STATUS OF NO_X CONTROL FOR RILEY STOKER WALL-FIRED AND TURBO® FURNACE BOILERS

by:
R. A. LISAUSKAS, Manager
Program Operations
Research and Development
and
A. H. RAWDEN, Staff Consultant

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Abstract

Large pilot scale and full size field data are presented on a new low NO_X retrofit burner design for pulverized coal wall-fired boilers. NO_X reductions of 50 to 60% have been achieved with this retrofit burner on three large (greater than 300 MW) utility boilers. An update of TURBO® Furnace NO_X controls is also given. NO_X field results are presented on the effects of underfire air and variable direction coal spreaders. In addition, the results of pilot scale burner aerodynamic tests are discussed, and the effects of staged combustion on furnace heat transfer are predicted.

INTRODUCTION

Two years ago Riley Stoker initiated a comprehensive R&D program to develop low NO_X combustion systems for both pulverized coal wall-fired and TURBO Furnace boilers. Our wall-fired burner program has led to the development of the Riley Controlled Combustion Venturi (CCV) burner. The CCV burner is a low-NO_X single register burner designed for installation on existing as well as new wall-fired steam generators.

This CCV burner development effort included both pilot scale tests, and field tests on three utility boilers. Pilot scale tests were conducted at 14.65 MW (50×10^6 Btu/hr) in a single-burner test facility. In addition to the CCV burner, pilot scale tests were also conducted on a prototype Riley Distributed Mixing Burner (DMB) design. Following the pilot scale tests, the CCV burner was retrofitted and tested on a single wall-fired 400 MW boiler, and two 360 MW opposed wall-fired boilers. All of these boilers had been previously equipped with Riley Flare burners. The installation of CCV burners resulted in a 50 to 60% reduction in NO_X emissions.

Our TURBO Furnace development program has included aerodynamic tests on a one half-scale Directional Flame burner model, and field tests on several utility dry bottom TURBO Furnaces. Field tests were conducted on TURBO units equipped with modified Directional Flame burners, and with a portion of the combustion air admitted beneath the burners. Burner modifications included the use of variable direction coal spreaders.

Currently, we are investigating advanced TURBO designs staged with both overfire and underfire air. An analytical furnace model is being used to study the effect of staged combustion on furnace heat transfer.

WALL-FIRED BOILERS

Prior to 1971, the majority of Riley Stoker pulverized coal-fired boilers were wall-fired. In fact, wall-fired boilers represent over 60% of the pulverized coal utility boilers put into service by Riley Stoker since the mid-50's.

Riley wall-fired boilers built prior to the New Source Performance Standards (NSPS) are equipped with either single (Figure 1) or double register Riley Flare burners. The Flare burner is a circular swirl stabilized burner. It is designed to maintain intense stable combustion over a wide load range. NO_X field emissions varying from 258.54 - 439.98 kg/min (570 - 970 ppm) [1, 3] have been measured on this conventional pre-NSPS Burner design.

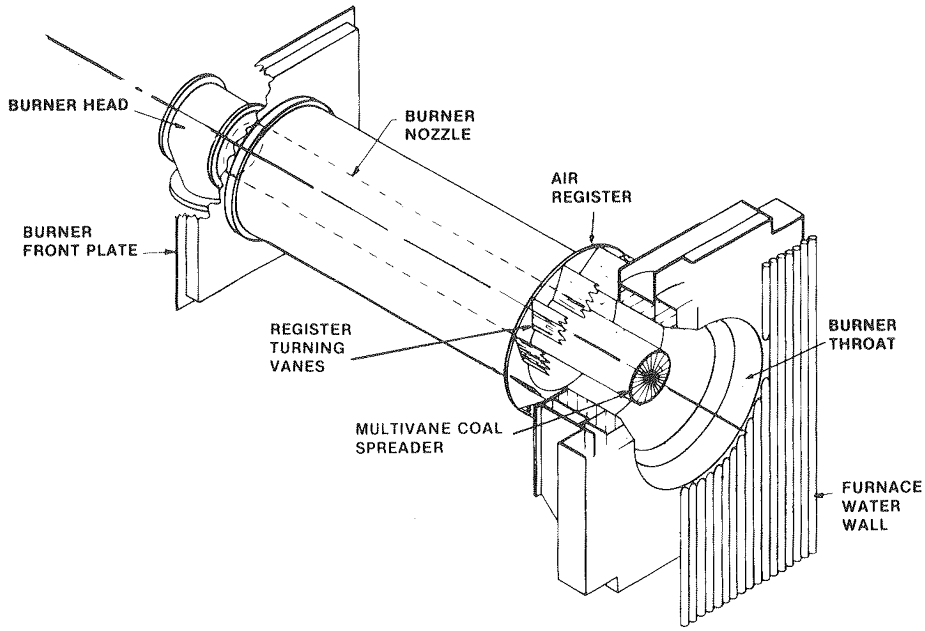

Figure 1 Flare Coal Burner

LOW NO_X BURNERS

Our low NO_X wall-fired burner program began in January of 1980. Under this program, pilot scale combustion tests were conducted on three one-third scale 14.65 MW (50 x 10^6 Btu/hr) circular burners:

- Flare Burner
- Controlled Combustion Venturi Burner
- Distributed Mixing Burner

Baseline performance was established on the pre-NSPS Flare burner. Pilot scale Flare burner data were also compared directly to performance data from specific full-scale field units.

Controlled Combustion Venturi Burner The CCV burner, shown in Figure 2, is similar in design to the pre-NSPS Flare burner. The coal nozzle and coal spreader, however, have both been modified. In contrast with the Flare burner, the CCV coal nozzle is smaller in diameter and includes a venturi section. The Flare burner multivane coal spreader has been replaced by a four-bladed conical shaped spreader. In the pilot scale burner, both spreader position and the nozzle set-back position were adjustable.

The CCV burner venturi section serves to concentrate the coal in the nozzle center creating a fuel rich zone with progressively leaner mixtures toward the nozzle periphery. The conical spreader divides the coal stream into distinct layers of fuel rich and lean mixtures. The axial velocity of this primary stream is closely matched to the secondary air velocity.

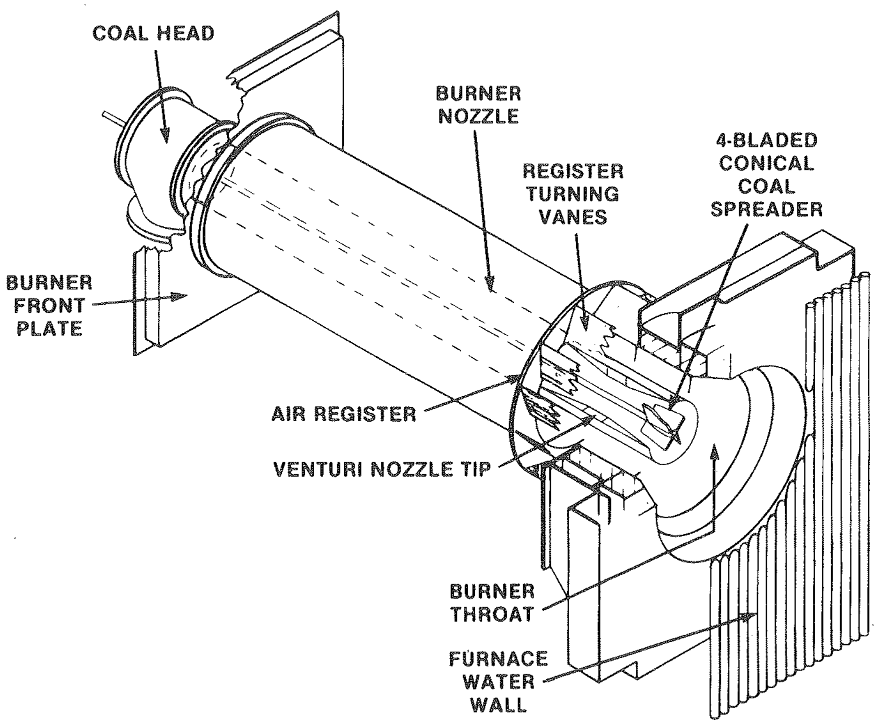

Figure 2 Controlled Combustion Venturi (CCV) Burner

Secondary air swirl is controlled by a single register. Both the register and required burner opening are identical to the Flare design.

Riley Distributed Mixing Burner As stated earlier, pilot scale tests were also conducted on a 14.65 MW (50 x 10^6 Btu/hr) prototype Riley Distributed Mixing Burner (DMB). The Riley DMB is designed according to criteria developed under several EPA low-NO_X burner development programs.[3, 4] As shown in Figure 3, the

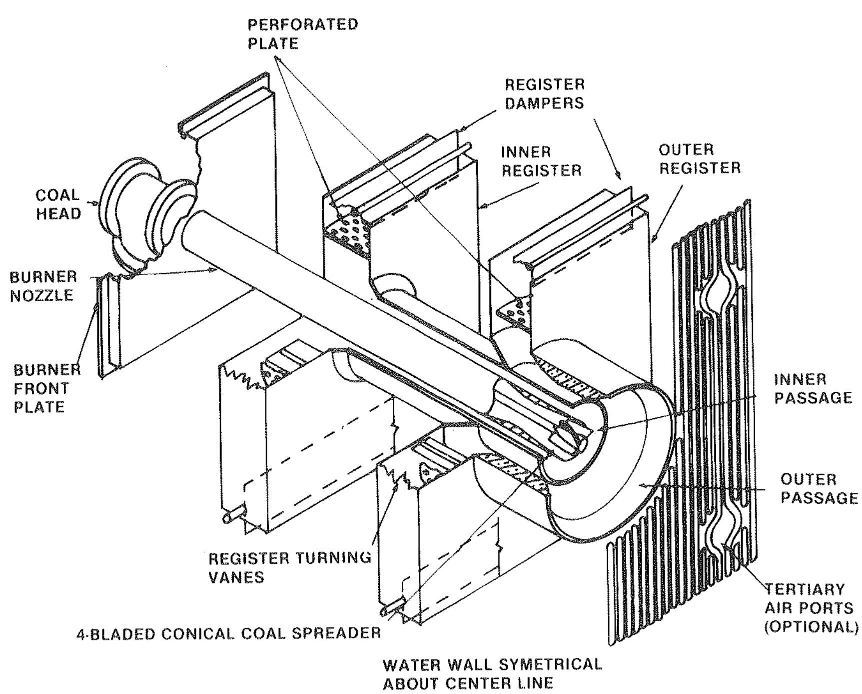

Figure 3 Distributed Mixing Burner

burner is equipped with outboard tertiary air ports for staged combustion. The Riley DMB also incorporates the same venturi coal nozzle and conical coal spreader as that used in the CCV burner.

The DMB is equipped with two registers for swirl control. A damper and perforated plate are located at each register inlet for flow control and measurement. This dual register design permits independent control of swirl and air flow rate to each secondary air passage.

Design characteristics for all three Riley circular burner designs are summarized in Table I.

FLARE BURNER
- **Single or Dual Register**
- **Pre-NSPS**
- **High Intensity-Rapid Mix**

CONTROLLED COMBUSTION VENTURI BURNER
- **Single Register**
- **Venturi Nozzle/Conical Spreader**
- **Flare Burner Outer Dimensions**
- **Delayed Mix**

DISTRIBUTED MIXING BURNER
- **Dual Register**
- **Venturi Nozzle/Conical Spreader**
- **Independent Flow and Swirl Control**
- **Flow Metering**
- **Tertiary Air Ports**

Table I Summary Riley Circular Burner Characteristics

PILOT SCALE TESTS

The single burner pilot scale combustion tests were conducted at the Energy and Environmental Research Corporation (EER) Test Facility in El Toro, California. The tests were conducted at firing rates up to 14.65 MW (50 x 10^6 Btu/hr) in the EER Medium Tunnel (MT) furnace. The MT furnace is a 4.26 m (14 ft.) diameter by 6.096 m (20 ft.) long horizontal axis steel vessel. The inside surface of the vessel is partially covered with insulating refractory to simulate the overall furnace heat absorption of field operating boilers. The entire exterior surface of the furnace is spray cooled.

Results of the pilot scale testing are shown in Figure 4 for a high volatile C bituminous coal. A comparison of pilot scale Flare burner results with field data indicated pilot scale flame characteristics and overall burner performance were representative of full-size Flare burners.

CCV burner NO_X emissions were approximately 55% lower than baseline Flare burner results. The DMB tests were conducted at various settings with the tertiary air ports closed and open. The unstaged DMB results were comparable with the CCV burner test results. NO_X emissions for the DMB staged (i.e., tertiary air ports open) to between 80 to 93% burner zone stoichiometry were approximately 64% lower than Flare burner emissions. The DMB test program was conducted largely for comparative purposes and did not include the range of design and operating conditions covered in the CCV burner test program. Consequently, the optimum DMB design was not determined during these tests.

In both the CCV burner and DMB tests we found burner performance was significantly affected by nozzle/spreader design. Nozzle/spreader design appears to have a significant impact on air/fuel mixing in the near burner region. The venturi nozzle/conical spreader design provides the necesary raange of control for achieving minimum NO_X emissions with satisfactory combustion efficiency.

NO_X EMISSIONS

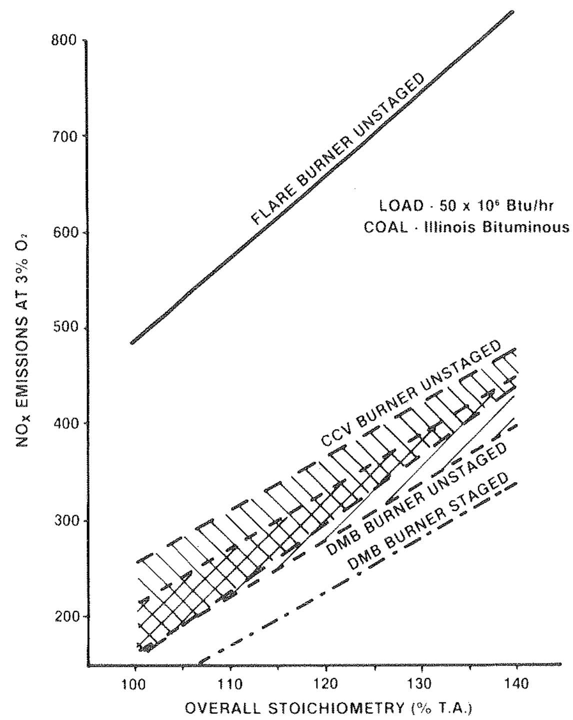

Figure 4 Pilot Scale Combustion Test Results

Flame shapes observed for both the pre-NSPS Flare burner and CCV burner are illustrated in Figure 5. The Flare burner produces a short, intense conical shaped flame. In contrast, the CCV burner produces a more gradually mixed flame with a short bulbous section close to the burner followed by a long downstream tail. The burner parameters controlling this flame shape are high swirl register settings and nozzle/spreader location and design.

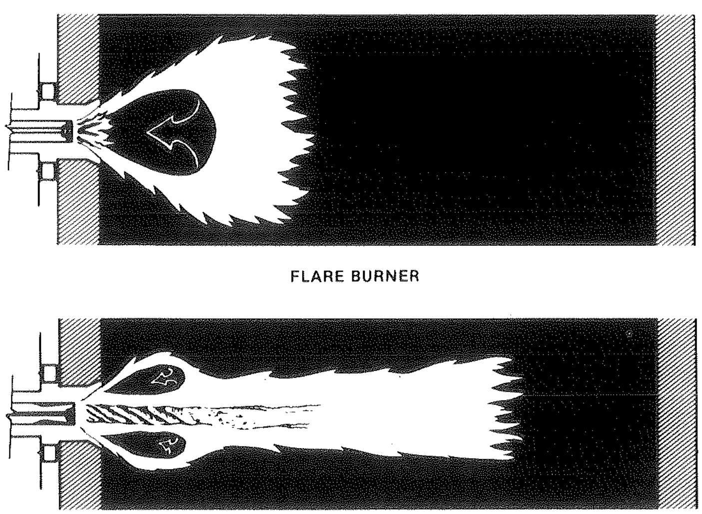

Figure 5 Schematic Typical Flame Forms

FIELD RETROFIT TESTS

Following the pilot scale testing, the CCV burner was retrofitted and tested on three utility boilers.

Single Wall-Fired Boiler Test The first field unit tested was Duck Creek Unit No. 1 owned and operated by The Central Illinois Light Company. As shown in Figure 6, Duck Creek Unit No. 1 is a 400 MW boiler with 24 burners mounted on the front wall. The original equipment burners were Riley Flare burners rated at 45.72 MW (156 x 10^6 Btu/hr). The fuel was an Illinois Crown II seam high volatile C bituminous coal with a heating value in the 2,520 - 2,772 kcal/kg (10,000 - 11,000 Btu/lb) range.

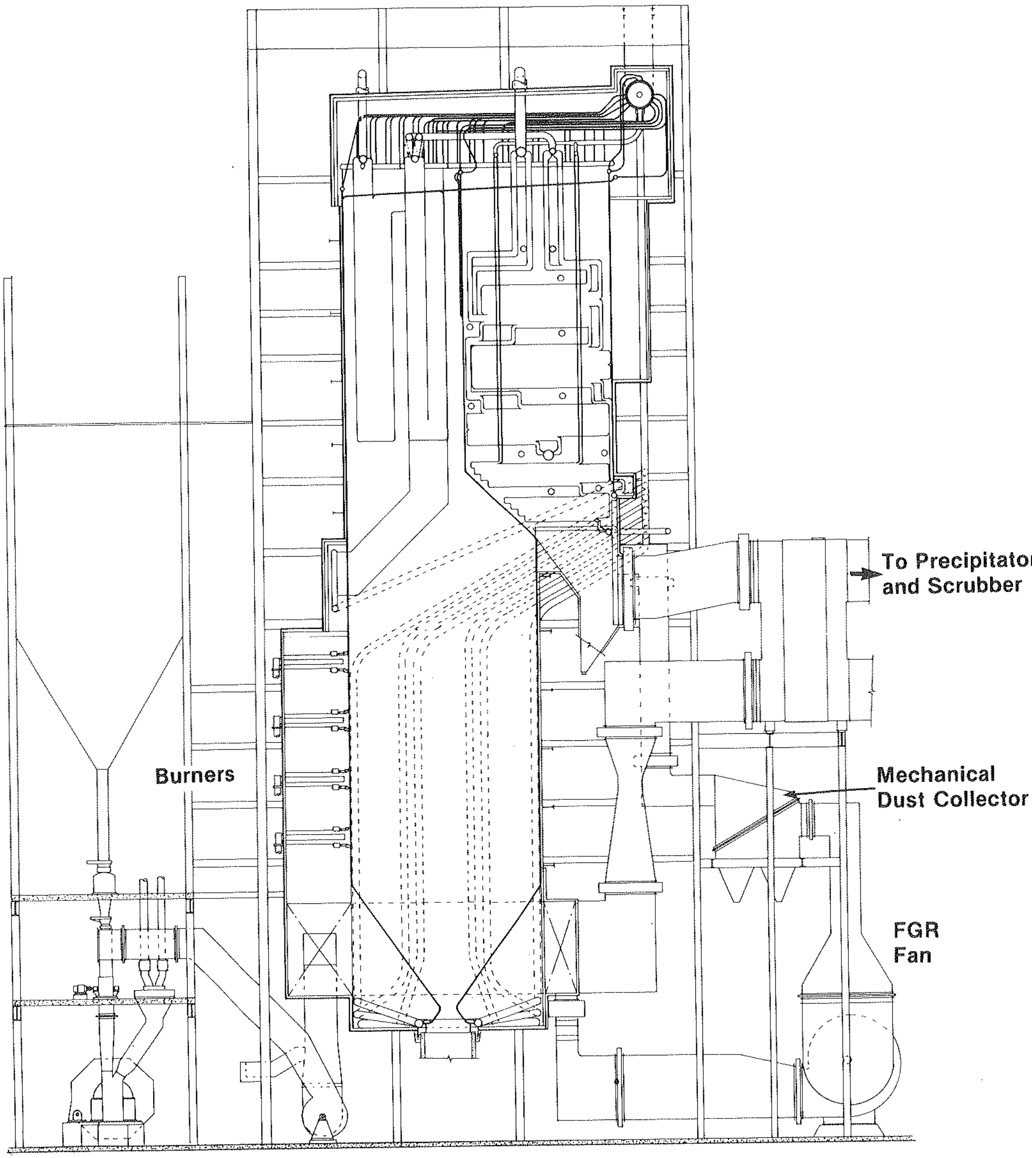

Figure 6 Central Illinois Light Co., Duck Creek Unit No. 1

Duck Creek Unit No. 1 was retrofitted with 24 CCV burners during the fall of 1981. Underfire air (UFA) ports were also installed below the lower burner row to control windbox pressure. In addition, flue gas recirculation, which originally entered the furnace through the burners, was rerouted to enter the furnace through the rear wall for steam temperature control. During boiler operation with the flue gas recirculation (FGR) fan off, 10% of the total combustion air was bypassed away from the windbox and introduced into the FGR ductwork for cooling purposes.

As shown in Figure 7, NO_X emissions 50% below baseline pre-NSPS levels were measured at design excess air levels with underfire air closed and 10% bypass air. Estimated full load emissions without bypass air are also shown. Measured CO levels are low and comparable to pilot scale test results. The effect of UFA on emissions levels is shown in Figure 8. At 22% excess air NO_X emissions were between 145.14 kg/min (320 PPM) and 199.58 kg/min (440 ppm) (3% O_2) depending on the amount of UFA and register vane position. The bypass air was off during these tests.

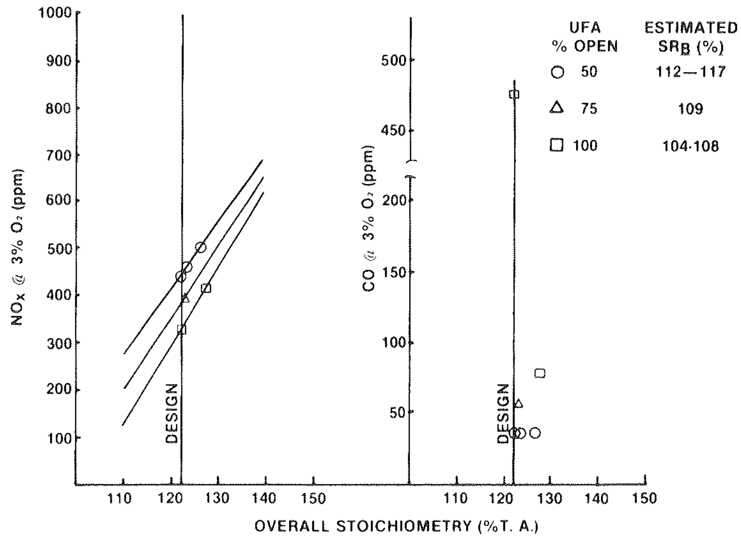

Figure 7 Field Test Results at Cilco Duck Creek Unit 1 (UFA) Ports Closed)

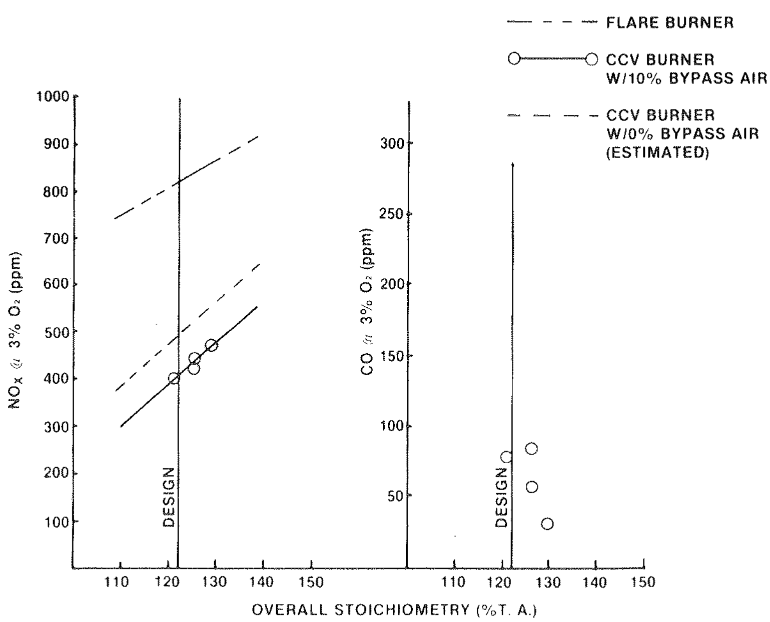

Figure 8 Field Test Results at Cilco Duck Creek Unit 1 (UFA Ports Open and Bypass Air Closed)

No significant change in the overall heat absorption characteristics of both the radiant furnace and superheater were observed during the CCV burner testing.[5]

Samples of furnace bottom ash, economizer hopper ash and precipitator ash were sampled during the testing and analyzed for loss on ignition according to ASTM procedures.[6] The results are compared for various test conditions in Table II. The total amount combustible in the ash is slightly higher for the CCV burner when compared with Flare burner operation with no flue gas recirculation. This increase, however, corresponds to a decrease of only 0.25% in boiler efficiency.[5] Precipitator ash ignition loss and CO data as a function of NO_X emission are presented in Figure 8. Although there is significant scatter in the data, both loss on ignition and CO increase as NO_X decreases.

		Loss on Ignition, % by Weight		
Burner	Test Condition	Bottom Ash	Economizer Ash	Precipitator Ash
Flare	0% FGR	0.1	0.4	1.9
	20% FGR	2.2	1.7	5.2
CCV	Unstaged	4.2	2.2	5.2
	UFA	5.4	0.65	7.4

Table II Furnace and Fly Ash Analysis, Cilco Duck Creek No. 1

Opposed Wall-Fired Boiler Tests CCV burners were also retrofitted on Carolina Power and Light Company Roxboro Units 4A and 4B. Twelve CCV burners, mounted on both front and rear waterwalls of each 360 MW unit, were installed to replace the pre-NSPS Flare burner equipment. Existing underfire air ports were used in conjunction with the CCV burners for both windbox pressure control and NO_X control.

As shown in Figure 9, Roxboro units 4A and 4B are also equipped with conventional overfire air ports. However, since low burner zone stoichiometries were not required to meet retrofit NO_X control goals, the overfire air ports were closed during CCV burner operation. The coal fired during these tests was a high volatile A bituminous coal with a heating value in the 3,024 - 3,276 kcal/kg (12,000 - 13,000 Btu/lb) range.

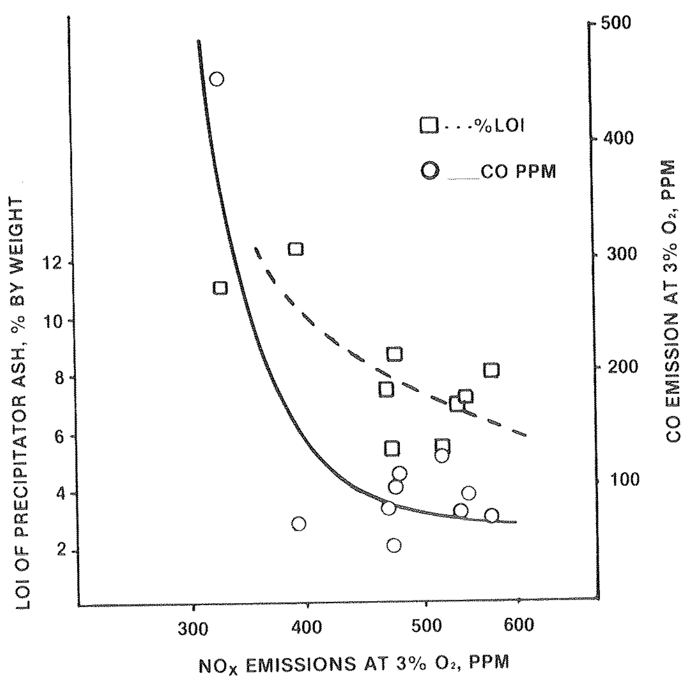

Figure 9 Loss on Ignition and CO Emissions as a Function of NO_X Emissions at Cilco Duck Creek 1

Unit 4A full load NO_X emission levels were reduced 50% below pre-NSPS levels with acceptable unit performance. As shown in Figure 10, at design excess air NO_X was reduced from 367.40 to 160.11 kg/min (810 to 353 ppm) with CCV burners installed and UFA fully open. Burner zone stoichiometry was 108%. Closing UFA ports increased NO_X to 180.07 kg/min (397 ppm) with the burners still operating slightly staged due to 6.0% combustion air leakage to other parts of the boiler.

Unit 4B full load test results also showed a 56% reduction in NO_X with acceptable unit performance. NO_X at these optimum burner conditions averaged 161.93 kg/min (357 ppm). As experienced at CILCO Duck Creek No. 1, no significant change in steam temperature and overall boiler performance was observed.[5]

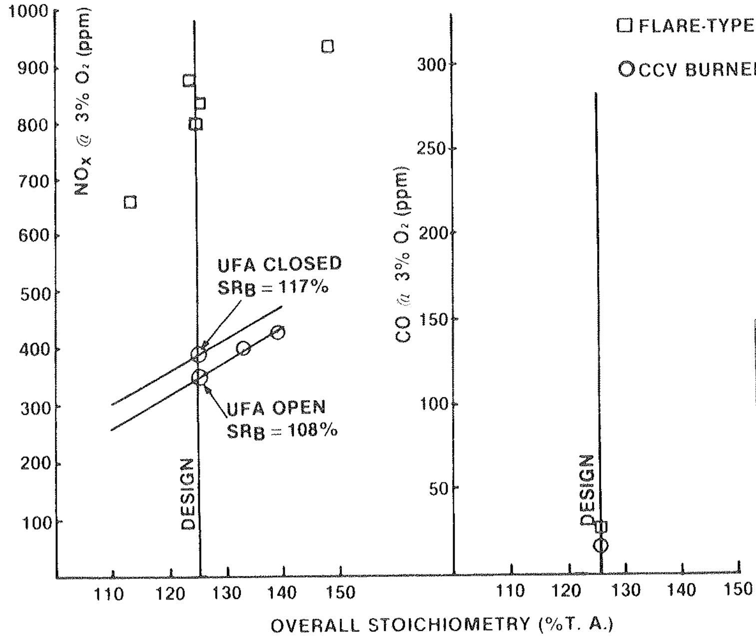

Figure 10 Field Test Results at CP&L Roxboro Unit 4A (UFA Ports Open and Closed)

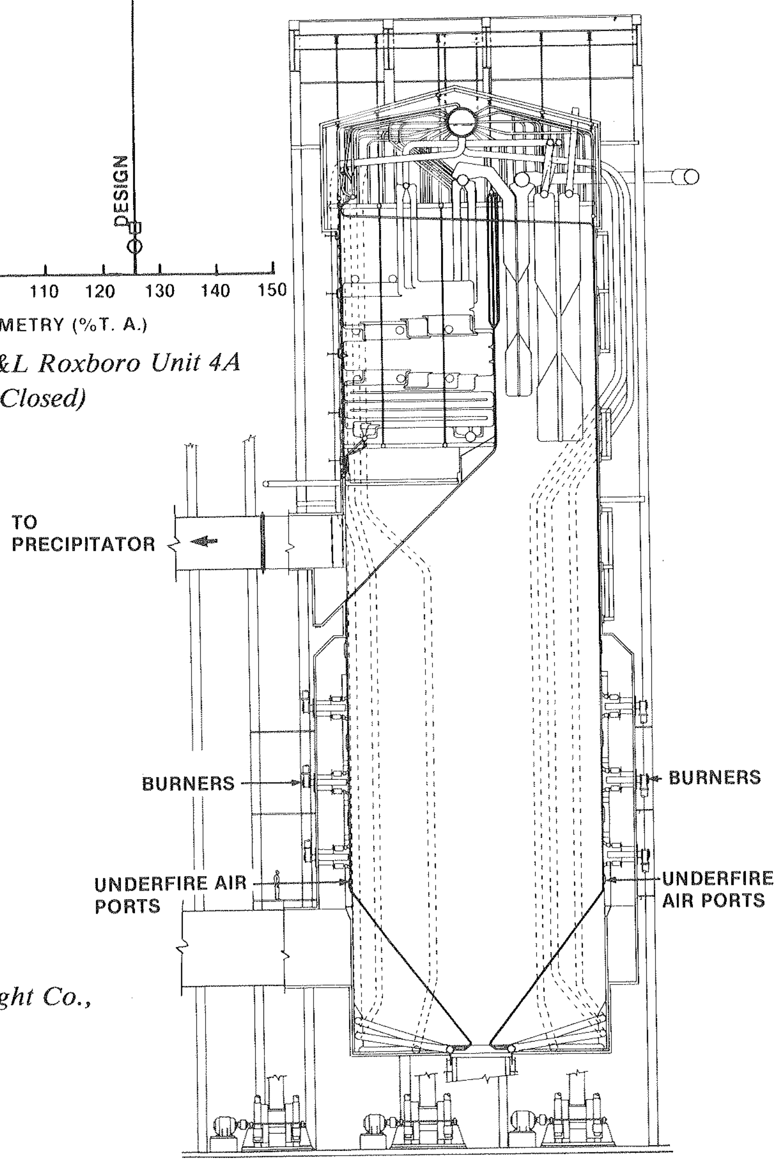

Figure 11 Carolina Power and Light Co., Roxboro Units 4A and 4B

COMPARISON OF PILOT SCALE AND FIELD TEST RESULTS

Pilot scale NO_X emissions for Riley pre-NSPS and low NO_X burners are compared with boiler test results from Duck Creek Unit 1 and Roxboro 4 in Figure 12. NO_X emissions are plotted as a function of Burning Area Heat Release[1, 2] or heat release per cooled area in the furnace heat release zone. NO_X emissions are 20 -30% higher under multiple burner field conditions than for single burner pilot scale conditions. Flue gas recirculation was found to have little effect on NO_X emissions in the 14.65 MW (50 x 10^6 Btu/hr) pilot scale tests.

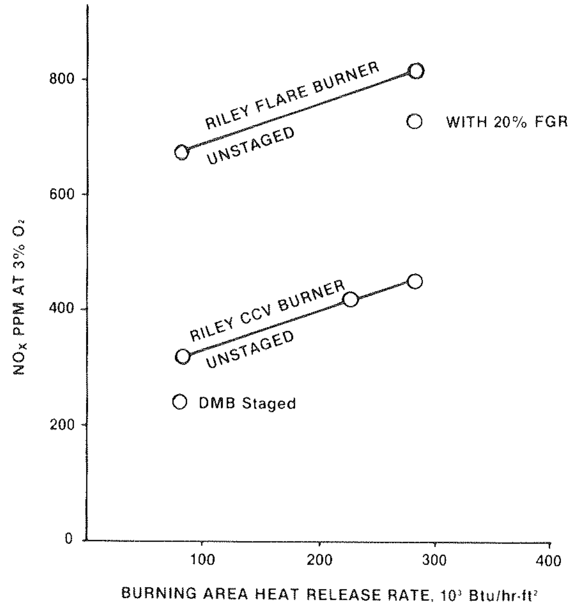

Figure 12 NO_X Emissions Pilot Scale on Wall-Fired Boiler Results

TURBO FURNACE BOILERS

In addition to developing circular burners for retrofit on wall-fired boilers, Riley Stoker is continuing its effort to evaluate and develop low NO_X TURBO Furnace combustion systems.

As illustrated in Figure 13, dry bottom TURBO Furnace boilers are characterized by a venturi shaped lower furnace. Directional Flame burners are installed in single rows on opposite downward facing walls. A schematic of the Directional Flame burner is shown in Figure 14. Axial flow is produced at the burner by essentially parallel secondary air and primary air coal jets. The jets are introduced to the furnace through slots formed in the furnace walls. This type of aerodynamic system produces long turbulent diffusion flames. In contrast to wall-fired boilers, these flames are dominated by far field effects.

The directional air vanes (Figure 14) are adjustable so that secondary air can be directed into or away from the primary stream. Conventionally staged TURBO Furnaces are equipped with overfire air ports located in the furnace "venturi throat."

This unique burner/furnace system produces downward directed intersecting flames which penetrate to the lower furnace, turn, and curl upward. Hot flue products recirculate from the lower furnace flowing upward past the burner level to the upper furnace where they mix with the remaining fuel and air.

BURNER AERODYNAMICS

The combustion chemistry of large scale systems cannot be uncoupled from fluid dynamics. Detailed measurements made by Michel and Payne[7] indicate that mixing is the determining mechanism in the combustion of long pulverized coal flames. Because of the difficulty and expense of making detailed measurements in large scale combustion systems, we are performing cold flow aerodynamic model studies to characterize the

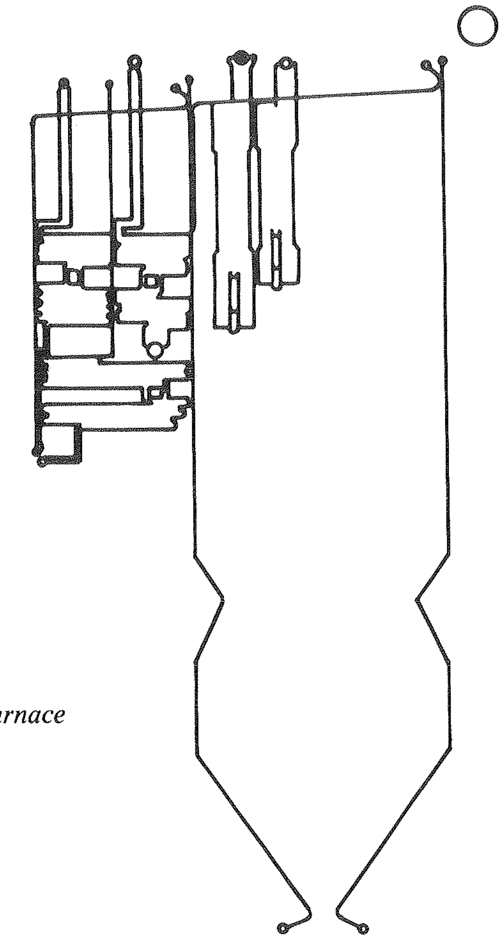

Figure 13   Dry Bottom TURBO Furnace

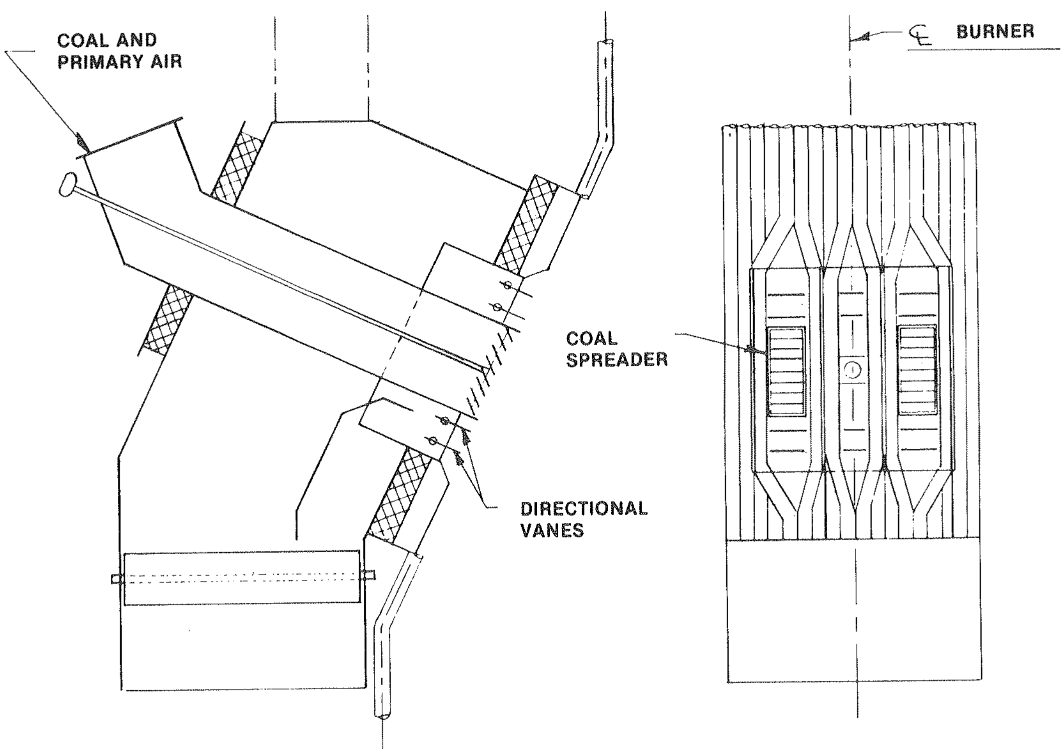

Figure 14   Riley Directional Flame Burner

effect of burner design parameters on mixing patterns. An automated five-hole pitot tube system is being used to map three dimensional flow fields immediately downstream of the burner nozzles. Axial velocity profiles measured on a one-half scale model of a 43.96 MW (150 x 10[6] Btu/hr) Directional Flame burner are presented in Figures 15 and 16.

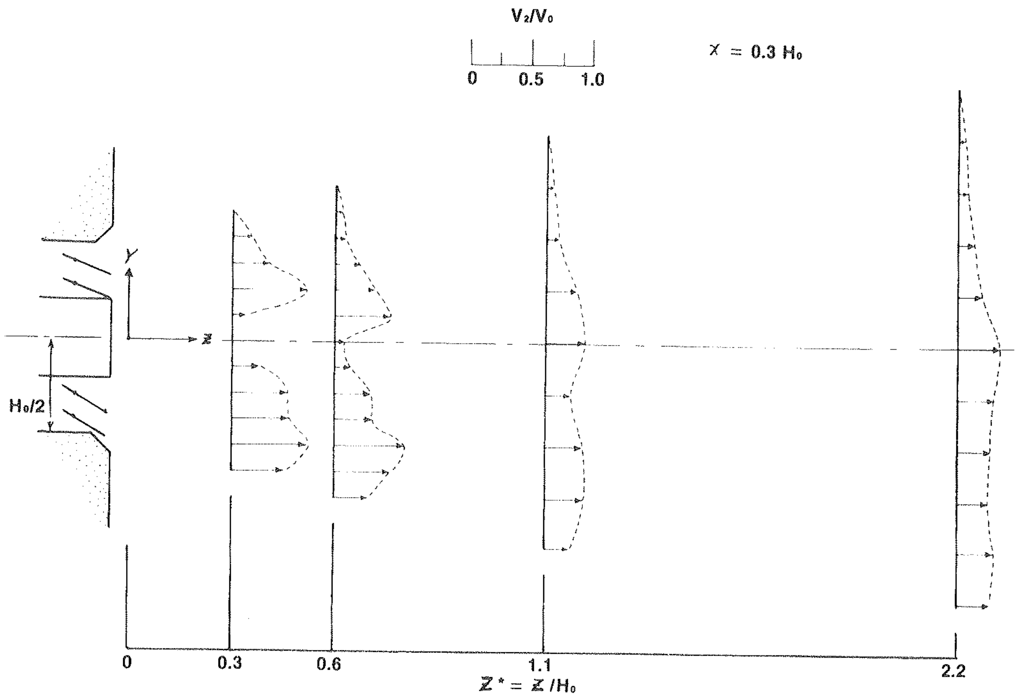

Figure 15 Measured Directional Flame Burner Axial Velocity Profiles Along a Vertical Plane in Front of the Coal Nozzle

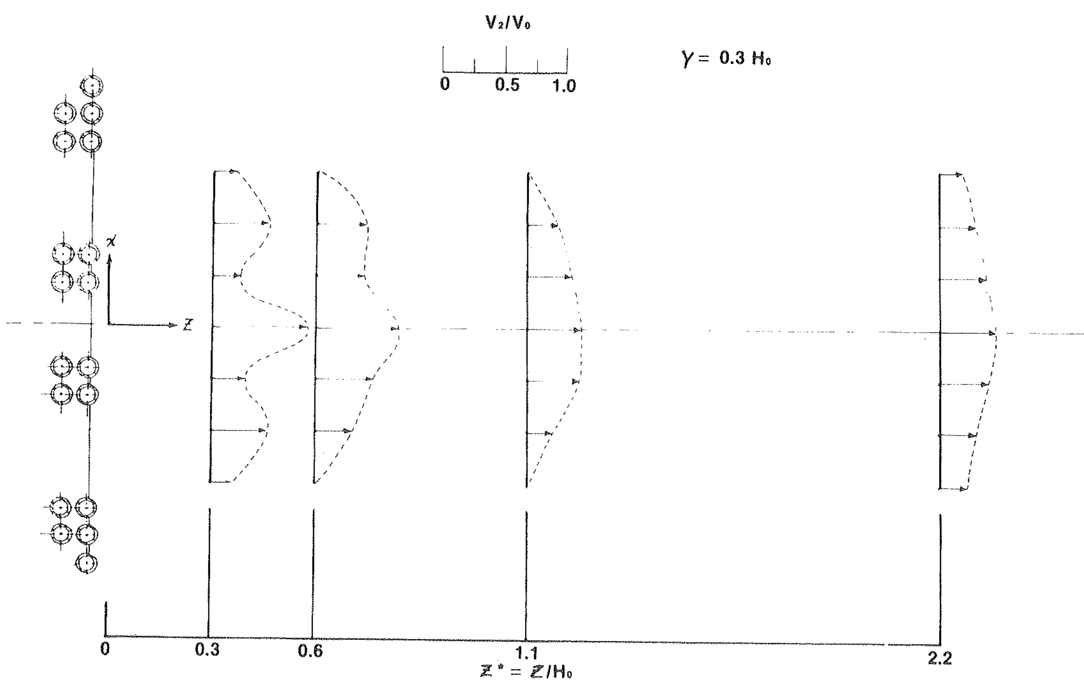

Figure 16 Measured Directional Flame Burner Axial Velocity Profiles Along a Horizontal Plane Below the Coal Nozzle

Figure 15 shows the development of downstream axial velocities in a vertical plane perpendicular to the coal nozzle. The air flow profiles are not axisymmetric. This reflects the influence of the secondary air vane position. A low velocity internal recirculation zone can be observed immediately downstream of the coal nozzle. The developing near-field mixing region appears to extend up to one characteristic burner dimension (throat height) downstream.

Axial downstream velocity profiles in a perpendicular horizontal plane located just beneath the coal nozzle are presented in Figure 16. The air flow profile in this plane is axisymmetric. Again, the central air jet is absorbed by the outer secondary air jets approximately one burner throat height downstream.

TURBO FURNACE FIELD TESTS

Nozzle geometry and secondary air vane position can significantly affect mixing patterns close to the burner. We have recently conducted field tests on two utility TURBO Furnaces with modified Directional Flame burners. These modifications included the installation of variable angle coal spreaders. Underfire air ports equipped with tilting vanes were also installed in the lower furnace side walls. As shown in Figure 14, the coal spreader was designed to direct the primary coal stream vertically downward. The underfire air ports were added as a means of staging the combustion. This firing approach is similar to that used on arch fired boilers.[8]

Field tests results from a 370 MW TURBO Furnace equipped with 24 Directional Flame burners and fired by Wyoming sub-bituminous coal (2,016 - 2,268 kcal/kg [8,000 - 9,000 Btu/lb]) are shown in Figure 17.

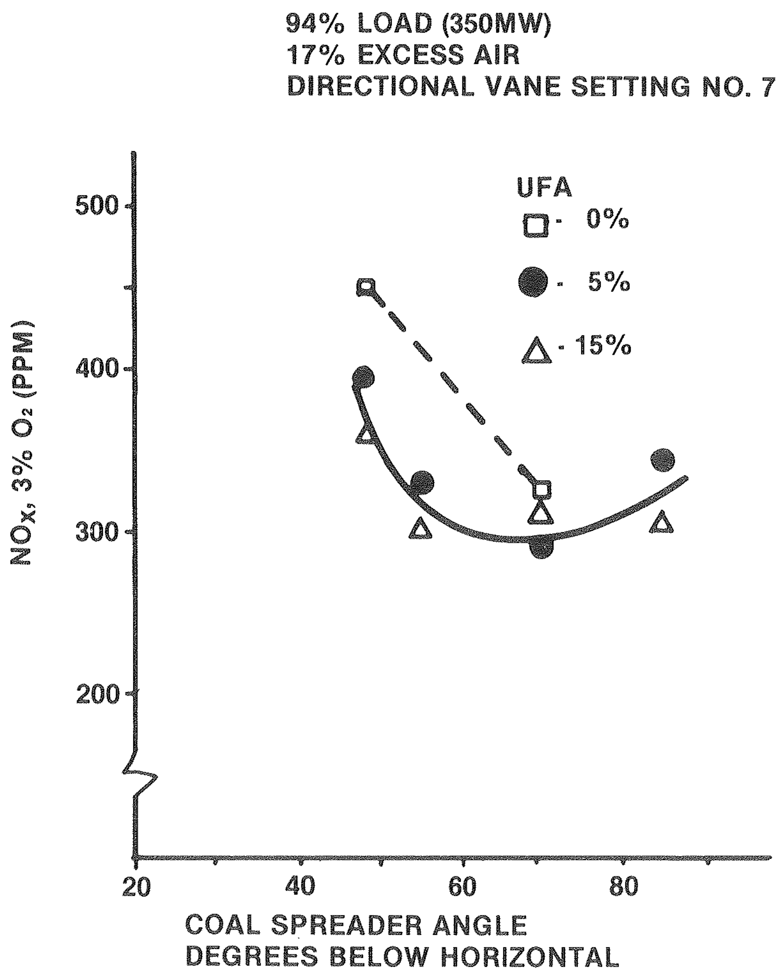

Figure 17 The Effect of Coal Spread by Angle and Underfire Air on TURBO Furnace NO_X Emissions

NO_X emissions are presented as a function of the downward spreader angle and underfire air. The amount of underfire air is expressed as a percentage of total air flow. A perforated plate was installed above the coal nozzle for these tests to block air flow and bias more secondary air downward beneath the coal nozzles. Coal spreader angle appears to have the strongest individual effect at these operating conditions and level of staging (5-15%). This is particularly true at the steeper (downward) angles. We believe the leveling off and slight increase of NO_X emissions beyond 70 degrees down may be due to the mechanical spreader design. A portion of the coal stream may be bypassing over the top of the spreader at this position. Underfire air, however, did reduce the carbon content of the furnace bottom ash.

Variable downswept coal spreaders have also been installed and field tested on a 540 MW TURBO furnace firing Montana sub-bituminous coal. Full load NO_X emissions varied with spreader angle and secondary air vane position ranging from 163.29 - 104.30 kg/min (360 - 230 ppm) (3% O_2). These emission levels were obtained unstaged, that is, without underfire air and without a perforated plate in the upper secondary air stream above the coal nozzle. Unstaged NO_X emission field data for this unit are presented in Figure 18 as a function of secondary air vane position. As discovered in previous TURBO Furnace field tests,[9] vane position No. 2, which directs both upper and lower secondary air streams away from the primary stream, results in the slowest mixing and lowest NO_X emission levels.

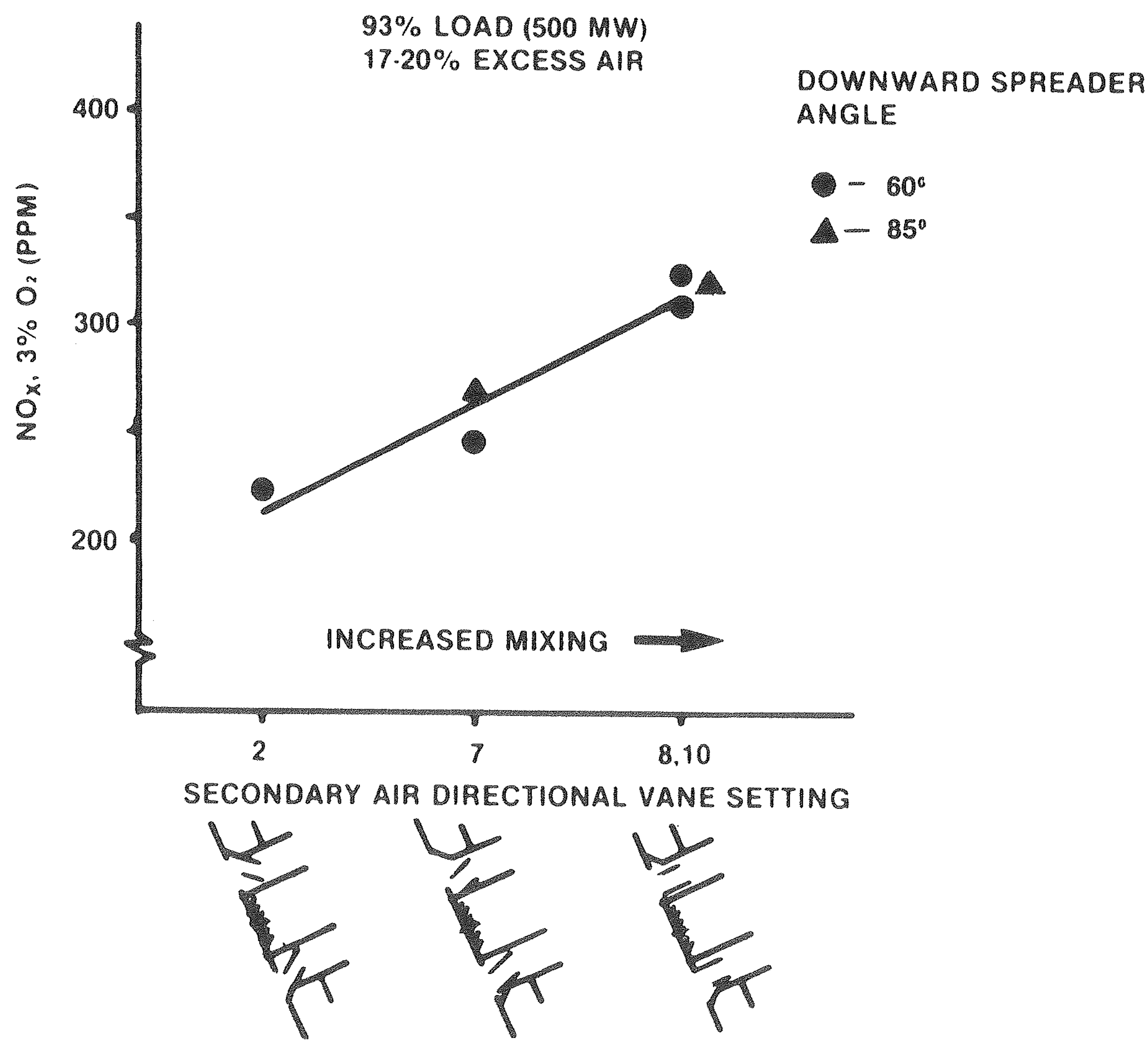

Figure 18 The Effect of Directional Air Vane Position on Unstaged TURBO Furnace NO_X Emissions

STAGED COMBUSTION HEAT TRANSFER

Riley Stoker is also evaluating the application of advanced staged combustion concepts to the TURBO Furnace design. A multi-zone furnace model is being used to assess the effect of these combustion techniques on heat absorption rates and temperature distribution in the radiant furnace. The model, shown schematically in Figure 19, incorporates the lower furnace geometry and flow pattern unique to the TURBO Furnace design. Model predictions have been verified against extensive field measurements obtained on a 490 MW pulverized coal-fired TURBO Furnace.

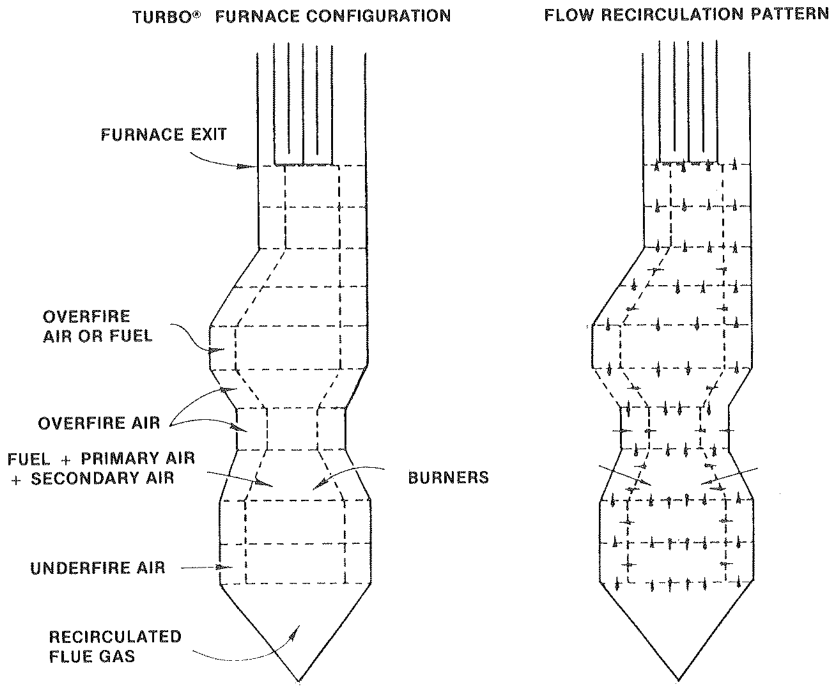

Figure 19 TURBO Furnace Temperature Profiles Staged Combustion Study

Predicted central gas zone temperatures for various degrees of staging with overfire air are presented in Figure 20. Lower temperatures are produced in the burner heat release zone as staging ratios are increased. This temperature decrease is caused by the combined effects of reduced lower furnace heat release and quenching by overfire air jets.

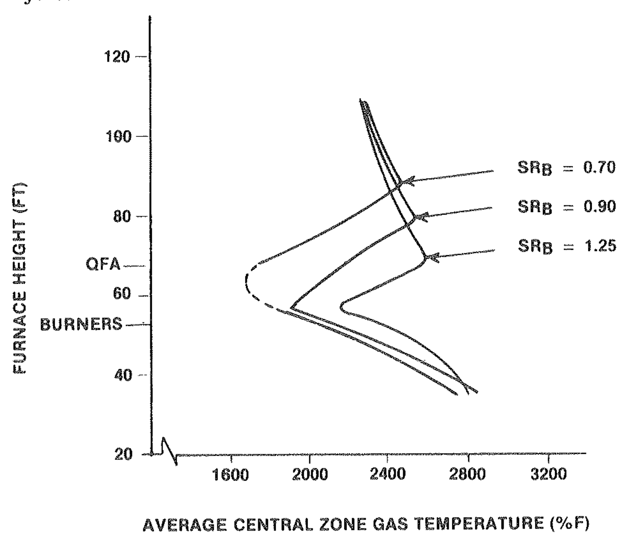

Figure 20 Riley Multi-Zone Furnace Model

FUTURE WORK

In the coming year, we plan to continue our development of both wall-fired and TURBO Furnace combustion systems. Further development tests will be conducted on our retrofit low NO_X burner design, the CCV burner, in the recently completed 29.31 MW (100 x 10^6 Btu/hr) Riley Coal Burning Test Facility (CBTF). This additional operating experience will be applied to advanced fuel and air staging tests which will also be conducted in the CBTF next year. These tests will be performed under a retrofit low NO_X control development program sponsored by the Electric Power Research Institute.

A 29.31 MW (100 x 10^6 Btu/hr) Riley DMB will be tested in EPA's large Watertube Simulator located at the Environmental Research Corp., El Toro, California, under EPA Program No. 68-02-3913. The Test Program will include direct injection of sorbents for combined in-flame NO_X and SO_X control.

In addition, advanced burners for TURBO Furnace applications will be tested in the Riley CBTF. Burner designs incorporating advcanced stage combustion and distributed mixing techniques will be investigated in this program.

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