DEVELOPMENT OF AN ECONOMICAL LOW NO_x FIRING SYSTEM FOR COAL FIRED STEAM GENERATORS

by
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RILEY
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Abstract

This paper will explain how Riley Stoker reduced NO_X emissions 40%-60% without detracting from overall boiler and burner performance. This achievement resulted from a program to develop a low NO_X firing system for coal fired steam generators, both old and new models alike. We will discuss the results of testing several low NO_X burners in a single burner test facility, from which the most effective burner design was selected for field evaluation.

The results of testing this burner design in three utility boilers: a front-fired 400 MW boiler and a 700 MW opposed fired twin-boiler single-turbine installation, are presented and compared to laboratory predictions. Discussions also include the theory of this NO_X reduction technique and its effects on boiler performance.

INTRODUCTION

In January, 1980, Riley Stoker initiated a program to reduce NO_X emissions from its wall fired steam generators. These units, equipped with rapidly mixed, swirl stabilized flare-type burners, were producing NO_X emissions exceeding the Federal New Source Performance Standard of 300 ng/J or 512 ppm corrected to 3% O_2. All NO_X values in this paper were measured by chemiluminescent analysis (CLA) and corrected to 3% O_2. We aimed primarily at reducing the emissions to below the Federal standards without adverse performance. Specific objectives included the following:

1. NO_X emissions must be less than 300 ng/J (0.7 lbs/10^6 Btu) or 512 ppm.
2. Burner operability, flame stability, burner turndown and capacity must be equivalent to the original flare-type burner equipment.
3. CO emissions and subsequent carbon loss must remain within acceptable levels.
4. Burner draft loss must remain acceptable.
5. Boiler efficiency, final steam temperatures, and overall boiler performance must not be adversely affected.

By reviewing literature (references 1, 2, 3, 4 and 5) and Riley's extensive experience that indicated the mixing and combustion characteristics necessary for low NO_X, Riley designed several potentially low NO_X burner configurations for wall-fired boilers. We then tested these designs in the laboratory prior to field installation and demonstration. The most effective burner design was evaluated in three full size utility boilers for its success in meeting the program objectives.

DEVELOPMENT PROGRAM

The burner development program included several major phases: goal definition, burner design, NO_X emissions field testing, laboratory testing, and commercialization.

Within a tight time framework, Riley established the goals and constraints of the burner development effort. The burner design phase included conceptualization of several low NO_X burner configurations as well as the design of scaled-down burners (including original equipment and new designs) for testing in the laboratory. Burner design efforts by Riley also included scaling the "best" test burner from the laboratory back to a full size configuration suitable for production.

To support the next two phases of the program, Riley contracted Energy and Environmental Research Corporation (EER) to assist in field testing emissions measurements as well as for providing combustion test facilities to evaluate the prototype burner designs. Field testing involved quantifying the performance of the original flare-type burner and boiler equipment over the entire operating range in a full-size wall fired utility boiler. Baseline NO_X emissions and overall boiler performance were correlated to specific operating conditions. Laboratory testing evaluated the performance of each potential low NO_X burner design. A single burner test facility, designed by EER to model the thermal environment of the burner in the field, supported the laboratory testing effort.

Riley Stoker completed the final phase of this burner development program by retrofitting the CCV burners and demonstrating NO_X compliance in three full size boilers with subsequent commercialization of the low NO_X burner design.

LABORATORY TEST FACILITY

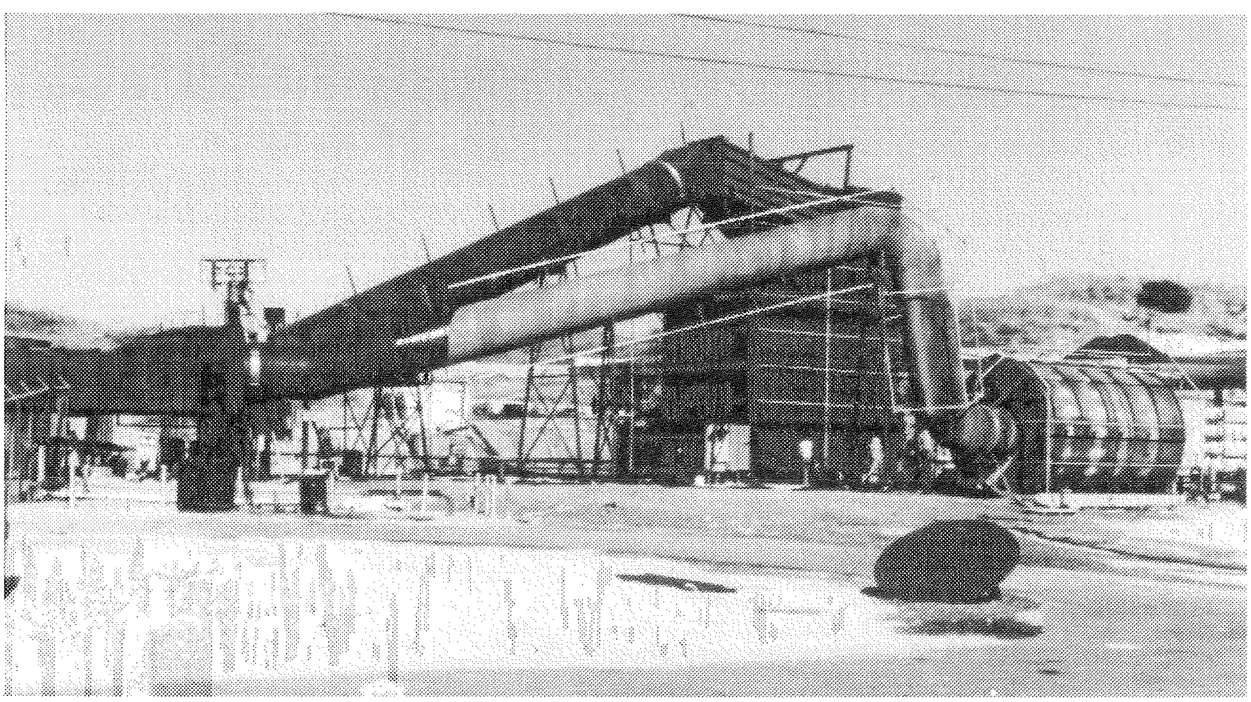


Figure 1 Medium Tunnel Combustion Test Facility Energy and Environmental Research Corporation

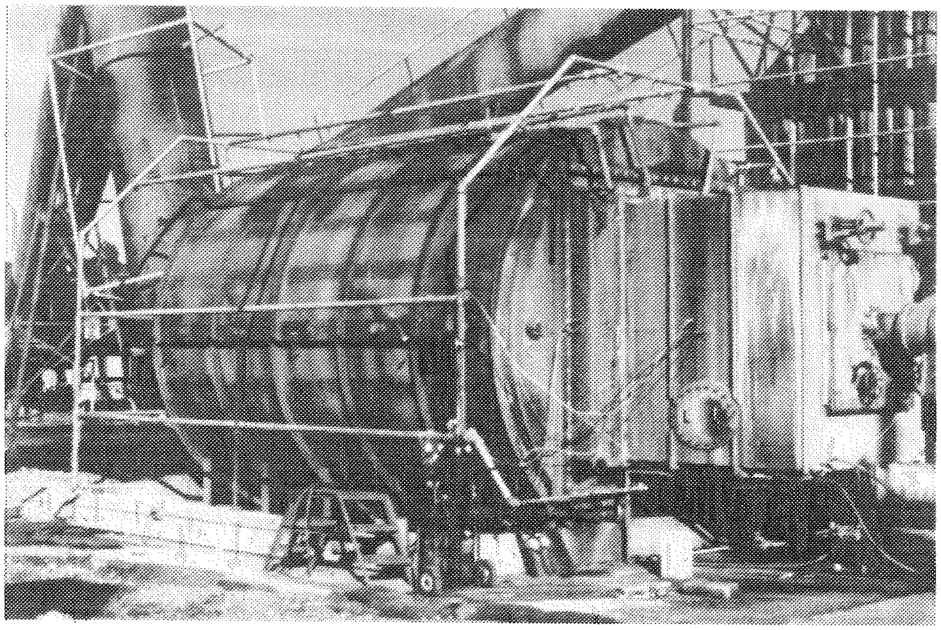


Figure 2 Combustion Test Furnace

We conducted the prototype burner testing in the Medium Tunnel Test Facility (MT) at EER in Irvine, California. This testing included the low NO_X as well as the original flare-type burner designs. The combustion test facility, shown in the foreground of Figure 1, included a 4.2 meter (14′) diameter by 6.1 meter (20′) long cylindrical furnace, oriented horizontally. Test burners and fuel/air supply equipment were mounted on the right hand end of the furnace with exhaust piping at the opposite end. Figure 2 shows a close-up view of the test furnace. To simulate the thermal environment of field operating units, the inside surface of the furnace was partially covered with insulating refractory. A network of piping, which surrounded the MT furnace and exhaust system, supplied water sprays to cool the exterior surface continuously.

To accommodate the capacity requirements of the MT, the flare-type burner and potential low NO_X burners were scaled down from a firing rate of 44 $MW_{thermal}$ (50 x 10^6 Btu/hr) to 14.5 $MW_{thermal}$ (150 x 10^6 Btu/hr). The burners were geometrically scaled to maintain the same flow velocities, pressure drops, swirl numbers (6) and flow patterns as those experienced in the full size burners.

While the prototype burner hardware was being fabricated and installed in the MT facility, we performed field testing in a wall-fired utility boiler to establish baseline conditions.

BASELINE FIELD TEST RESULTS

As a representative unit to collect baseline NO_X information, we selected Central Illinois Light Company (CILCO) Duck Creek Unit No. 1. It is a 400 MW boiler with twenty-four standard flare-type burners mounted on the front wall. As shown in Figure 3, this unit was equipped originally with flue gas recirculation (FGR) added through the burners to control steam temperature and NO_X. Figure 4 illustrates the flare-type burner design installed at Duck Creek and in other typical Riley wall-fired boilers. It consists of a single air register, central coal nozzle and a multi-vane coal spreader.

During the CILCO tests, we continuously monitored flue gas concentrations of NO_X, O_2, CO, and CO_2 at the economizer outlet ducts over a wide range of unit adjustments, with and without FGR. To ensure that representative gas samples were collected, we installed an eight point sampling grid in both economizer outlet ducts.

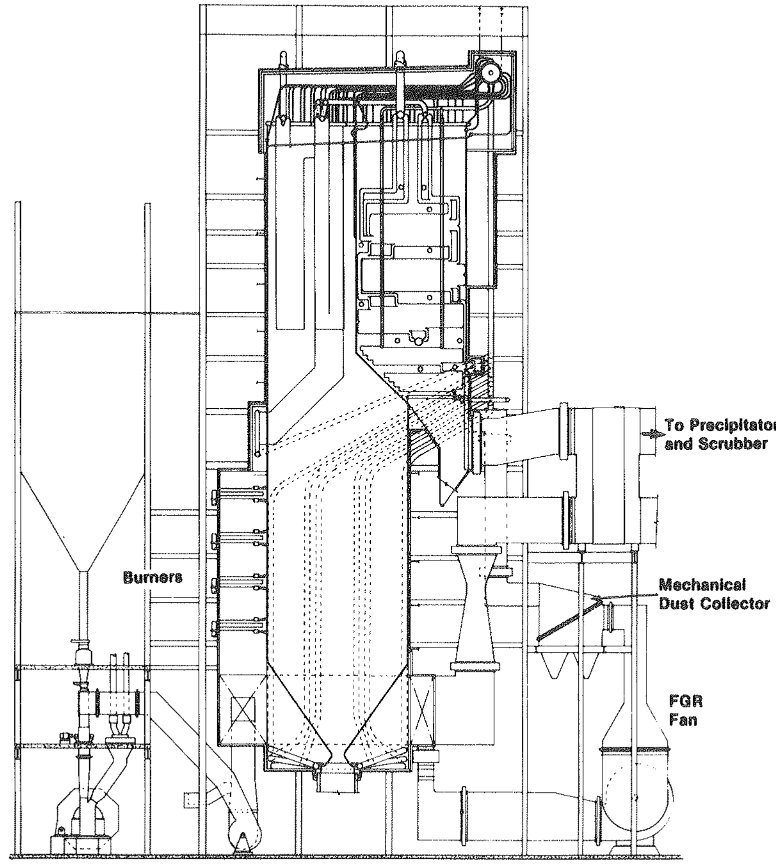


Figure 3 Central Illinois Light Co., Duck Creek Unit No. 1, Canton, Illinois

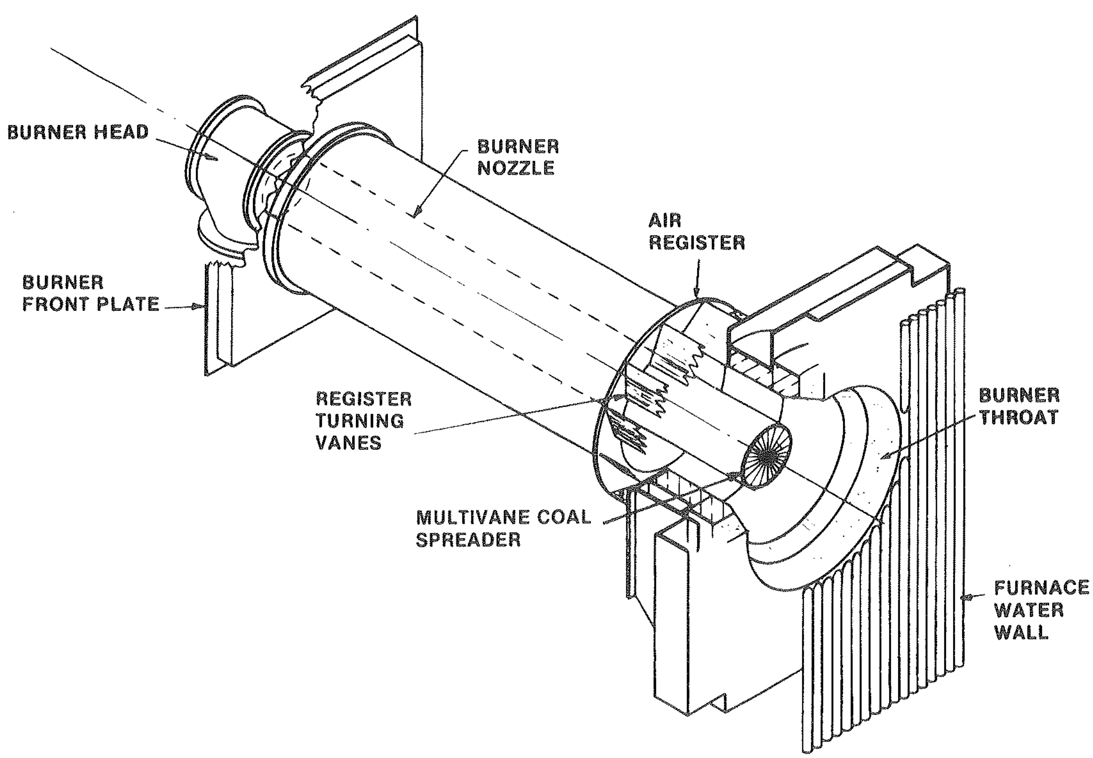


Figure 4 Flare-Type Burner

With original equipment installed, Figure 5 shows the NO_X and CO emissions measured at normal full load operating conditions as a function of overall stoichiometry, SR_{TOT} (% theoretical air). As expected, NO_X emissions increase with increasing SR_{TOT}. At 22% excess air or 122% overall stoichiometry (normal boiler operation) NO_X emissions averaged 819 ppm without FGR and 726 ppm with 20% FGR. Boiler emissions and combustible loss were as tabulated below:

PERCENT FGR	PPM @ 3% O_2 NO_X	PPM @ 3% O_2 CO	PERCENT LOSS ON IGNITION
0	819	150	1.72
20	726	136	4.43

Percent loss on ignition (LOI) is defined as total unburned combustibles in dry weight collected in the precipitator, economizer and bottom ash.

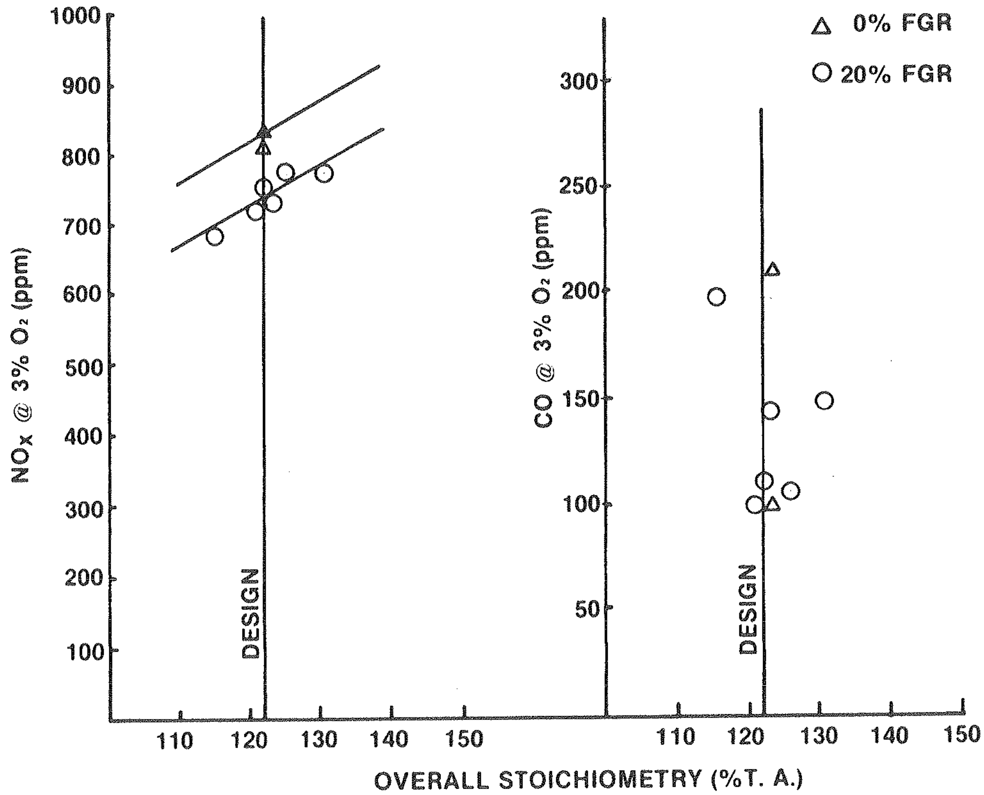


Figure 5 Baseline Field Test Results at Cilco Duck Creek Unit 1

LABORATORY TEST RESULTS

Flare-type Burner

We first tested the CILCO flare-type burner, scaled to 33% heat input, in the MT facility using the Crown II coal from Duck Creek Unit 1 (see Table I). Flame characteristics and overall burner performance were representative of the full-size burners. Similar to the baseline field testing, NO_X, O_2, CO and CO_2 gas concentrations were monitored in the test furnace exhaust duct over a similar range of operating conditions for direct comparisons with full scale testing at Duck Creek Unit 1. This established a NO_X scaling factor that we used to project the performance of the prototype designs tested in the laboratory to field conditions.

UNIT		DUCK CREEK	MT-EER
Sample		Field	Laboratory
Coal Type		Crown II	Crown II
Burner Design		Flare-type	Prototype
Proximate Analysis (as rec'd)			
Moisture	(%)	15.7	10.51
Volatile	(%)	34.4	—
Ash	(%)	9.2	—
Fixed Carbon	(%)	40.7	—
Heating Valve (Btu/lb)		10,474	—
Ultimate Analysis	(Dry)		
Carbon	(%)	69.0	67.42
Hydrogen	(%)	4.9	4.67
Nitrogen	(%)	1.23	1.28
Oxygen	(%)	9.87	12.72
Sulfur	(%)	4.1	4.22
Ash	(%)	10.9	9.69

Table I Coal Analyses Field and Laboratory

Figure 6 shows the scaled flare-type burner testing results measured at full load normal operating conditions compared to field results at comparable operating conditions. The magnitude and slopes of the NO_X curves were similar. Flue gas recirculation did not, however, reduce NO_X emissions in the test furnace as in the field due to the slightly colder thermal environment in the test furnace and corresponding lower thermal NO_X levels. This did not concern us because we were out to develop a low NO_X burner that would eliminate any need for FGR.

NO_X was quantified for the scaled-down flare-type burner without FGR at 22% excess air to be 672 ppm. The NO_X scaling factor, therefore, was established as follows:

$$NO_X \text{ Scaling Factor} = \frac{NO_X \text{ FIELD}}{NO_X \text{ MODEL}} = \frac{819}{672} = 1.22$$

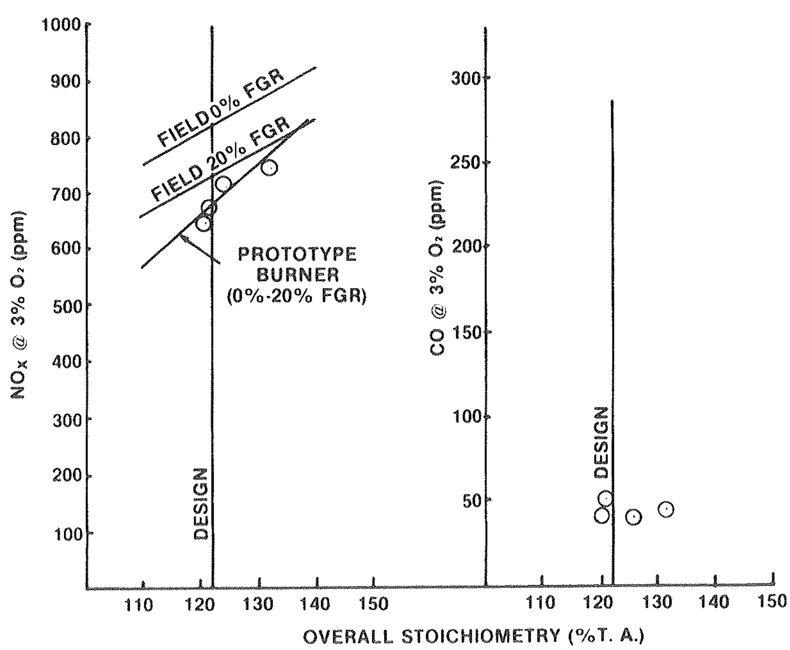


Figure 6 Laboratory Test Results, Flare-Type Burner

Next, we tested two alternate spreader designs in the scaled flare burner. In general, results indicated that a different spreader design could reduce NO_X emissions significantly.

We then tested two potentially low NO_X burner designs in the MT furnace and used the 1.22 scaling factor for projecting lab results to the field.

Shrouded Flare-type Burner

To study the effects of outboard staging on NO_X, Riley designed and fabricated the burner design shown in Figure 7. This design, called the Shrouded Flare-Type Burner, incorporated a shroud box located around the burner register with tertiary air ports above and below the burner throat. We adjusted the shroud dampers to regulate the amount of combustion air passing through the burner throat and the tertiary air ports. This enabled the burner to operate in a "staged" firing condition. Improving upon the original flare-type burner design, separate operators controlled the register vanes and degree of swirl independent of the amount of combustion air flow.

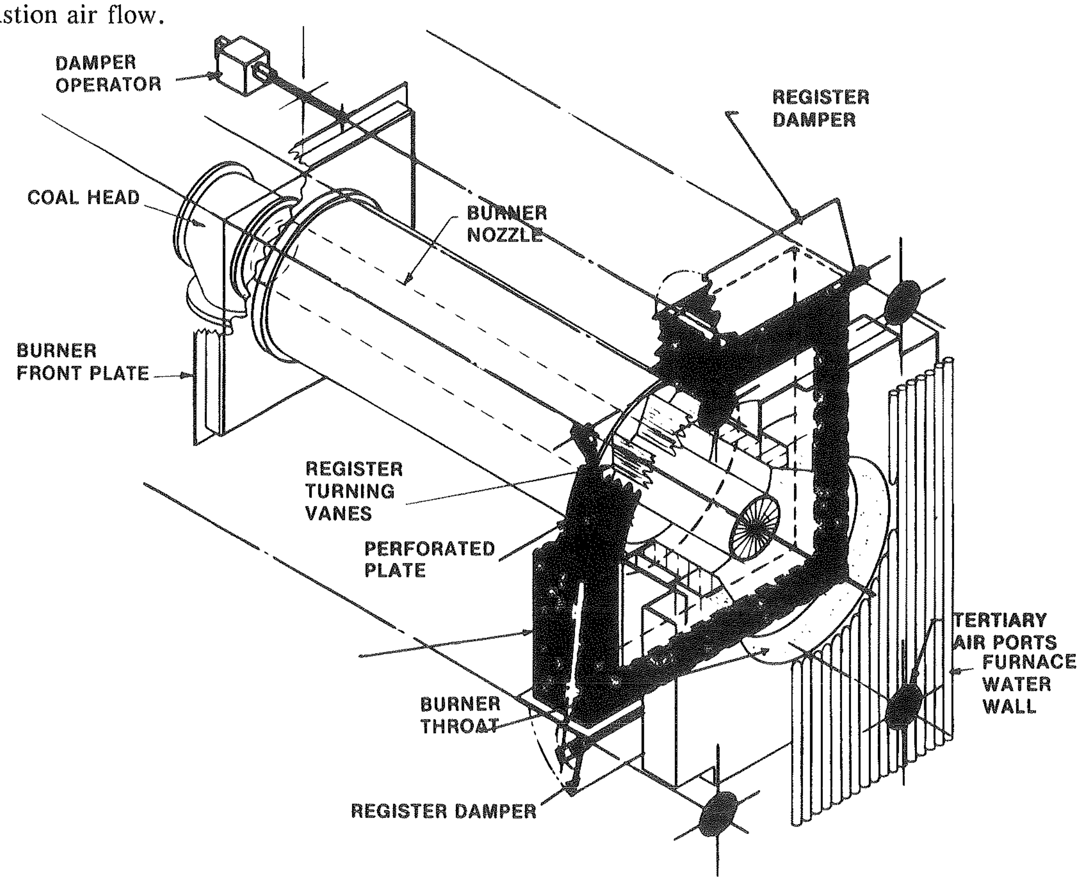


Figure 7 Shrouded Flare-Type Burner

Testing showed a 33% reduction in NO_X emissions from that measured in the original flare-type burner. Figure 8 outlines the NO_X and CO emissions measured over a range of total excess air levels. NO_X emissions decreased with increasing levels of staging, i.e. with decreasing burner zone stoichiometry (SR_B). CO emissions, carbon loss (LOI) and burner pressure drop remained at acceptable levels.

As indicated during the original flare-type burner testing, NO_X emissions could have been reduced further in this burner design by modifications to the coal spreader geometry. However, the cost of installing tertiary air ports in old and new wall fired units is potentially high. Therefore, to satisfy the objectives of this program, we eliminated this burner design from further consideration.

Distributed Mixing Burner

Riley designed the second low NO_X burner to the Environmental Protection Agency's design criteria for

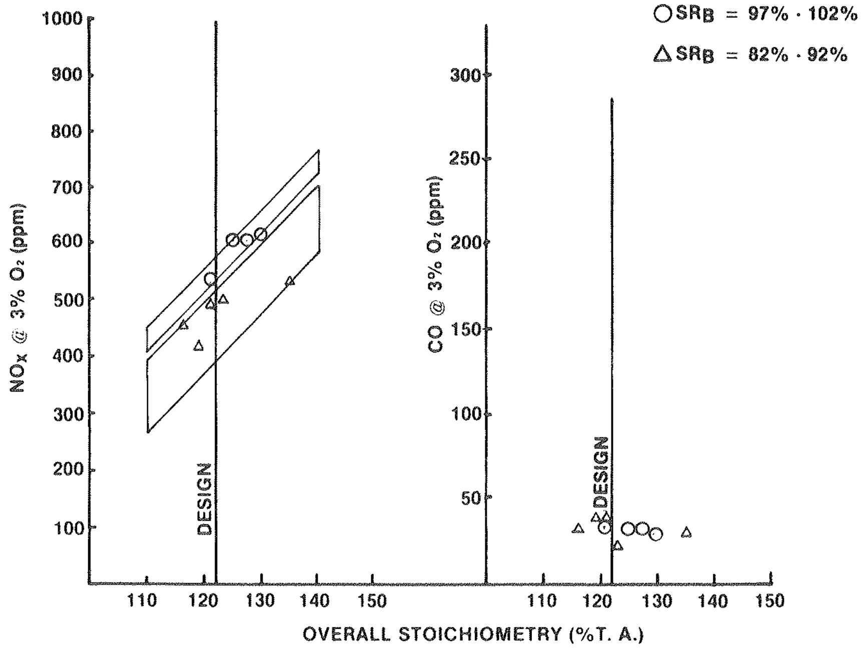


Figure 8 Laboratory Test Results, Shrouded Flare-Type Burner

low NO_X[5]. Similar to the shrouded Flare-type burner, the Distributed Mixing Burner (DMB) also incorporated tertiary ports and shroud boxes surrounding its two burner registers.

As shown in Figure 9, the additional register divided the burner throat into two sections: an inner and an outer secondary air passage. By adjustments to the register dampers and swirl vanes, this divided throat provided a wide variation in the distribution of both axial and tangential secondary air velocities as well as flow quantity. We studied the effects of burner throat or inboard staging with the tertiary air ports closed, and evaluated outboard staging with them open.

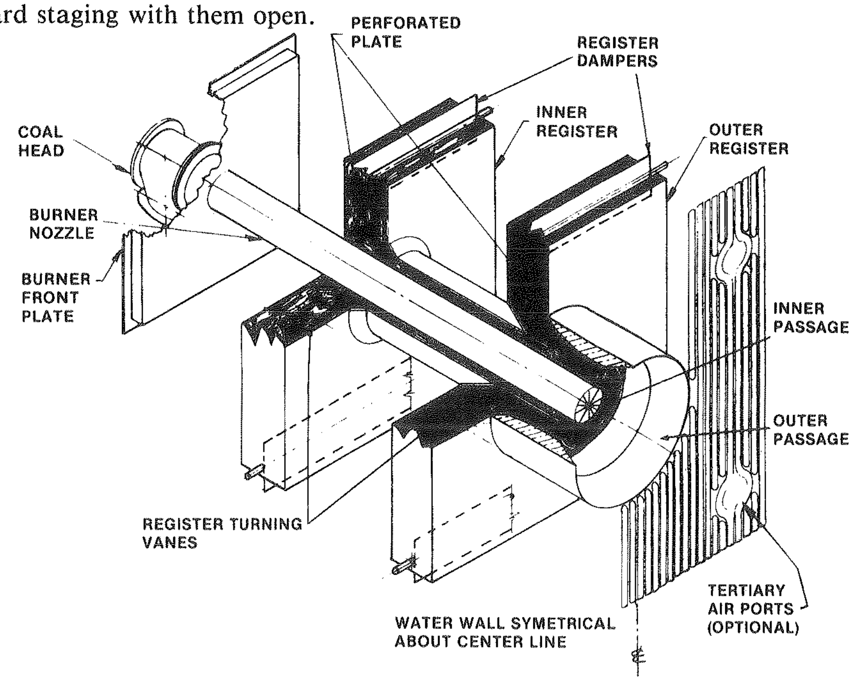


Figure 9 Distributed Mixing Burner

We did, however, recognize the same concern regarding the cost of tertiary air ports. The DMB was tested primarily to minimize NO_X emissions without the need for tertiary air. Testing focused on alternate coal spreader designs as well as variations in flow distribution and swirl.

Of the several designs tested, the coal spreader and nozzle, which produced minimum NO_X with acceptable overall burner performance, is shown in Figure 10. We modified the burner nozzle with a venturi section at the discharge or furnace end of the nozzle, and replaced the multivane coal spreader with a three-bladed conical shaped spreader. As discussed later in this paper, these modifications aimed to produce mixing and combustion characteristics necessary for low NO_X emissions.

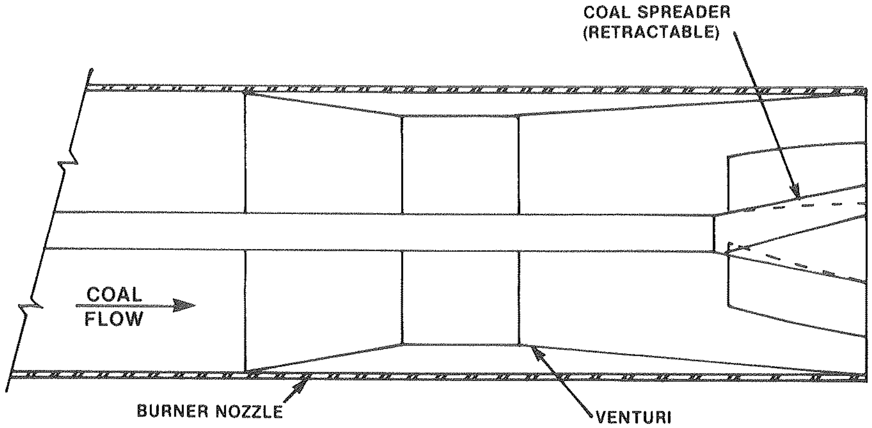


Figure 10 Venturi Coal Nozzle Tip and 3-Bladed Conical Coal Spreader

Results of testing this spreader/nozzle configuration in the DMB at various burner settings with tertiary air ports closed is shown in Figure 11. Operating the burner with 60%-80% of theoretical air passing through the burner nozzle and inner register($SR_{B_{IN}}$), reduced NO_X emissions 50% with acceptable burner performance. CO emissions remained below 30 ppm over a wide range of excess air operation. Continued burner adjustments for further reduction of $SR_{B_{IN}}$ to between 54% and 58% decreased NO_X emissions an additional 10%. However, the DMB could be operated down to only 115% overall stoichiometry without an increase in CO emissions, which was undesirable.

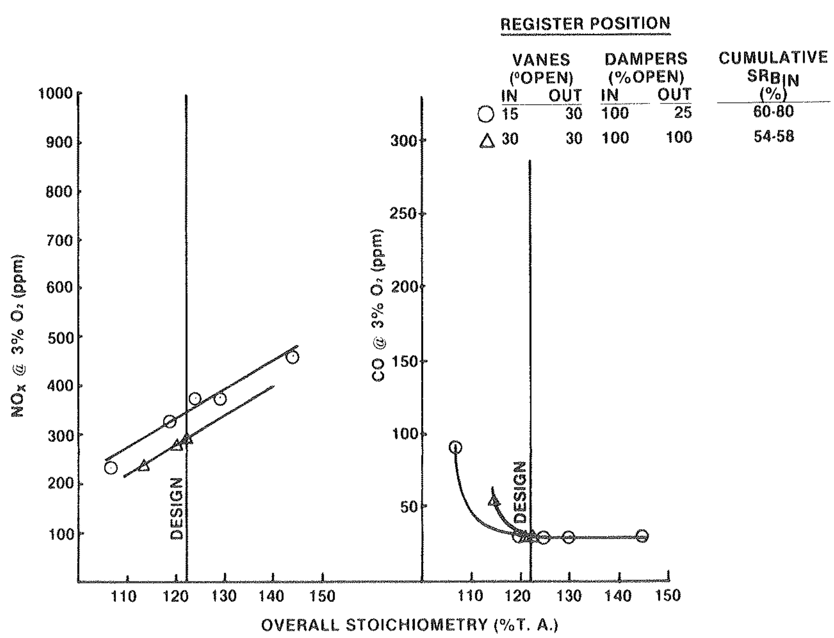


Figure 11 Laboratory Test Results - Distributed Mixing Burner (Tertiary Air Ports Closed)

Testing also demonstrated that we could not reduce NO_X emissions significantly by register adjustments alone. Modifications to the coal spreader and nozzle geometry dominated the effects on NO_X emissions. Therefore, at 22% excess air, NO_X was quantified for the previous operating condition to be 345 ppm. The 1.22 scaling factor predicted the NO_X emission in the field at 421 ppm.

As shown in Figure 12, when we tested the DMB, staged at between 80% and 93% burner zone stoichiometry (SR_{BOUT}) with tertiary air ports open, NO_X decreased 64% from baseline conditions. At 18% excess air, however, CO emissions increased rapidly.

Incorporation of the modified coal nozzle and spreader design enabled the DMB, without tertiary air, to meet the program objectives. The potential high cost of dual registers in the Distributed Mixing Burner design prompted us to study further the effects of spreader/nozzle modifications in the single register burner design.

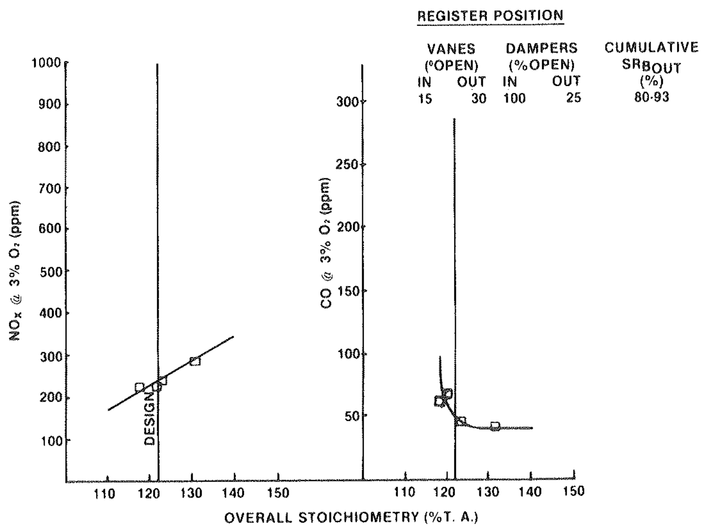


Figure 12 Laboratory Test Results - Distributed Mixing Burner (Tertiary Air Ports Open)

Controlled Combustion Venturi Burner

We tested several coal nozzle/spreader configurations, installed in the original flare-type burner, which resembled the best design developed from the DMB testing. Results indicated that the flare-type burner design can also attain low NO_X emissions with these spreaders installed. As Figure 13 shows, at optimum burner settings with the best spreader design installed, NO_X emissions were reduced 45% to 375 ppm without significantly increasing CO emissions and carbon loss. This NO_X level was only 30 ppm higher than achieved with the DMB at optimum conditions.

The test achieved all program objectives with one exception. The burner register vane settings, necessary for low NO_X (30 deg - 37 deg open), caused unacceptable burner pressure drop and windbox pressure. This is a problem we would have to address in the field.

The above results were produced by the Controlled Combustion Venturi (CCV) Burner, shown in Figure 14. It consisted of the original flare-type burner design modified with a venturi coal nozzle tip and a four bladed conical coal spreader.

As will be discussed later in this paper, the flame shape changed from a short V-shape to a long tubular shape, indicative of venturi enhanced coal/air mixing, controlled combustion and subsequent low NO_X production. The 1.22 scaling factor predicted NO_X emissions in the field at 457 ppm.

We retrofitted the CCV burner into the unit at Duck Creek because it was recognized that this approach was more economical than retrofitting with the DMB or the Shrouded Flare-type Burner.

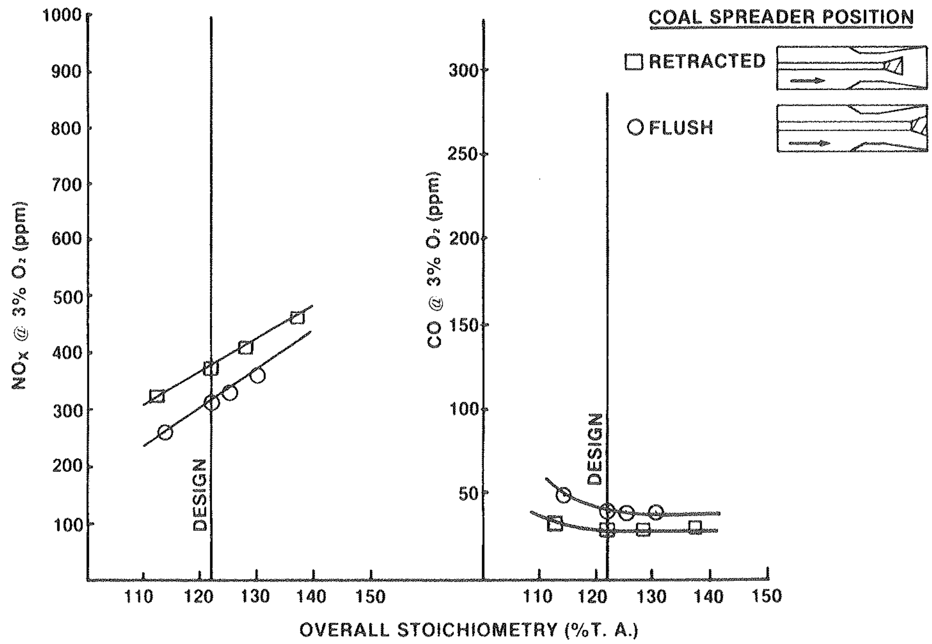


Figure 13 Laboratory Test Results - Controlled Combustion Venturi Burner

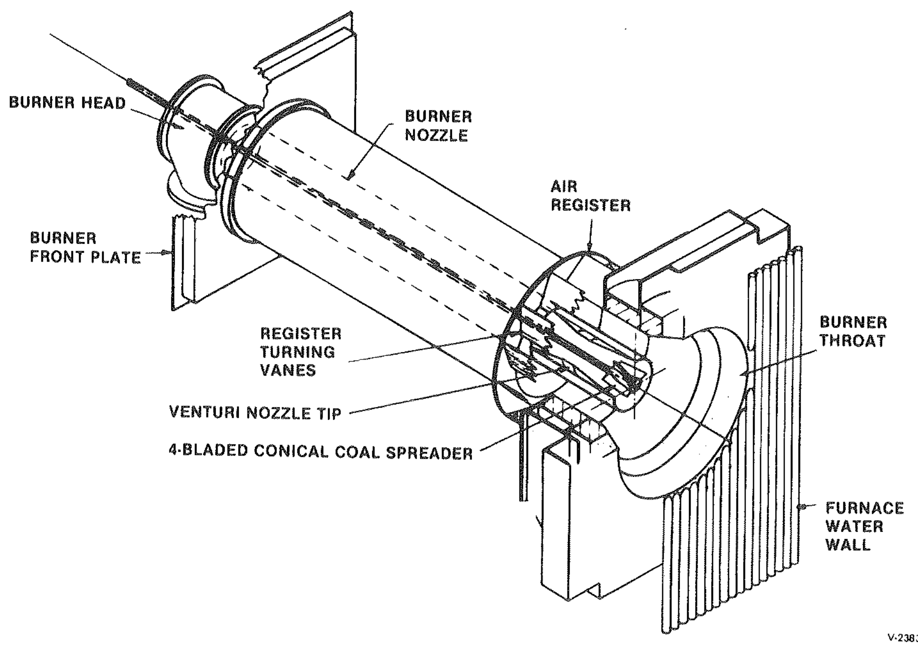


Figure 14 Controlled Combustion Venturi (CCV) Burner

FIELD TEST RESULTS

Central Illinois Light Company

During the fall of 1981, Unit 1 boiler at Central Illinois Light Company Duck Creek site was retrofitted with CCV burners to control NO_X, and with tube openings or underfire (UFA) slots below the lower burner level to control windbox pressure. Flue gas recirculation, which originally entered the furnace through the burners for NO_X and steam temperature control, was rerouted to enter the furnace through the rear wall for steam temperature control at all loads. Further, to cool the FGR ductwork, for test situations when the FGR fan is off, we had to bypass or reroute 10% of the windbox air into the ductwork.

As shown in Figure 15, with 10% bypass air, for cooling purposes, and underfire air closed, we reduced NO_X emissions by 50%. The estimated NO_X, *without* bypass air, is also shown for direct comparison with the original prediction. At 22% excess air, the NO_X emission was 490 ppm compared to the predicted 457 ppm, only 7% higher. If one considers all the differences between a laboratory test furnace and a full-size utility boiler, the scaling factor proved accurate.

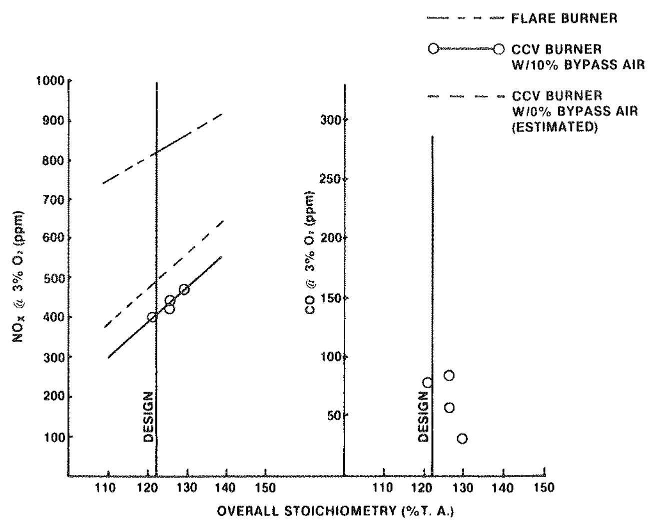


Figure 15 Field Test Results at Cilco Duck Creek Unit 1 (UFA Ports Closed)

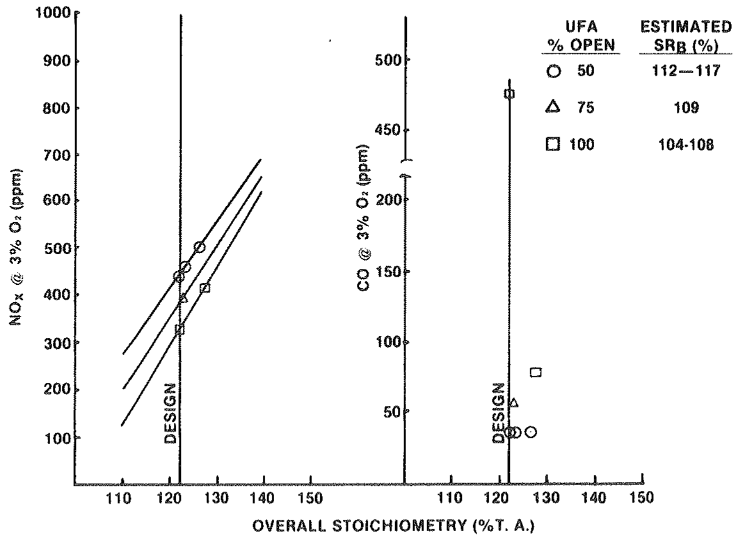


Figure 16 Field Test results at Cilco Duck Creek Unit 1 (UFA Ports Open and Bypass Air Closed)

With 10% bypass air, 22% excess air, and normal boiler operation, the NO_X measured 440 ppm, well below the required 512 ppm limit. As anticipated, however, the windbox pressure was high and opening the underfire air ports reduced the pressure acceptably. As shown in Figure 16, with the FGR fan on and bypass air closed we reduced NO_X to between 320 ppm and 440 ppm, depending on the degree of burner staging and position of the register vanes.

We decided to operate Duck Creek Unit 1 under boiler-burner conditions, which would minimize carbon loss and yet not exceed a NO_X emission of 512 ppm. This was accomplished with a small increase in unburned combustibles, causing boiler efficiency to decrease only 0.25%, still above acceptable limits. With conditions optimum, the test achieved 475 ppm. CO emissions remained below 82 ppm. As shown below, total unburned combustibles increased from 1.72% for original equipment burners to 4.23% with CCV burners. (Total unburned combustibles comprise the percentage of combustibles by weight in precipitator, economizer, and bottom ash, dry.) Superheat and reheat steam temperatures showed no significant changes.

BURNER DESIGN	SR_{TOT}	SR_B	PPM @ 3% O_2 NO_X	CO	PERCENT LOSS ON IGNITION
Flare	122	122	819	150	1.72
CCV	122	115	475	50	4.23

Carolina Power and Light Company

CCV burners were also retrofitted in Carolina Power & Light Company Roxboro Units 4A and 4B, a 700 MW twin boiler, single turbine installation shown in Figure 17. Twenty-four CCV burners, mounted on front and rear waterwalls of each unit, were installed to replace the original flare-type burner equipment. Underfire air ports, previously installed during initial boiler erection, were used in conjunction with the CCV burners to control windbox pressure and NO_X emission.

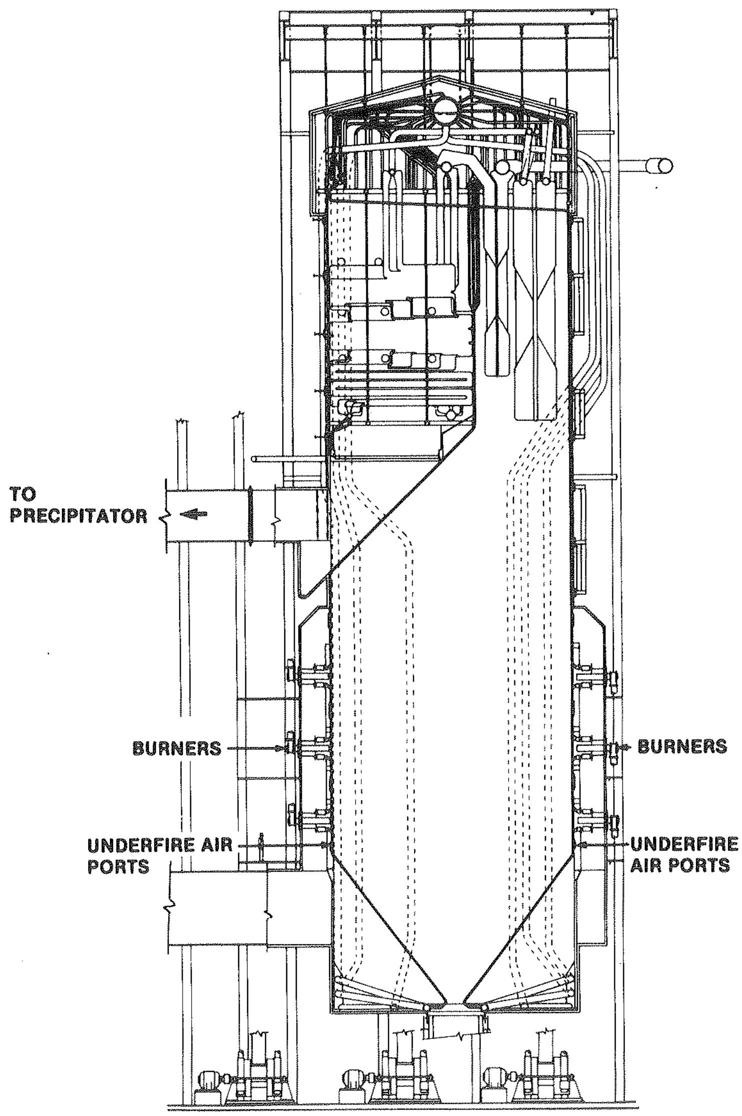


Figure 17 Carolina Power and Light Co., Roxboro Units 4A and 4B, Roxboro, North Carolina

Testing of Unit 4A at full load showed a 56% reduction in NO_X, with acceptable unit performance. As shown in Figure 18 and the table below, with the original burner equipment, NO_X was measured at 810 ppm. With CCV burners and UFA fully open (SR_B = 108%) it was measured at 353 ppm. CO emissions at boiler exit averaged less than 50 ppm. The amount of carbon in the precipitator ash increased slightly from 3.5% to 6.5%. However, like test results at Duck Creek, this corresponds to only an 0.3% decrease in boiler efficiency. Superheat and reheat steam temperatures did not change appreciably.

BURNER DESIGN	SR_{TOT}	SR_B	PPM @ 3% O_2 NO_X	PPM @ 3% O_2 CO	PERCENT LOSS ON IGNITION
Flare	125	117	810	30	3.5
CCV	125	108	353	40	6.5

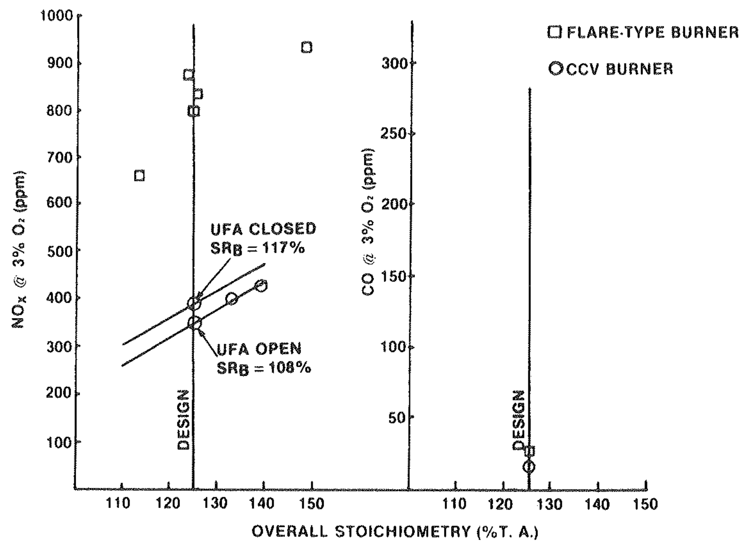


Figure 18 Field Test Results at CP&L Roxboro Unit 4A (UFA Ports Open and Closed)

With UFA closed and a 6% leakage through the closed dampers - those in the original overfire and side auxiliary air system - NO_X increased to 397 ppm. Again, windbox pressure was high, so, we elected to operate the CCV burners with the underfire air ports open.

Unit 4B test results at full load also showed a 56% reduction in NO_X with acceptable unit performance. NO_X, at optimum burner conditions, averaged 357 ppm. CO emissions were not measured. However, similar to Unit 4A, carbon loss was approximately 6.5%. Superheat and reheat steam temperatures showed no significant changes.

An explanation for lower NO_X measured at Roxboro than at Duck Creek along with the theory behind NO_X reduction in CCV burners now follows:

THEORY

NO_X Formation

Several investigators (references 2, 7, 8, 9, 12 and 13) have established that during combustion of pulverized coal the formation of nitrogen oxides, collectively referred to as NO_X, derives from two sources:

1. The thermal fixation of molecular nitrogen in the combustion air with oxygen at high combustion temperatures, called thermal NO_X.
2. The oxidation of chemically combined nitrogen compounds produced during the pyrolysis of pulverized coal, called fuel NO_X.

The formation of thermal NO_X depends greatly on the combustion temperature, residence time, and oxygen level in the primary combustion zone. Fuel NO_X, which accounts for approximately 60%-80% of the total NO_X emission from coal fired boilers, is governed by (a) fuel/air mixing characteristics as they affect the flame zone chemistry and (b) the coal composition (references 7 and 14).

Rapid mixing resulting in short intense, V-shaped, swirl stabilized flames, characterize the original flare-type burners at Duck Creek and Roxboro. Such flames promote both thermal and fuel NO_X formation. High peak combustion temperatures combined with high oxygen availability in the primary combustion zone resulted in greater than 800 ppm NO_X emission levels.

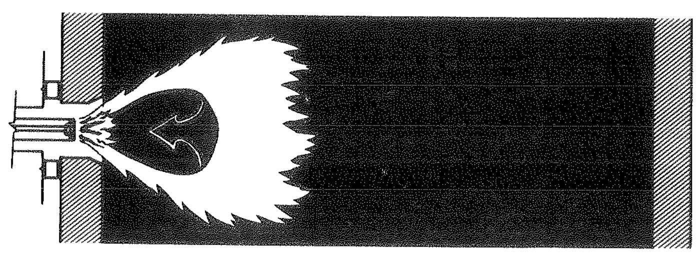
NO_X Reduction

The following methods reduce both thermal and fuel NO_X formation: (references 1 and 7)

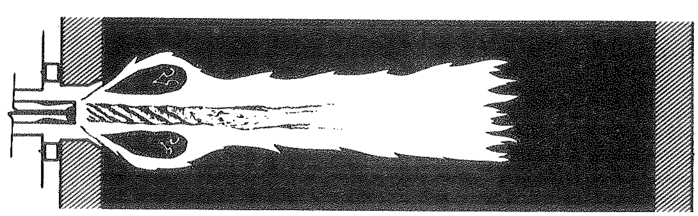
1. Reducing peak flame temperature
2. Reducing residence time at peak flame temperature.
3. Reducing O_2 availability in primary combustion zone.
4. Decreasing rate of fuel/air mixing.

The CCV burner (Figure 14), developed during this program, satisfied these conditions for low NO_X. Similar to the original burner operation, coal and primary air from the pulverizer enters the CCV burner head, where it is evenly distributed and intermixed. It then travels down the coal nozzle towards the venturi section. The venturi concentrates the coal in the center of the nozzle, creating a fuel rich zone with progressively leaner mixtures towards the periphery of the nozzle. As the rich coal/air mixture passes over the conical spreader the four blades divide the coal stream into four distinct layers of fuel rich and lean mixtures which enters the furnace with an axial velocity that approaches the velocity of the secondary air. The result is more distributed, controlled, and gradual mixing of the coal and air.

In addition, as the primary air/coal mixture flows over the conical spreader, an inner recirculation zone is formed adjacent to the venturi nozzle discharge. A strong torroidal recirculation zone produced by the swirling secondary air surrounds this inner recirculation zone and produces a short bulbous flame section close to the burner and a long tail downstream. Figure 19 depicts the flame shape produced by the CCV burner as compared to the flame shape that typifies the original flare-type burner equipment. As discussed in references (2, 4), the CCV burner flame shape resembles a Type I flame shape whereas the flare-type burner is typical of a Type II. Tests have demonstrated that Type I flame shapes produce less NO_X.



FLARE-TYPE BURNER (TYPE II)



CONTROLLED COMBUSTION VENTURI BURNER (TYPE I)

Figure 19 Typical Flame Shapes

The concentrated fuel-rich mixture produces a reducing atmosphere in the bulbous section of the CCV burner flame. Volatiles in the coal are rapidly driven off here and partially oxidized. Oxygen is then not available to combine with the fuel nitrogen compounds. This leads to their reduction to nitrogen gas. Fuel NO_X formation is thus minimized. Controlled coal/air mixing produced by the CCV burner reduces peak flame temperatures and combustion intensity. As a result, thermal NO_X formation is also minimized.

Boiler Operation Effects

Mechanical adjustments to the coal spreader and register vane position in the CCV burner were used to attain the combustion characteristics necessary for both low NO_X and low CO emissions. As discussed previously during low NO_X operation, no significant change in boiler performance was observed. Specifically, burner capacity, turndown, draft loss, stability, and operability were equivalent to the original flare-type burner equipment. UFA ports did, however, need to be closed during low load operation and boiler startup to maintain stable fires. Boiler efficiency and final steam temperatures remained at acceptable levels while fouling of the boiler elements did not change appreciably. The amount of lower furnace slagging did increase, due to the modified combustion process, but was easily controlled by periodic soot blowing.

The effect of low NO_X operation specifically on steam temperature was a major concern of ours at the onset of this program. Riley believes steam temperatures were unaffected by low NO_X operation for the following reasons:

1. CCV burners changed only near-field mixing patterns, and modified the overall combustion process but slightly.
2. Peak flame temperatures were felt to be reduced, but the total average flame temperature is believed to have not changed significantly.
3. Any possible loss in radiation caused by lower peak flame temperatures was offset or regained by the overall combustion process reaching closer to the boiler elements.

Comparison of Duck Creek and Roxboro NO_X Results

Field test results indicated the CCV burners installed at Roxboro were producing 14%-18% lower NO_X emissions than at Duck Creek. Table II outlines the NO_X emissions for these two boilers at comparable operating conditions along with a comparison of physical boiler parameters. We evaluated the NO_X values reported using the field data shown in Figures 17 and 19 at similar overall burner zone stoichiometries.

Based on past data from wall-fired units, Burning Area Heat Release (BAHR) has a major effect on NO_X emissions[9]. BAHR is defined as the gross heat input to the furnace, divided by the surface area available for cooling the primary flame to below the point where thermal NO_X fixation reactions are quenched. We included burner heat input and furnace size in the calculation of BAHR reported in Table II. Past data indicates an 8% reduction in BAHR, comparable to the difference between Duck Creek and Roxboro installations, will result in approximately 50 ppm reduction in thermal NO_X. This would account for approximately 90% of the total NO_X difference between Duck Creek and Roxboro.

We felt that the additional 10% difference was caused by variations in burner spacing, flame interaction (type of firing), furnace slagging conditions and fuel analyses.

We suspected that under similar conditions the higher fuel nitrogen content of the Roxboro coal would have increased total NO_X emissions over Duck Creek. Table III shows a comparison of the fuel analysis. However, recent investigations by DyKema[7] actually show a decrease in the conversion efficiency of fuel-bound nitrogen to NO_X with an increase in fuel nitrogen content. An exact correlation between NO_X emissions and fuel nitrogen content alone cannot be exactly defined[10]. Therefore, the different nitrogen contents between Duck Creek and Roxboro coals caused us no concern.

Martin and Bowen[8] and Brown[11] plan to study how the intersection of the combustion products of two flames affect NO_X emissions. They expect to find it reduces them. We explored the possibility that intersecting flames at Roxboro, caused by the opposed firing configuration, might be the reason why Roxboro emitted less NO_X than Duck Creek.

Dimensions in U. S. Customary Units

PARAMETER	UNITS	DUCK CREEK	ROXBORO
1. Type of Firing	—	Front	Opposed
2. Furnace Size:			
Width	ft	55	49.5
Depth	ft	38	49.5
3. Burning Area Heat Release	$Kbtu/hr\text{-}ft^2$	288	264
4. Burner Heat Input	MBtu/hr	150	130
5. Burner Spacing:			
Horizontal	ft	7.75	10.75
Vertical	ft	12.0	15.0
6. Fuel N_2 (dry)	%	1.19	1.42
7. Overall Stoichiometry	%	125	125
8. NO_X @ 3% O_2 for Burner Zone Stoichiometry = 117%	ppm	470	397
9. NO_X @ 3% O_2 for Burner Zone Stoichiometry = 108%	ppm	405	353

Dimensions in Metric Units

PARAMETER	UNITS	DUCK CREEK	ROXBORO
1. Type of Firing	—	Front	Opposed
2. Furnace Size:			
Width	M	16.8	15.1
Depth	M	11.6	15.1
3. Burning Area Heat Release	$Kbtu/KJ/hr\text{-}M^2$	2.94	2.70
4. Burner Heat Input	$MW_{thermal}$	44	38
5. Burner Spacing:			
Horizontal	M	2.4	3.3
Vertical	M	3.6	4.6
6. Fuel N_2 (dry)	%	125	125
7. Overall Stoichiometry	%	125	125
8. NO_X @ 3% O_2 for Burner Zone Stoichiometry = 117%	ppm	470	397
9. NO_X @ 3% O_2 for Burner Zone Stoichiometry = 108%	ppm	405	353

Table II Comparison of Duck Creek and Roxboro NO_X Emissions

UNIT		DUCK CREEK	ROXBORO
Sample		Field	Field
Coal Type		Crown II	Lesley/ Marrowbone
Burner Design		CCV	CCV
Proximate Analysis (as rec'd)			
Moisture	(%)	16.2	6.4
Volatile	(%)	34.3	32.8
Ash	(%)	9.6	10.1
Fixed Carbon	(%)	39.9	50.7
Heating Value (Btu/lb)		10,345	12,379
Ultimate Analysis	(Dry)		
Carbon	(%)	68.7	74.4
Hydrogen	(%)	4.9	5.0
Nitrogen	(%)	1.19	1.42
Oxygen	(%)	9.91	7.68
Sulfur	(%)	3.8	0.70
Ash	(%)	11.5	10.80

Table III Coal Analyses Duck Creek and Roxboro

According to Martin and Bowen, intersection will best reduce NO_X under two conditions: (a) if the intersection takes place before all the volatiles are consumed in the second flame and (b) if fuel intermediates (H_2, CO, NH_3, etc.) are available to reduce the NO_X to N_2. The fuel intermediates will form in the primary combustion zone of a pulverized coal flame.

In TURBO® Furnace units, such as the one shown in Figure 20, the combustion products of both flames in the primary combustion zone intersect themselves near the burner exit. In opposed wall fired boilers, the firing configuration is not suitable to this type of flame intersection. Therefore, application of this NO_X reduction mechanism to Roxboro was eliminated from further consideration. It holds promise for reduction in a turbo furnace configuration.

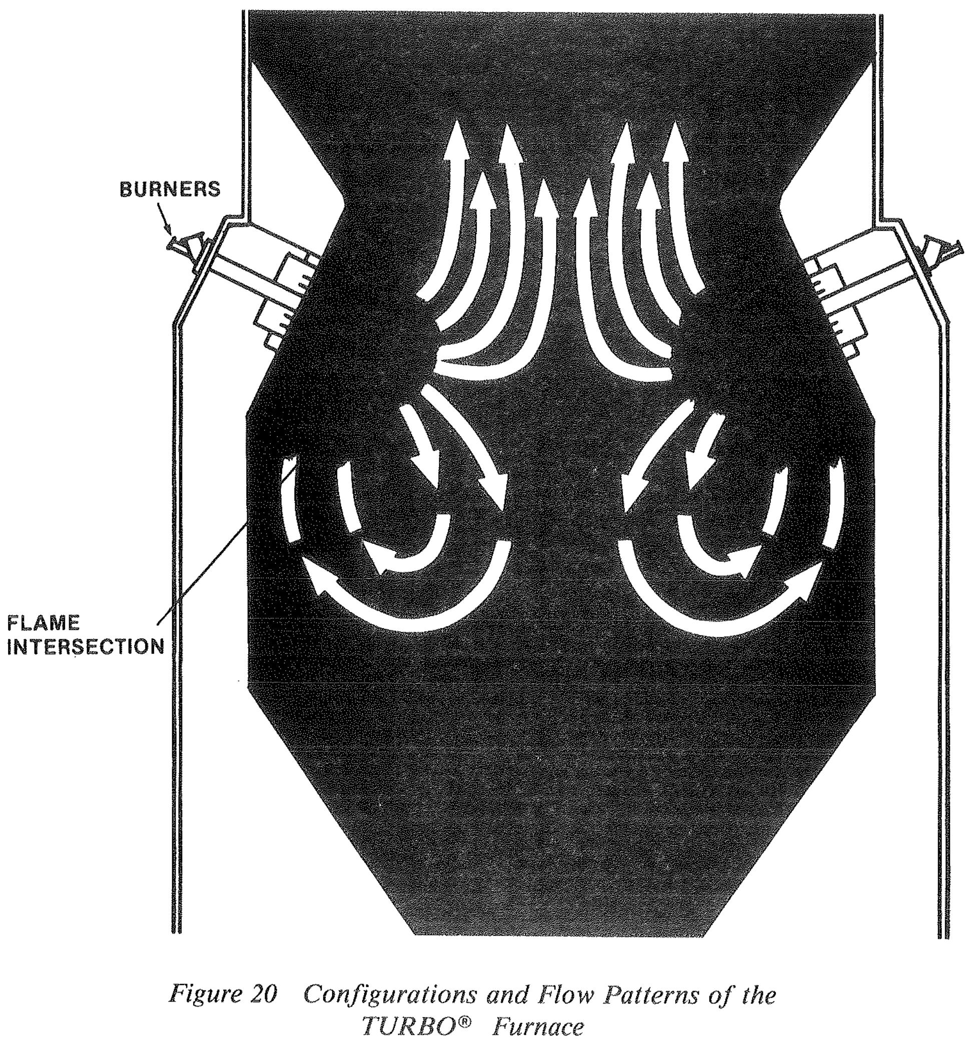


Figure 20 Configurations and Flow Patterns of the TURBO® Furnace

We concluded, therefore, that the additional 10% difference in NO_X emissions between Duck Creek and Roxboro was because of the relatively larger burner spacing and lesser amounts of slag build-up on the lower furnace waterwalls. These conditions altered the thermal environment in the burner zone such that thermal NO_X formation was lower at Roxboro than at Duck Creek.

FUTURE WORK

We will continue to advance our burner designs to further reduce NO_X emissions from the CCV burner. Our test facility at Riley Research, shown in Figure 21, can evaluate burners up to $30MW_{thermal}$ capacity (100×10^6 Btu/hr). Testing will investigate coal spreader and nozzle modifications along with tertiary air designs. The field data base of CCV burner installations will be expanded to include industrial as well as other utility size boilers. This will aid our predicting emissions and other performance parameters from low NO_X swirl stabilized burners.

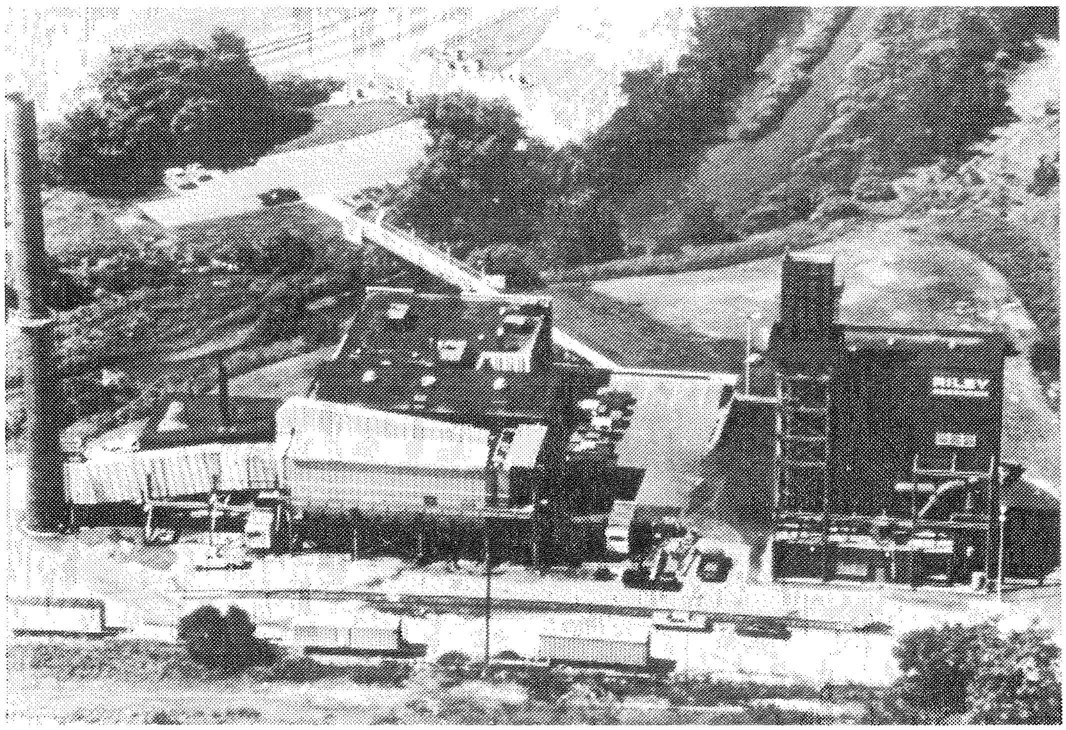


Figure 21 Riley Research Center

Laboratory and field testing will actively continue on the Riley Turbo Furnace and related equipment to meet future, more stringent NO_X emissions requirements for combustion of pulverized coal. Riley Stoker strongly feels the Turbo Furnace coupled with the proper advanced staged combustion technology will be the ultimate answer in NO_X reduction. Ongoing development programs are targeted to achieve NO_X emissions below 90 ng/J (0.2 lb/10^6 Btu) with reliable boiler operations.

CONCLUSIONS

In three full-size wall-fired utility boilers burning pulverized coal, the Riley CCV burner reduced NO_X emissions 40% to 60% without detracting from overall unit performance.

From the laboratory and field testing we concluded the following:

1. Alterations to coal spreader and nozzle geometry reduces NO_X emissions significantly.
2. Reducing burner zone stoichiometry through the use of tertiary air or underfire air ports lowers NO_X emissions.
3. With the proper spreader and nozzle design, the single register CCV burner will perform similarly to the dual register Distributed Mixing Burner.
4. In this study, a 1.22 scaling factor was used to predict NO_X emissions from the laboratory test furnace to the field. Field test results from the CCV burner indicated the final scaling factor was 1.32, only 8% higher.

5. Provided the thermal environment is similar, geometrically scaled prototype burners can be tested in a laboratory furnace and performance accurately predicted to the field.

To reduce NO_X emissions, the Riley CCV burner could easily be retrofitted into other pulverized coal wall-fired boilers without degradation of unit performance.

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