V_o/V_F = 1
  10-20% of the total OFA flow

The estimated capital cost for these alternate front wall designs ranges from 1.4 to 1.7 $/kW.

SUMMARY

Flow modeling techniques have been used to evaluate new OFA designs and to develop preliminary design guidelines for front-fired boilers. Further work is required to develop similar guidelines for other boiler configurations. Since the improved designed concepts discussed here have not been implemented commercially, combustion tests are required to evaluate impacts on boiler performance parameters such as carbon burnout.

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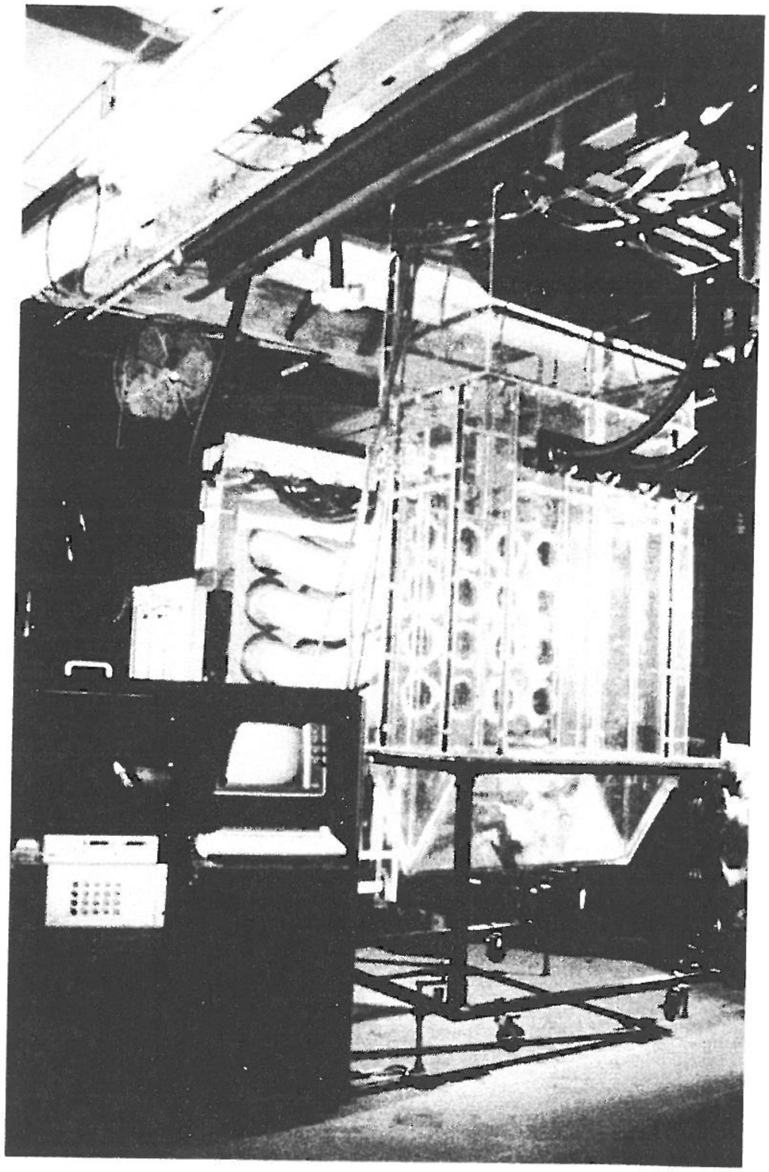


Laboratory Flow Model

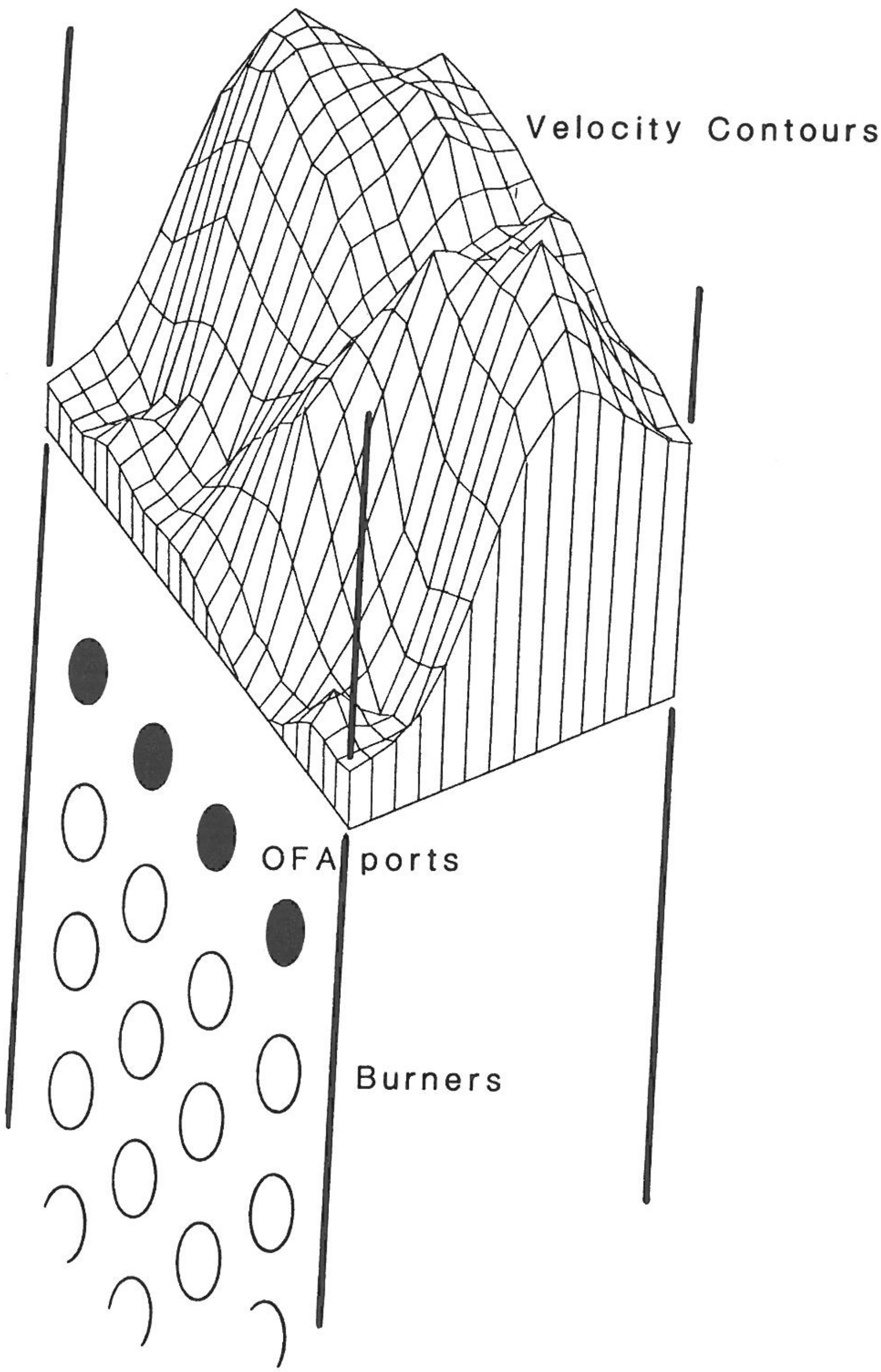


Figure 2. Velocity Profile in Single Wall-Fired Boiler Flow Model

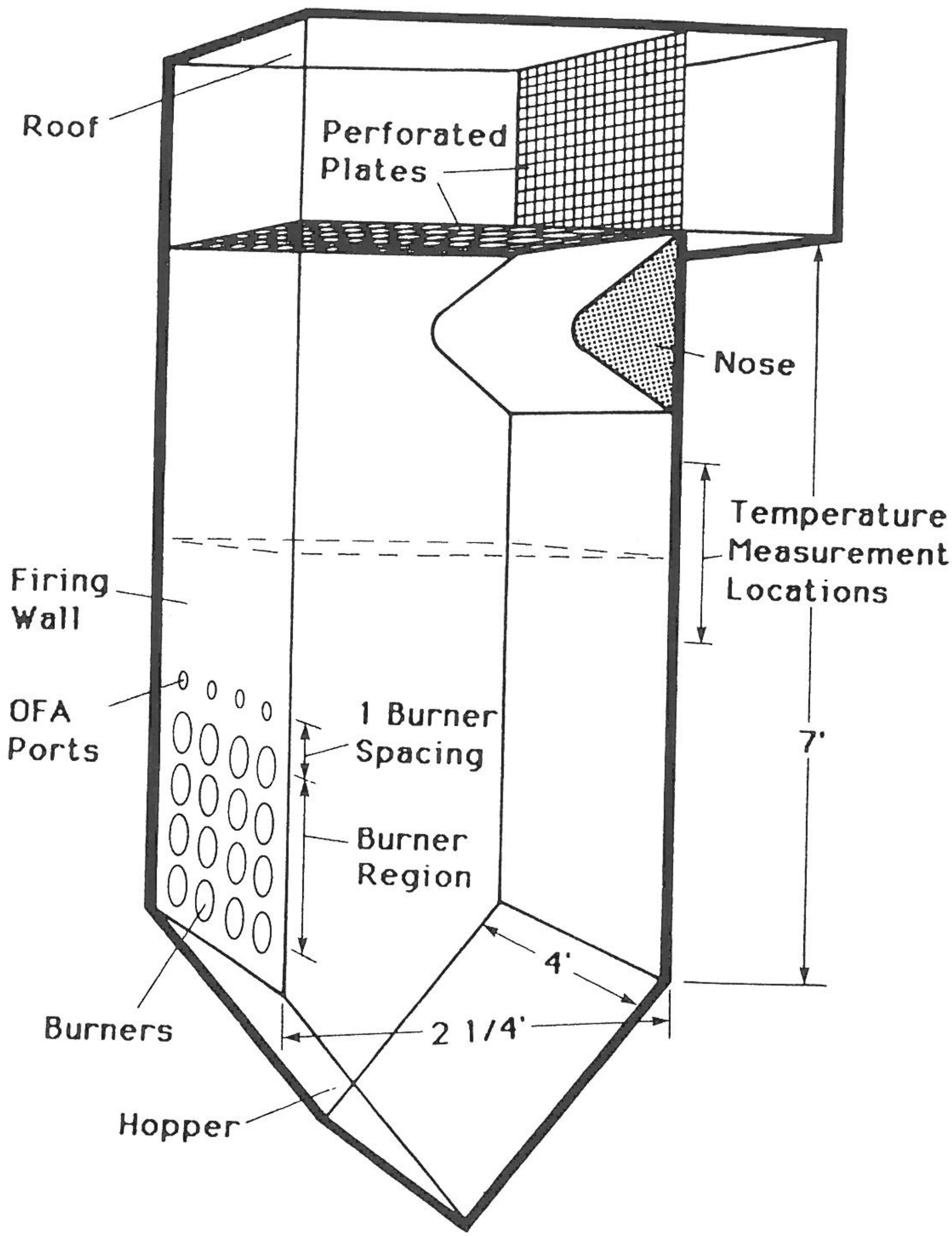


Figure 3. Furnace Flow Model

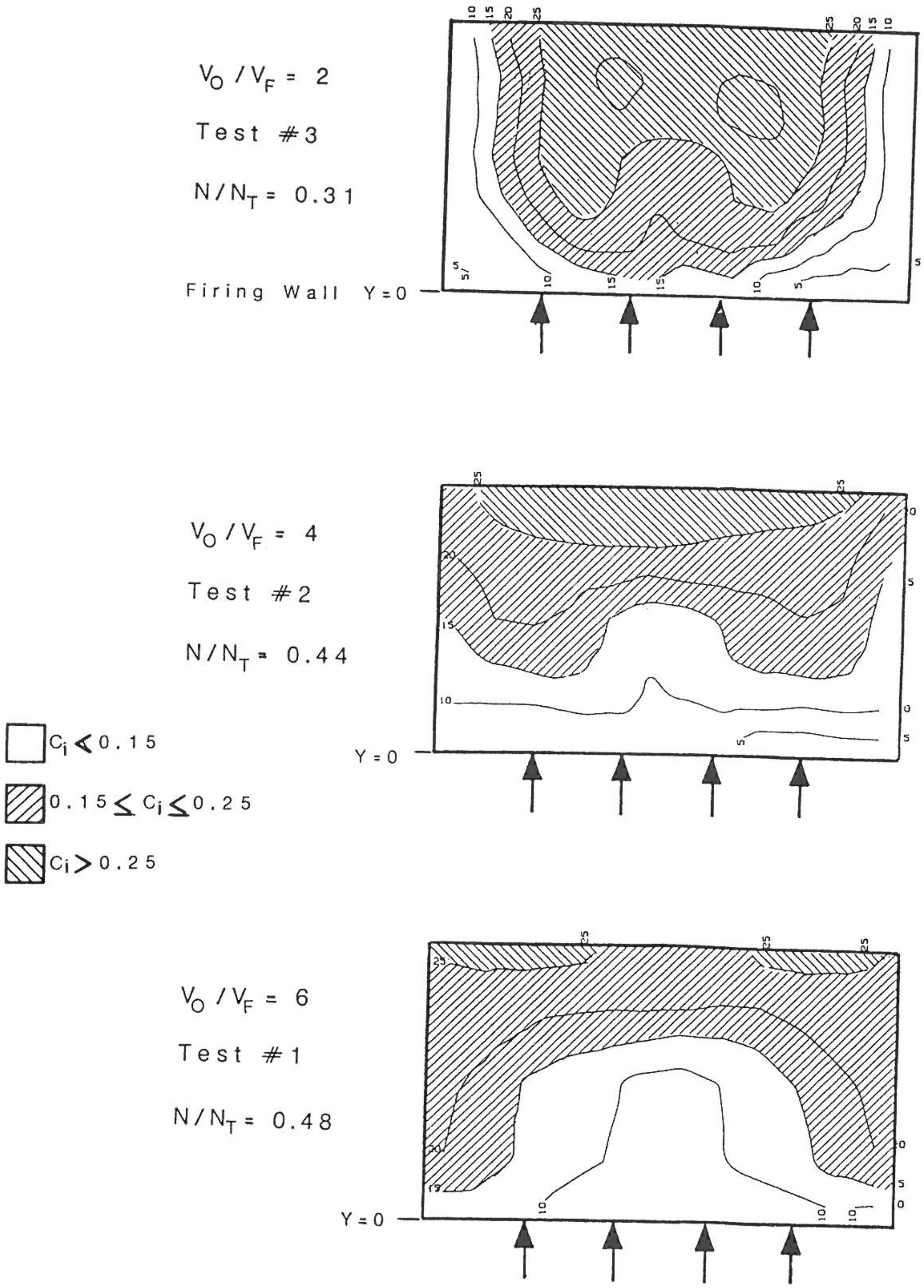


Figure 4. Influence of Overfire Air Injection Velocity Ratio on Mixing in the Flow Model

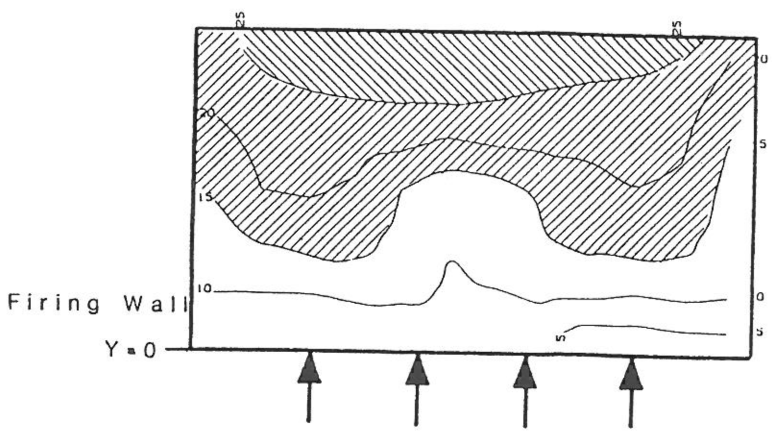


Figure 5a. One Port Above Each Burner Column (Test #2, $N/N_T = 0.44$)

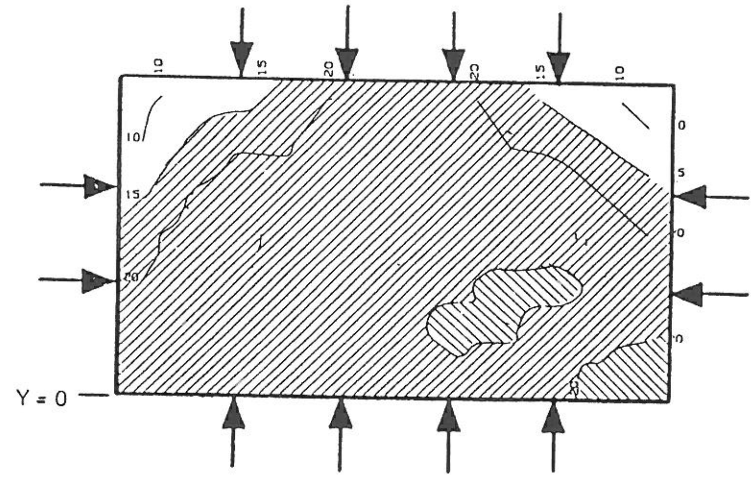


Figure 5b. Ports on Four Walls (Test #6, $N/N_T = 0.89$)

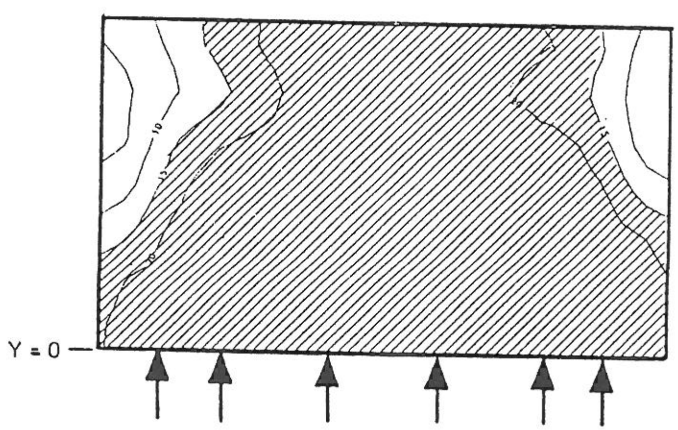
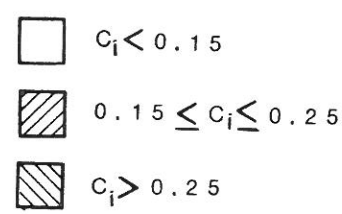


Figure 5c. Central Plus Wing Ports With Flow Bias (Test #11, $N/N_T = 0.83$)



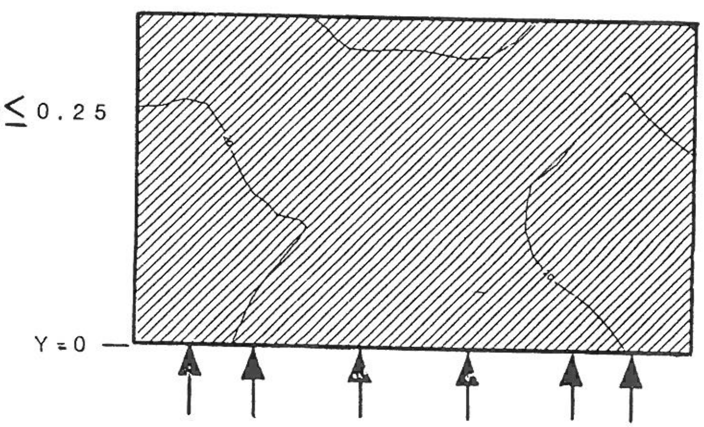


Figure 5d. Central Plus Wing Ports With Flow and Velocity Bias (Test #12, $N/N_T = 1.0$)

Figure 5. Comparison of OFA Mixing Achieved with Novel OFA Port Arrangements

Center and Wing OFA Ports with Biased Flow (Test #12)

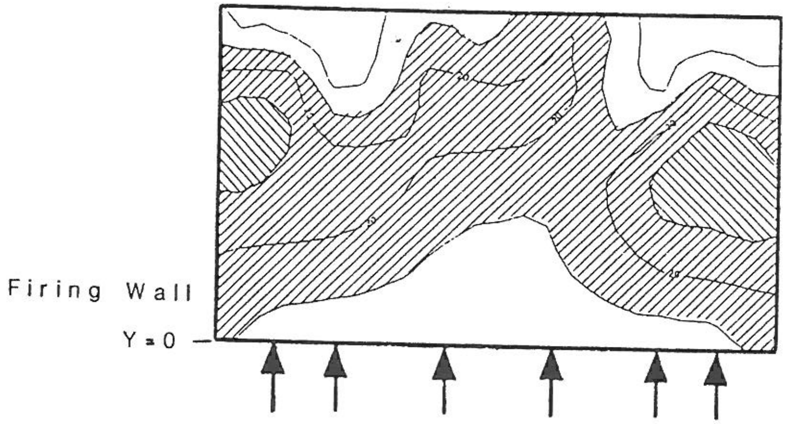


Figure 6a. Mixing Measured Between OFA Ports and Furnace Arch (N/N_T = 0.55)

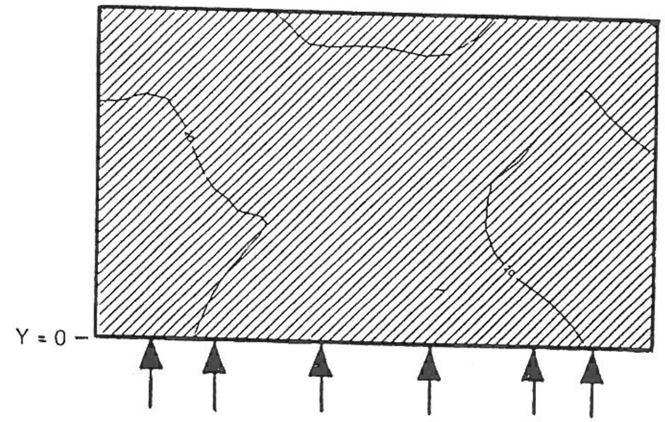


Figure 6b. Mixing Measured at Furnace Arch (N/N_T = 1.0)

$c_i < 0.15$ | $0.15 \le c_i \le 0.25$ | $c_i > 0.25$

Center, Wing, and Auxilliary Ports with Biased Flow (Test #14)

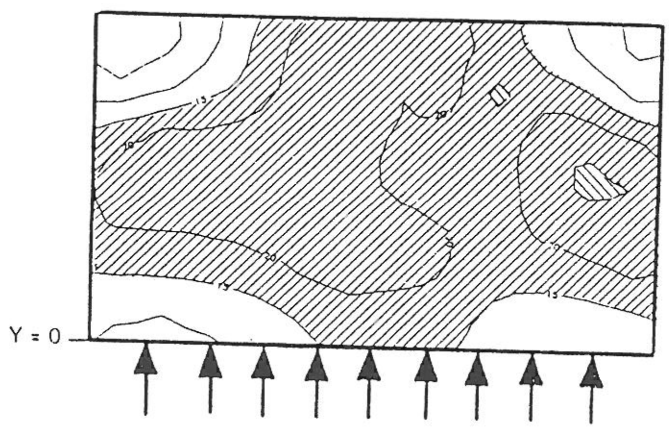


Figure 6c. Mixing Measured Between OFA Ports and Furnace Arch (N/N_T = 0.76)

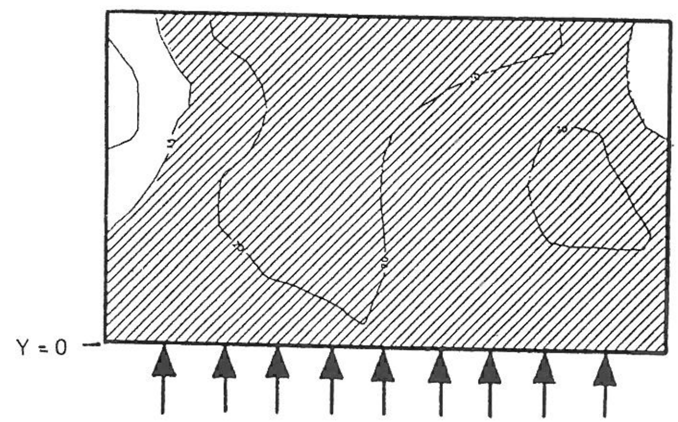


Figure 6d. Mixing Measured at Furnace Arch (N/N_T = 0.92)

Figure 6. Influence of Auxilliary OFA Jets on Mixing in the Flow Model

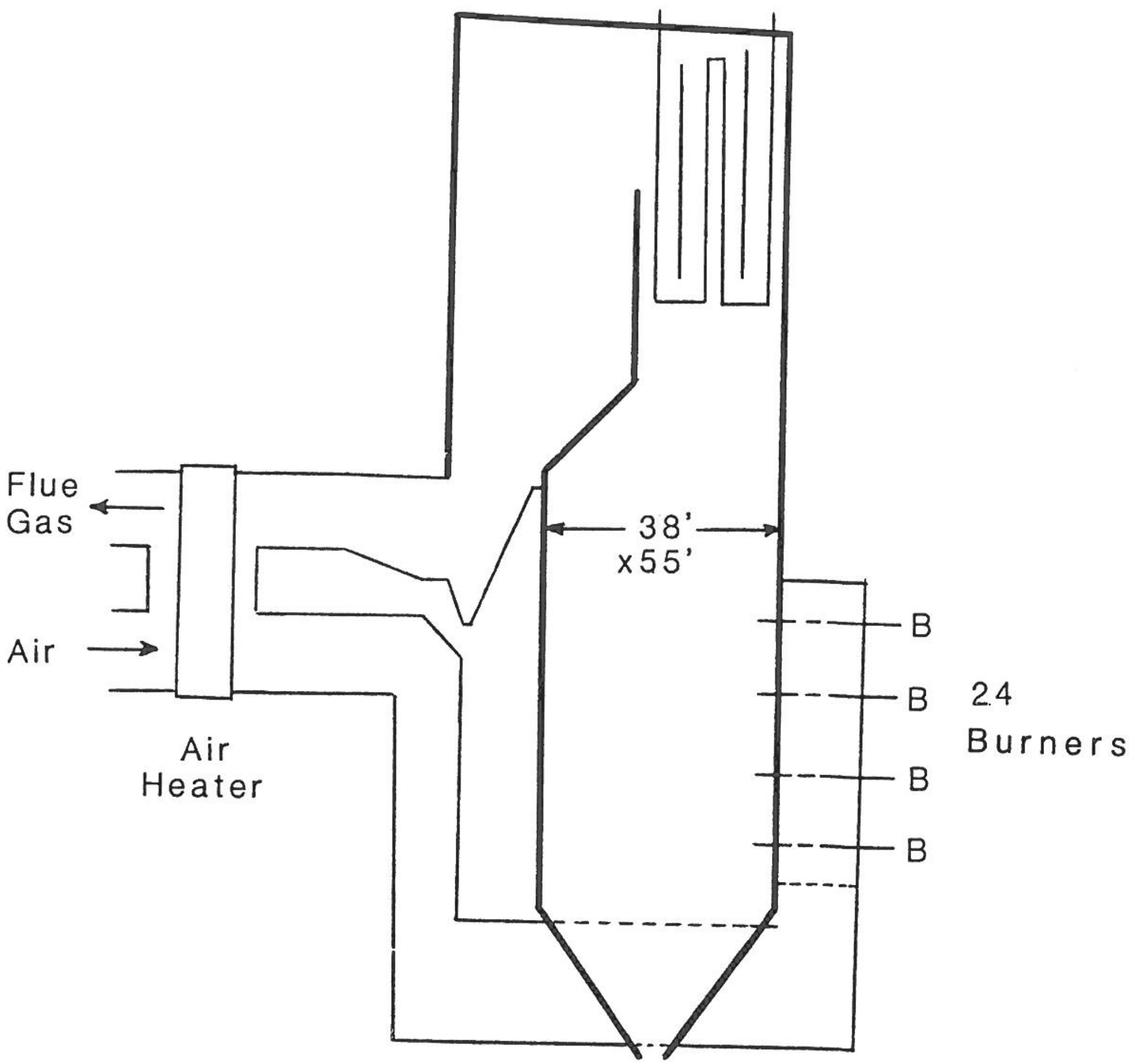
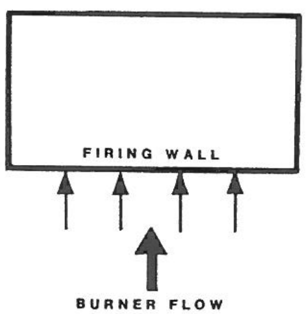


Figure 7. 400 MW Feasibility Study Boiler

Table 1

Traditional OFA System Tests

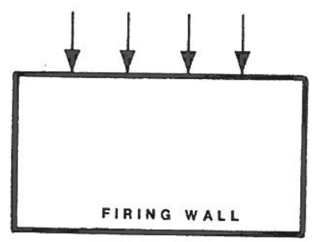
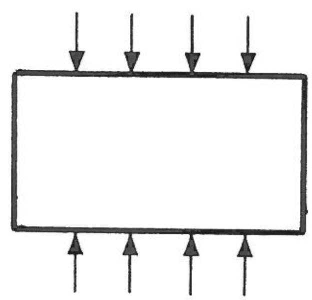
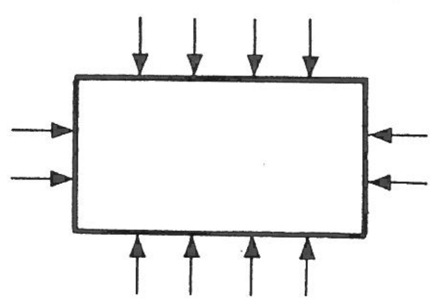
(one OFA port above each burner column, 20% OFA)

Test Case	System Sketch (Plan View)	Flowrate Per Port (%)	V_o/V_F	Mixing Index N/NT Z_1*	Z_2*
1		25	6	0.37	0.48
2		25	4	0.30	0.44
3		25	2	0.20	0.31

*Z_1 Midway between OFA ports and furnace arch
Z_2 Furnace arch elevation

Table 2

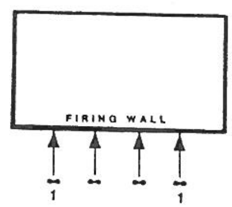
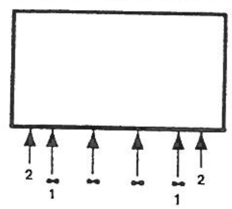
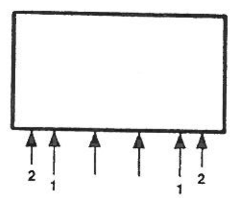
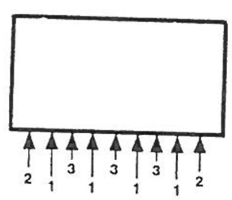
Alternate Boiler Wall OFA System Tests (20% OFA)

Test Case	System Sketch (Plan View)	Flowrate Per Port (%)	V_o/V_F	Mixing Index N/NT Z_1*	Z_2*
4		25	6	0.25	0.30
5		12.5	2	0.35	0.50
6		0.83	2	0.74	0.89

*Z_1 Midway between OFA ports and furnace arch
Z_2 Furnace arch elevation

Table 3

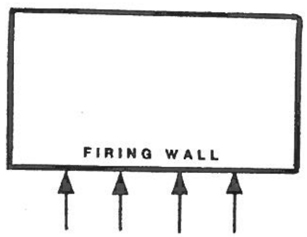
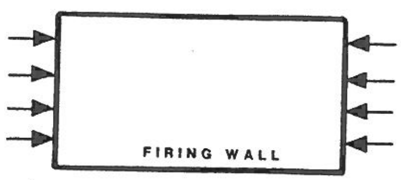
Alternate Front Wall OFA System Tests (20% OFA)

Test Case	System Sketch (Plan View)	Port #	Flowrate Per Port (%)	V_o/V_F	Mixing Index N/NT Z_1*	Z_2*
7		1	25	4	0.43	0.48
8		1	16.7	1.5	0.16	0.32
		2	16.7	3		
9		1	15	3	0.50	0.70
		2	20	3		
10		1	16.7	2	0.11	0.39
		2	16.7	2		
11		1	15	3	0.63	0.83
		2	20	3		
12		1	15	3	0.55	1.0
		2	20	4.5		
13		1	12	4	0.60	0.99
		2	20	4.5		
		3	4	2		
14		1	14.5	4	0.76	0.92
		2	15	5.5		
		3	4	1		

*Z_1: Midway between OFA ports and furnace arch
Z_2: Furnace arch elevation

Table 4

Advanced OFA System Tests (40% OFA)

Test Case	System Sketch (Plan View)	Flowrate Per Port (%)	V_o/V_F	Mixing Index N/NT Z_1*	Z_2*
15		25	4	0.29	0.33
16		12.5	4	0.39	0.51

*Z_1 Midway between OFA ports and furnace arch
Z_2 Furnace arch elevation

Table 5
FEASIBILITY STUDY RESULTS

Case No.	OFA System Description	Mixing Index N/NT	Total Capital Requirements ($/kW)
1	Conventional OFA (20% staged air); one OFA port above each burner column; $V_O/V_F = 4$	0.44	1.3
2	Conventional OFA; ports on all four furnace walls; $V_O/V_F = 2$	0.89	7.2
3	Conventional OFA; one center port above each burner column plus "wing" ports; bias OFA flow between ports	1.0	1.4
4	Conventional OFA; center, wing, and auxiliary ports; bias OFA flow among ports	0.92	1.7
5	Advanced OFA (40% staged air); one center port above each burner column plus wing ports; bias OFA flow between ports	N/A	5.7