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FIELD EVALUATION OF LOW-EMISSION COAL BURNER TECHNOLOGY ON UTILITY BOILERS

VOLUME II

Second Generation Low-NO_x Burners

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16. ABSTRACT The report describes tests to evaluate the performance characteristics of three Second Generation Low-NOx burner designs: the Dual Register burner (DRB), the Babcock-Hitachi NOx Reducing (HNR) burner, and the XCL burner. The three represent a progression in development based on the orginal Babcock and Wilcox DRB. Of particular interest was the identification of burner configurations which would be suitable for application in the EPA LIMB (Limestone Injection Multistage Burner) technology demonstration program at Ohio Edison's Edgewater Station, Unit 4. The retrofit requirements for this unit were used to establish burner performance criteria. The testing was conducted with nominal full-scale burner designs, having a capacity of 78 million Btu/hr (22.9 MW). Each burner was tested over a wide range of operating conditions and hardware configurations, and with different coals. With appropriate adjustments, all burners were capable of achieving NOx emissions below 350 ppm (0% O2, dry), ~~with flame lengths less than 22 ft (6.7 m),~~ and with acceptable carbon in ash. However, the XCL burner was judged to have the best overall performance and to meet all the Edgewater boiler retrofit requirements. Additional brief tests were conducted to evaluate the impact of burner design on SO2 removal by injected sorbent materials.

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Pollution	Calcium Carbonates	Pollution Control	13B
Coal	Calcium Oxides	Stationary Sources	21D
Combustion	Electric Utilities	Low-NOx Burners	21B
Nitrogen Oxides		Dual Register Burners	07B
Sulfur Oxides		HNR Burners	
Burners		XCL Burners	13A

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ABSTRACT

This report describes a series of tests designed to evaluate the performance characteristics of three Second Generation Low-NO_x burner designs. These burner designs were, the Dual Register Burner (DRB), the Babcock-Hitachi NO_x Reducing (HNR) burner, and the XCL burner, which represent a progression in development based upon the original Babcock & Wilcox DRB. Of particular interest was the identification of burner configurations which would be suitable for application in the EPA Limestone Injection Multistage Burner (LIMB) technology demonstration program at Ohio Edison's Edgewater Station, Unit 4. The retrofit requirements for this unit were used to establish burner performance criteria.

The testing was conducted with nominal full-scale burner designs, having a capacity of 78 x 10^6 Btu/hr (22.9 MW). Each burner was tested over a wide range of operating conditions and hardware configurations, and with different coal types. With appropriate adjustments, all burners were capable of achieving NO_x emissions below 350 ppm (0%,O_2, dry), with flame lengths less than 22 feet (6.7m), and with acceptable carbon in ash. However, the XCL burner was judged to have the best overall performance and to meet all the Edgewater boiler retrofit requirements.

An additional brief series of tests was conducted to evaluate the impact of burner design on SO_2 removal by injected sorbent materials. When limestone and hydrated lime were injected into the upper furnace, remote from the burners, no impact of burner design was observed. Significant differences in SO_2 removal were measured only when sorbent was injected through the burner secondary air passage.

This work was carried out by Energy and Environmental Research Corporation under EPA Contract 68-02-3130, through Babcock and Wilcox Subcontract 940962 NR.

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1.0 SUMMARY

The objective of this contract was to evaluate the performance of low-emission burner technology, specifically the U.S. Environmental Protection Agency developed Distributed Mixing Burner (DMB), in a utility boiler application. The initiation of the LIMB (Limestone Injection Multistage Burner) technology demonstration at the Ohio Edison Edgewater Station, Unit 4, provided an opportunity to broaden the overall scope of this project.. The objective of this LIMB program with respect to burner design was to provide a commercial pulverized coal burner that demonstrates a reduction in nitrogen oxide (NO_x) emissions of at least 50 percent relative to uncontrolled performance of the original Babcock & Wilcox (B&W) Circular burners. This performance must be achieved within the following requirements for the Edgewater boiler:

- 78×10^6 Btu/hr heat input per burner.
- Throat diameter no greater than 35 inches.
- Mechanical reliability meeting commercial standards.
- Flame length less than the firing depth of the boiler, 22 ft 3 in.
- Burner pressure drop within fan limitations nominally 5 in. W.G.
- Acceptable combustion efficiency.

The three B&W low-NO_x burner designs considered; the Dual Register Burner (DRB), Babcock-Hitachi NO_x Reducing (HNR) burner, and the XCL burner, were tested at full scale in the EPA Large Watertube Simulator (LWS) to determine the optimum design for use at the Edgewater boiler as part of this contract. Full size 78×10^6 Btu/hr burners can be accommodated by the LWS, minimizing scale-up questions, and, by coincidence, the LWS has a firing depth of 22 ft, essentially the same as Edgewater Unit 4. Screening tests of the three basic burner designs were conducted firing Pittsburgh #8 coal, the coal to be used during the LIMB demonstration, to determine optimum operating conditions. In addition to available burner adjustments, a number of burner hardware components were also evaluated to establish the optimum burner design. A brief set of sorbent injection tests was completed for a selected configuration of each basic burner to determine the affect of burner design on SO_2 capture. Following the screening tests of the three burners, selected XCL burner configurations were characterized with three additional, distinctly different coals to broaden the application of this new burner.

1.1 Test Burners

The three Second Generation Low-NO_x burner designs considered for this program represent a progression in development which began with the B&W Dual Register Burner. The burners are based on the same basic concept, using multiple air zones to allow controlled, delayed-mixing of the fuel and combustion air. The Dual Register Burner was the first in the line of development. Data from tests of two DRB designs are presented: a DRB designed to fit the same burner exit as the HNR and XCL burners, denoted the Low-Velocity DRB and a standard Phase V DRB tested under B&W P.O. 635-0A008408 DM. The Babcock-Hitachi NR burner, in turn, incorporated modifications to the basic DRB by varying air flow distribution and velocities and by adding hardware enhancements. The hardware enhancements were an extended baffle, or Air Separation Plate, between the inner and outer secondary air zones and a Flame Stabilizing Ring at the exit of the coal nozzle. The XCL burner represents the product of B&W development to improve the HNR burner with enhanced mechanical reliability and reduced pressure drop, and air measurement capability.

The burners all consist of three concentric passages: a central, cylindrical coal nozzle surrounded by two annular secondary air passages. Both secondary air passages for all three incorporate swirl generators, either axial spin vanes or radial register louvers. Each burner also has some control, over air distribution between the inner and outer air zones. The key components of each basic burner design are summarized in Table 1-1.

A number of alternative burner components were evaluated with each of the three basic burners. Components that can be classified as coal pipe devices included:

TABLE 1-1. COMPONENTS OF BASIC BURNER DESIGNS

Component	DRB	HNR	XCL
Coal Dispersal	Diffuser	Flame Stability Ring Swirler	Diffuser
Inner Secondary Swirl	Adjustable Axial Spin Vanes	Adjustable Axial Spin Vanes	Adjustable Axial Spin Vanes
Outer Secondary Swirl	Register of Radial Louver	High Swirl Radial Register	Adjustable Axial Spin Vanes
Inner Secondary Flow Control	Sliding Sleeve Damper	Sliding Sleeve Damper	Sliding Sleeve Damper
Outer Secondary Flow Control	Dependant on Swirl	Dependant on Swirl	Sliding Sleeve Damper
Inner/Outer Secondary Separation	Internal Divider	Extended Air Separation Plate	Extended Air Separation Plate
Secondary Air Flow Measurement	None	None	Inner/Outer Zone Pitot Grids

- Coal diffuser--a bluff body dispersal device located at the inlet of the coal nozzle (tested with DRB, HNR, and XCL).

- Coal pipe venturi--a coal dispersal device located at the inlet of the coal nozzle consisting of a venturi to concentrate then disperse the coal stream (tested only with Phase V DRB).

- $DeNO_X$ Stabilizer--a proprietary B&W device designed for easy insertion into the coal nozzle. (Tested with Low-Velocity DRB and XCL burners).

Five coal impellers and swirlers were evaluated:

- 75^{o} included angle impeller (Low-Velocity DRB)
- 20^{o} included angle impeller (XCL)
- 30^{o} included angle impeller (XCL)
- Open impeller (XCL)
- HNR burner swirler

Two coal nozzle exit devices were tested: the Flame Stabilizing Ring, tested with all three burner designs, and an expanded nozzle tip tried only with the XCL burner. Modifications to the secondary air zones included modifications to widen outer air vanes (HNR and XCL burners), addition of an extended Air Separation Plate (all three burners), and installation of fixed swirl vanes in the outer zone (XCL burner only).

1.2 Fuels and Sorbents

Four different coals were utilized during the Second Generation Low-NO_X burner tests. Table 1-2 summarizes the composition of the coals. The Pittsburgh #8 coal was the primary fuel used throughout the burner tests. Pittsburgh #8 coal is a high-volatile A bituminous coal selected for the LIMB demonstration project at Edgewater Station Unit 4. Since the ultimate goal

TABLE 1-2. COMPOSITION OF TEST COALS

Coal	Pittsburgh #8		Utah		Comanche		Lower Kittanning	
Reporting Basis	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry
Proximate (wt %)								
Moisture	3.50	0.00	6.11	0.00	22.44	0.00	2.43	0.00
Ash	12.92	13.40	8.02	8.55	5.00	6.45	10.19	10.44
Volatile	33.75	34.98	41.26	43.96	36.12	44.87	23.93	24.52
Fixed C	49.83	51.62	44.60	46.73	37.72	48.68	63.45	65.04
Heating Value								
Btu/lb	12,177	12,618	12,288	13,088	9,325	12,026	13,551	13,888
MMF Btu/lb		14,876		14,440		12,939		15,701
MAF Btu/lb		14,626		14,311		12,855		15,507
Ultimate (wt %)								
Moisture	3.50	0.00	6.11	0.00	22.44	0.00	2.43	0.00
Carbon	68.13	70.59	68.58	71.86	54.25	69.97	76.82	78.73
Hydrogen	4.63	4.79	5.16	5.49	3.80	4.91	4.54	4.65
Nitrogen	1.21	1.26	1.28	1.36	0.76	0.98	1.12	1.15
Sulfur	3.22	3.30	0.60	0.64	0.43	0.56	1.13	1.16
Ash	12.92	13.40	8.02	8.55	5.00	6.45	10.19	10.44
Oxygen*	6.41	6.63	10.24	10.91	13.32	17.14	3.77	3.87
Forms of Sulfur (wt %)								
Sulfate	0.22	0.23	0.01	0.01	0.02	0.02	0.01	0.01
Pyritic	1.62	1.65	0.13	0.13	0.09	0.12	0.53	0.54
Organic	1.38	1.42	0.46	0.50	0.32	0.42	0.60	0.62

*Oxygen determined by difference.

of these burner tests was the selection of the optimum burner for retrofit at the Edgewater boiler, the use of the same coal enabled direct projection of expected burner performance. The other three coals represent a wide range of coal types and were used to characterize the performance of the optimized XCL burner. Utah coal is a western high-volatile A bituminous coal from the Starpoint mines in Wattis, Utah. Utah coal has been used at EER as the base fuel for most of the low-emission, high-efficiency burner development projects. Use of this coal allows comparison of the Second Generation low-NO_x burner performance with an existing data base of other burners. The Comanche coal is a subbituminous coal from Wyoming. The Lower Kittanning is a medium-volatile bituminous coal.

Two sorbents were used during these tests to evaluate SO_2 reduction potential by in-furnace injection, Vicron 45-3 limestone and Colton hydrated lime. These sorbents have been used at EER as typical limestone and hydrated lime materials in the development of LIMB technology. Vicron is nominally 99 percent pure $CaCO_3$ with a mass median diameter of 9.8 μm. The Colton hydrated lime is nominally 96 percent $Ca(OH)_2$ with a median particle size of 4.0 μm.

1.3 Burner Performance and NO_x Emissions

Optimization tests of the three basic burner designs screened the available burner adjustments as well as the various burner component configurations. The three basic components of each burner; the coal injector, inner secondary air zone, and outer secondary air zone, were evaluated in these screening tests. The results from these tests can be easily generalized for all three low-NO_x burners with respect to sensitivity of performance. In each case, the coal injector was the dominant factor that determined the key performance characteristics of NO_x, flame length, and carbon burnout. Both the design of the coal injector and the available adjustments could produce up to 67 percent reduction in NO_x emissions. The outer secondary air zone, the degree of swirl and the air flow rate through the outer passage, was second in importance to burner performance. The inner air zone parameters of swirl and air flow rate generally had the least effect on performance.

Consistent and recurring throughout the screening tests of all three burners was the close correlation of NO_x emissions with flame length. Data from tests of the Dual Register Burner, HNR burners, and the initial screening tests of the XCL burner, summarized in Figure 1-1, clearly shows this correlation. At 20 percent excess air and full load conditions, this data indicates that for a flame less than the firing depth of the Edgewater boiler, NO_x emissions in the range of about 300-400 ppm* were achieved by several burner configurations. With flame length as the most severe constraint at the Edgewater boiler, only eight of the 20 burner configurations tested in this program and five Phase V DRB configurations achieved flames less than 22 ft in length. These are listed in Table 1-3.

Dual Register Burner. The Low-Velocity DRB designed to fit within the same throat as the other two candidate burners, the HNR and XCL, produced excessively long flames for three of the four configurations. Only an unoptimized 75° impeller design produced a flame less than the 22 ft furnace firing depth. Full load NO_x emissions for the three configurations which produced flames over 22 ft long were low, ranging from 264 to 386 ppm. The 75° impeller-equipped configuration produced an average of 732 ppm NO_x at full load with 17-18 ft flames. Available data from the B&W sponsored test program suggest that the performance of this Low-Velocity DRB is not representative of the current commercial Phase V DRB. Flames less than 22 ft long could be achieved with five different configurations of the Phase V DRB with its slightly higher velocities, albeit with slightly higher NO_x emissions (292-372 ppm). To achieve that performance required tightly closed burner settings, uncharacteristic of typical DRB operation, which produced burner pressure drops over 6 in. W.G.

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*All emission concentrations reported corrected to 0 percent O_2 on a dry basis, except where indicated.

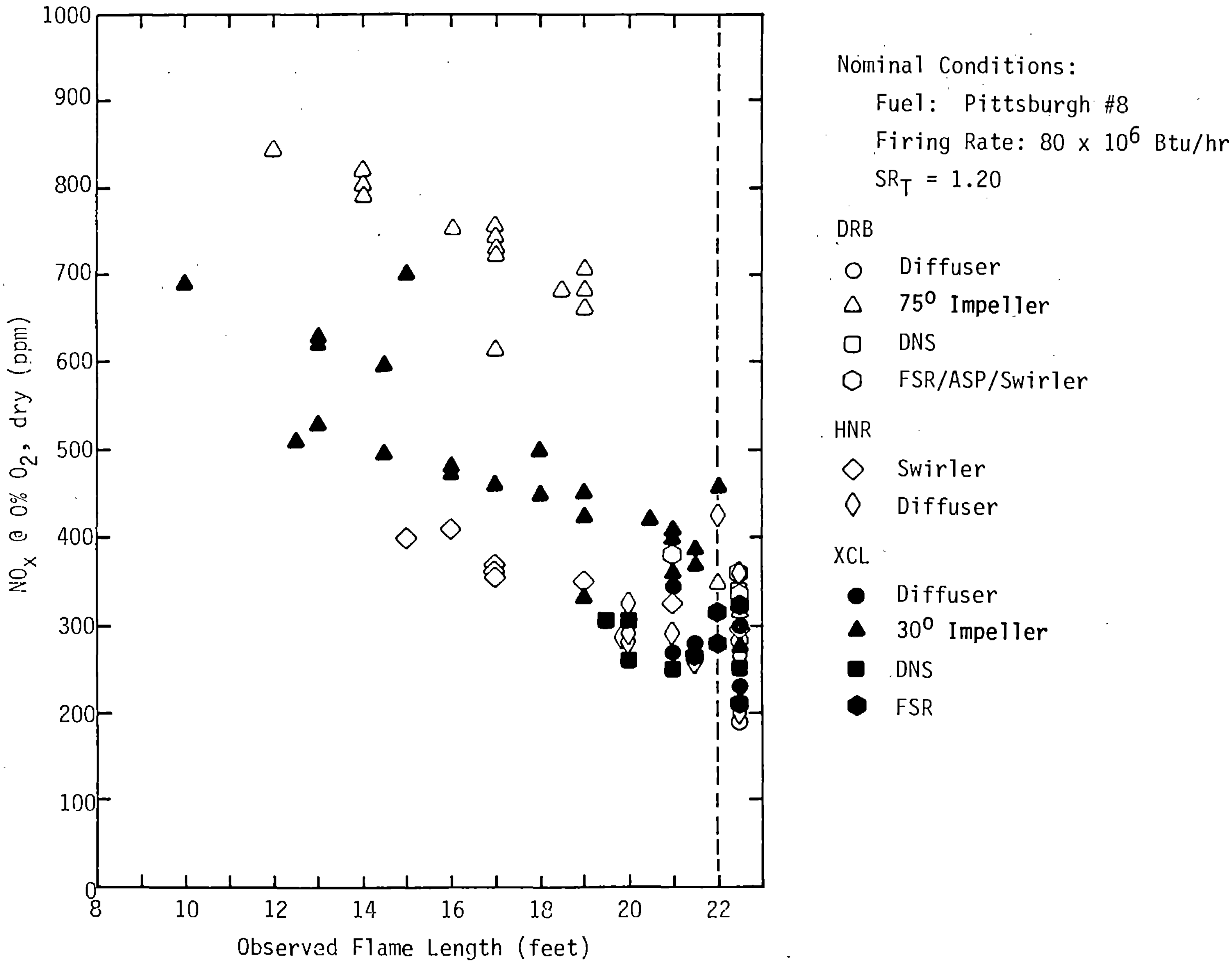


Figure 1-1. Correlation of NO_x emissions with flame length.

TABLE 1-3. SECOND GENERATION LOW NO_x BURNERS WITH FLAMES ≤22 FT LONG (78×10^6 Btu/hr, $SR_T = 1.20$)

Burner	Configuration	NO_x @ 0% O_2 (ppm)	Flame Length (ft)	Fly Ash Carbon (wt.%)	Burner ΔP (in. W.G.)
Low-Velocity DRB	75° Impeller	708	18	7.28	6.0
Phase V DRB	Diffuser	372	20-21	6.12	10.8
	Venturi	350	20-21	6.45	11.0
	Diffuser, ASP	326	22	3.20	6.4
	Diffuser, FSR	292	22	6.96	10.5
	Diffuser, FSR, ASP	328	22	5.16	11.0
HNR	Swirler	348	18-20	N/A	7.20
	Diffuser	289	20	3.34	7.50
XCL	DNS	288	20	N/A	8.20
	30° Impeller, Standard Nozzle	374	20-22	4.42	3.30
	30° Impeller, Expanded Nozzle	546	19-20	1.36	4.30
	20° Impeller, Expanded Nozzle	338	21	4.92*	4.90
	30° Impeller, Standard Nozzle, Fixed Outer Vanes	420	21-22	3.40	4.60

*Data for $SR_T = 1.16$

Babcock-Hitachi NR Burner. The Babcock-Hitachi NR burner relies on biasing the secondary combustion air to the outer zone coupled with a very high degree of swirl for flame shaping and NO_x control. Minimum NO_x emissions were 222 ppm with a flame over 22 ft long using burner settings typical of Babcock-Hitachi practice. The two other configurations evaluated produced higher NO_x emission, 289-348 ppm, but with correspondingly shorter flames, 18-20 ft long. In each case, however, burner pressure drop was about 7 in. W. G.

XCL Burner. The XCL burner, which represents the latest development in the B&W Dual Register Burner evolution, was tested in 13 configurations during 2 series of tests. This burner design demonstrated the most potential to meet the LIMB demonstration goals because of its inherent flexibility. NO_x emissions ranged from 194-700 ppm with flames from 12 to over 22 ft long. Only five configurations yielded flames less than 22 ft long with NO_x emissions from 288 to 546 ppm. The unique B&W DeNO_x Stabilizer achieved the lowest emissions but required burner settings producing a burner pressure drop of 8.20 in. W. G. The other configurations were based on either a 20^o or 30^o coal impeller design. The impeller-equipped XCL configurations could achieve a wide range of NO_x and flame length by the adjustment of the impeller position, all with burner pressure drop less than 5 in. W. G. At optimum conditions, the 20^o impeller in an expanded coal nozzle gave 338 ppm NO_x while the 30^o impeller in the standard coal nozzle gave 374 ppm.

From these numerous burner configurations, two stand out as suitable for application for the LIMB demonstration. All configurations tested met the requirements of a firing capacity of 78 x 10^6 Btu/hr burner, a throat diameter no greater than 35 inches, and mechanical reliability meeting commercial standards. The Edgewater boiler also imposed the constraint on flame length, 22 ft, and on maximum tolerable burner pressure drop, about 5 in. W.G. In addition, the burners had to produce a stable flame with low emissions but high combustion efficiency. The two configurations meeting all those conditions were:

- XCL burner with 30^o impeller in the standard coal nozzle with appropriate outer vane design.

- XCL burner with 20^o impeller in an expanded coal nozzle.

Performance of these two configurations is summarized in Table 1-4. In addition to meeting all Edgewater boiler requirements, the two impeller-equipped XCL burner configurations offer a very effective means of optimizing performance to suit the application. This control mechanism is the adjustable position of the coal impeller. For both designs, flame length and NO_x emissions can be varied simply by moving the impeller a matter of inches. The impeller adjustment can thus be used to tune the burner for maximum NO_x reduction within the constraints of available firing depth.

1.4 SO_2 Reduction Potential

A brief series of sorbent injection tests were performed for a selected configuration of each burner design; DRB, HNR and XCL burners. Two near burner locations and two upper furnace locations were evaluated at nominal full-load conditions. Vicron 45-3 limestone was injected through the three locations closest the burner and Colton hydrated lime was injected through the two upper furnace locations.

As expected, SO_2 capture was not influenced by burner design when sorbent was injected through the two upper-furnace locations. At the lower level, corresponding to a gas temperature of about 2500^{o}F, limestone achieved 33 percent capture at Ca/S molar ratio of 2 while the hydrated lime achieved 36 percent capture. At the uppermost level, corresponding to 2150^{o}F gas temperature, the hydrated lime achieved 38 percent capture at a Ca/S molar ratio of 2.

The two near-burner locations considered were injection with the coal and injection through four high-velocity nozzles in the outer secondary air passage. Limestone injected with the coal achieved only 28-32 percent capture at a Ca/S molar ratio of 2 for all three burners. The injection of

TABLE 1-4. OPTIMUM BURNER CONFIGURATIONS FOR EDGEWATER UNIT 4 (78×10^6 Btu/hr SR_T = 1.20)

Burner	NO_x @ 0% O_2 (ppm)	Flame Length (ft)	Fly Ash Carbon (wt %)	Burner ΔP (in. W.G.)
XCL w/30° Impeller, Standard Coal Nozzle	374	20-22	4.42	3.30
XCL w/20° Impeller, Expanded Coal Nozzle	338	21	4.92	4.90

limestone through the outer secondary air passage yielded higher SO_2 capture for the DRB equipped with the 75° impeller (40 percent at CaS molar ratio of 2) than for the HNR and XCL burners (30 percent capture). This difference in results is not fully understood, but appears to be associated with the near-burner flow field as suggested by flame shape.

2.0 INTRODUCTION

In the broad context of the title of this project, the objective of this program is the evaluation of low-emission burner technology for utility boiler application. The particular burner technology of interest was the Distributed Mixing Burner (DMB), developed by the U.S. Environmental Protection Agency (EPA) at Energy and Environmental Research Corporation (EER). The effectiveness of the DMB was to be determined by direct comparison with the original equipment burners in one representative operating utility boiler. Difficulties in finding a host boiler to participate in a demonstration, retrofitting existing burners with the new DMB technology resulted in delays to the overall program. These delays, in turn, caused escalating costs for a full utility boiler retrofit with DMBs. Because of these problems, the program was restructured to achieve its objective without installation of the DMB in a utility boiler. The approach taken was extensive testing of DMBs at two scales and two B&W commercial burner designs in the EPA Large Watertube Simulator (LWS) coupled with field tests at utility boilers equipped with the two B&W commercial burners. This approach provided data for burner scaleup, performance characteristics of the DMB compared to commercial burners, and commercial burner performance in utility boilers. With this data, the expected performance of DMBs could be extrapolated to utility boilers with some confidence.

The EPA Limestone Injection Multistage Burner (LIMB) demonstration provided motivation to further extend the scope of this program. The LIMB project, being conducted at Ohio Edison's Edgewater Station, Unit No. 4, is a demonstration of combined NO_x and SO_2 control with low-NOx burners and in-furnace sorbent injection for SO_2 control. The objective of this LIMB demonstration with respect to burner design and NO_x emissions is to achieve 50 percent NO_x reduction compared to uncontrolled baseline performance of the original burners. This performance must be achieved within the constraints of the Edgewater boiler. These constraints or requirements include:

- High combustion efficiency.
- 78 x 10^6 Btu/hr heat input per burner.

- Throat diameter no greater than 35 inches.
- Flame length less than the firing of the boiler, 22 feet, 3 inches.
- Burner pressure drop commensurate with fan limitations, nominally 5 inches W.G.
- Mechanical reliability meeting commercial standards.

Three B&W low-NO_X burner designs were under consideration for the LIMB demonstration at the Edgewater boiler: the Dual Register Burner (DRB), Babcock-Hitachi NO_X Reducing burner (HNR), and the XCL burner. The DRB and the HNR burners have demonstrated low emissions in utility boilers and are commercially available equipment. The XCL burner was developed based on the HNR burner concept, but incorporating mechanical enhancements. The Edgewater boiler design, the shallow firing depth in particular, imposes a severe constraint on these low-NO_X burners. Boilers of its vintage (1950-60) were designed with high swirl, high turbulence Circular burners which produce short, wide flames conducive to good combustion and high NO_X emissions. Low-NO_X burners have longer, narrower flames from the inherent delayed mixing designs. This constraint was a key motivation to test full size burners prior to installation at Edgewater to demonstrate compatibility to the boiler firing depth.

This low-emission burner technology evaluation program provided a unique opportunity to benefit both this low-emission burner evaluation program and the LIMB demonstration. This program benefited by broadening the data base of low-emission burner technology with three additional burners and by directly participating in the application of low-NOx burners to an operating utility boiler. The LIMB project, in turn, was provided with an opportunity to develop and demonstrate a burner that would provide optimum performance within the constraints of the Edgewater boiler prior to installation. By coincidence, the test facility used for this program, the LWS, has a firing depth of 22 feet and thus provided the same constraint as the Edgewater boiler. Full size, 78×10^6 Btu/hr burners can be accommodated and questions of scale-up are minimized.

The specific goals for the evaluation of these second generation low-NO_x burners were to:

1. Evaluate and optimize the performance of three low-emission burners.

2. Determine the compatibility of each burner to the Edgewater boiler.

3. Project emissions performance of the optimized burner to Edgewater Unit 4.

These objectives were accomplished in two series of tests in the LWS. The first series consisted of screening tests to optimize the performance of each burner in terms of low-NO_x emissions, flame length, and combustion efficiency. These screening tests included evaluation of both adjustable burner parameters and selected hardware modifications over a range of firing rate and excess air. A brief set of in-furnace sorbent injection tests was completed for each burner to determine the influence of burner design. The optimum configuration from these initial screening tests was further refined in the second test series. The final burner configuration was then characterized with four distinct coal types, including typical eastern bituminous, subbituminous, western bituminous, and medium-volatile bituminous. The final burner configuration became the low-NO_x burner selected for the LIMB demonstration.

3.0 BURNER DESIGNS AND EXPERIMENTAL SYSTEMS

The evaluation of B&W second generation low-NO_x burners involved testing three coal burner designs:

- Dual Register Burner
- Babcock Hitachi NO_x Reducing Burner
- XCL Burner

These burners evolved from the same basic concept, using multiple air zones to allow controlled, delayed-mixing of the fuel and combustion air. In fact, these three burners represent a progression of development which began with the B&W Dual Register Burner. Babcock-Hitachi, in turn, incorporated modifications to the basic DRB by varying air flow distribution and velocities and by adding burner hardware enhancements. The XCL burner represents the product of B&W development to improve the HNR burner with enhanced mechanical reliability, air flow measurement capabilities, and reduced burner pressure drop. The test burners were designed to meet the requirements at the Edgewater boiler, having a firing capacity of 78 x 10^6 Btu/hr and a throat diameter no greater than 35 inches.

The tests were conducted by EER in the EPA Large Watertube Simulator at EER's El Toro, California, test facility. Parametric screening tests, including hardware modifications, were conducted for each burner to optimize their performance for low-NO_x emissions, high combustion efficiency, flame length less than 22 feet, and burner pressure drop. The coal used for burner optimization was Pittsburgh No. 8 coal, the high volatile eastern bituminous coal to be used during the LIMB demonstration at Edgewater Unit 4. The final optimized burner was evaluated with three alternate coals which represent a wide range of coal types: Utah western bituminous, Lower Kittaning medium-volatile bituminous, and Comanche, a western sub-bituminous coal. In addition to optimizing the burners for low-NO_x emissions, a brief series of sorbent injection tests were also conducted for each burner to determine whether burner design affects the degree of SO_2 control. All testing was conducted in accordance with established Quality Assurance procedures following EPA guidelines. Documentation of the Quality Assurance program is in Part V, Appendix A, of this report.

3.1 Dual Register Burners

The Dual Register burner was developed by B&W to replace the Circular burner. The DRB has undergone several phases of development, incorporating modifications to improve operability and combustion efficiency while achieving low-NO_x emissions[1-4]. For this program, B&W designed a DRB to fit the requirements at the Edgewater boiler. The test burner was designed for a nominal firing rate of 78 x 10^6 Btu/hr, but was sized to fit the same throat as the HNR and XCL burners. This was done by B&W to facilitate burner changes in the LWS and to directly compare the effects of burner hardware. This resulted in secondary air velocities lower than standard DRBs. While this Low Velocity DRB was the subject of this program, a 78 x 10^6 Btu/hr Phase V DRB with standard design velocities was the subject of B&W sponsored tests (B&W P.O. 635-0A008408 DM) in the LWS outside this project. A summary of the standard Phase V DRB tests is included in this report for comparison.

The basic configuration of the Low Velocity DRB and the standard Phase V DRB is the same. A cross-section of the basic DRB is shown in Figure 3-1. The burner consists of three concentric passages: a central, cylindrical coal nozzle surrounded by two annular secondary air passages. Coal, transported by primary air, enters the coal nozzle through a 90^o elbow. In the basic configuration, a bluff body diffuser is located at the inlet to the coal nozzle. This diffuser produces a uniform coal distribution across the coal nozzle without imparting any swirl to the primary air/coal stream. The secondary air is split between two annular passages. The inner passage is equipped with an adjustable damper for flow control and a set of adjustable axial spin vanes for swirl control. The outer secondary air passage utilizes adjustable radial register vanes, or doors, for both flow and swirl control. The DRBs, as well as the HNR and XCL burners, utilized a steel throat and exit which were water-cooled during the tests in the LWS. In actual boiler installations, the burner exit is generally formed by tube bends in the water wall covered by a thin refractory layer.

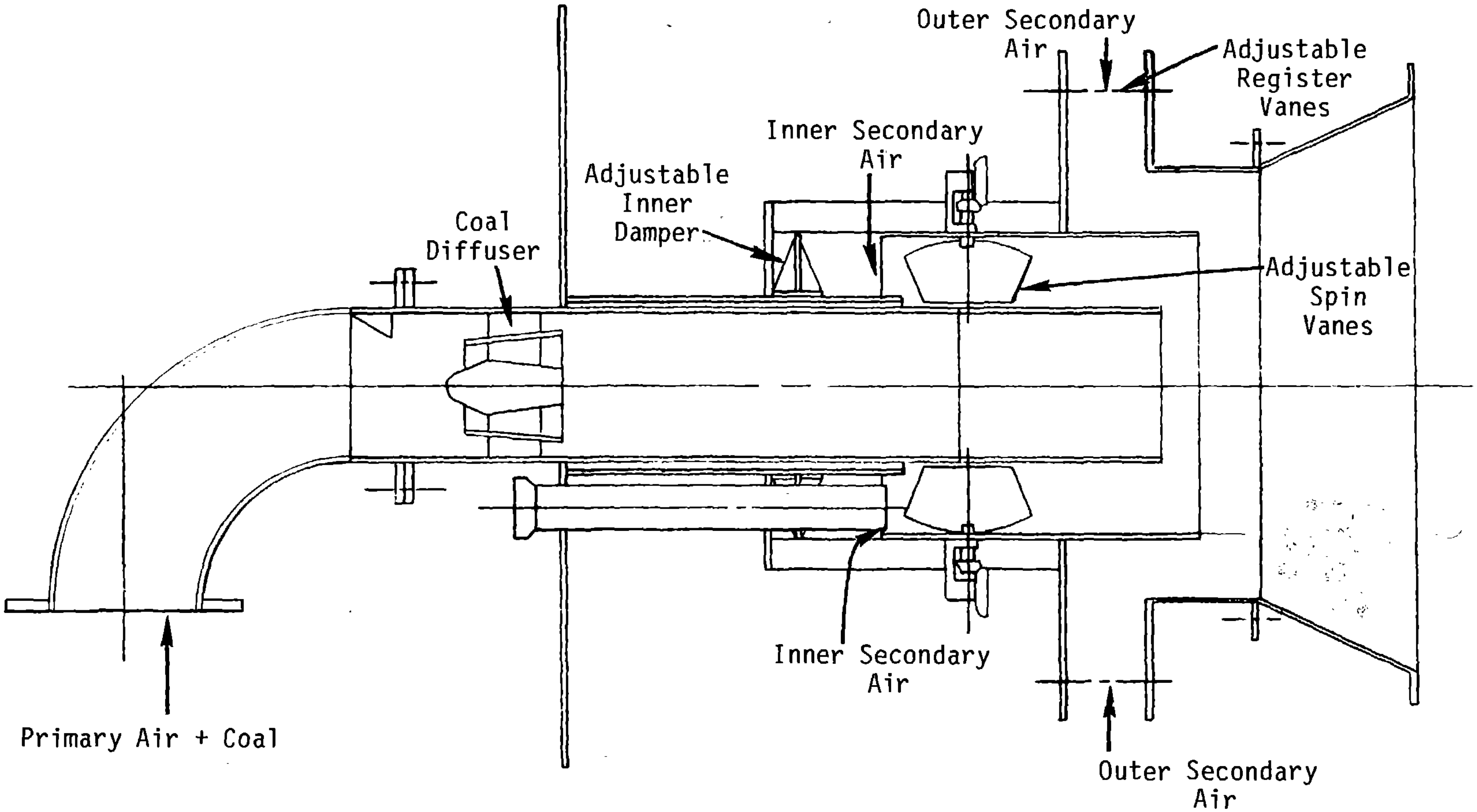


Figure 3-1. Cross-sectional view of the B&W Dual Register Burner.

In addition to the basic configuration of the Low Velocity DRB and standard Phase V DRB, several hardware modifications were evaluated to shorten the flame length and/or enhance flame stability. The modifications evaluated with each DRB are listed in Table 3-1. These modifications are described in Section 3.4.

3.2 Babcock-Hitachi NO_x Reducing Burner

The Babcock-Hitachi NR burner, shown in Figure 3-2, was developed from the basic DRB configuration to meet the stringent emissions limits in Japan. The HNR burner retains the general design features of the DRB, namely a central coal nozzle surrounded by two concentric annular secondary air passages; axial spin vanes for the inner zone; a sliding damper to control air flow to the inner zone, and a register of radial vanes to control the outer secondary air. From this basic concept, Babcock-Hitachi developed modifications to achieve lower emissions than the DRB. The modifications included air flow distribution between the inner and outer secondary air passages, secondary air velocities, and burner hardware enhancements to produce a unique flow pattern.

The burner hardware enhancements that are integral components to the HNR burner include: a Flame Stabilizing Ring (FSR), Air Separation Plate (ASP), and an outer secondary air register with a larger number of vanes. The Flame Stabilizing Ring is located at the exit of the coal nozzle. This device is designed to produce a stable flame core by creating recirculation eddies at the coal nozzle exit. The Air Separation Plate is a baffle between the inner and outer secondary air passages that extends the division of the two air zones into the exit. This delays mixing between the inner and outer air zones. The angle of this Air Separation Plate also deflects the outer secondary air away from the flame core to delay mixing and shape the flame. Babcock-Hitachi also modified the outer secondary air register to increase the degree of swirl generated. This was done by increasing the number of register vanes of the basic DRB outer register assembly.

TABLE 3-1. DUAL REGISTER BURNER HARDWARE MODIFICATIONS

Hardware Modification	Low Velocity DRB	Phase V DRB
Coal Diffuser--Current DRB Standard	X	X
Coal Venturi--Original DRB Practice		X
Impeller--10-in. Diameter 75° Included Angle	X	
$DeNO_x$ Stabilizer	X	
Air Separation Plate		X
Flame Stabilizing Ring		X
Air Separation Plate + Flame Stabilizing Ring	X	X

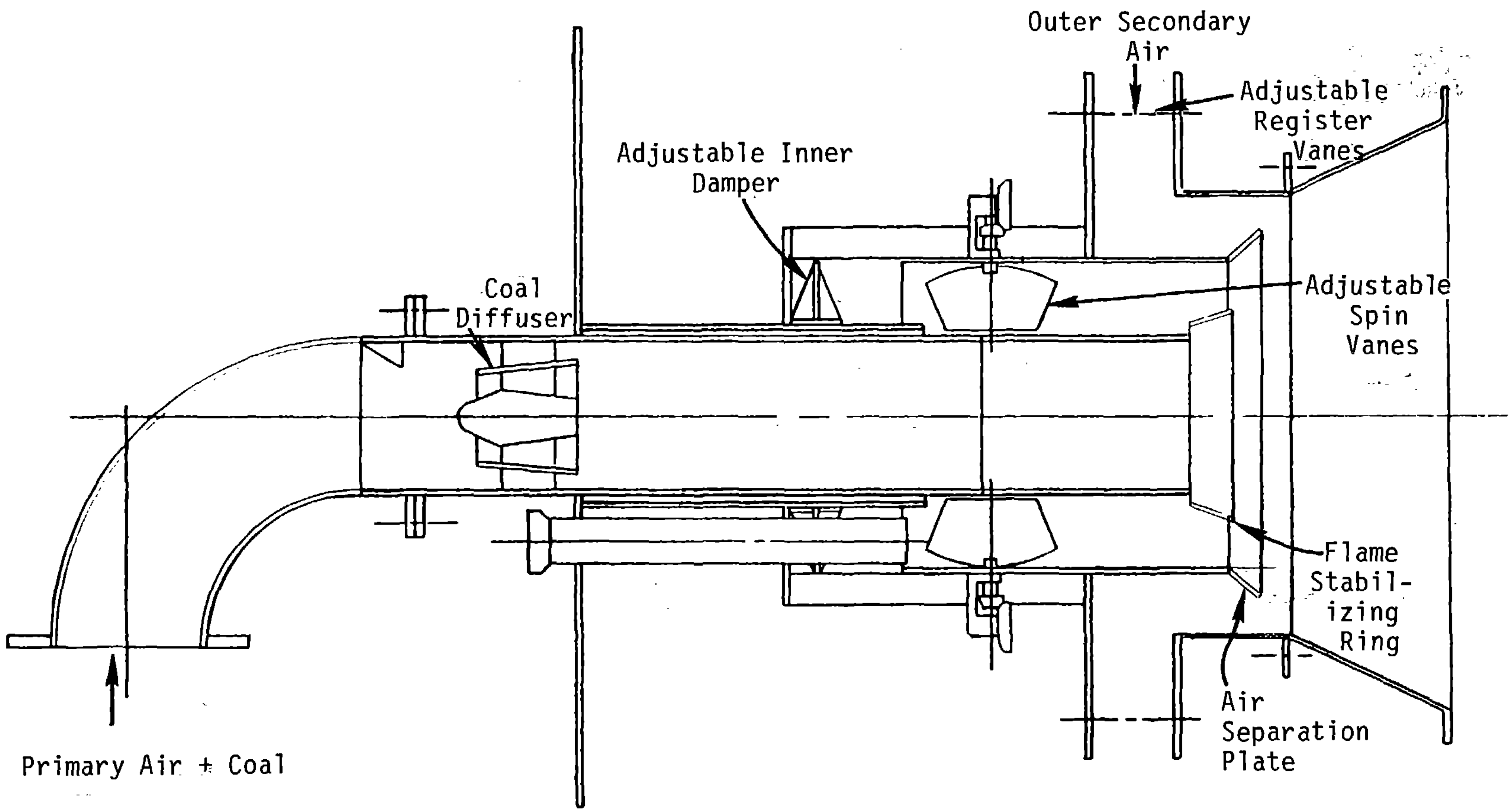


Figure 3-2. Cross-sectional view of the Babcock-Hitachi NO_x Reducing Burner.

During the combustion tests of the HNR burner in the LWS, optimization included evaluating several variations of the basic burner arrangement. The configurations evaluated were the HNR burner with a coal swirler, the HNR burner with the B&W coal diffuser, and the HNR burner with a modified outer register assembly. The coal swirler, shown in Figure 3-3, is located in the coal pipe just upstream of the Flame Stabilizing Ring. The relatively open design of the swirler imparts a small amount of spin to the primary coal stream. The swirler is incorporated in the basic configuration of the HNR burner. The standard B&W coal diffuser, the current coal nozzle device used in the standard DRB, was evaluated as an alternative to the swirler in the HNR burner. The diffuser is a proven low wear device and low NO_x device, and thus could improve the reliability of the HNR burner. The outer register assembly was also modified to meet Babcock-Hitachi vane clearance specifications. The assembly supplied by B&W for the tests apparently had excessive clearances around the vanes that decreased the effectiveness of swirl generation by allowing air to leak around the vanes. The vanes were widened to reduce this leakage.

3.3 XCL Burner

The B&W XCL burner, shown in Figure 3-4, is the most recent development in the evolution of DRB technology. Building on the HNR burner concept, B&W incorporated features to improve burner operability by enhancing mechanical reliability, adding air measurement capabilities, and reducing burner pressure drop. As the other two burners, the XCL is a multi-passage burner having a central cylindrical coal nozzle, two concentric annular air passages, and an identical 90° elbow coal inlet. The basic XCL burner incorporates the B&W coal diffuser at the coal nozzle inlet to produce a uniform coal distribution at the burner exit. The XCL burner also incorporates an Air Separation Plate similar to the HNR design. The inner secondary air passage is equipped with a sliding damper for flow control and adjustable axial spin vanes for swirl control similar to both the DRB and HNR burner.

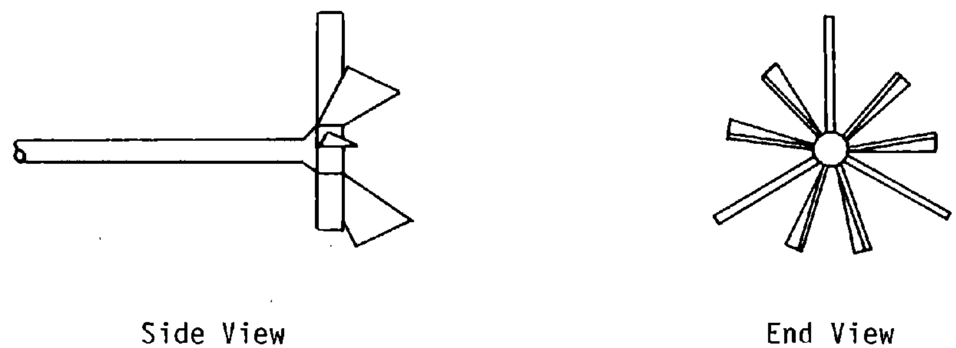


Figure 3-3. Babcock-Hitachi NR burner coal swirler.

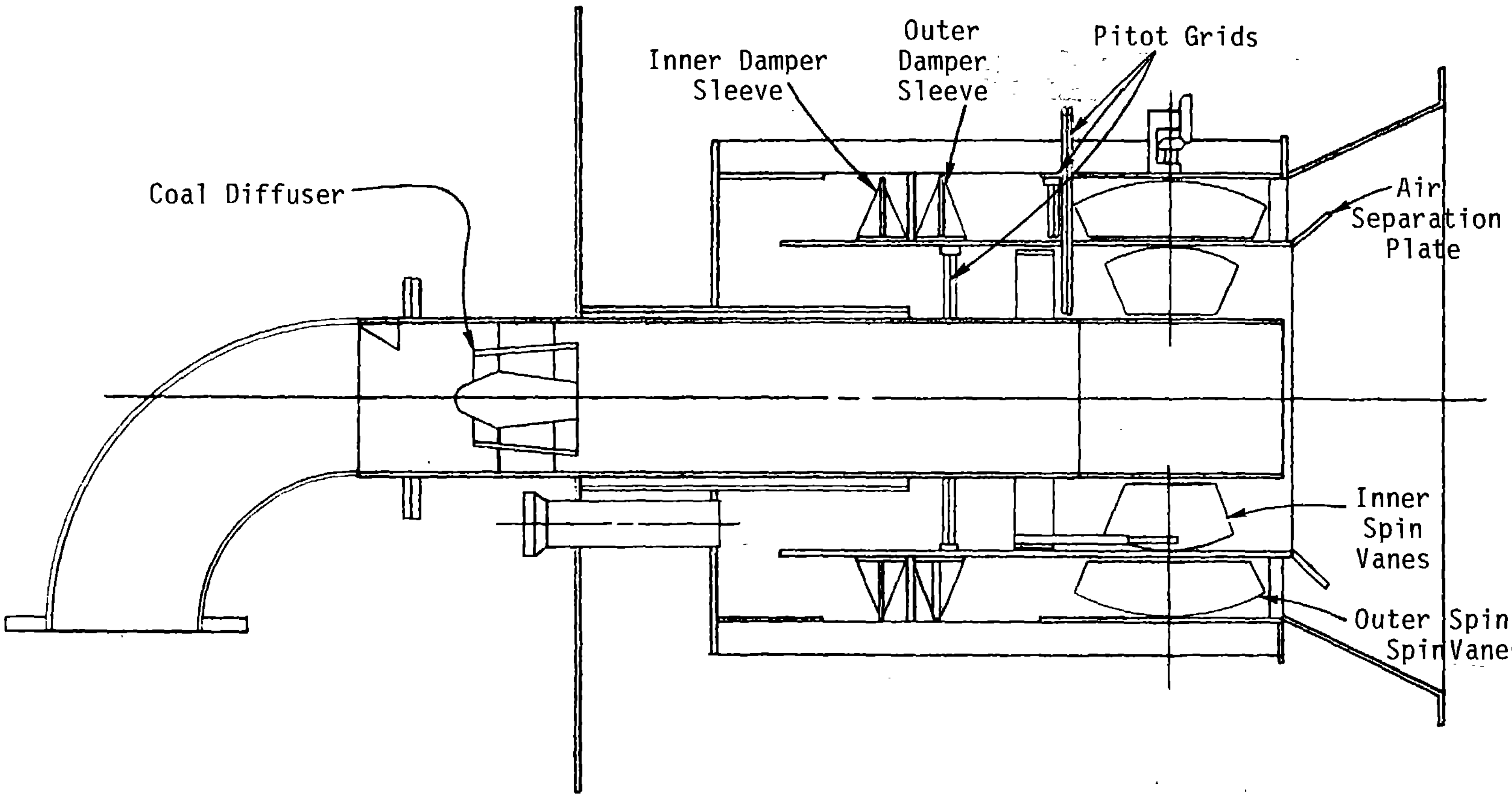


Figure 3-4. Cross-sectional view of the B&W XCL Burner.

The major mechanical changes that make the XCL unique are the outer air passage assembly and pitot grids for flow measurement. The outer secondary register of radial vanes, used in both the DRB and HNR burner, was replaced with a sliding damper for air flow control and adjustable axial spin vanes for swirl generation. Thus, the inner and outer secondary air passages are mechanically the same in the XCL burner. Because of the importance of air flow distribution between the burner passages and among burners in a multi-burner boiler installation, B&W incorporated pitot measurement grids in the secondary air passages. These pitot grids will be valuable for burner optimization in field applications.

Because of the developmental nature of this burner, the XCL was tested in a number of configurations in its parametric optimization tests. The focus of the different configurations evaluated were coal nozzle changes. In addition, two modifications were made to the outer secondary air passage. The XCL configurations in two series of tests included:

- Flame Stabilizing Ring with coal diffuser.
- Flame Stabilizing Ring with coal diffuser and increased outer spin vane width.
- $DeNO_x$ stabilizer
- 30^o included angle coal impeller
- Coal diffuser
- 20^o included angle coal impeller
- Open impeller
- Expanded nozzle with coal diffuser
- Expanded nozzle with 20^o included angle impeller.
- Expanded nozzle with 30^o included angle impeller.
- 30^o included angle impeller and fixed outer vane assembly.
- Diffuser and fixed outer vane assembly

The various coal nozzle configurations are described in Section 3.4.

In addition to the basic outer assembly, two modifications were evaluated. Because of the improvement in HNR burner performance from widening the outer register vanes thereby decreasing leakage, the outer spin vanes were widened for the XCL burner. The second modification was the incorporation of fixed outer vanes. These fixed vanes produce effective swirl generation with reduced pressure drop. The reduction of pressure drop was achieved by directional vanes upstream of the fixed 45° angle spin vanes, shown in Figure 3-5.

3.4 Burner Hardware Components

During the evaluation and optimization of the B&W Second Generation Low-NO_x burners, a number of burner components were incorporated into the burners. These burner components included coal impellers or similar coal nozzle devices to disperse the coal, coal nozzle modifications, and secondary air passage modifications.

3.4.1 Coal Dispersal Designs

The coal dispersal devices evaluated in the three low-NO_x burner designs were of several types: coal pipe devices, coal impellers and swirlers, and coal nozzle devices.

The coal pipe devices were:

- Coal diffuser/deflector
- Coal pipe venturi
- DeNO_x stabilizer

The coal diffuser/deflector assembly is the standard coal dispersal device utilized by B&W in the DRB. This device has been illustrated in Figures 3-1, 3-2, and 3-4. The coal diffuser/deflector is positioned at the inlet of the coal pipe just downstream of the coal inlet elbow. It produces a uniform coal distribution across the coal pipe, breaking up any roping of coal along the elbow with the deflector and the bluff body diffuser. The diffuser was

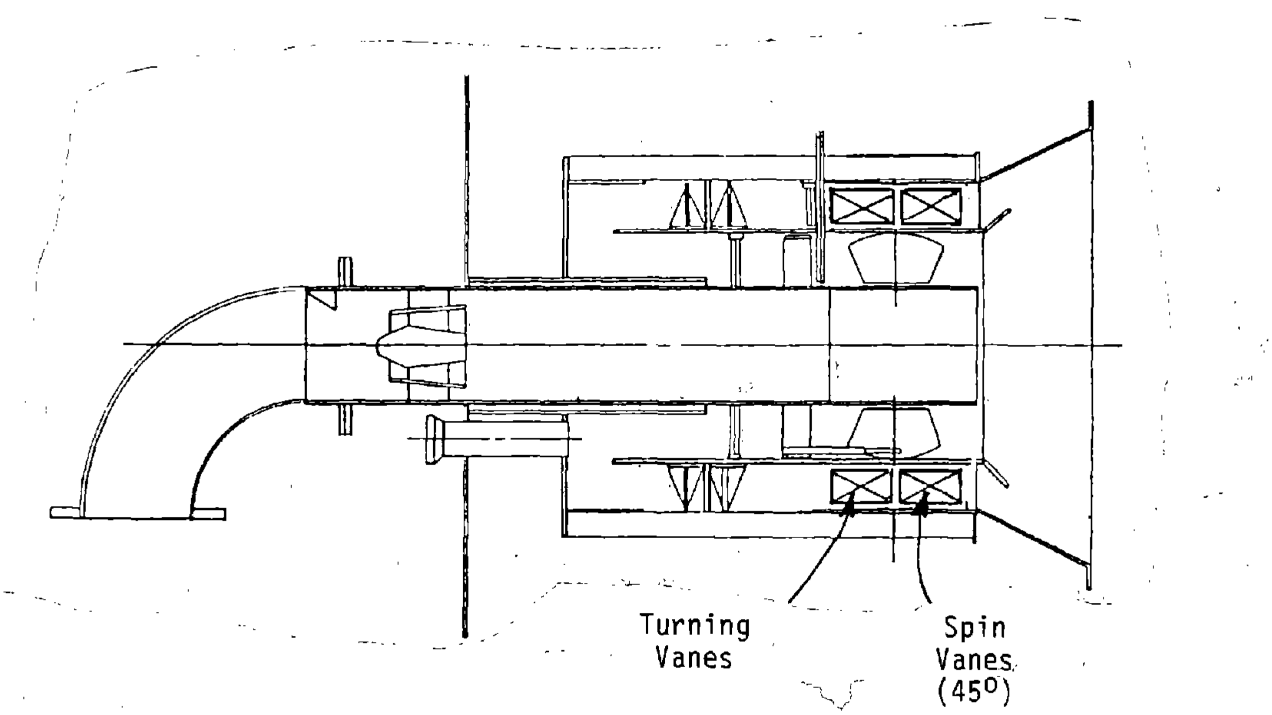


Figure 3-5. XCL burner with fixed outer vanes.

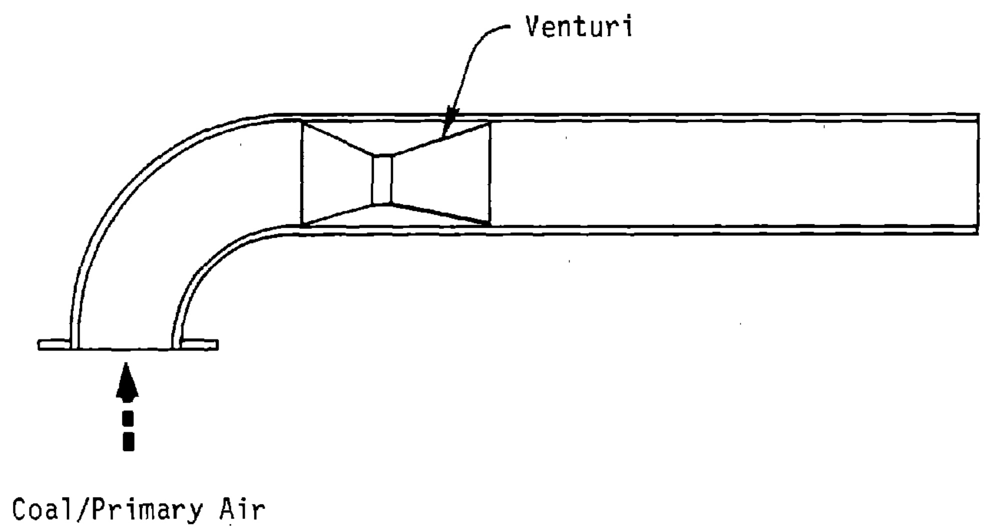
utilized in all three burner designs. The coal pipe venturi, shown in Figure 3-6, was the original coal dispersal device developed for the DRB. This device, also located at the coal nozzle inlet, produced a uniform coal distribution across the pipe by the acceleration and concentration of the pulverized coal through the venturi throat followed by an expansion to the coal pipe diameter. This device was tested only in the standard Phase V DRB under B&W funding. The $DeNO_x$ Stabilizer is a proprietary B&W coal pipe device developed for potential retrofit for existing DRBs. This device was designed to produce a stable, fuel-rich flame core expected to also decrease NO_x. The $DeNO_x$ stabilizer was evaluated in the low-velocity DRB and XCL burner.

Five coal impellers or swirlers were evaluated during these tests. These devices included:

- 75^o included angle impeller
- 20^o included angle impeller
- 30^o included angle impeller
- Open impeller
- HNR burner swirler

The four impeller designs are shown in Figure 3-7. They all share the basic B&W design concept, utilizing multiple, concentric conical rings to impart a radial component to the primary air/coal stream at the coal nozzle exit. The 75^o, 20^o, and 30^o impellers are similar in design differing only in the angle of the conical rings. Each has a center conical bluff body, surrounded by 2 to 4 conical rings. The open impeller was essentially the 30^o impeller, but with the central conical bluff body eliminated. The HNR burner swirler was described previously in section 3-2 and was used only with the HNR burner. The 75^o impeller was tested only with the low-velocity DRB. The other impellers were tested only with the XCL burner.

Two coal nozzle exit devices were evaluated, the Flame Stabilizing Ring and a short expanded nozzle tip. The Flame Stabilizing Ring, shown in



Note: Not to scale.

Figure 3-6. B&W coal pipe venturi.

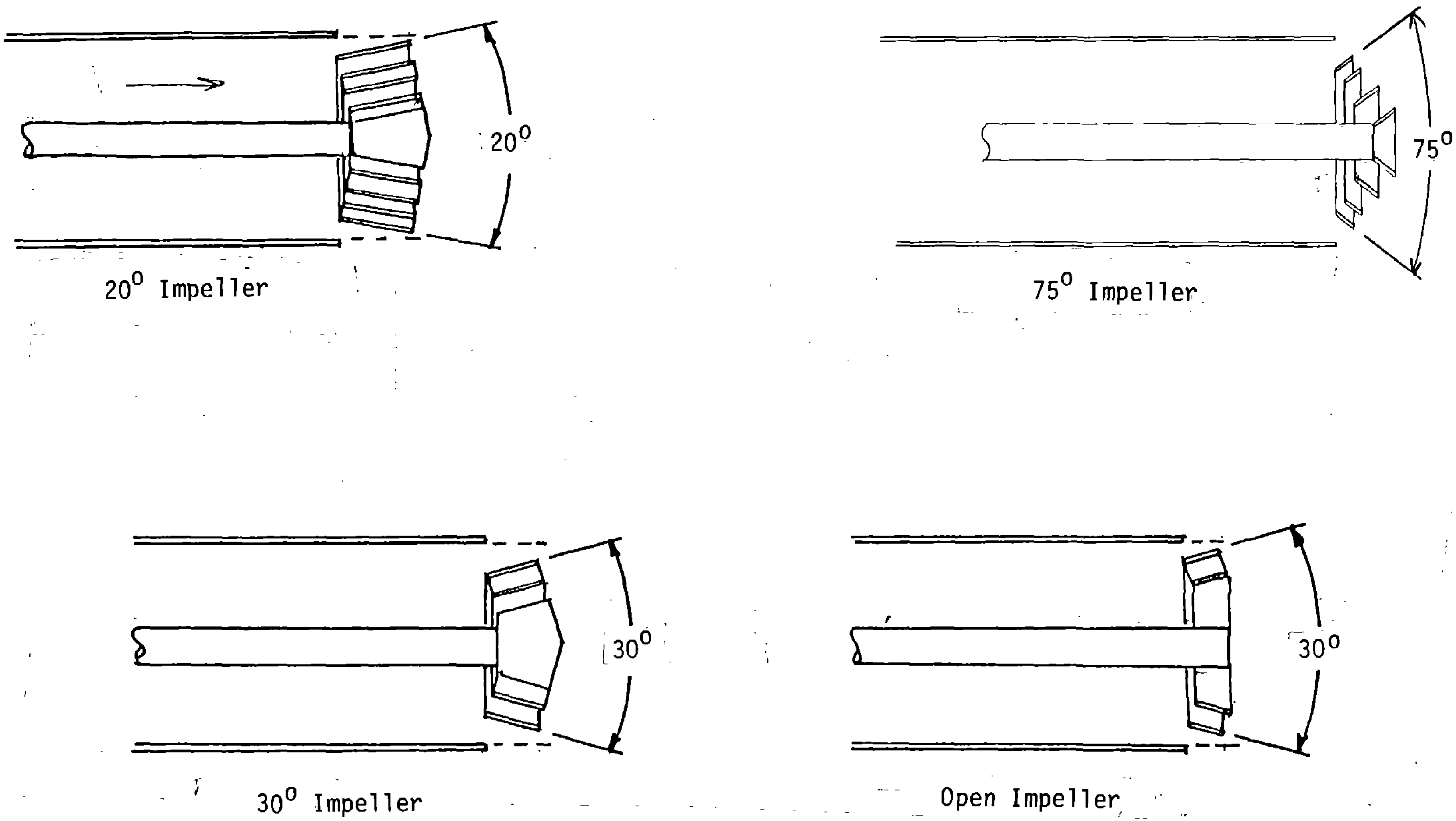


Figure 3-7. Coal impellers used during Second Generation low-NO_x burner testing.

Figure 3-8, is located at the end of the coal nozzle. It was developed by Babcock-Hitachi for the HNR burner. The Flame Stabilizing Ring acts as an orifice, with "teeth" on the circumference of the coal pipe. The FSR then expands into the inner secondary passage. This construction facilitates a small recirculation zone at the exit of the coal nozzle and thus enhances flame stability. This device was tested on the Phase V DRB (under B&W funding), the HNR burner (as standard equipment), and the XCL burner. The expanded nozzle tip, shown in Figure 3-9, was installed on the XCL burner only, to produce a lower primary velocity at the exit. The tip was short, 5.5 inches long, and increased the coal nozzle diameter by about 2 inches.

3.4.2 Secondary Air Modifications

Besides modifications to widen outer secondary air vanes and increase swirl effectiveness for the HNR and XCL burners, two other hardware components were evaluated. The Air Separation Plate (ASP) was tested on all three burners and a fixed outer secondary vane assembly was tested on the XCL burner. The Air Separation Plate is standard equipment on the HNR and XCL burners. The ASP is an extended baffle between the inner and outer air passages that deflects the outer secondary air radially from the inner zones. This delays mixing of coal with combustion air and shapes the flame. An assembly of fixed axial vanes set at about 45^{o} angle was tested on the XCL burner. This fixed vane assembly, previously shown in position in Figure 3-5, was intended as a mechanical simplification to improve burner reliability and to reduce burner pressure drop. It was also hoped that the fixed vanes would improve air distribution around the periphery of the burner, thereby improving combustion efficiency.

3.5 Fuels and Sorbents

Four different coals were utilized during the Second Generation Low-NO_x burner tests. Tables 3-2 and 3-3 summarizes the composition of the coals and their corresponding ashes, respectively. The Pittsburgh #8 coal was the primary fuel used throughout the burner tests. Pittsburgh #8 is a high volatile A bituminous coal selected for the LIMB demonstration project at Edgewater

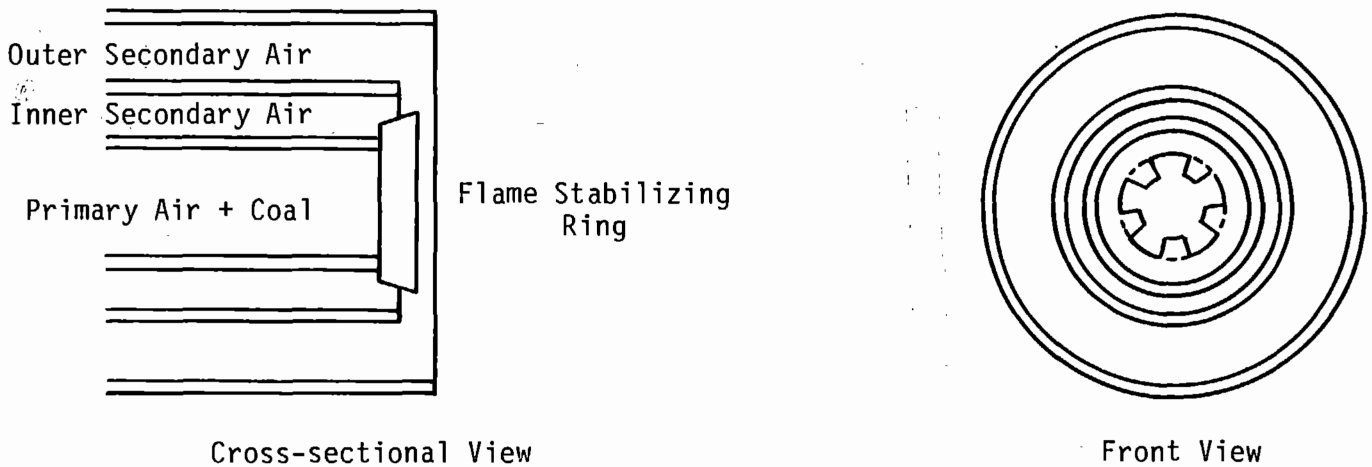


Figure 3-8. Flame stabilizing ring.

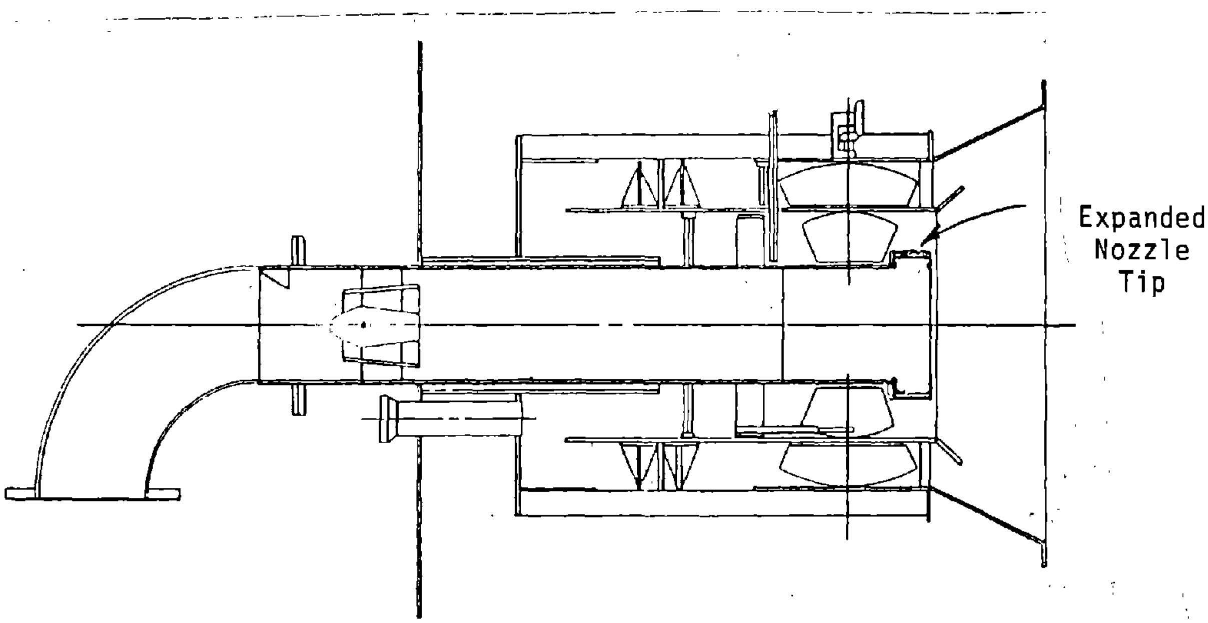


Figure 3-9. Expanded nozzle tip on the XCL burner.

TABLE 3-2. COMPOSITION OF TEST COALS

Coal	Pittsburgh #8		Utah		Comanche		Lower Kittanning	
Reporting Basis	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry
Proximate (wt %)								
Moisture	3.50	0.00	6.11	0.00	22.44	0.00	2.43	0.00
Ash	12.92	13.40	8.02	8.55	5.00	6.45	10.19	10.44
Volatile	33.75	34.98	41.26	43.96	36.12	44.87	23.93	24.52
Fixed C	49.83	51.62	44.60	46.73	37.72	48.68	63.45	65.04
Heating Value								
Btu/lb	12,177	12,618	12,288	13,088	9,325	12,026	13,551	13,888
MMF Btu/lb		14,876		14,440		12,939		15,701
MAF Btu/lb		14,626		14,311		12,855		15,507
Ultimate (wt %)								
Moisture	3.50	0.00	6.11	0.00	22.44	0.00	2.43	0.00
Carbon	68.13	70.59	68.58	71.86	54.25	69.97	76.82	78.73
Hydrogen	4.63	4.79	5.16	5.49	3.80	4.91	4.54	4.65
Nitrogen	1.21	1.26	1.28	1.36	0.76	0.98	1.12	1.15
Sulfur	3.22	3.30	0.60	0.64	0.43	0.56	1.13	1.16
Ash	12.92	13.40	8.02	8.55	5.00	6.45	10.19	10.44
Oxygen*	6.41	6.63	10.24	10.91	13.32	17.14	3.77	3.87
Forms of Sulfur (wt %)								
Sulfate	0.22	0.23	0.01	0.01	0.02	0.02	0.01	0.01
Pyritic	1.62	1.65	0.13	0.13	0.09	0.12	0.53	0.54
Organic	1.38	1.42	0.46	0.50	0.32	0.42	0.60	0.62

*Oxygen determined by difference.

TABLE 3-3. COAL ASH CHARACTERISTICS

Coal	Pittsburgh #8	Utah	Comanche	Lower Kittanning
Elemental Ash (wt %)				
SiO_2	48.67	58.40	23.18	49.24
Al_2O_3	20.19	19.96	13.99	26.81
TiO_2	0.84	0.77	1.04	1.20
Fe_2O_3	23.87	4.18	5.07	14.83
CaO	1.60	4.56	28.42	1.67
MgO	0.60	1.05	5.15	0.87
Na_2O	2.00	1.54	1.20	0.28
K_2O	0.31	1.06	0.29	2.50
P_2O_5	0.39	0.51	1.41	0.26
SO_3	1.25	4.77	17.50	1.15
Ash Fusion Temperatures (°F)				
Oxidizing				
IDT	2377	2350	2390	2660
ST	2554	2448	2412	2700
HT	2580	2546	2425	2700
FT	2616	2653	2451	2700
Reducing				
IDT	2171	2297	2316	2635
ST	2298	2388	2342	2700
HT	2459	2502	2351	2700
FT	2498	2621	2383	2700

Station Unit 4. Since the ultimate goal of these burner tests was the selection of the optimum burner for retrofit at the Edgewater boiler, the use of the same coal eliminated coal composition as a factor in the projection of expected burner performance. The other three coals represent a wide range of coal types and were used to characterize the performance of the optimized XCL burner. Utah coal is a western high volatile B bituminous coal from the Starpoint mines in Wattis, Utah. This Utah coal has been used at EER as the base fuel for most of the low-emission, high-efficiency burner development projects. Use of this coal allows comparison of the Second Generation low-NO_x burner performance with an existing data base of other burners. The Comanche coal is a subbituminous coal from Wyoming. The Lower Kittaning is a medium volatile bituminous coal.

Predictions of expected NO_x emissions based on coal composition have been developed at EER to rank coal types. Empirical correlations have been developed in a laboratory combustor for NO_x emissions based on coal properties for several distinct combustion conditions.[5] Application of these correlations yielded the results summarized in Table 3-4. The NO predictions given include theoretical total conversion of fuel nitrogen to NO and NO emissions predicted for different mixing conditions; a premixed flame, a radial diffusion flame, and physically staged combustion air conditions for minimum NO_x emissions. The absolute values of the NO predictions are for the specific laboratory combustor and would be expected to vary with combustor design and operation. High turbulence, pre-NSPS type burners would be representative of conditions between premixed and radial diffusion. For the subject coals, NO emissions would be expected to be higher for the Utah coal followed by Pittsburgh #8, Comanche, and Lower Kittaning. However, the correlations predict that the Utah coal is more amenable to staging than either the Pittsburgh #8 or Lower Kittaning, but the Comanche subbituminous would be expected to produce the lowest emissions under staged conditions.

As-fired pulverized coal samples were obtained on a daily basis throughout the testing period. The pulverized coal was sampled downstream of the primary air exhauster following ASME PTC 4.2 procedures. The objective of this sampling was to verify the composition and fineness of the coal. The

TABLE 3-4. PREDICTIONS OF NO_x EMISSIONS BASED ON COAL COMPOSITION

Coal	Pittsburgh #8	Utah	Comanche	Lower Kittanning
Rank	High Volatile A Bituminous	High Volatile B Bituminous	Subbituminous B	Medium Volatile Bituminous
Composition (wt %, daf)				
Nitrogen	1.45	1.49	1.05	1.28
Volatile Matter	40.39	48.07	47.96	27.38
Fixed Carbon	59.61	51.10	52.04	72.62
NO Predictions (ppm @ 0% O_2)				
Theoretical	2790	2987	2297	2323
Premixed	1058	1188	911	832
Radial Diffusion	825	876	694	718
Minimum Staged	288	275	242	291

TABLE 3-5. DAILY COAL VARIATIONS

Coal	Pittsburgh #8		Utah	Comanche	Lower Kittanning
	Mean	Std.Dev.	Mean	Mean	Mean
Composition (dry, wt %)					
Carbon	69.24	1.81	71.92	66.03	76.11
Hydrogen	4.65	0.13	5.29	4.79	4.56
Nitrogen	1.43	0.25	1.45	0.97	1.23
Sulfur	3.30	0.25	0.69	0.47	1.27
Ash	12.01	1.05	7.15	6.60	11.37

average ultimate composition and relative standard deviation of these daily samples are summarized in Table 3-5. Only the Pittsburgh #8 was tested and thus sampled more than one test day. The standard deviation for the Pittsburgh #8 coal was less than 2 percent for each component, suggesting very consistent coal composition. The Utah, Comanche, and Lower Kittaning coals were only sampled once during the brief test duration, thus standard deviation could not be determined.

The typical particle size distributions for the four coals are shown in Figure 3-10. Daily variations of coal fineness are summarized in Table 3-6. Adjustments to the mill and its classifier achieved similar size distributions for each coal type. Coal fineness was maintained nominally at 70 percent through 200 mesh (75 μm) with measured values ranging from 66.7 percent for Utah coal to 73.35 percent for Lower Kittaning coal.

Two sorbents were used during these tests to evaluate SO_2 reduction potential by in-furnace injection, Vicron 45-3 limestone and Colton hydrated lime. These sorbents have been used at EER as typical limestone and hydrated lime materials in the development of LIMB technology. The physical and chemical characteristics of these two sorbents are listed in Table 3-7 and the corresponding size distributions are shown in Figure 3-11. Vicron is nominally 99 percent pure $CaCO_3$ with a mass median diameter of 9.8 μm. The Colton hydrated lime is nominally 96 percent $Ca(OH)_2$ with a median particle size of 4.0 μm.

3.6 LWS Configuration

The Second Generation Low-NO_x burners were tested in the EPA Large Watertube Simulator shown in Figure 3-12. This facility and test procedures used, are described in detail in Part I, Sections 4.3 and 4.4 of this report. Key features of the test facility important to these tests were:

- Furnace dimensions, especially width (16 ft) and depth (22 ft). The depth of the LWS, coincidentally is essentially the same as that of the Edgewater boiler (22 ft, 3 inches). This feature

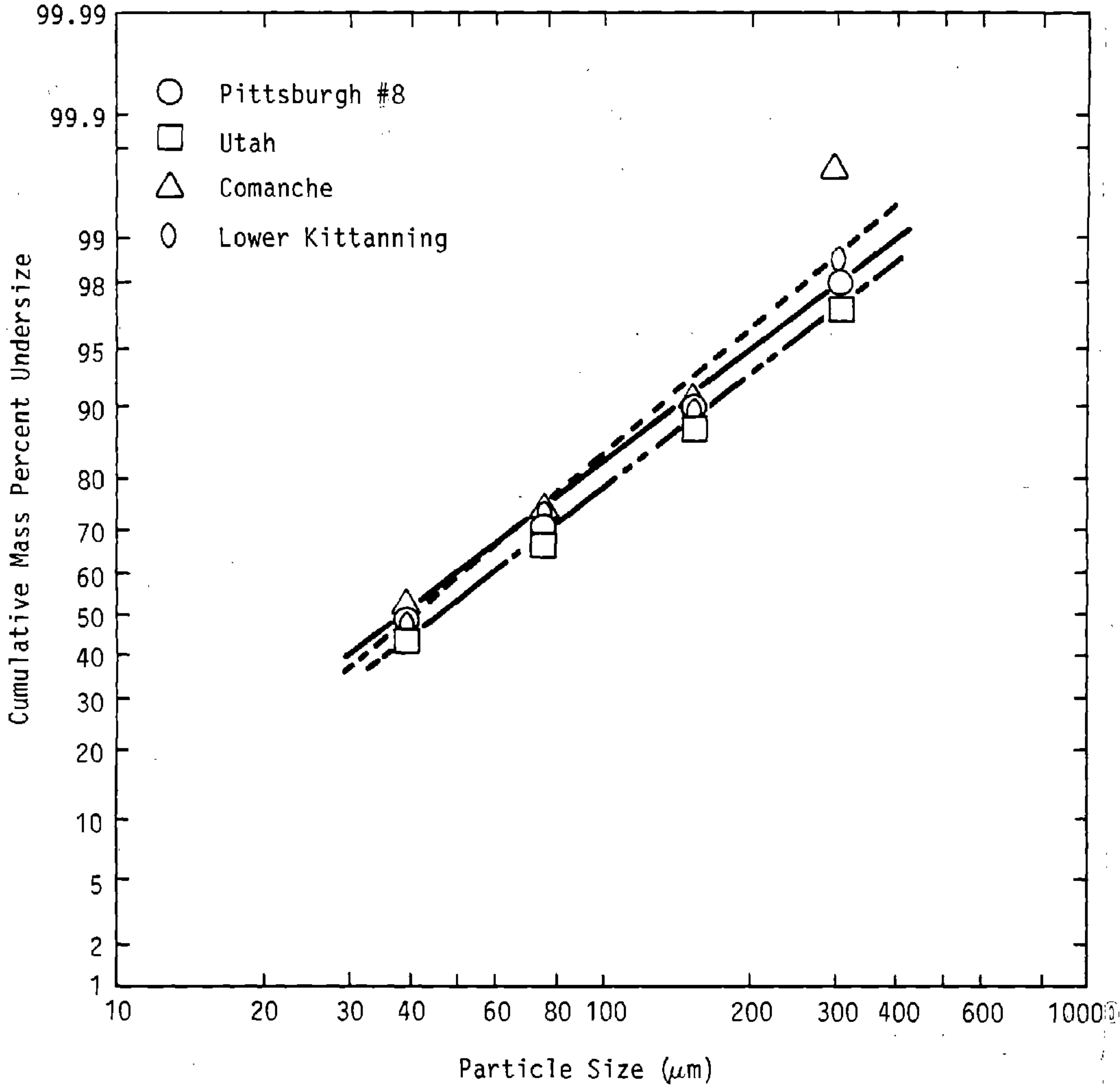


Figure 3-10. Typical coal particle size distributions.

TABLE 3-6. COAL FINENESS VARIATIONS--CUMULATIVE MASS PERCENT UNDERSIZE

Coal	Pittsburgh #8		Utah	Comanche	Lower Kittanning
	Mean	Std.Dev.	Mean	Mean	Mean
Particle Size (μm)					
38	48.18	4.01	43.23	50.64	49.26
75	71.83	3.14	66.7	72.5	73.35
150	89.43	3.08	87.09	91.11	88.89
300	97.91	1.04	97.15	99.71	98.58

TABLE 3-7. PHYSICAL AND CHEMICAL PROPERTIES OF TESTED SORBENT

Sorbent	Theoretical Characteristics	Physical Properties			Elemental Ash (wt %)									
		Median Diameter (m)	Density (gm/cm^3)	LOI @ 1000°C (wt %)	CaO	Fe_2O_3	Al_2O_3	Na_2O	MgO	K_2O	SiO_2	TiO_2	P_2O_5	SiO_3
Vicron 45-3	$CaCO_3$	9.8	2.706	42.49	55.64	0.08	0.03	0.01	0.54	0.01	0.20	0.01	0.01	0.02
Hydrated Lime	$Ca(OH)_2$	4.0	2.279	22.91	72.67	0.15	0.40	0.01	0.42	0.06	7.06	0.02	0.01	0.07

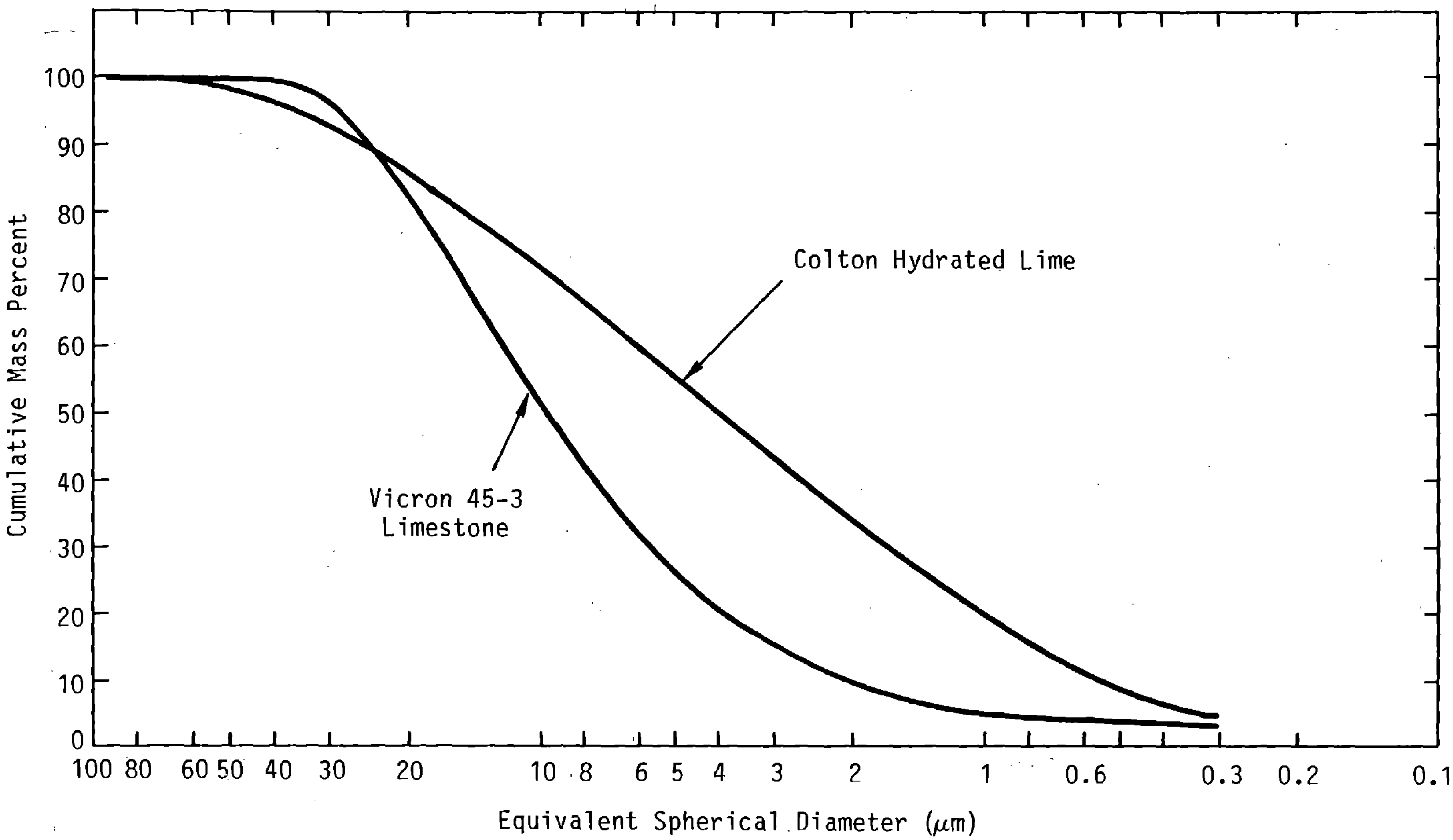


Figure 3-11. Sorbent particle size distribution.

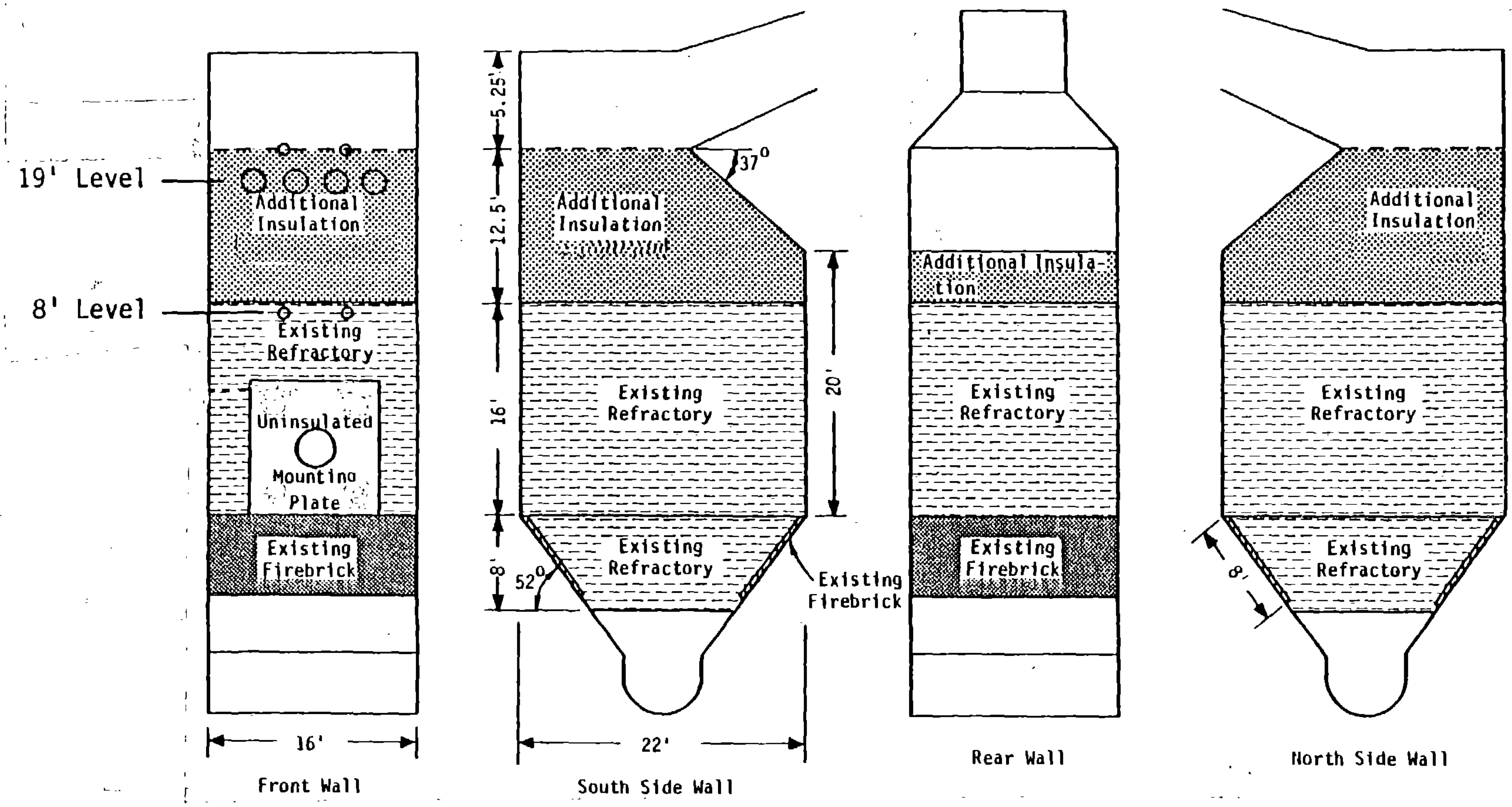


Figure 3-12. Insulation pattern in the LWS for Second Generation Low NO_x Burner Tests.

facilitated optimization of emission and flame length tradeoffs for Edgewater with confidence.

- Additional insulation was added to the LWS to produce a thermal environment more representative of operating boilers. This was difficult to achieve because of the relatively low firing rate for the test burns, 78 x 10^6 Btu/hr. With this additional insulation, average flue gas exit temperatures were measured to be 1855^{o}F.

- The burner installation onto the LWS was facilitated by B&W design of the test burners to utilize a common windbox and burner exit. The common windbox provided air to both the inner and outer secondary air passages without direct measurement of air flow distribution. Only the XCL burner was equipped with air measurement grids.

- A separate oil burner was installed adjacent to the pulverized coal burners. This burner was supplied with its own oil supply and metered air stream. This assured a clean burning oil flame during furnace warmup, startup oxygen balance, as well as ignition of the test burners.

Standard test procedures, described in detail in Part I, Section 4.4, were utilized throughout the project. Because flame length was a critical performance parameter for these tests, special procedures were used to determine flame length. Simple visual observation is used routinely; however, judgement of pulverized coal flame boundaries can be subjective. To confirm flame length observations and any possible flame impingement on the rear wall of the LWS, the following measurements were taken at all appropriate conditions:

- CO levels at the rear of the furnace
- Furnace wall temperatures
- Unburned carbon content (UBC) of fly ash

The latter two measurements were qualitative and useful only to determine whether there was flame impingement on the rear wall.

Measurements of CO at the rear of the furnace were more useful in actually determining and confirming flame length. Figure 3-13 and Table 3-8 present results of these measurements for selected test conditions. A profile of CO concentrations from the rear wall toward the flame is shown in Figure 3-13. As the probe approaches the end of the observed flame, the CO level increases abruptly. CO measurements on the rear wall are listed for a number of conditions in Table 3-8. For long flames, flames exceeding the depth of the furnace (> 22 feet), CO levels generally exceeded 10,000 ppm. Low CO levels, less than 200 ppm, were measured at the rear wall for flames observed to be shorter than about 20 feet. These measurements confirm the consistency of the visual flame observations made during the tests.

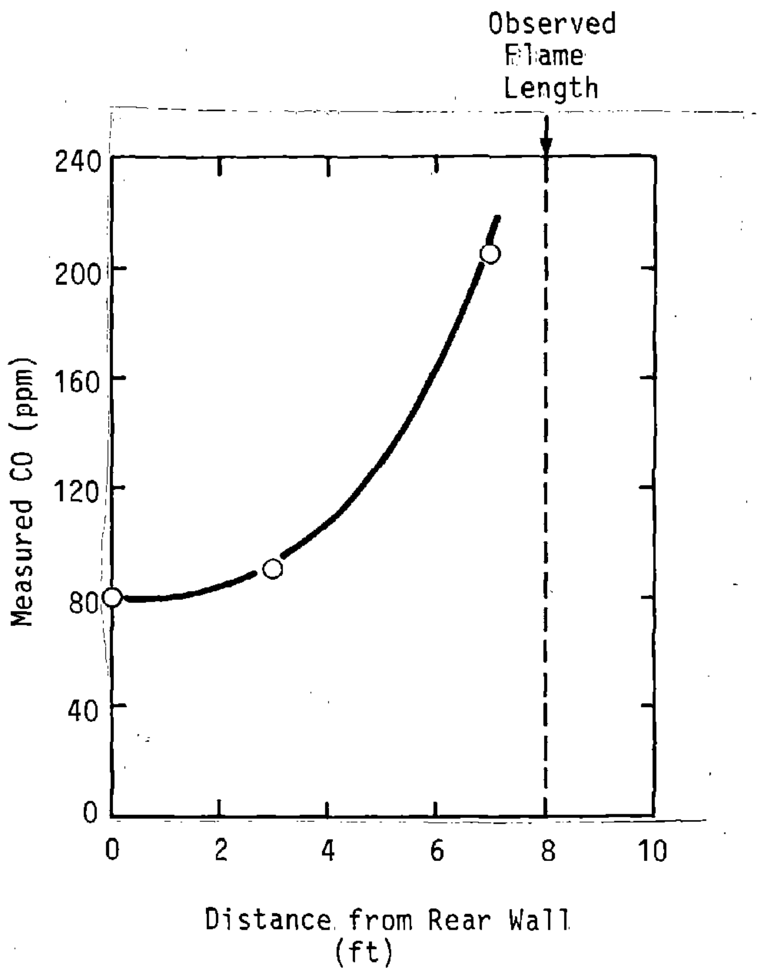


Figure 3-13. Typical results from rear wall probing for CO levels.

TABLE 3-8. CO MEASUREMENTS AT REAR WALL FOR SELECTED CONDITIONS

BURNER	TEST NO.	OBSERVED FLAME LENGTH (FT)	CO (PPM, MEASURED)
DRB	1.04	>22	11,000-15,000
DRB	1.07	>22	7,000-11,000
DRB	1.13	>22	10,000-11,000
DRB	2.03	>22	9,000-13,000
DRB	2.06	>22	13,000
DRB	2.17	>22	9,000-14,000
DRB	2.28	>22	5,000- 6,000
DRB	2.33	18-20	6,000- 7,000
DRB	4.01	18-20	80
DRB	4.02	14	55
DRB	4.03	12	40
DRB	4.04	14	80
DRB	4.05	14	200-1,000
DRB	4.06	16	150-200
DRB	4.07	>22	10,000
DRB	4.08	20-22	12,000-15,000
DRB	4.09	18-20	60-130
DRB	6.02	>22	32,000
DRB	6.05	>22	35,000-43,000
DRB	7.07	>22	23,000-28,000
DRB	7.12	22	10,000-15,000
DRB	7.13	22	6,000- 9,000
HNR	2.27	>22	18,000-21,000
HNR	4.01	>22	15,000-20,000
XCL	3.22	22+	9,000-13,000

4.0 BURNER PERFORMANCE AND NO_x EMISSIONS

Three B&W Second Generation Low NO_x Burner designs were tested in the LWS to evaluate their performance and NO_x reduction potential. The burner designs included:

- Dual Register Burner
- Babcock-Hitachi NO_x Reducing Burner
- XCL Burner

The tests were conducted in two series. Initially, parametric screening tests including hardware modifications were conducted. The objective of these screening tests was to determine the burner configuration which yielded optimum performance within the constraints imposed by the Edgewater Unit 4 boiler, of which firing depth was most severe. The LWS, coincidentally, has essentially the same depth as the subject boiler and provided an ideal test configuration to achieve the objectives. Following the screening tests, the burner configuration which showed the greatest potential for satisfying the objectives and constraints for the LIMB demonstration boiler was optimized. This optimized burner, determined to be a configuration of the XCL burner, was characterized with three additional, distinctly different coal types.

4.1 Dual Register Burners

Following are the test results of two 78 x 10^6 Btu/hr Dual Register Burners; a Low Velocity DRB and a standard Phase V DRB described previously. The Low Velocity DRB, tested under this program, was designed to fit the same exit opening as the HNR and XCL burners. This resulted in lower burner velocities than current B&W standards for DRB designs. In a separate B&W sponsored LWS test program, a standard Phase V DRB was evaluated. The results from those tests are summarized for comparison.

4.1.1 Low Velocity Dual Register Burner

The 78 x 10^6 Btu/hr Low Velocity DRB was evaluated in four configurations:

- With standard coal diffuser
- With a 75° included angle impeller
- With $DeNO_x$ Stabilizer
- With Air Separation Plate and Flame Stabilizing Ring

Each of these configurations was tested over a range of burner adjustments, excess air, and firing rate to optimize and characterize its performance. The range of test conditions are summarized in Table 4-1. Nominal operating conditions maintained through screening the adjustable parameters were:

Firing Rate = 78 x 10^6 Btu/hr

SR_P = 0.18

SR_T = 1.20

Primary Air Temperature = 150°F

Combustion Air (Windbox) Temp = 550°F

The fuel used during the screening tests was Pittsburgh #8 coal.

The base configuration of the Low Velocity DRB utilized the diffuser alone. Initial tests of this base configuration at the above-listed full load operating conditions produced flames over 22 feet long, that is, flames exceeding the depth of the LWS. Observed flame impingement on the back wall was confirmed by measured CO levels over 10,000 ppm. The available burner adjustments were not effective in shaping the flame within the constraints of the LWS furnace dimensions for this configuration at full load. Even with high turbulence, opposed swirl settings of 20° CCW open on the inner spin vanes and 15° CW open on the outer register, the flame length exceeded 22 ft.

TABLE 4-1. RANGE OF SCREENING TESTS FOR LOW-VELOCITY DUAL REGISTER BURNER

Configuration	Diffuser	DNS	ASP/FSR Swirler	75° Impeller
<u>Burner Settings:</u>				
Inner Spin Vanes	20°CW-25°CCW	30°CW-20°CCW	20°CW-20°CCW	50°CW-50°CCW
Outer Register	10°-45°CW	15°-55°CW	15°-55°CCW	5-75°CW
Inner Sleeve Damper	25-100% Open	25-50% Open	12-25% Open	12-25% Open
Impeller Position	N/A	N/A	-1 to -10 in.	-6 to +8 in.
<u>Performance Range:</u>				
NO_x @ 0% O_2, Dry (ppm)	188-281	242-336	332 - 420	314 - 917
Flame Length (ft)	> 22	>22	>22	12 - >22
Burner ΔP (in W.G.)	3.0-7.6	3.6-10.5	4.6-9.2	3.2-11.8
UCB %	2.5-10.6	5.9	1.85-4.44	1.05-1.65

NO_x emissions for this setting at full load and 20 percent excess air were 264 ppm,* with fly ash carbon content of 4.8 weight percent.

Sensitivity of the performance for the different Low Velocity DRB configurations to the available burner adjustments are summarized in Figures 4-1 and 4-2. The configurations with the diffuser, $DeNO_x$ Stabilizer, and Flame Stabilizing Ring/Air Separation Plate/Swirler, shown in Figure 4-1, produced flames over 22 feet long for essentially all the conditions tested. For this reason, only the sensitivity of NO_x to burner adjustments is shown. For the Low Velocity DRB with the 75^o impeller, however, both NO_x and flame length are shown as functions of burner settings in Figure 4-2.

Because of the excessive flame length, most of the screening tests with the diffuser were conducted at reduced load, nominally 60 x 10^6 Btu/hr. These are the data presented on Figure 4-1 representing the Low Velocity DRB with diffuser. The data for the other two configurations in this figure are at nominal full load operation. From these screening tests, the outer register vane position proved to be the dominant burner adjustment. The inner sleeve, which affects air flow distribution between inner and outer zones, and the swirler position were secondary in effect on emissions. The inner spin vanes had little or no effect on emissions.

The addition of the 75^o impeller to the Low Velocity DRB had a significant effect on performance, particularly flame length. As shown in Figure 4-2, the impeller and its position became the dominant factor in burner performance. In this configuration, flame length could be varied from 12 to over 22 feet simply by moving the axial position of the impeller. In addition, NO_x emissions were inversely proportional to flame length. NO_x emissions as low as 300 ppm could be achieved by retracting the impeller 6 inches into the coal nozzle, at the expense of a flame which exceeded the furnace depth. The outer register vane position was a secondary factor in

*Note: All emission concentrations reported corrected to 0 percent O_2 on a dry basis, except where indicated.

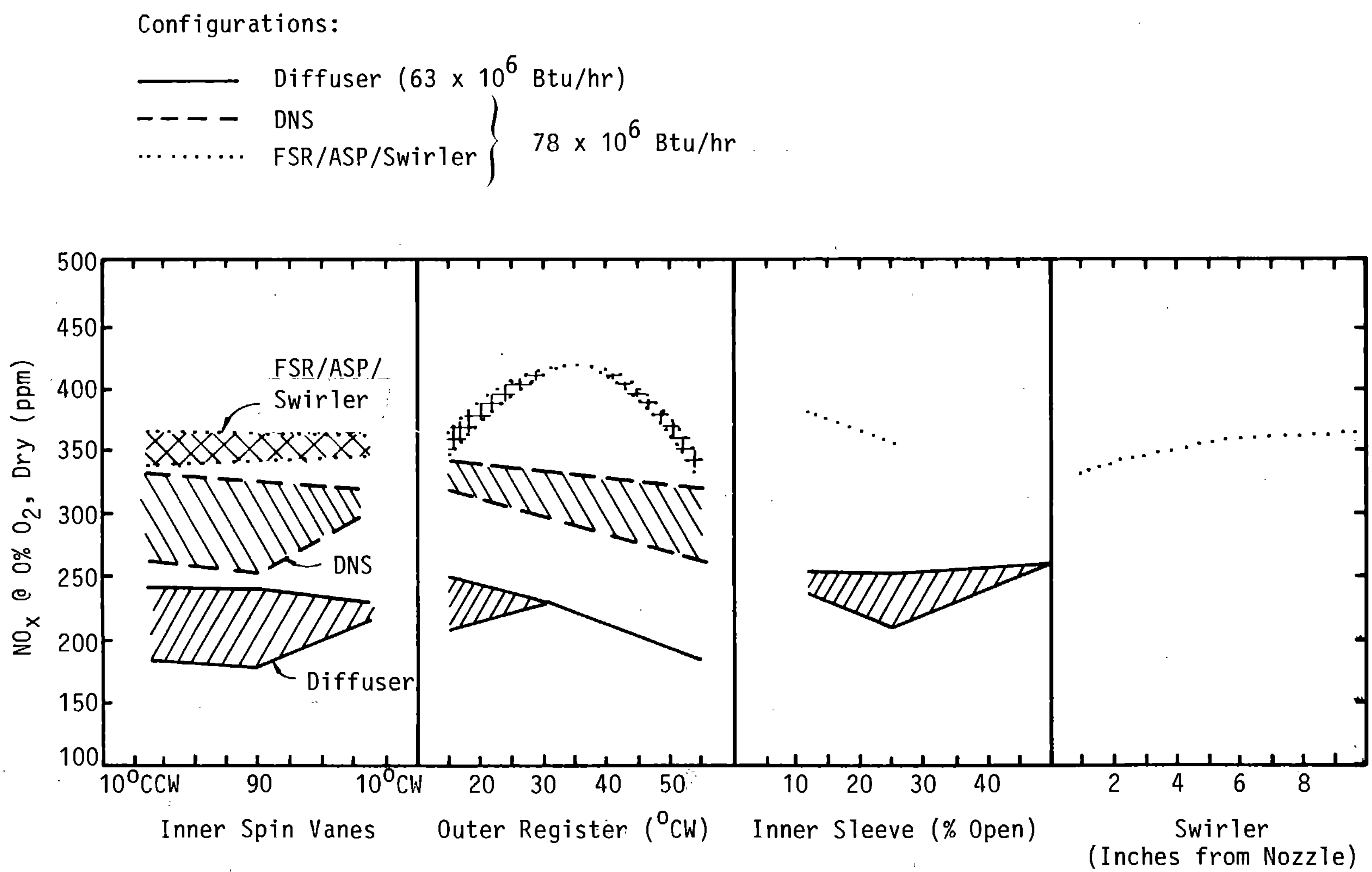


Figure 4-1. Sensitivity of low velocity DRB NO_x emissions to burner adjustments.

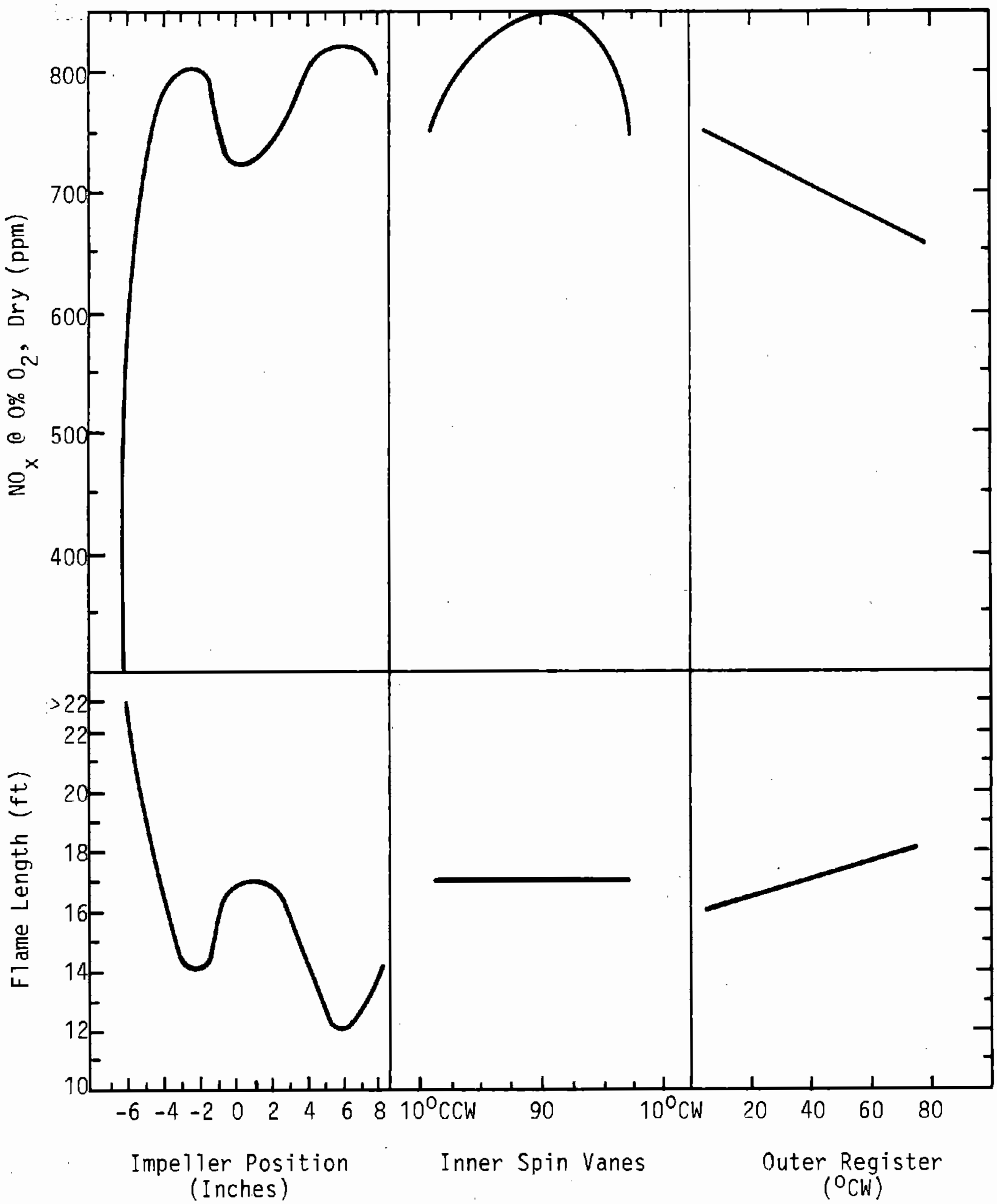


Figure 4-2. Sensitivity of low velocity DRB with 75° impeller to burner adjustments.

NO_x emissions, also demonstrating that NO_x emissions decreased with an increase in flame length. As the degree of swirl decreased by opening the register vanes, the slower mixing that resulted caused an increase in flame length and corresponding decrease in NO_x.

The data from the screening tests indicated that the following common burner settings produced optimum performance (with regard to flame length) for each Low Velocity DRB configuration:

Inner Spin Vanes: 20° CCW open

Outer Register: 15° CW open

Inner Sleeve Damper: 25% open (50% open for 75° impeller)

For the configuration with the 75° impeller, the impeller positioned at the nozzle exit was determined to be optimum. This position corresponded to a stable minimum NO_x point with a flame shorter than the furnace depth. A coal swirler position of 5 inches behind the coal nozzle tip was determined to be optimum for the Low Velocity DRB assembly that incorporated HNR-type components (Flame Stabilizing Ring, Air Separation Plate, and coal swirler).

Each of these configurations was evaluated over a range of firing rate and excess air at their selected optimum settings. The results for each configuration are shown in Figures 4-3 through 4-6. These figures present NO_x and combustion efficiency, as indicated by fly ash carbon content and/or CO concentration, as a function of excess air and firing rate. The performance of the diffuser configuration is shown in Figure 4-3 for three firing rates. As expected, NO_x emissions were highest for the full load, 78×10^6 Btu/hr, and decreased for progressively lower firing rates. At full load and an overall stoichiometry (SR_T) of 1.20, NO_x emissions were 264 ppm. At firing rates of 60×10^6 Btu/hr and 53×10^6 Btu/hr, NO_x emissions were 240 and 200 ppm, respectively. The combustion efficiency is shown as a characteristic family of fly ash carbon data, with the lowest level of unburned carbon for the highest firing rate. The data also show the increase in unburned carbon as excess air is decreased. Fly ash carbon at 20 percent excess air ranges from 4.80 percent at full load up to 8.53 percent at 53×10^6 Btu/hr.

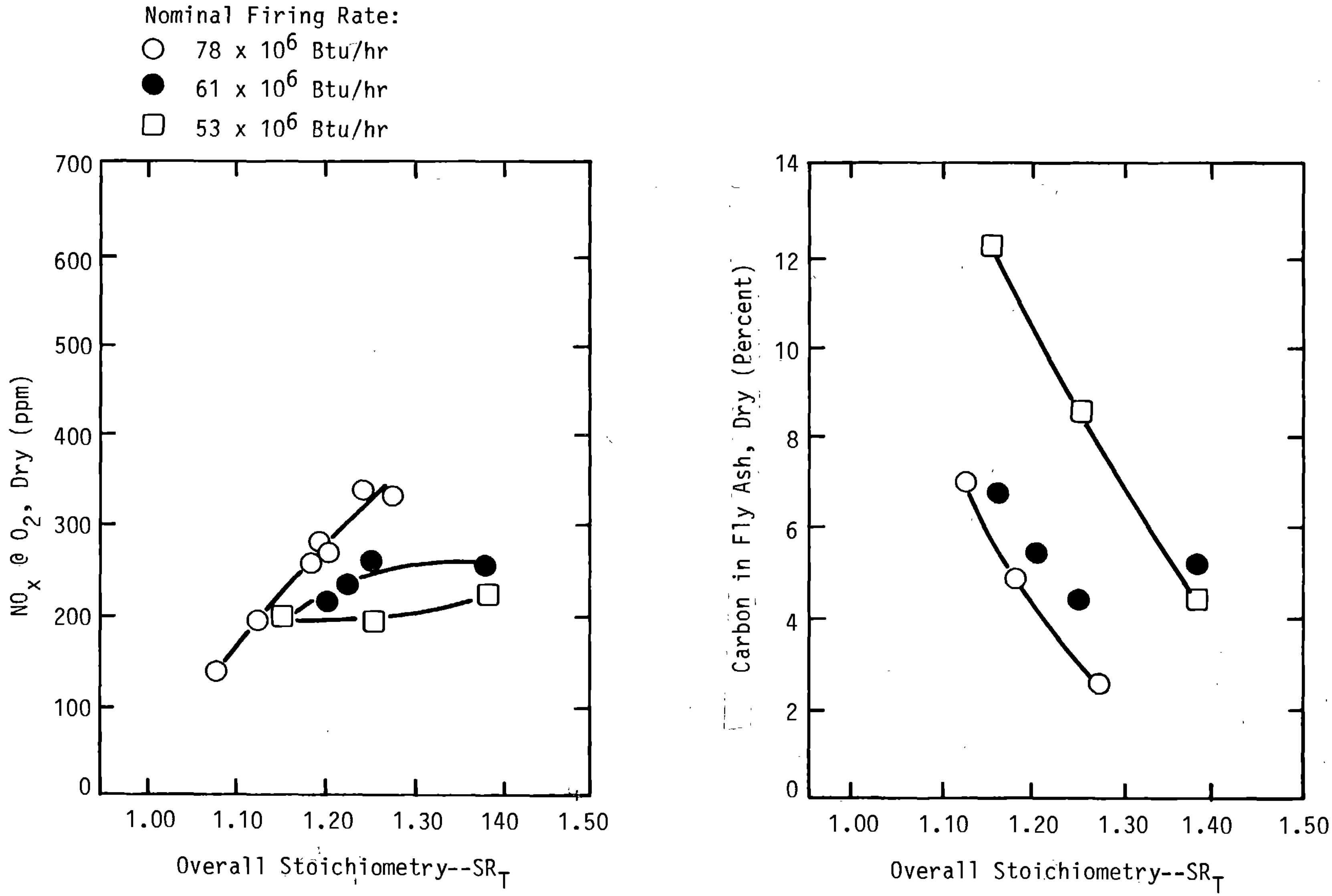


Figure 4-3. Performance of Low Velocity DRB with diffuser as a function of Excess Air and Firing Rate.

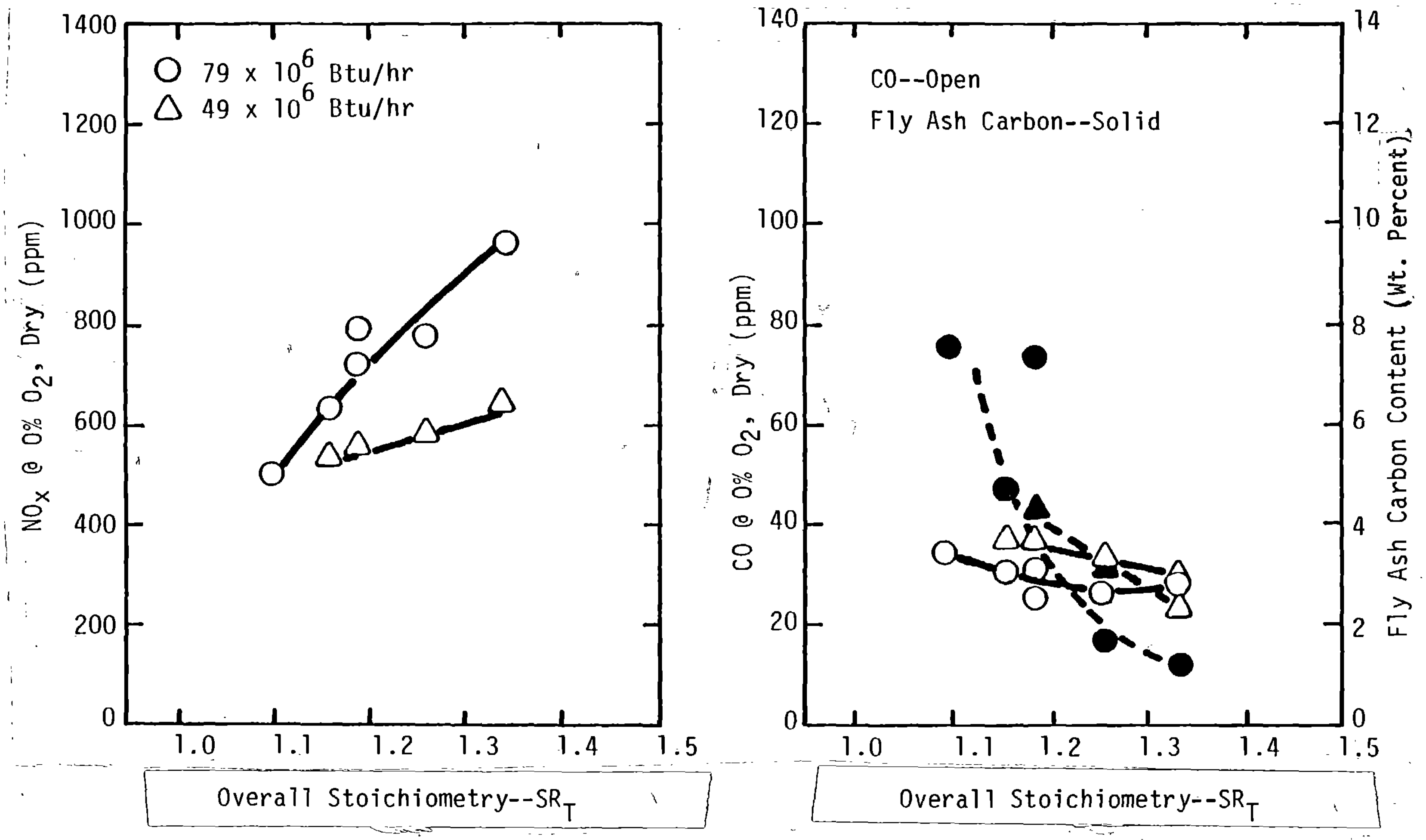


Figure 4-4. Performance of low-velocity DRB with 75° impeller as a function of excess air and firing rate.

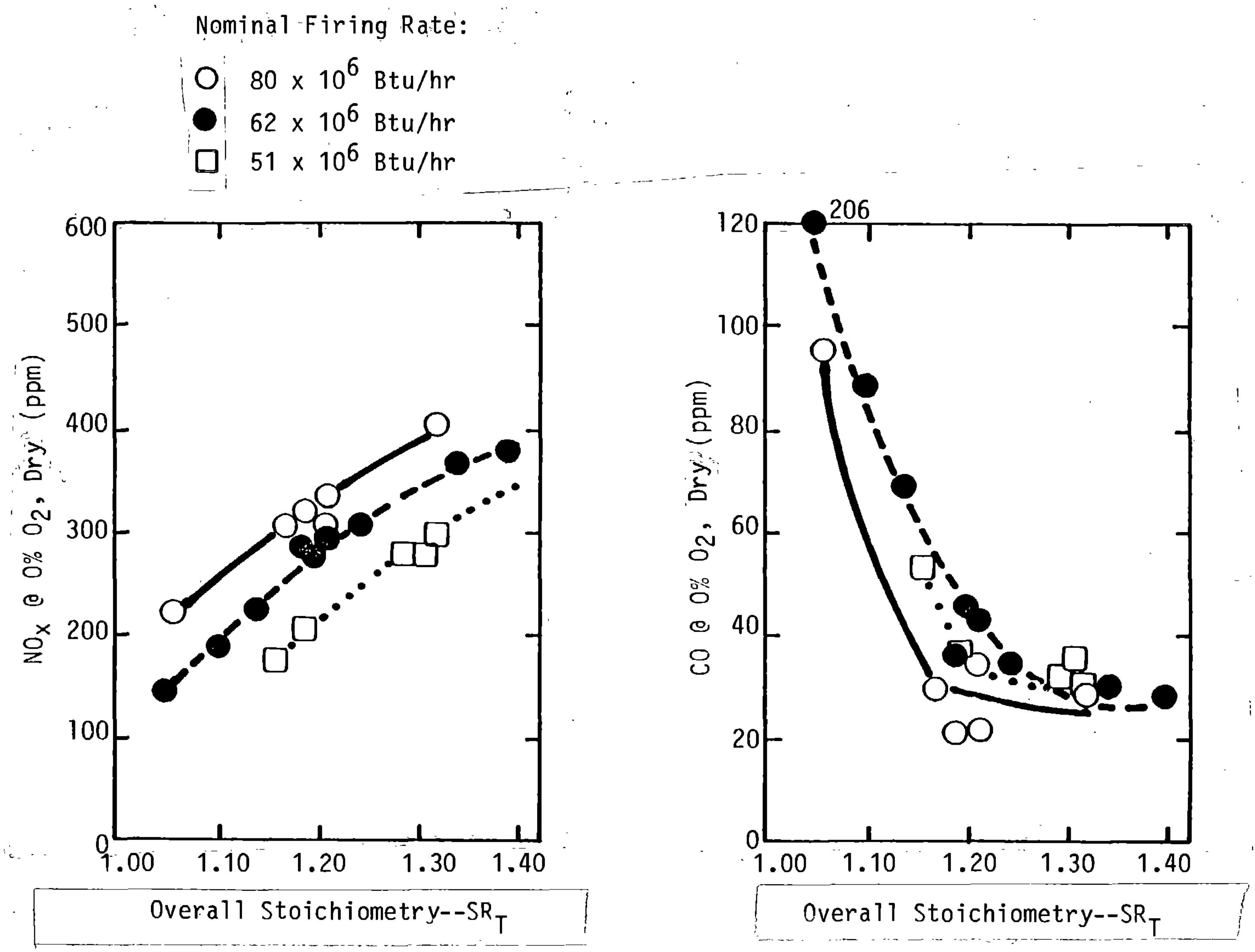


Figure 4-5. Performance of low-velocity DRB with $DeNO_x$ stabilizer as a function of excess air and firing rate.

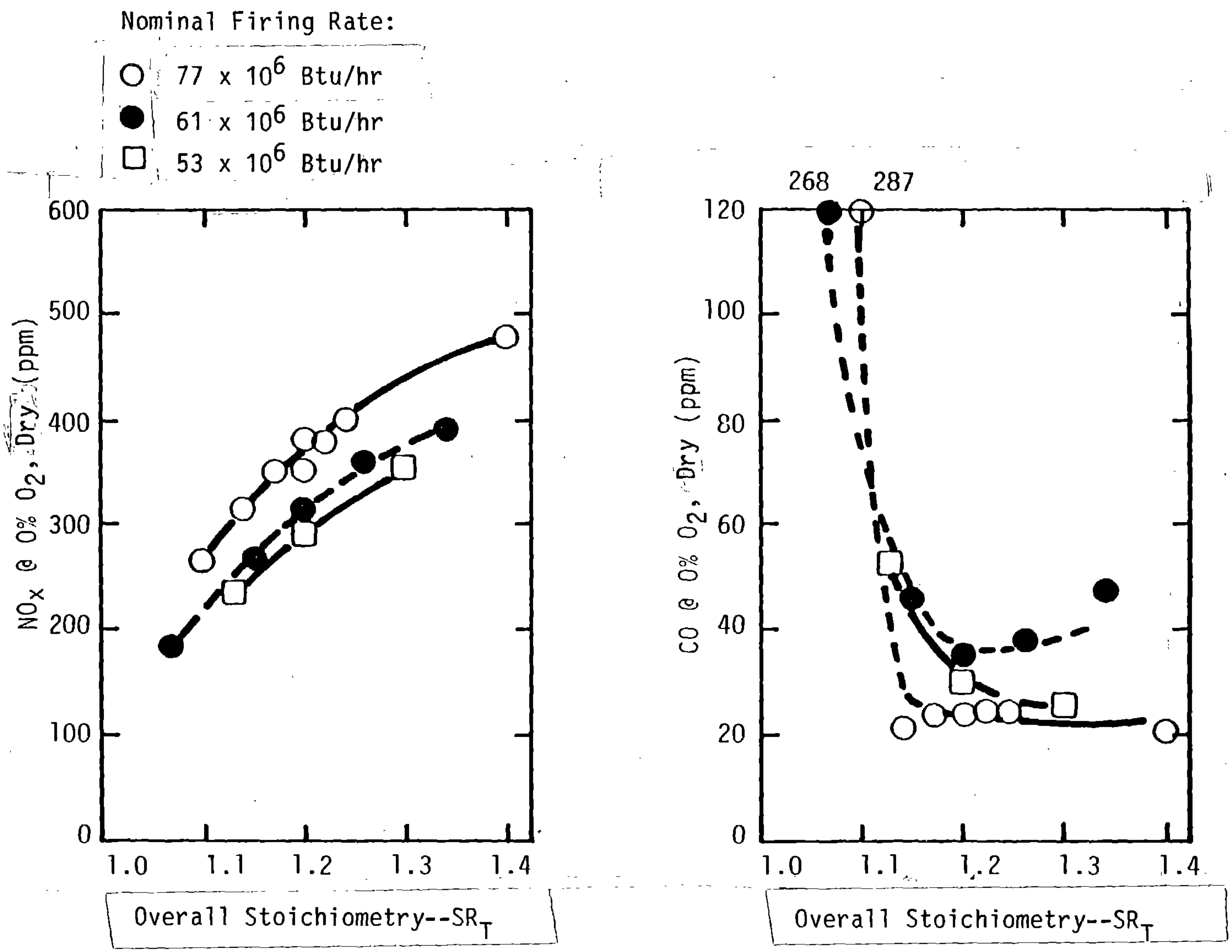


Figure 4-6. Performance of low-velocity DRB with FSR/ASP/Swirler Assembly as a function of excess air and firing rate.

This family of unburned carbon data indicates the sensitivity of this configuration in the LWS to excess air and the necessity to operate at higher excess air levels as load is decreased to maintain carbon burnout.

The performance characteristics of the 75^{o} impeller DRB configuration are shown in Figure 4-4. These data are for two firing rates, 79×10^6 Btu/hr and 49×10^6 Btu/hr. Again, NO_x emissions were higher and fly ash carbon/CO lower for full load operation than reduced load. At an overall stoichiometry of 1.20, NO_x emissions were 710 and 550 ppm for 79×10^6 and 49×10^6 Btu/hr, respectively. Corresponding flame lengths were 16-18 feet at full load and about 12 feet at the lower firing rate. Fly ash carbon content was also sensitive to excess air level, although the difference between the two firing rates was not as great as for the diffuser configuration.

Performance characteristics for the $DeNO_x$ stabilizer and the assembly of components from the HNR burner design (FSR, ASP, and swirler) are shown in Figures 4-5 and 4-6, respectively. For each case, the NO_x emissions for the three firing rates are a family of essentially parallel curves with the NO_x decreasing with decreasing firing rate. NO_x emissions for the DNS-equipped DRB at an overall stoichiometry of 1.20 were 320, 280, and 210 ppm for firing rates of 80, 62, and 51×10^6 Btu/hr, respectively. The DRB equipped with the HNR components produced NO_x emissions at an overall stoichiometry of 1.20 of 375, 315, and 290 ppm for firing rates of 77, 61, and 53×10^6 Btu/hr, respectively. Combustion efficiency, indicated by CO levels, was more sensitive to excess air levels for these two configurations than the coal impeller equipped DRB. This would be expected for the slower mixing and longer flames produced by the DNS and FSR/ASP/coal swirler configurations.

Figure 4-7 provides a direct comparison of performance for the four Low Velocity DRB configurations tested at nominal full load. Highest NO_x emissions were produced with the 75^{o} impeller equipped configuration while the lowest emissions were produced by the base, diffuser equipped configuration. Combustion efficiency, as indicated by fly ash carbon content was similar for the four configurations. However, as the key test data in Table 4-2 shows, only the impeller-equipped DRB produced a flame less than

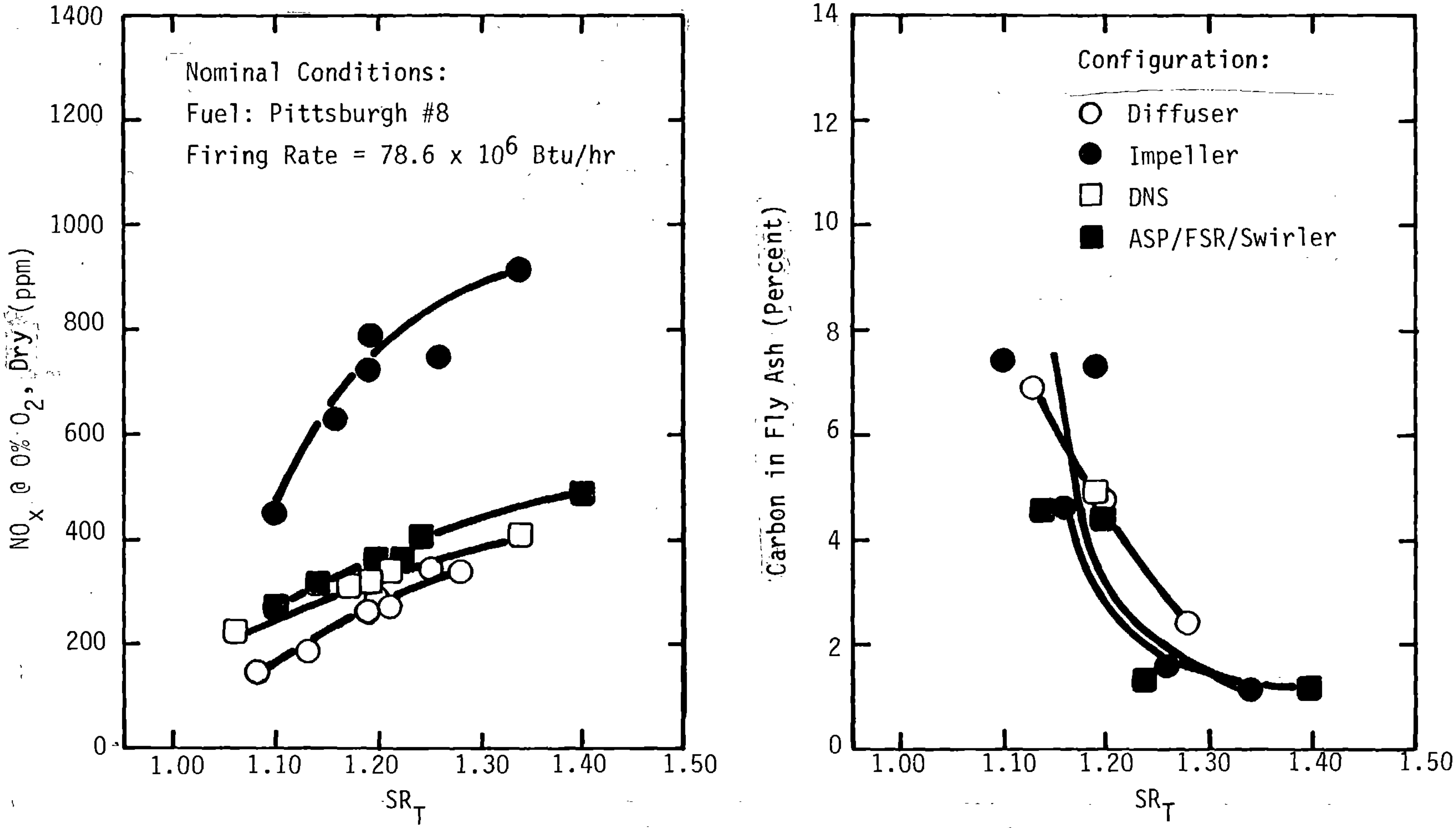


Figure 4-7. Comparison of performance of low-velocity DRB configurations.

the furnace firing depth (22 feet). Because the conditions selected as optimum for each configuration were similar, the windbox-to-furnace pressure differential was also similar. The tightly closed, high swirl settings chosen to produce relatively shorter flames resulted in high press differentials, from 6 to 10 in. W.G at full load and 20 percent excess air. In commercial applications, pressure drop across the DRB is typically 3 to 5" W.G. (when flame length is not a constraint).

4.1.2 Characterization of Standard Phase V DRB

In a separately funded test program sponsored by B&W, a standard Phase V DRB was evaluated in the LWS. As described previously, the principal difference between this Phase V DRB and the Low Velocity DRB that was the subject of this Second Generation Low Burner evaluation was the exit diameter. The Phase V DRB has a smaller exit, resulting in higher secondary air velocities. The Phase V DRB was evaluated in five configurations:

- Basic coal diffuser
- Coal venturi
- Diffuser with Air Separation Plate
- Diffuser with Flame Stabilizing Ring
- Diffuser, Flame Stabilizing Ring, and Air Separation Plate

The nominal operating conditions maintained through parametric screening tests of these configurations were:

Firing Rate = 78 x 10^6 Btu/hr

SR_P = 0.18

SR_T = 1.20

Primary Air Temperature = 150^oF

Combustion Air Temperature = 550^oF

These conditions are the same as those for the Low Velocity DRB. The fuel used was also the same Pittsburgh #8 coal.

TABLE 4-2. LOW VELOCITY DRB PERFORMANCE SUMMARY

Configuration	Swirl Vanes Inner	Swirl Vanes Outer	Inner Sleeve (% Open)	Spreader Position (Inches)	Firing Rate (10^6 Btu/hr)	SR_T	Emissions (@ 0% O_2) NO_x	Emissions (@ 0% O_2) CO	Flame Length (ft)	Fly Ash Carbon (wt.%)	Windbox Pres. (in. H_2O)
Diffuser	20°CCW	15°CW	25	N/A	76.9	1.19	264	48	22	4.80	7.10
Diffuser	20°CCW	15°CW	25	N/A	69.7	1.19	240	72	22	6.52	6.20
Diffuser	20°CCW	15°CW	25	N/A	61.7	1.21	212	66	22	5.38	4.60
Impeller	20°CCW	15°CW	50	0.0	79.4	1.19	708	24	18	7.28	6.00
Impeller	20°CCW	15°CW	50	0.0	57.5	1.20	579	30	14	5.25	3.30
Impeller	20°CCW	15°CW	50	0.0	49.4	1.19	552	36	12	4.11	2.40
DNS	20°CCW	15°CW	25	N/A	79.9	1.19	318	21	22	5.89	10.20
DNS	20°CCW	15°CW	25	N/A	60.7	1.20	278	45	22	6.70	5.90
DNS	20°CCW	15°CW	25	N/A	51.1	1.19	204	36	18-20	6.85	4.20
FSR, ASP, Swirler	20°CCW	15°CW	25	-5.0	79.4	1.20	386	24	22	4.44	9.20
FSR, ASP, Swirler	20°CCW	15°CW	25	-5.0	60.7	1.20	314	36	20-22	2.77	4.90
FSR, ASP	20°CCW	15°CW	25	-5.0	52.6	1.20	290	30	20	3.63	3.50

The range of test conditions for each configuration of the Phase V DRB are listed in Table 4-3. A key objective in the evaluation of the five configurations was to determine the effect of each subject component on burner performance and the degree of synergism when several components are used together. Underlying these tests was a comparison of the Phase V DRB with the Low Velocity DRB. To this end, the screening tests had a dual purpose: to optimize the Phase V DRB configurations and also to evaluate burner settings which duplicated the previous Low Velocity DRB tests.

The results of the screening tests indicated similar trends for the Phase V DRB and the Low Velocity DRB. The outer register vanes were the dominant parameter affecting burner performance. A set of data for each configuration demonstrating this sensitivity is shown in Figure 4-8. Reducing the degree of swirl generated and also increasing outer zone air flow by opening the outer register decreased NO_x emissions for each configuration with a corresponding increase in flame length. The inner sleeve damper position, which controls the air flow distribution between the inner and outer air zones, and the inner spin vanes had a secondary effect on burner performance.

From the screening tests, two sets of conditions were identified to characterize all the configurations. These conditions, listed in Table 4-4, can be described as: (1) duplicate of Low Velocity DRB optimum settings, and (2) nominal, optimum commercial conditions. The Low Velocity DRB duplicate conditions are characterized as highly turbulent with opposed inner and outer zone swirl and tightly closed inner and outer vanes for high swirl generation. These conditions produce a relatively short flame albeit with higher NO_x emissions. Because of the tightly closed settings, the burner pressure drop is about 11 in. W.G. at nominal full load conditions. The other set of conditions are more representative of typical commercial practice, with more open swirl vanes and registers and co-swirling inner and outer zones. These conditions produced a longer flame (22 to over 22 feet) with lower emissions and also reduced the burner pressure drop to 5-6 in. W.G.

TABLE 4-3. RANGE OF SCREENING TESTS FOR STANDARD PHASE V DRB

Configuration	Diffuser	Venturi	Diffuser + ASP	Diffuser + FSR	Diffuser + ASP/FSR
Burner Settings:					
Inner Spin Vanes	18°CCW-16°CW	18°CCW-26°CW	18°CCW-26°CW	18°CCW-26°CW	18°CCW-7°CW
Outer Register	15°-45°CW	15°-55°CW	15°-55°CW	15°-45°CW	15°-45°CW
Inner Sleeve Damper	25-100% Open	25-100% Open	25-100% Open	25-100% Open	25-100% Open
Performance Range:					
NO_x @% O_2 Dry (ppm)	243-372	252-370	314-392	243-298	309-352
Flame Length (ft)	20->22	20->22	14->22	22->22	22->22
Burner P (in. W.G.)	4.9-10.8	5.0-11.0	6.0-11.8	4.5-10.5	5.7-11.0

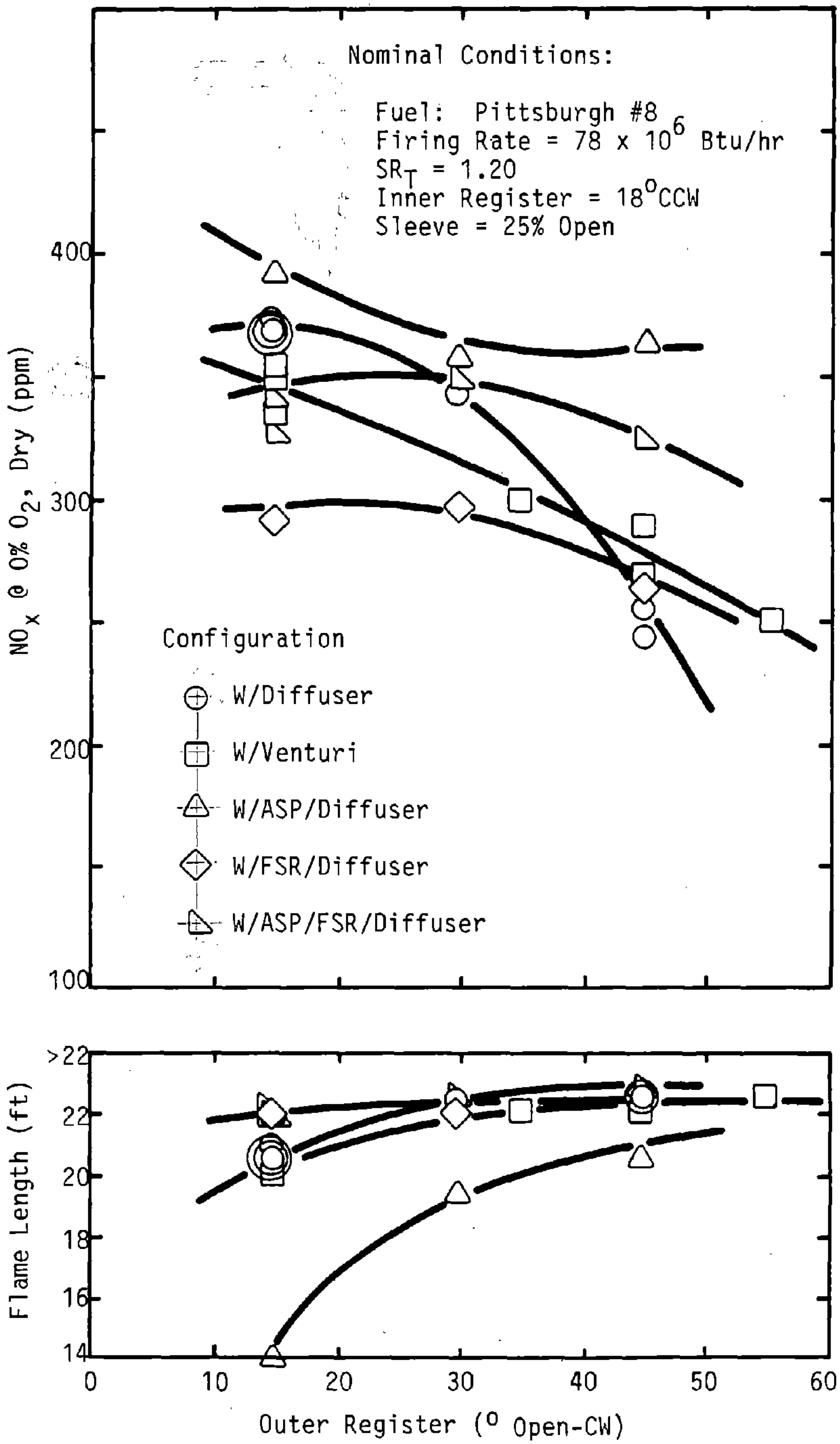


Figure 4-8. Sensitivity of Phase V DRB configurations to outer register position.

TABLE 4-4. SELECTED OPTIMUM SETTINGS FOR PHASE V DRB

Parameter	Low Velocity DRB	Commercial Practice
Inner Spin Vanes	18^{o} CCW	26^{o} CW
Outer Register	15^{o} CW	35^{o} CW
Inner Sleeve Damper	25% Open	100% Open
Nominal Burner ΔP	11 in. W.G.	5-6 in. W.G.

The performance of the five configurations evaluated is compared in Figures 4-9 and 4-10 as a function of excess air and firing rate, respectively. These data show the effect of each component on burner performance implicitly. The lowest NO_x emissions at full load were produced by the diffuser and Flame Stabilizing Ring configurations, both with about 290 ppm NO_x and flames over 22 feet long for the commercial burner settings. The venturi, Air Separation Plate alone, and the combined Air Separation Plate/ Flame Stabilizing Ring yielded similar, but higher, NO_x emissions 330-350 ppm. Only the Air Separation Plate produced a flame observed not to impinge on the rear wall at the commercial settings. Combustion efficiency, as indicated by fly ash carbon content, fell within a fairly narrow band for 4 of the 5 configurations. The diffuser had slightly high unburned carbon levels over the excess air range tested. The effect of firing rate on performance is not as clear with respect to ranking the emissions performance of the various configurations over the range tested. Each configuration did demonstrate a decrease in NO_x with load coupled with an increase in unburned carbon.

Considering the effectiveness of each burner component, the coal diffuser yielded approximately 12 percent lower NO_x emissions, and slightly longer flames, than did the coal venturi. Each device is positioned at the coal pipe inlet well upstream of the coal nozzle exit. The Flame Stabilizing Ring with the coal diffuser achieved performance very similar to that of the diffuser alone. However, their function is somewhat different. The FSR is attached at the exit of the coal nozzle producing small stabilizing recirculation zones near the nozzle and promoting a higher velocity central coal jet. The small differences with co-swirling inner and outer zones is again surprising. The Air Separation Plate, whose intended function is to separate the inner and outer air streams, seemed to do the opposite. Upon inspection, it appears the angle and outlet velocity may produce an unintended eddy which actually enhances mixing between the inner and outer zones. The basic principal of such a baffle is sound, but the data suggests that the design of this device is critical to the resulting performance. The performance of the combined ASP/FSR configuration was between that measured for the two components alone. In those terms, the effect of the combined

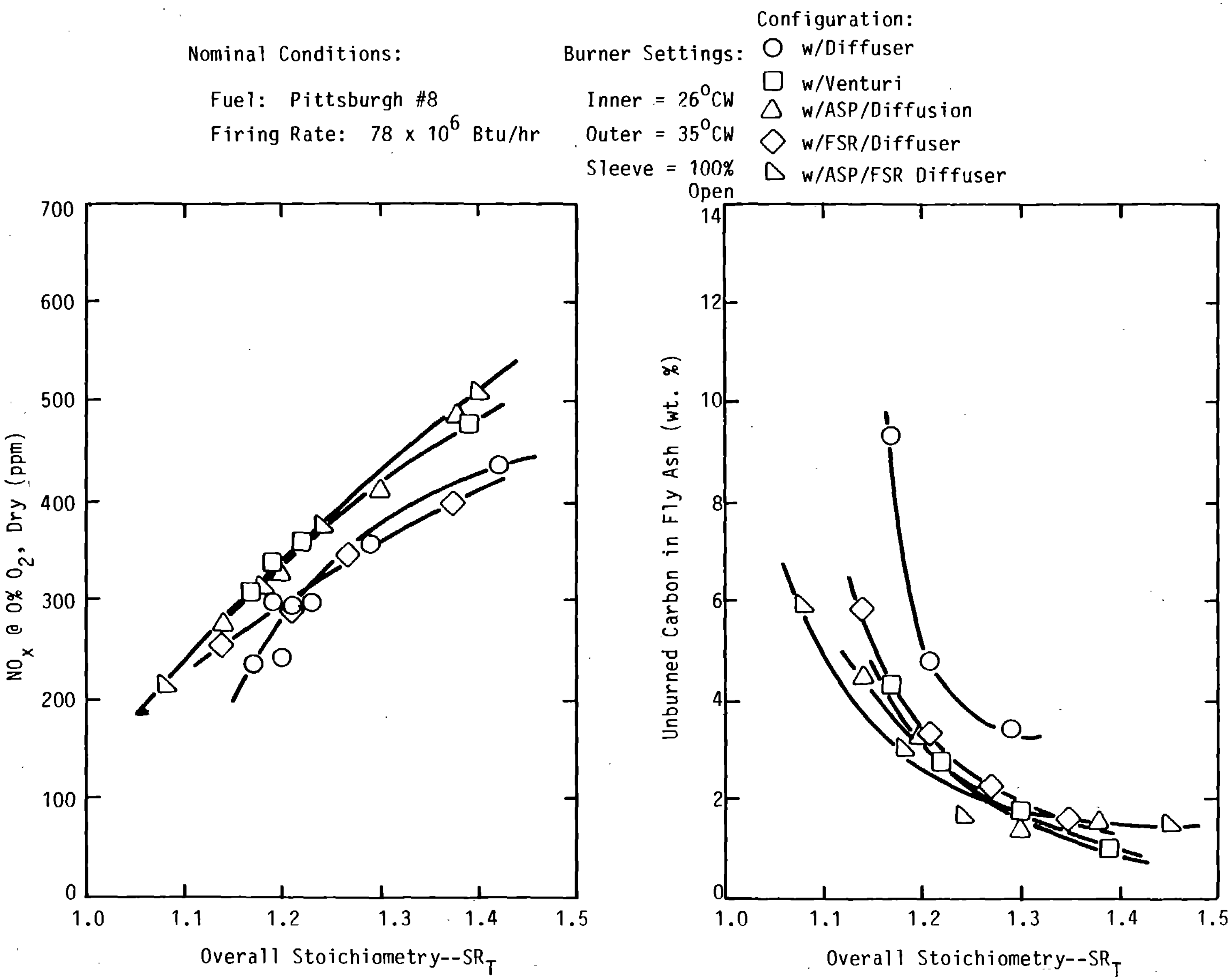


Figure 4-9. Effect of excess air on Phase V DRB configurations' performance.

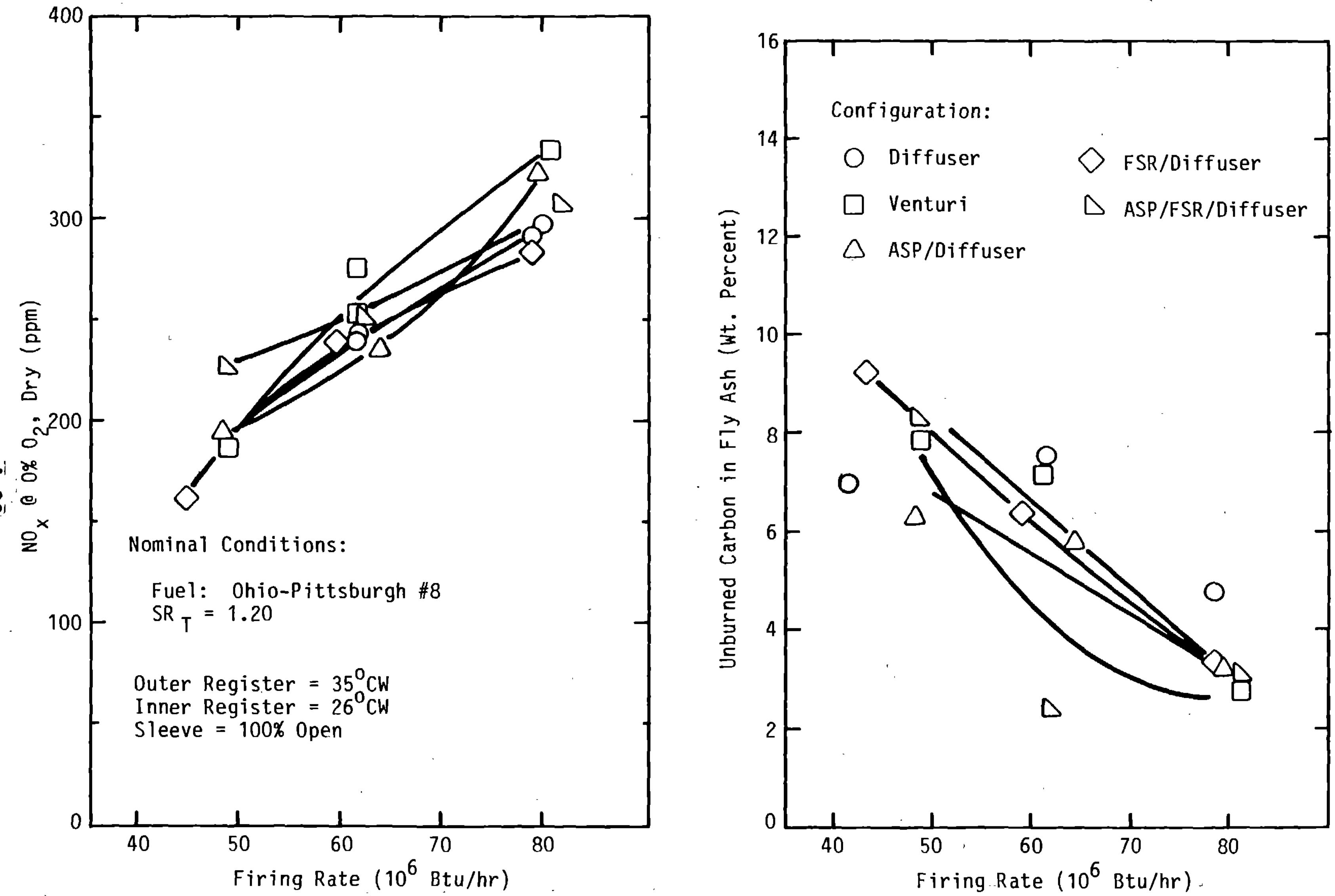


Figure 4-10. Effect of firing rate on Phase V DRB configurations' performance.

components can be thought to be additive, with neither promoting the effectiveness of the other. Table 4-5 summarizes the key test conditions with the various Phase V DRB configurations. Primary benefit of the ASP and the FSR was the reduction in unburned carbon in ash.

Direct comparison of the Phase V DRB can be made with the Low Velocity DRB, given that each was evaluated in the same furnace with the same fuel and at the same scale. This comparison is shown in Figure 4-11 for the two burners in their basic configurations, utilizing a coal diffuser alone. Given the same high turbulence burner settings, the Phase V DRB produced higher NO_x emissions (372 ppm) than did the Low Velocity DRB (264 ppm). The flame was correspondingly shorter for the Phase V DRB (20-21 ft) than for the Low Velocity DRB (> 22 ft). Unburned carbon levels, however, were comparable for the two burners. The Phase V DRB with more conventional burner settings achieved performance very similar to that of the Low Velocity DRB with its high turbulence settings, namely NO_x emissions of 295 ppm, flame length over 22 feet, and 4.75 percent carbon in ash. This comparison indicates the importance of burner velocities to resultant performance and confirms that one of the basic design principal of low-emission burners is lower combustion air velocities.

4.2 Evaluation of the Babcock-Hitachi NO_x Reducing Burner

The Babcock-Hitachi NO_x Reducing burner was tested in two basic configurations. One configuration utilized a coal swirler positioned just upstream of the Flame Stabilizing Ring and the other replaced this coal swirler with the standard diffuser at the inlet of the coal nozzle. In addition, inspection of the HNR burner assembly after initial screening tests revealed excessive clearance in the outer register vanes. Shims were installed to reduce this clearance and thus increase swirl generation effectiveness. This outer register modification constituted a variation of the HNR with diffuser.

TABLE 4-5. SUMMARY OF KEY PHASE V DRB TEST CONDITIONS

Configuration	Registers Inner	Registers Outer	Sleeve (% Open)	Firing Rate (10^6 Btu/hr)	SR_T	NO_x @ 0% O_2	CO @ 0% O_2	Flame Length (ft)	Fly Ash Carbon (wt %)	Burner ΔP (In. W.G.)
Diffuser	18°CCW	15°CW	25	79.3	1.19	372	24	20-21	6.12	10.8
Diffuser	26°CW	35°CW	100	78.7	1.21	293	24	>22	4.75	4.9
Diffuser	26°CW	35°CW	100	61.6	1.19	240	42	>22	7.47	2.9
Venturi	18°CCW	15°CW	25	80.8	1.18	350	18	20-21	6.45	11.0
Venturi	26°CW	35°CW	100	81.6	1.22	356	25	>22	2.70	5.7
Venturi	26°CW	35°CW	100	61.6	1.20	253	33	22	7.10	3.0
ASP	18°CCW	15°CW	25	81.5	1.18	392	25	14-15	9.74	11.8
ASP	26°CW	35°CW	100	79.5	1.20	326	25	22	3.20	6.4
ASP	26°CW	35°CW	100	64.4	1.18	237	27	22	5.74	3.8
FSR	18°CCW	15°CW	25	80.6	1.19	292	26	22	6.96	10.5
FSR	26°CW	35°CW	100	78.9	1.21	285	24	>22	3.29	4.9
FSR	26°CW	35°CW	100	59.4	1.19	240	28	22	6.32	2.7
ASP/FSR	18°CCW	15°CW	25	80.4	1.19	328	24	22	5.16	11.0
ASP/FSR	26°CW	35°CW	100	81.6	1.18	309	24	>22	3.02	6.1
ASP/FSR	26°CW	35°CW	100	61.9	1.19	252	18	21-2	2.36	3.7

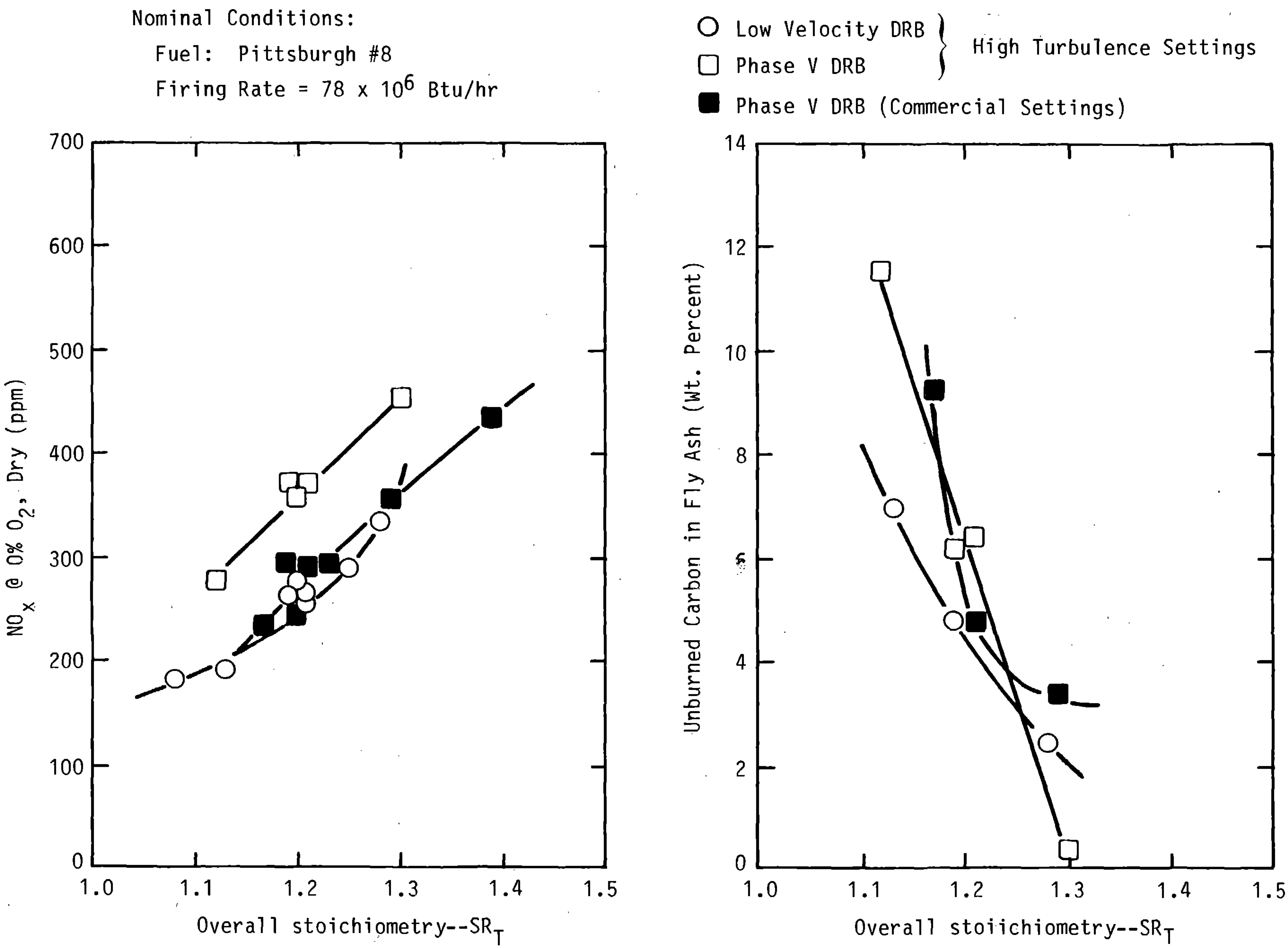


Figure 4-11. Comparison of the Phase V DRB with the Low Velocity DRB.

As with all the Second Generation Low NO_x burners, screening tests to identify optimum performance were conducted at the following nominal operating conditions with the Pittsburgh #8 coal:

Firing Rate = 78×10^6 Btu/hr

SR_P = 0.18

SR_T = 1.20

Primary Air Temperature = 150°F

Combustion Air Temperature = 550°F

The parametric screening tests were conducted over the range of settings listed in Table 4-6. For the HNR burner, the swirl direction of the two air zones was maintained in the same clockwise orientation. No opposed swirl cases were evaluated.

Results of the screening tests are summarized in Figure 4-12. Performance of the HNR burner was most sensitive to the outer zone variables. Low NO_x emissions and reasonable flame lengths could be achieved by biasing air to the outer register by closing the inner damper coupled with the outer vanes closed to produce a high degree of swirl. The HNR configuration with the coal swirler produced higher NO_x emissions, 348 ppm at 20 percent excess air, with a correspondingly shorter flame, 18-20 ft long than did the HNR with coal diffuser, 290 ppm NO_x and a 20 ft-long flame. With the modified outer register, NO_x emissions were reduced further down to 222 ppm with a correspondingly longer flame, over 22 ft. The tight burner settings that achieved these low emissions with the modified outer register resulted in a high burner pressure drop, nominally 7 in. W.G.

The performance characteristics, in terms of NO_x emissions and unburned carbon in the fly ash, are summarized for the HNR burner with diffuser and modified outer register in Figures 4-13 and 4-14, respectively. The NO_x

TABLE 4-6. RANGE OF SCREENING TESTS FOR HNR BURNER

Configuration	Coal Swirler	Coal Diffuser
Burner Settings:		
Inner Spin Vanes	10^{o}-30^{o}CW	10^{o}-70^{o}CW
Outer Register	15^{o}-45^{o}CW	10^{o}-75^{o}CW
Inner Sleeve Damper	0-50% Open	0-50% Open
Swirler Position	-5 to -10 in.	N/A
Performance Range:		
NO_x @ 0% O_2, Dry (ppm)	294-416	198-426
Flame Length (ft)	13->22	18->22
Burner ΔP (in. W.G.)	4.2-8.9	4.6-13.2

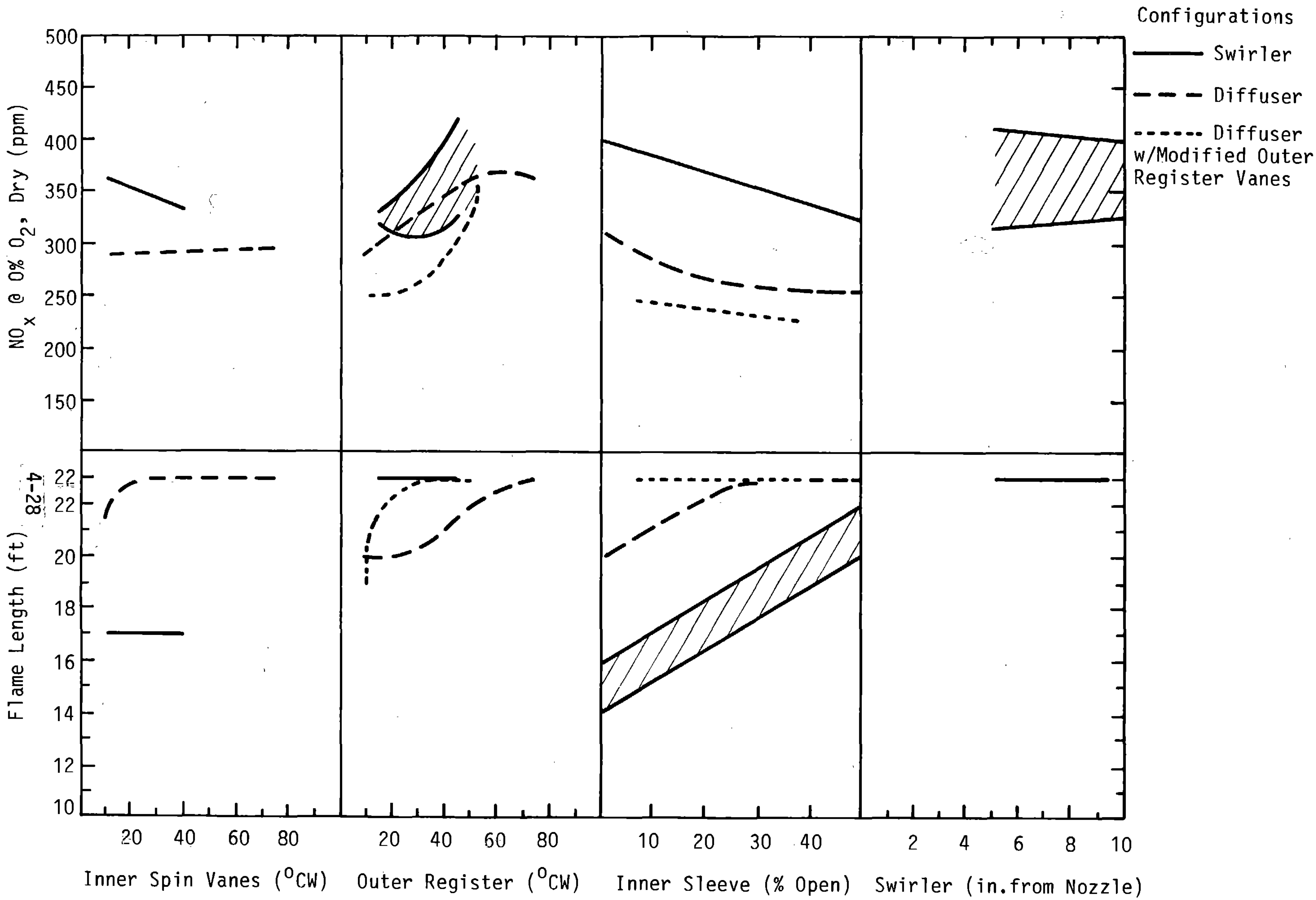


Figure 4-12. Sensitivity of HNR burner performance to burner adjustments.

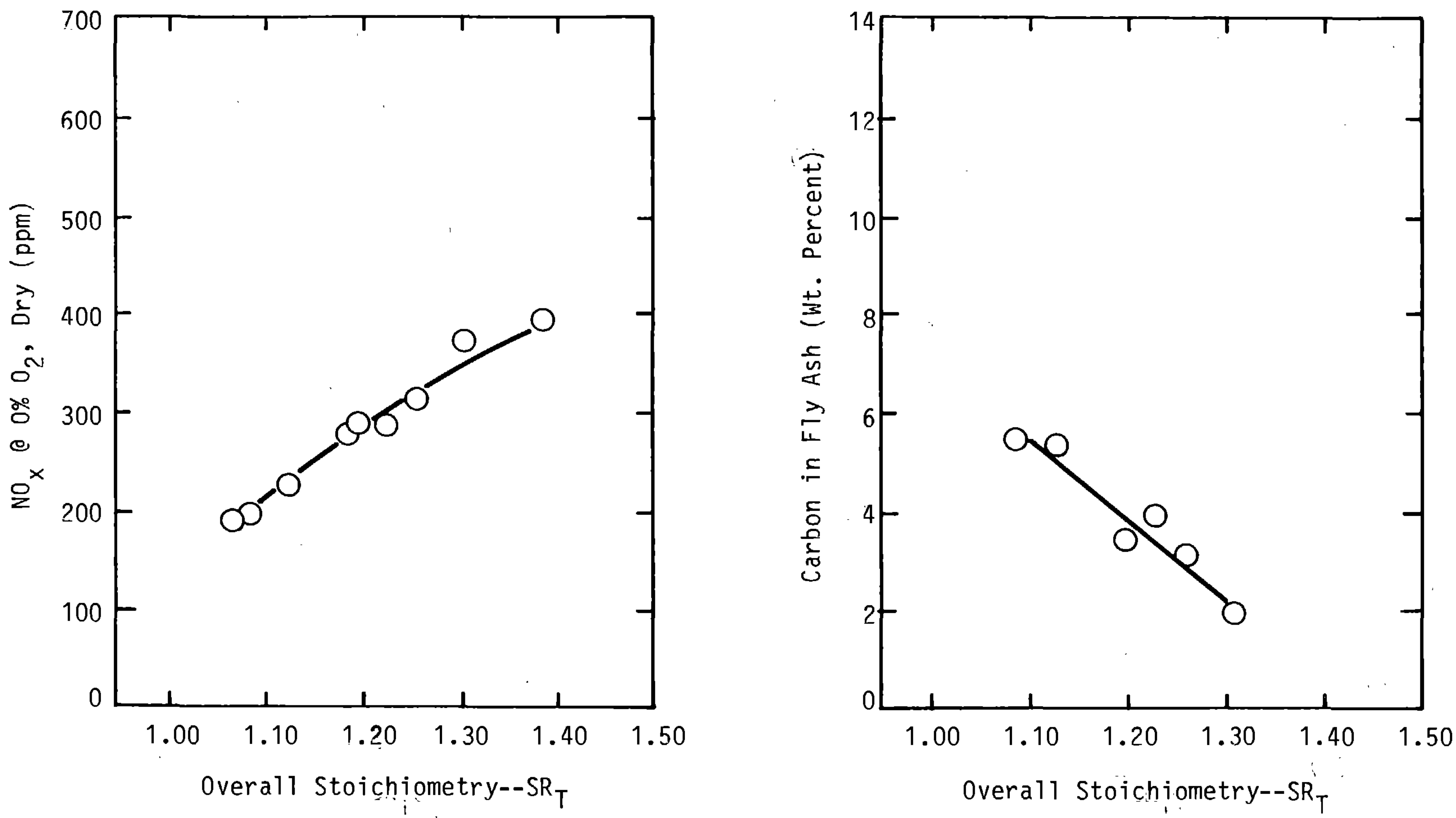


Figure 4-13. Effect of excess on performance of HNR burner with coal diffuser at 78 x 10^6 Btu/hr.

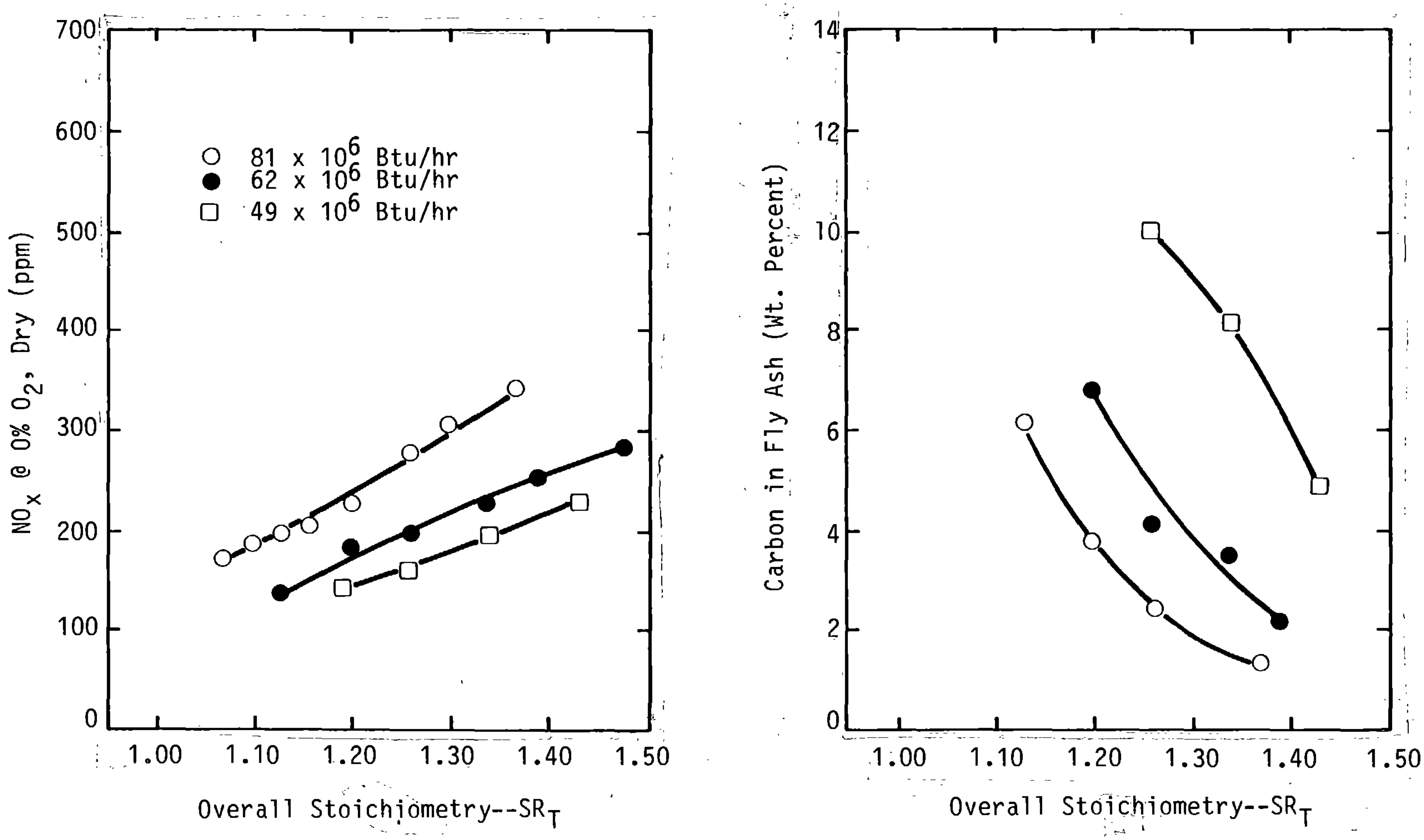


Figure 4-14. Effect of excess air and firing rate on performance of HNR burner with modified outer register.

emissions for the HNR burner with coal diffuser decreased essentially linearly with excess air, down to less than 200 ppm and an overall stoichiometry of 1.07. Fly ash carbon content increased linearly as excess air decreased, but remained less than 6 percent at very low excess air levels. The HNR burner equipped with a coal diffuser and the modified outer register vanes yielded a family of data for three firing rates. Both the NO_x emission and fly ash carbon data formed nearly parallel curves for the three firing rates over the excess air range tested. As expected, NO_x emissions were highest and fly ash carbon content lowest for full load. Combustion efficiency for this HNR configuration was very sensitive to excess air and firing rate.

The performance of the HNR burner with and without the modified outer register is directly compared in Figure 4-15. The modified outer register produced the lower NO_x emissions with no significant impact on combustion efficiency. There was a tradeoff, however, in flame length. The lower NO_x emissions with the modified outer register were achieved at the expense of flame lengths exceeding 22 ft at full load. Table 4-7 summarizes the key conditions for the HNR burner.

4.3 XCL Burner

The XCL burner was evaluated in two series of tests. The initial series considered the following configurations to determine the hardware arrangement for optimum performance within the Edgewater boiler constraints:

- Flame Stabilizing Ring with coal diffuser.
- Flame Stabilizing Ring with coal diffuser and modified outer spin vanes.
- $DeNO_x$ Stabilizer
- 30^o coal impeller
- Coal diffuser

The initial tests were conducted with Pittsburgh #8 coal at operating conditions comparable to the DRB and HNR burner tests:

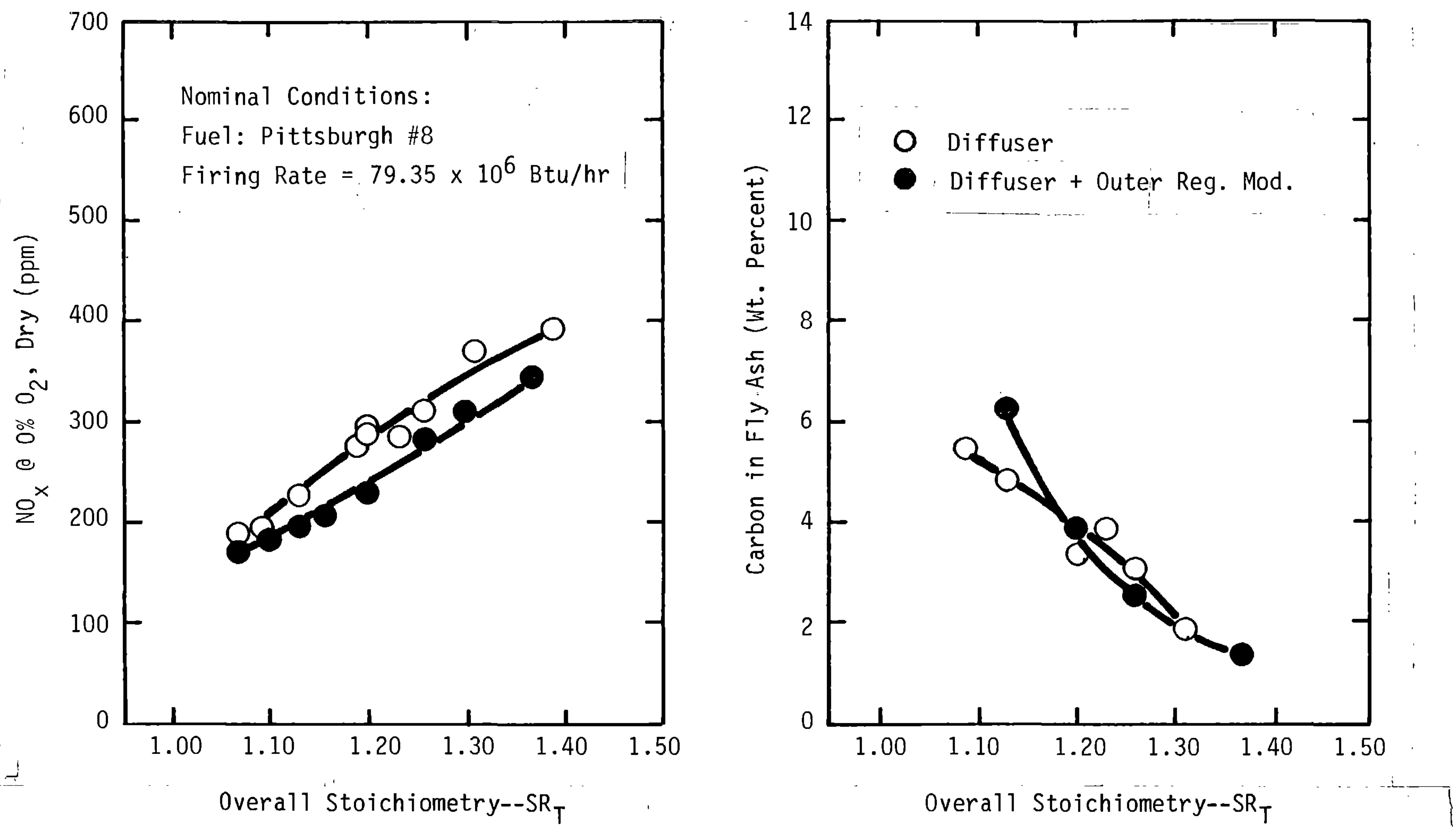


Figure 4-15. Comparison of HNR burner configurations' performance.

TABLE 4-7. SUMMARY OF KEY HNR BURNER TEST CONDITIONS

Configuration	Registers		Inner Sleeve Damper (% Open)	Spreader Position (in.)	Firing Rate (10^6 Btu /hr)	SR_T	Emissions (@ 0% O_2)		Flame Length (ft)	Fly Ash Carbon (wt.%)	Windbox Pres. (in.W.G.)
	Inner	Outer					NO_x	CO			
Swirler	10°CW	15°CW	25	-10	79.0	1.19	348	18	18-20		7.20
Diffuser	10°CW	20°CW	12	Diffuser	77.7	1.20	289	30	20	3.34	7.50
Out Reg. Mod.	10°CW	20°CW	25	Diffuser	79.1	1.19	222	24	22	2.65	6.80
Out Reg. Mod.	10°CW	20°CW	25	Diffuser	61.9	1.20	181	42	22	6.86	4.10
Out Reg. Mod.	10°CW	20°CW	25	Diffuser	51.0	1.19	144	138	18-19		2.70

Firing Rate = 78 x 10^6 Btu/hr

SR_P = 0.18

SR_T 1.20

Primary Air Temperature = 150°F

Combustion Air Temperature = 550°F

Based on the initial test series results, the XCL burner was identified as having the most potential to satisfy the requirements of the LIMB demonstration. The additional hardware configurations considered in the second XCL optimization test series included:

- 20° coal impeller
- Open impeller
- Expanded nozzle with coal diffuser
- Expanded nozzle with 20° impeller
- Expanded nozzle with 30° impeller
- 30° impeller and fixed outer vane assembly
- Diffuser and fixed outer vane assembly

The second optimization series was conducted at a lower overall stoichiometry, 1.16. This condition, specified by B&W, was representative of operation in most B&W boilers. At this lower excess air level, the lower air flow would result in lower burner pressure drop as well as lower NO_x emissions. Optimizing burner performance at this lower excess air level was expected to provide data that would fulfill Edgewater boiler constraints. Following the optimization of XCL burner hardware in this second series, the final configuration was characterized with three alternate coals.

4.3.1 Optimization of Burner Hardware

The initial screening tests to determine optimum XCL burner hardware were conducted over the range of burner variables listed in Table 4-8.

TABLE 4-8. RANGE OF INITIAL SCREENING TESTS OF XCL BURNER

Configuration	Diffuser/ FSR	Diffuser/FSR w/Mod. Outer Vanes	DNS	30_o Impeller	Diffuser
Burner Settings:					
Inner Spin Vanes	10-30°CW	10-50°CW	10-50°CW	20-70°CW	20-50°CW
Outer Spin Vanes	20-60°CW	10-85°CW	10-50°CW	20-50°CW	20-70°CW
Inner Sleeve Damper	25% Open	0-37.5% Open	25-100% Open	25-100% Open	25-75% Open
*Outer Sleeve Damper	85% Open	77% Open	100% Open	100% Open	61.5-85% Open
Impeller Position	N/A	N/A	N/A	-6 to +6 in.	N/A
Performance Range:					
NO_x @ 0% O_2, Dry (ppm)	216-314	211-322	228-306	252-700	229-346
Flame Length (ft)	22->22	21->22	19->22	12->22	20->22
Burner P (in. W.G.)	1.2-12.0	0.9-12.5	3.1-13.0	2.5-10.6	2.8-9.5

Results of these screening tests are summarized in Figures 4-16 and 4-17. NO_x emissions less than 300 ppm could be achieved with both FSR-equipped XCL burner configurations, the $DeNO_x$ stabilizer, and the standard B&W coal diffuser for a number of conditions, as shown in Figure 4-16. However, for most burner settings with these burner components the flame length associated with these low-NO_x levels exceeded 22 ft. The XCL burner with the $DeNO_x$ stabilizer could achieve low NO_x emissions, 288 ppm, and a reasonable flame length, 20 ft, with tightly closed, high-swirl inner and outer spin vane positions. These spin vane positions, however, resulted in a high burner pressure drop, 8.2 in. W.G. As for the DRB and HNR burner, the outer zone was the dominant burner adjustment affecting burner performance.

The coal diffuser produced low emissions and adjustments could be made to yield a flame about 22 ft. long with pulses exceeding the furnace depth (> 22 ft). At optimum settings for the XCL burner with diffuser, NO_x emissions were 276, 205, and 194 ppm at firing rates of 80.8, 59.9, and 50.4 x 10^6 Btu/hr, respectively. The effect of excess air on the performance of the XCL burner with the coal diffuser at these three firing rates is summarized in Figure 4-18.

The 30^o impeller installed in the XCL burner had a dramatic effect on performance and burner sensitivity, as shown in Figure 4-17. Position of the impeller in relation to the coal nozzle was a critical parameter in burner performance. Inner and outer zone adjustments were of secondary importance, functioning to fine tune burner performance. Moving the impeller a matter of inches changed NO_x emissions from 600 ppm to 250 ppm with a corresponding change in flame shape and length, from a widely flaring, short flame to a long, narrow flame. In addition, a hysteresis was observed during adjustment of impeller position. Retracting the impeller back into the coal nozzle (denoted as the negative direction) had little effect on NO_x emissions and flame length until the impeller was 5 inches inside the coal nozzle. At this point there was a step change in performance, with the flame narrowing and increasing to over 22 feet in length. NO_x emissions dropped correspondingly. When pushing the impeller back toward the coal nozzle exit (positive

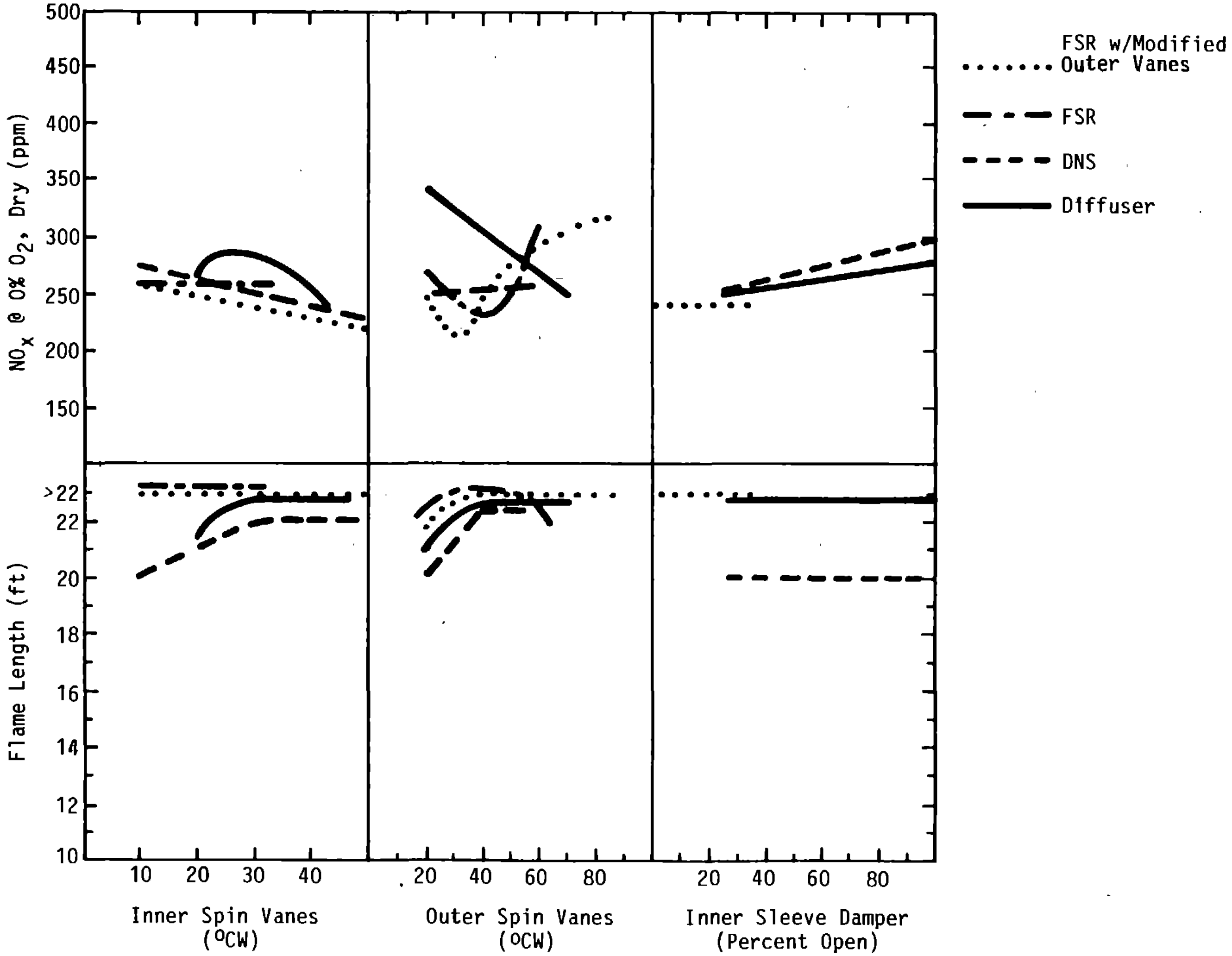


Figure 4-16. Results of initial screening tests of XCL burner for four configurations.

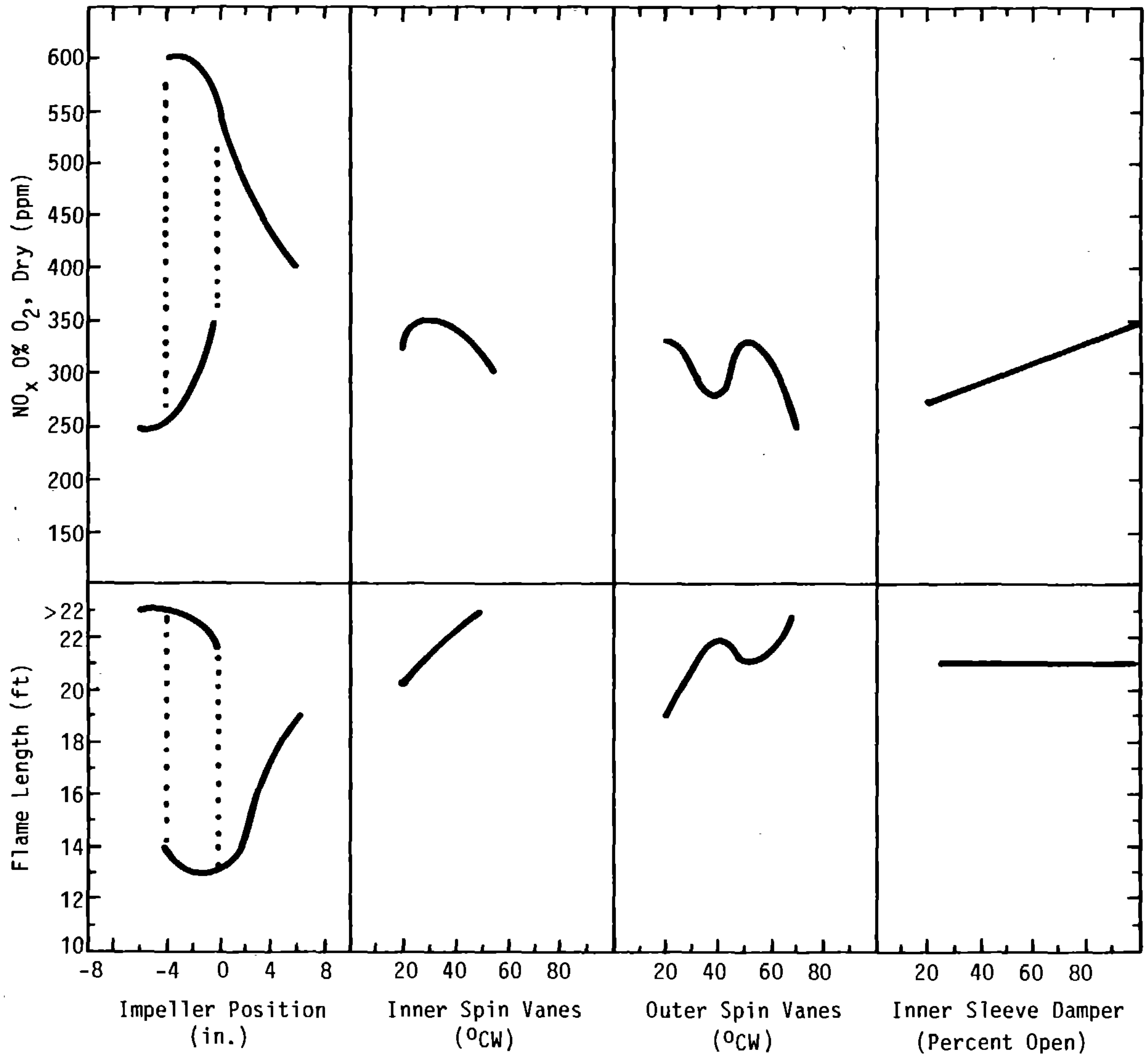


Figure 4-17. Results of initial screening tests of XCL burner with 30° impeller.

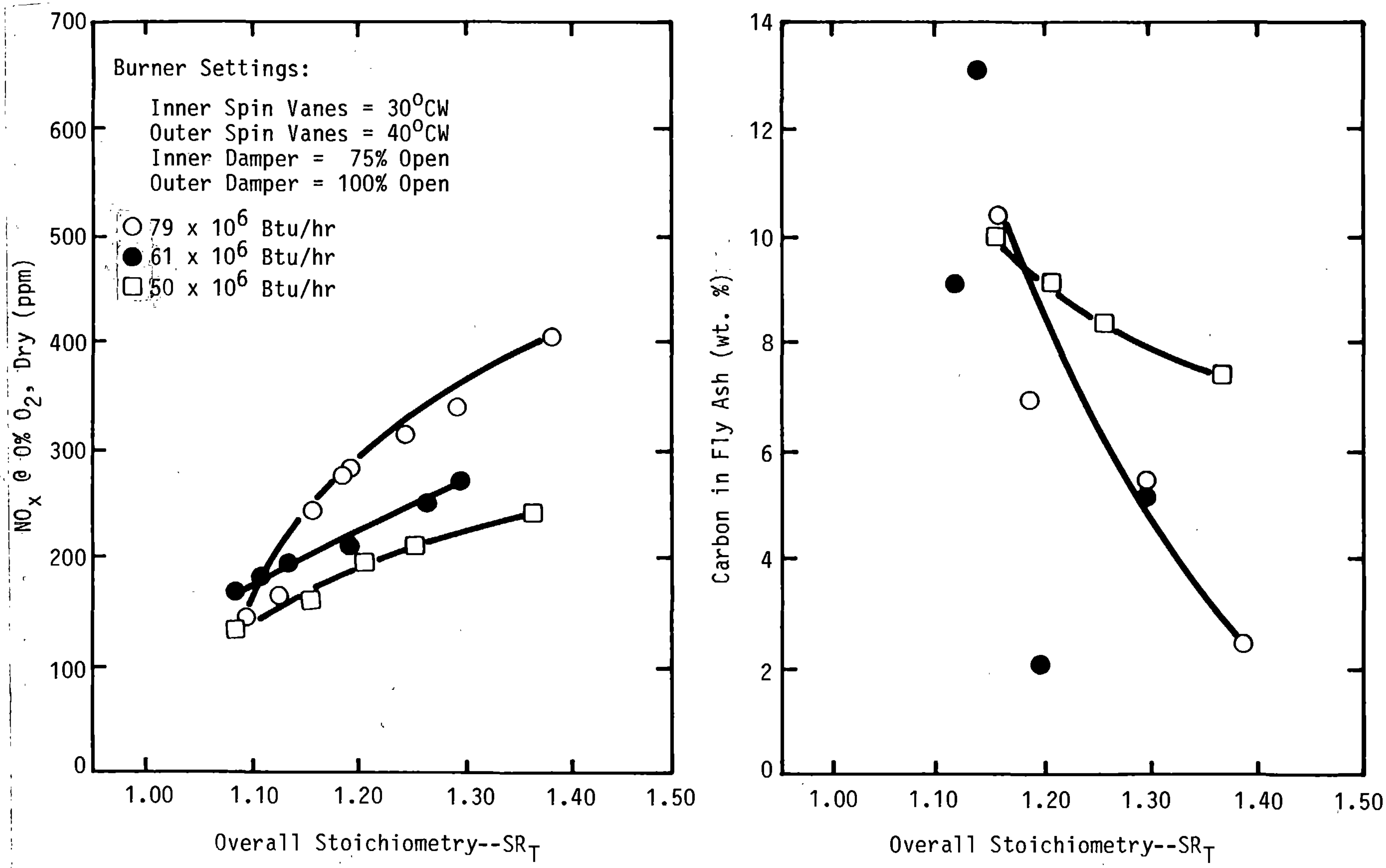


Figure 4-18. Effect of excess air on performance of XCL burner with coal diffuser.

direction), the flame remained over 22 ft long until the impeller reached its "0" position, the trailing edge flush with the end of the coal nozzle.

Because of this bistable phenomena, the adjustable burner parameters were optimized at two different impeller positions representing either side of the bistable settings, 0 and -5 inches from the nozzle. With the impeller at the 0 position, NO_x emissions were 449 ppm with an 18 ft long flame at nominal full load conditions (78×10^6 Btu/hr and SR_T = 1.20). With the impeller retracted into the nozzle 5 inches, NO_x emissions were 374 ppm with a 20-22 ft long flame. The XCL burner with the 30° impeller at -5 in. was characterized over a range of excess air and firing rate, with the results shown in Figure 4-19. For this configuration, combustion efficiency as fly ash carbon content was very good down to about 10 percent excess air even at reduced load. The data indicate that relatively low emissions can be achieved with good carbon burnout and reasonable flame length.

These initial screening tests indicated that the XCL burner had potential to meet the LIMB demonstration goals at Edgewater. Of the configurations and conditions evaluated, listed in Table 4-9, the coal diffuser and coal impeller were most promising. Although the coal diffuser produced a flame slightly longer than the furnace depth, NO_x emissions were very low and warranted consideration. The 30° impeller could achieve relatively low emissions and acceptable flame lengths and, more importantly, provided a wide range of adjustment to performance. The performance of the XCL burner with these two components is compared in Figure 4-20. The NO_x emissions from these two configurations followed the same trends over a range of excess air, with diffuser producing about 100 ppm less NO_x. The 30° impeller, however, had significantly better carbon burnout permitting operation at lower excess air levels.

The encouraging results from this initial series of screening tests provided direction to the second test series. The second series of tests focused on additional development of the coal nozzle/impeller design. Further refinement of the coal nozzle/impeller was expected to achieve an optimum compromise between the very low NO_x produced by the diffuser and the

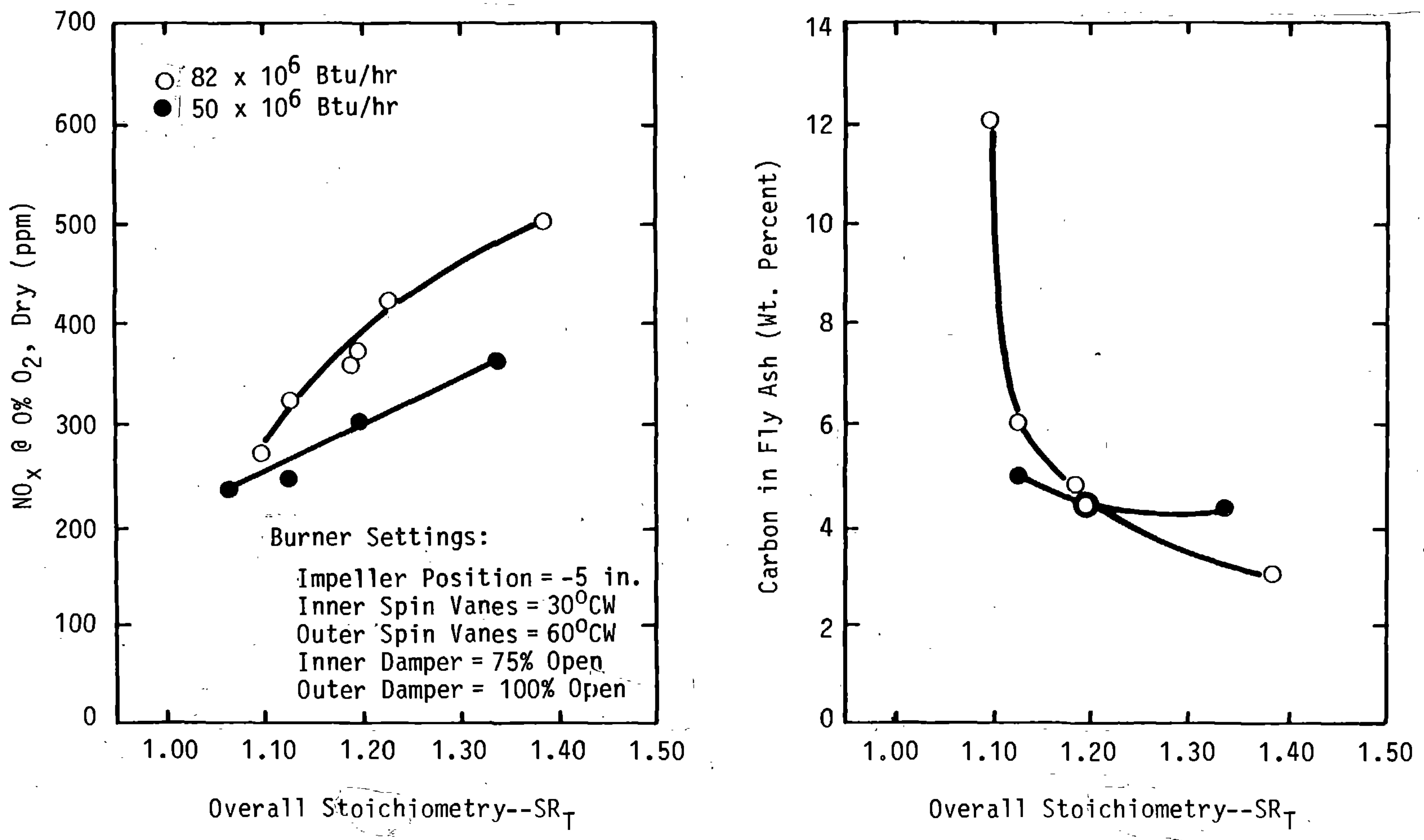


Figure 4-19. Effect of excess air on performance of XCL burner with 30^{o} Impeller.

TABLE 4-9. SUMMARY OF KEY TEST CONDITIONS FROM INITIAL XCL BURNER SCREENING TESTS

Configuration	Registers		Sleeves		Impeller Position (Inches)	Firing Rate (10^6 Btu /hr)	SR_T	Emissions		Flame Length (ft)	Fly Ash Carbon (wt.%)	Windbox Pres. (in.W.G.
	Inner	Outer	Inner (% Open)	Outer (% Open)				@ 0% NO_x	@ 0% CO			
FSR, O.R.MOD	30°CW	40°CW	25	77	N/A	78.0	1.19	222	36	>22		3.10
FSR	20°CW	40°CW	25	85	N/A	78.4	1.19	246	36	>22		3.20
Diffuser	30°CW	40°CW	75	100	N/A	80.8	1.19	276	48	22+	6.97	5.10
Diffuser	30°CW	40°CW	75	100	N/A	59.9	1.20	205	42	22+	1.98	2.50
Diffuser	30°CW	40°CW	75	100	N/A	50.4	1.21	194	64	22+	9.20	1.50
DNS	20°CW	30°CW	75	100	N/A	77.8	1.19	288	36	20		8.20
30° Impeller	30°CW	60°CW	75	100	0	77.7	1.21	449	14	18		3.50
30° Impeller	30°CW	60°CW	75	100	-5	79.9	1.20	374	24	20-22	4.42	3.30
30° Impeller	30°CW	60°CW	75	100	-5	59.6	1.19	306	26	20-22	5.18	1.60
30° Impeller	30°CW	60°CW	75	100	-5	49.8	1.20	301	30	19-22	4.44	1.00

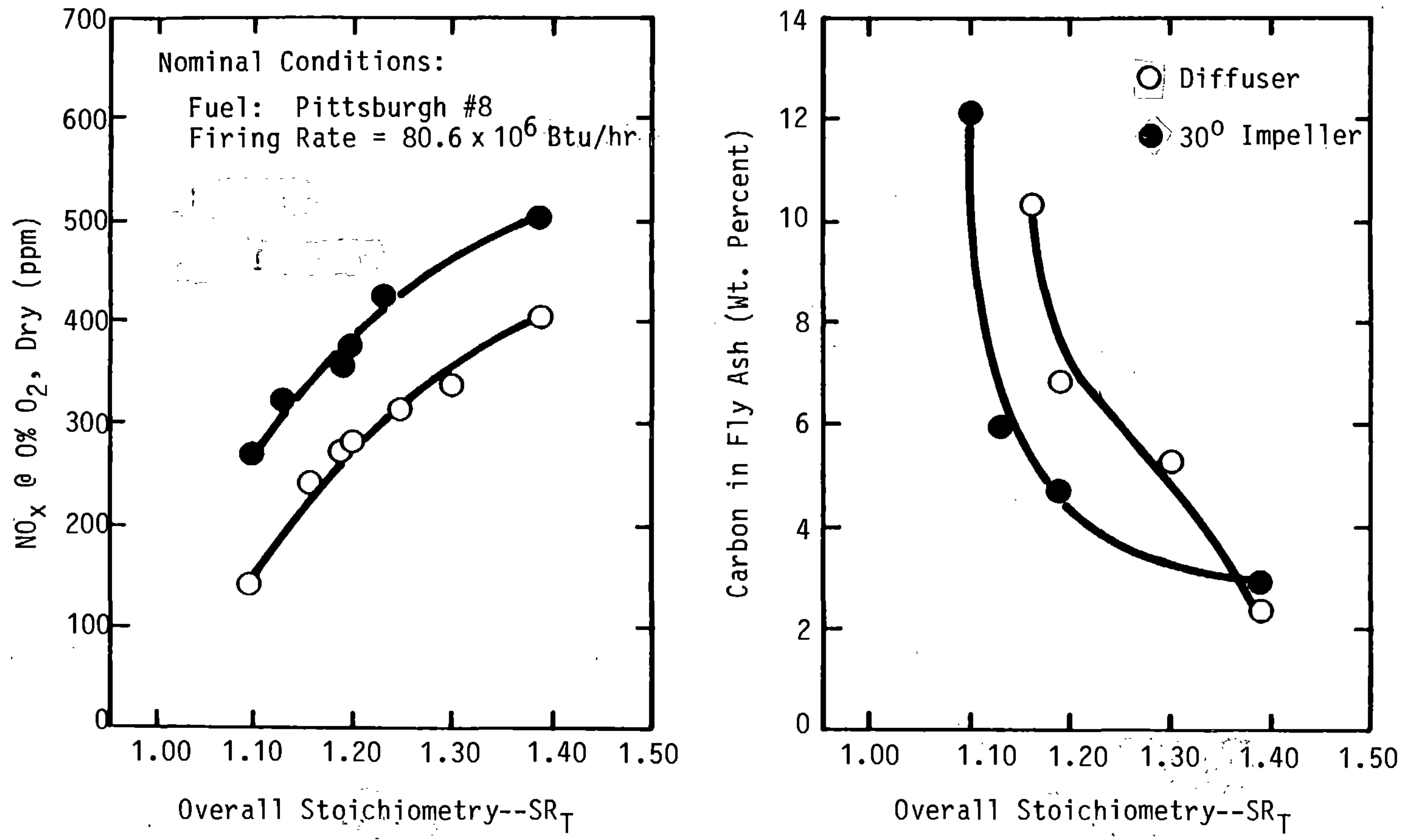


Figure 4-20. Comparison of coal diffuser and 30° impeller XCL burner configurations.

effective flame shaping control and exceptional burnout achieved with the 30° impeller. In addition, the potential to minimize burner pressure drop and enhance mechanical reliability was evaluated using fixed position outer swirl vanes.

The range of these final screening tests for the XCL burner is listed in Table 4-10. As described previously, these final tests were conducted at lower excess air, an SR_T = 1.16, than the previous tests, SR_T = 1.20. These tests can be grouped in three sets:

- Impeller evaluation with standard coal nozzle
- Evaluation of expanded coal nozzle tip
- Evaluation of fixed outer swirl vanes

Results of screening tests of three impeller designs with the standard coal nozzle are summarized in Figure 4-21. The impellers evaluated included the previously tested 30° impeller, 20° included angle impeller, and an open-design 30° impeller. Because there was a span of time between the initial XCL screening tests and the final series, repeat of the 30° impeller served to verify similarity between tests and provided a basis with which to compare the new designs. General trends of performance with burner adjustments were similar for the initial and final screening tests of the 30° impeller configuration. However, the hysteresis in performance related to impeller position observed during the initial test series did not occur. Because the impeller affects the aerodynamics near the burner, the change in performance between the two test series is probably due to differences in burner conditions, namely excess air level and spin vane position. The lower flow rate of air through the burner lowers both the axial and tangential momentum of the burner. During this final series, NO_x emissions ranged from 310 to 467 ppm with flames from 16 to 22 ft long.

The 20° impeller was intended to be a compromise design between the 30° impeller and the coal diffuser. The 20° included angle impeller was designed to impart a radial component less than that from the 30° impeller but more than the purely axial flow from the diffuser. Burner performance with the

TABLE 4-10. RANGE OF FINAL SCREENING TESTS OF XCL BURNER

Configuration	20° Impeller	30° Impeller	Open Impeller	Diffuser w/ Expanded Nozzle	20° Impeller w/Expanded Nozzle	30° Impeller w/Expanded Nozzle	30° Impeller w/Fixed Vanes
Burner Settings:							
Inner Spin Vanes	20-40°CW	20-40°CW	30°CW	30°CW	20-35°CW	20-35°CW	20-40°C
Outer Spin Vanes	30-50°CW	30-60°CW	30-50°CW	10-40°CW	30-50°CW	30-60°CW	45°CW
Inner Sleeve Damper	75% Open	12.5-100% Open	37.5-75% Open	12.5-75% Open	37.5-75% Open	37.5-75% Open	12.5-75 Open
Outer Sleeve Damper	100% Open	100% Open	100% Open	100% Open	100% Open	100% Open	42-100% Open
Impeller Position	-6 to +3 Inches	-6 to +3 Inches	-3 to +3 Inches	N/A	-5 to 3 Inches	-5.5 to 3.0 in.	-3.0 to +3.0 in.
Performance Range:							
NO_x @ 0% O_2, Dry (ppm)	252-397	310-467	233-310	173-291	196-618	397-560	280-557
Flame Length (ft)	20->22	16-22	>22	>22	15->22	14-20	15->22
Burner P (in.W.G.)	4.1-7.0	3.4-6.7	4.5-8.0	6.0-10.6	4.2-6.9	3.0-7.1	3.5-6.2

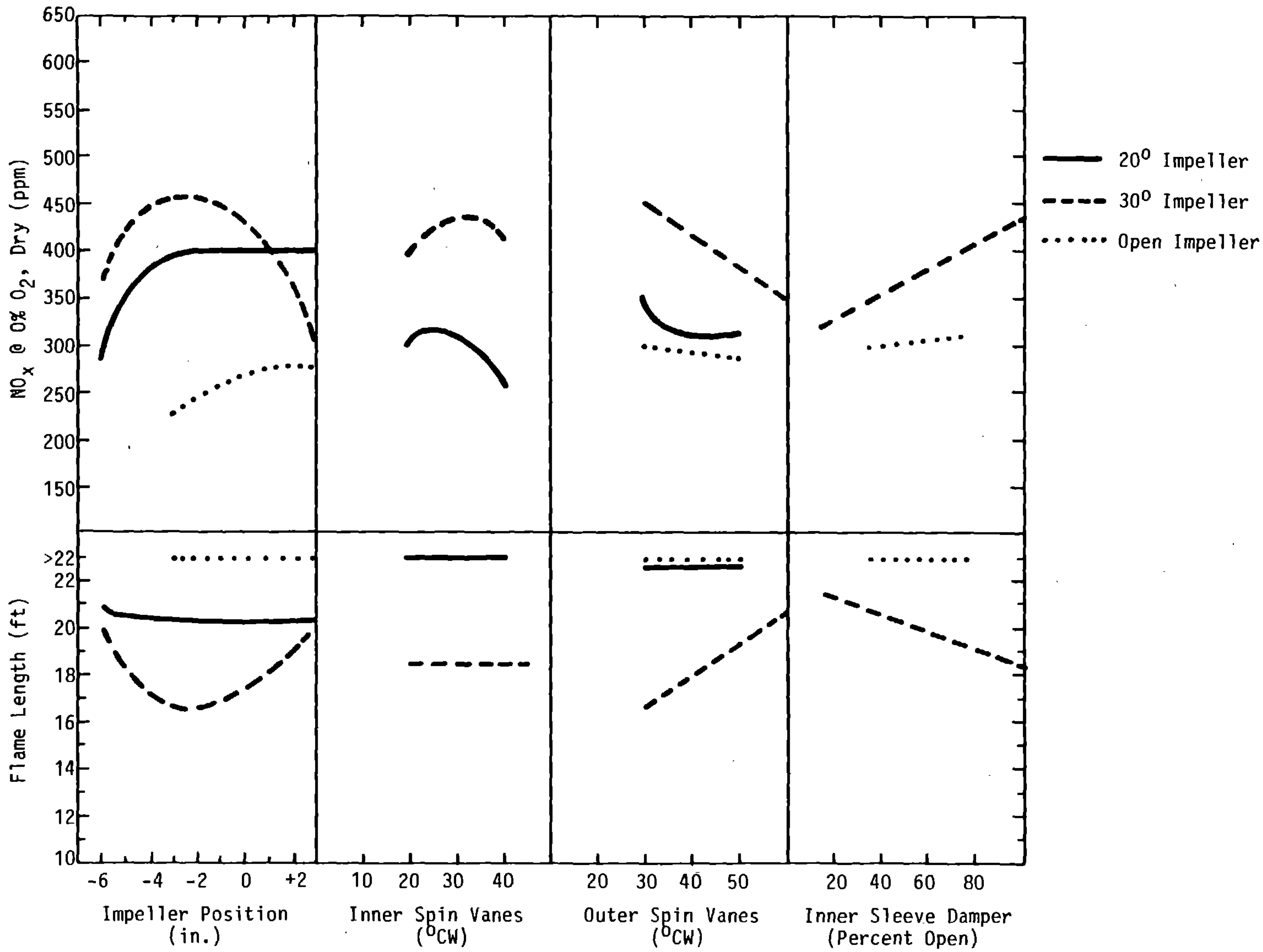


Figure 4-21. Results of final XCL burner screening tests with standard coal nozzle.

20° impeller was most sensitive to impeller position and outer spin vane position. As for all other configurations, NO_x emissions and flame length were closely related. NO_x emissions ranged from 252 to 397 ppm with relatively narrow flames 20 to over 22 ft long.

The open impeller consisted of a large central opening surrounded by two conical rings with a 30° included angle. The principle behind the design was to strip a fraction of the coal from an axial flow and divert it directly into the swirling secondary air to provide stability. The remaining coal would be introduced through the open center in an axial jet. It was hoped that this configuration would produce a compromise between the low-NO_x, long flames from the diffuser and the high-NO_x, short flames from the 30° impeller. The actual performance was comparable to the conical diffuser, with low NO_x emissions (233 to 310 ppm) and long flames (over 22 feet). Apparently the outer rings did not deflect much of the coal into the secondary air stream. The bulk of the coal was introduced axially through a smaller, higher momentum jet, thus resulting in long flames.

The expanded nozzle consisted of a short, abrupt expansion replacing the end of the straight coal nozzle. This larger diameter was installed to evaluate the effect of lower coal velocities on burner performance. Although primary air flow could be varied, decreasing the primary air flowrate not only decreased velocity but also lowered the stoichiometry in this primary air zone. By making the physical change, the aerodynamics would be evaluated independently of combustion stoichiometry. This expanded nozzle tip was tested with the standard coal diffuser, a slightly modified 20° impeller, and the 30° impeller. The results of the screening tests with the expanded nozzle are shown in Figure 4-22.

The performance of the XCL burner with the coal diffuser, located far upstream of the coal nozzle tip, was not significantly affected by the expanded nozzle tip. The resulting emissions were 173 to 198 ppm with flames over 22 feet long. The short nozzle tip, less than 0.5 coal pipe diameters, probably did not allow the coal jet to fully expand to the larger diameter

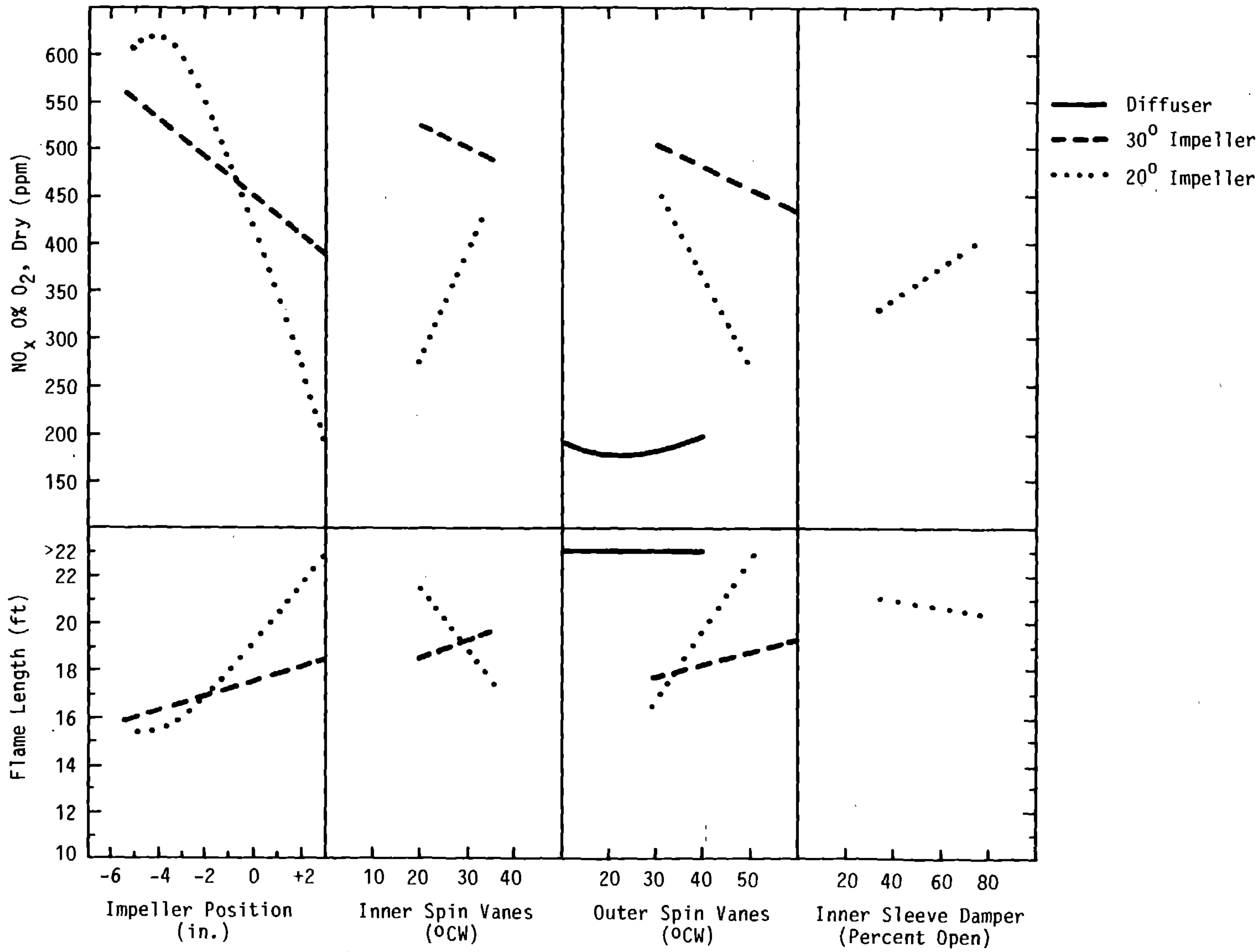


Figure 4-22. Results of final SCL burner screening tests with expanded nozzle tip.

before exiting the coal pipe. Thus, the effective coal jet velocity was probably not significantly different than the standard nozzle.

The 20° impeller was slightly modified to fit the expanded nozzle. An additional conical ring was added to enlarge the diameter of the impeller and more fully fill the expanded nozzle. The NO_x emissions achieved ranged from 196 to 618 ppm with flames from 15 to 22 feet long. Again there was a very close correlation of NO_x with flame length. This configuration demonstrated effective burner performance control with impeller position. NO_x emissions decreased essentially linearly from 618 ppm to 196 ppm (flame length from 15.16 to over 22 feet) as the impeller was moved from -3 to +3 inches. In the short test period, there did not appear to be any hysteresis in performance. As with the other impeller configurations, outer register vane position was also an effective control. Apparently, the low velocity from the expanded tip could be taken advantage of with a device that filled the entire large diameter.

The 30° impeller, with no modifications to accommodate the larger diameter nozzle tip, was also evaluated with this expanded nozzle configuration. Again there was a nearly linear response in NO_x emissions as the impeller was moved. There was, however, an indication that some hysteresis might be present upon startup at the impeller "0" position. With NO_x emissions ranging from 397 to 560 ppm and, corresponding 20 to 14 foot long flames, further evaluation of this "hysteresis" was not warranted.

The effect of the expanded coal nozzle tip is shown explicitly in Figure 4-23. Data with the standard and expanded nozzles are compared for the 20° impeller and 30° impeller, respectively. The 30° impeller, which was not modified and thus had the same outside diameter, yielded similar performance in both coal nozzles. The performance of the XCL burner with the 20° impeller, however, was significantly different with the expanded nozzle tip. The lower velocity at the nozzle tip coupled with the enlarged 20° impeller achieved NO_x emissions, which could be varied from 600 ppm to 200 ppm simply by moving the impeller 6 inches. The NO_x performance was coupled to flame length ranging from about 16 ft to over 22 ft.

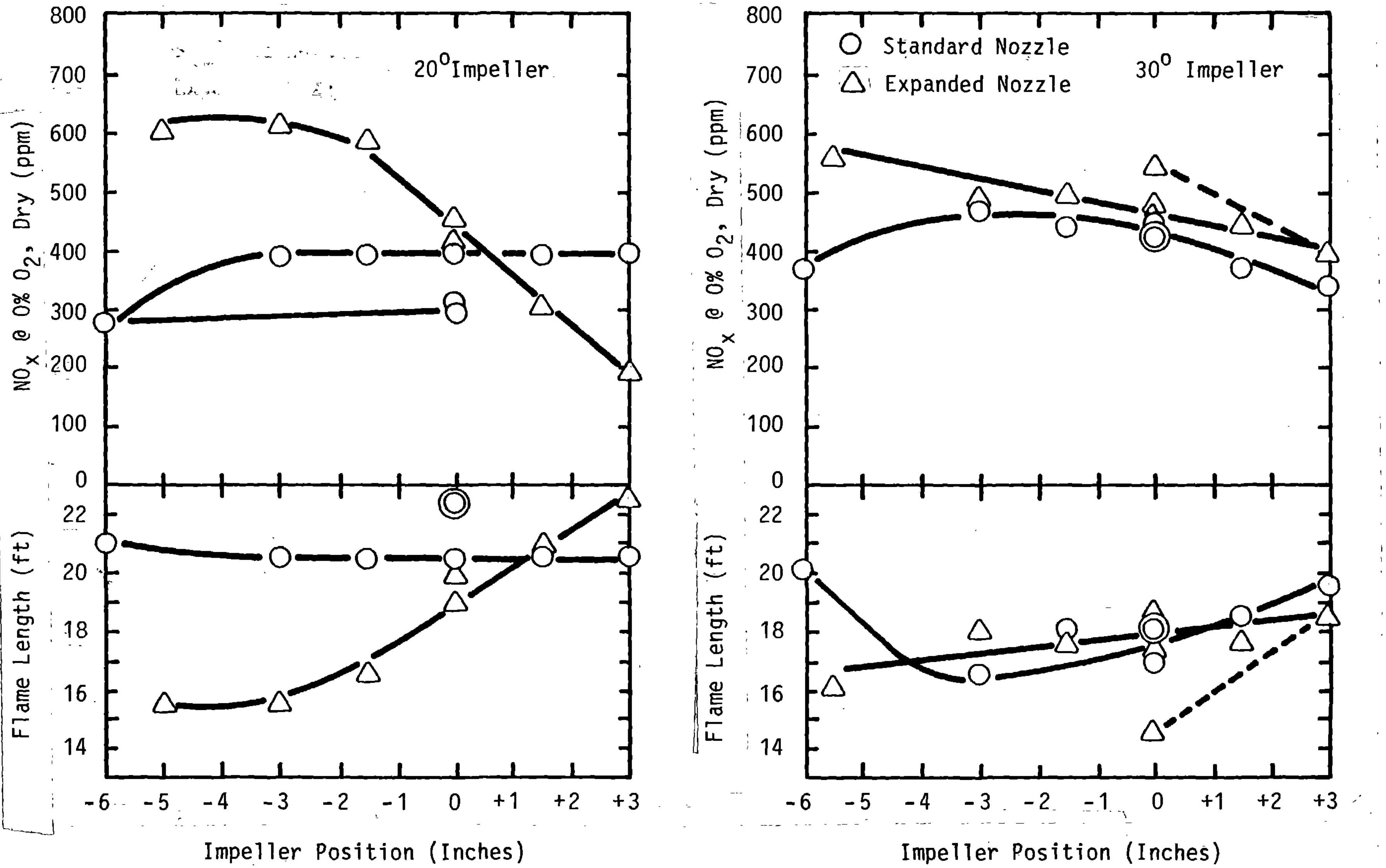


Figure 4-23. Effect of coal nozzle diameter on XCL burner performance.

The final XCL burner component evaluated was a set of fixed position outer secondary air axial swirl blades. These fixed outer vanes, set at a 45^{o} angle, represent a mechanical simplification and, with appropriate design, allow efficient swirl generation with low pressure drop. Both of these factors are important in commercial application. The fixed vanes were tested with the 30^{o} impeller and briefly with the coal diffuser in the standard coal nozzle. The screening test results with the 30^{o} impeller are shown in Figure 4-24. Again burner performance was most sensitive to impeller position. NO_x emissions ranged from 280 to 557 ppm with corresponding flames from over 22 ft to 15 ft long. With the diffuser, the XCL burner and fixed outer vanes yielded 287 ppm NO_x with a flame length over 22 ft. The fixed outer vane design gained a modest decrease in burner pressure drop--about 0.5 in W.G., over the adjustable vane design.

Key conditions from these parametric optimization tests are summarized in Table 4-11 for all eight configurations. Five of the configurations were also evaluated over a range of excess air at full load. These results are shown in Figure 4-25. Lowest NO_x emissions with flames less than 22 ft long over the range of excess air evaluated were obtained with the 30^{o} impeller and the 20^{o} impeller/expanded nozzle. The performance for these two configurations was essentially the same with the 20^{o} impeller achieving somewhat better combustion efficiency.

4.3.2 Characterization of XCL Burner Performance

The XCL burner design represents an advancement of B&W technology, but with specific operational experience limited to this test program. To gain further experience with the XCL burner and to broaden its application, two configurations were selected for further evaluation. The two configurations selected were the coal diffuser in the standard coal nozzle with fixed outer vanes and the 30^{o} impeller in the standard coal nozzle with fixed outer vanes. The coal diffuser configuration represents minimum NO_x emissions in a practical burner design. Its use would be restricted to applications whose firing depth can accommodate long flames. The 30^{o} impeller arrangement is suitable for tight boilers, such as Edgewater Unit 4, with its ability to

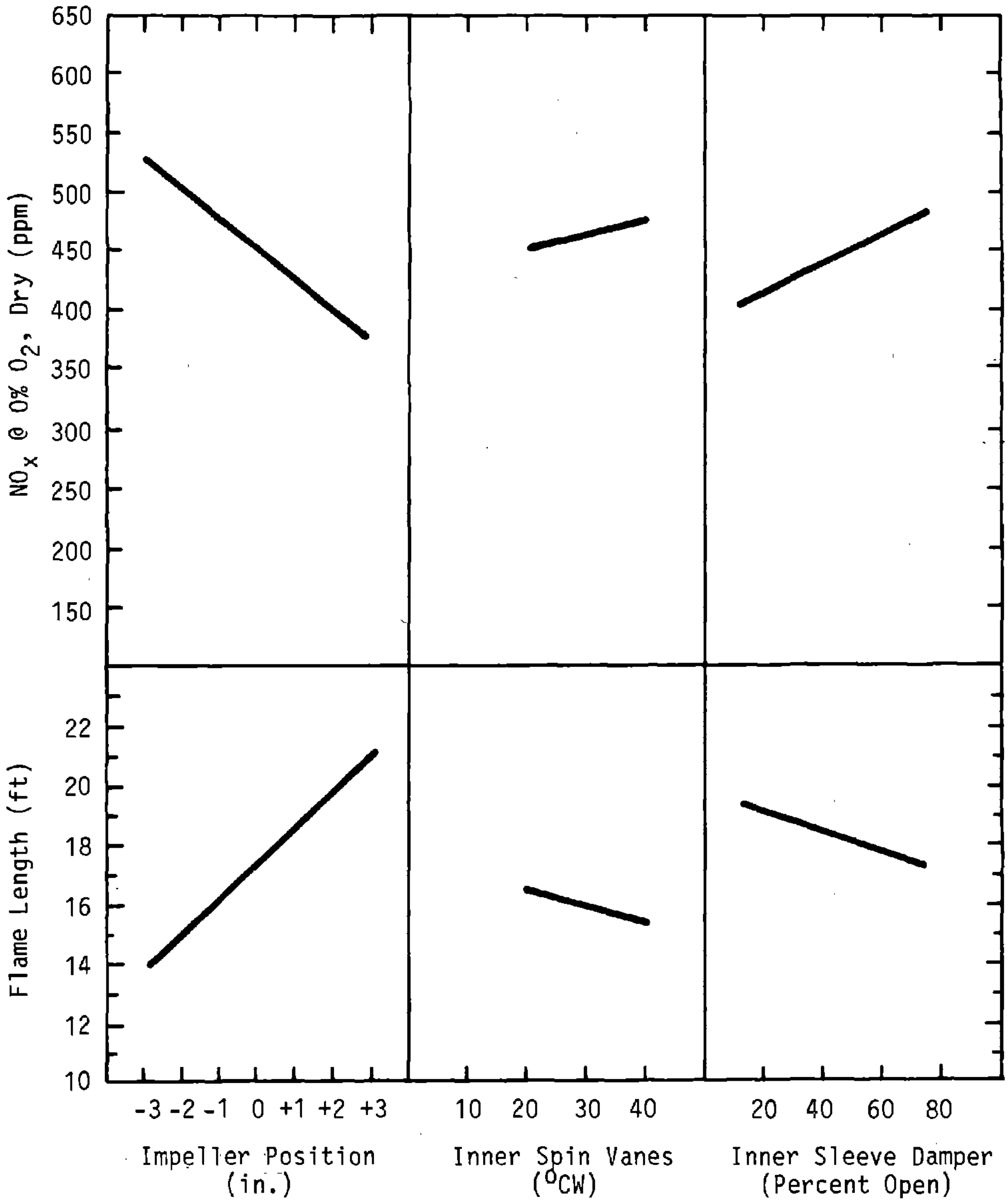


Figure 4-24. Results of final XCL burner screening tests with 30^o impeller and fixed outer vanes.

TABLE 4-11. SUMMARY OF FINAL XCL BURNER SCREENING TEST CONDITIONS

Configuration	Registers		Sleeves		Spreader Position (Inches)	Firing Rate (10^6 Btu /hr)	SR_T	NO_x @ 0% O_2	CO @ 0% O_2	Flame Length (ft)	Fly Ash Carbon (wt.%)	Windbox Pres. (in.H_2O)	Coal
	Inner	Outer	Inner (% Open)	Outer (% Open)									
20° Impeller	30°CW	40°CW	75	100	0.0	80.0	1.16	315	29	22+	-	5.30	Pitt. #8
30° Impeller	30°CW	50°CW	38	100	0.0	76.9	1.17	317	33	21	6.11*	4.30	Pitt. #8
Open Impeller	30°CW	40°CW	75	100	0.0	79.1	1.16	268	43	>22	-	5.10	Pitt. #8
Expanded Nozzle w/Diffuser	30°CW	50°CW	75	100	NA	59.7	1.19	198	90	>22	-	-	Pitt. #8
Expanded Nozzle w/ 30° Impeller	30°CW	50°CW	38	100	0.0	76.4	1.16	499	17	19-20	1.36	4.30	Pitt. #8
Expanded Nozzle w/ 20° Impeller	30°CW	50°CW	38	100	0.0	80.0	1.16	338	47	21	4.92	4.90	Pitt. #8
Fixed Outer Register w/ 30° Impeller	40°CW	45°CW	38	100	1.5	79.1	1.16	385	23	21-22	2.87	4.60	Pitt. #8
Fixed Outer Register w/Diffuser	30°	45°CW	75	100	-	77.6	1.17	287	30	>22	-	4.30	Pitt. #8

*UBC Data Listed for SR_T = 1.19

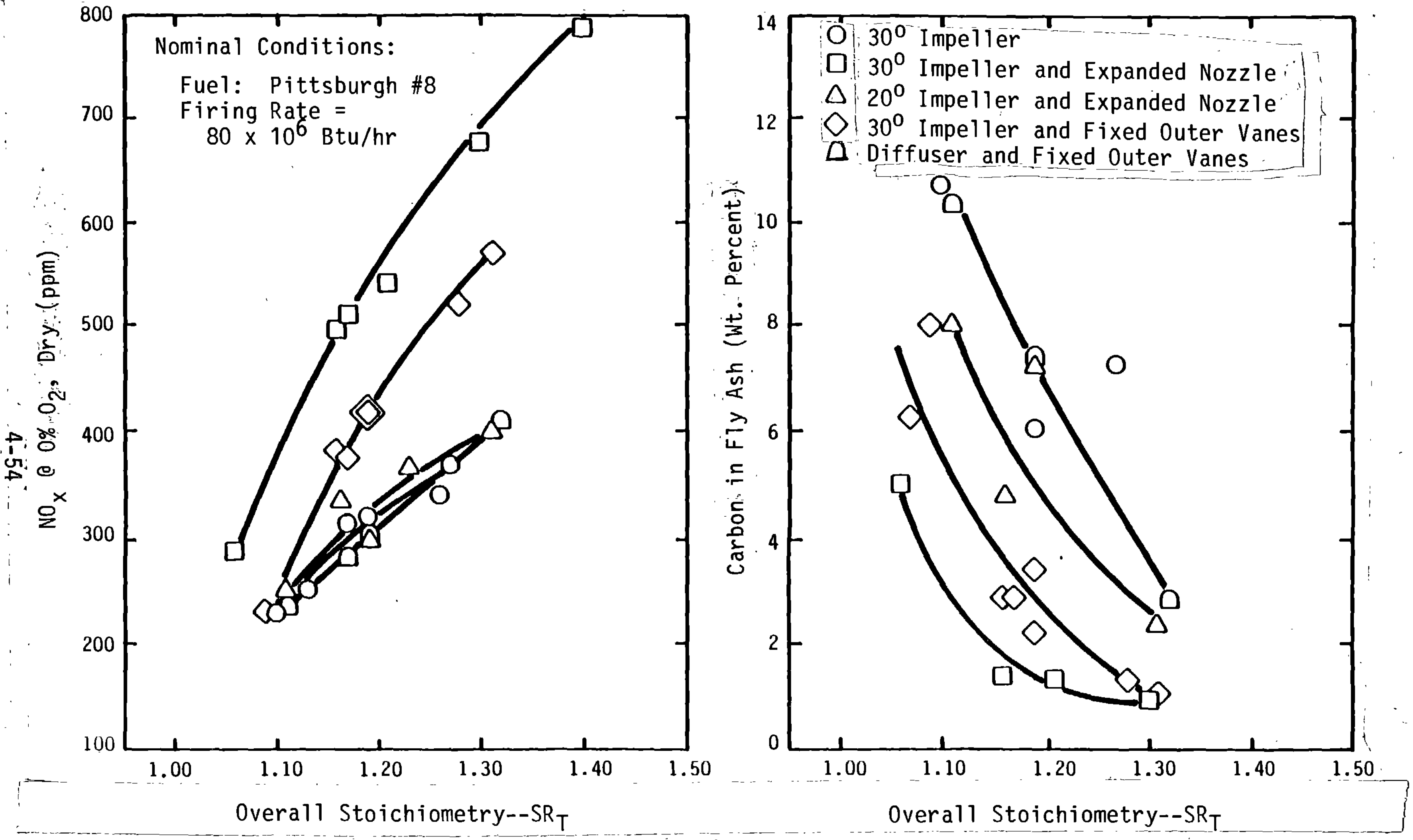


Figure 4-25. Performance characteristics for five XCL burner configurations.

adjust performance using impeller position. The additional testing consisted of evaluating the XCL burner with three additional coals at nominal full-load operating conditions over a range of excess air. The alternate coals were a Utah high-volatile bituminous coal, Lower Kittanning medium volatile bituminous coal, and a Wyoming subbituminous coal used at Colorado Public Service Comanche station.

The burner settings for the characterization tests of the impeller equipped XCL burner were:

Impeller position = +1.5 in.

Inner Spin Vanes = 40° CW

Fixed Outer Vanes = 45° CW

Inner Damper = 38% Open

Outer Damper = 100% Open

The performance results for this configuration are shown in Figures 4-26, 27, and 28 for Pittsburgh #8, Utah, and Lower Kittanning coals, respectively. The general trends for each coal are the same, with higher NO_x emissions and lower unburned carbon levels (UBC) for higher firing rates and excess air levels. For an overall stoichiometry of 1.20, the results for each coal were:

Nominal Firing Rate (10^6 Btu/hr)	Pittsburgh #8		Utah		Lower Kittanning	
	NO_x	UBC	NO_x	UBC	NO_x	UBC
80	420	3.4	414	2.9	573	6.5
62	306	4.9	276	5.9	390	6.5
49	229	6.5	187	10.6	210	22.0

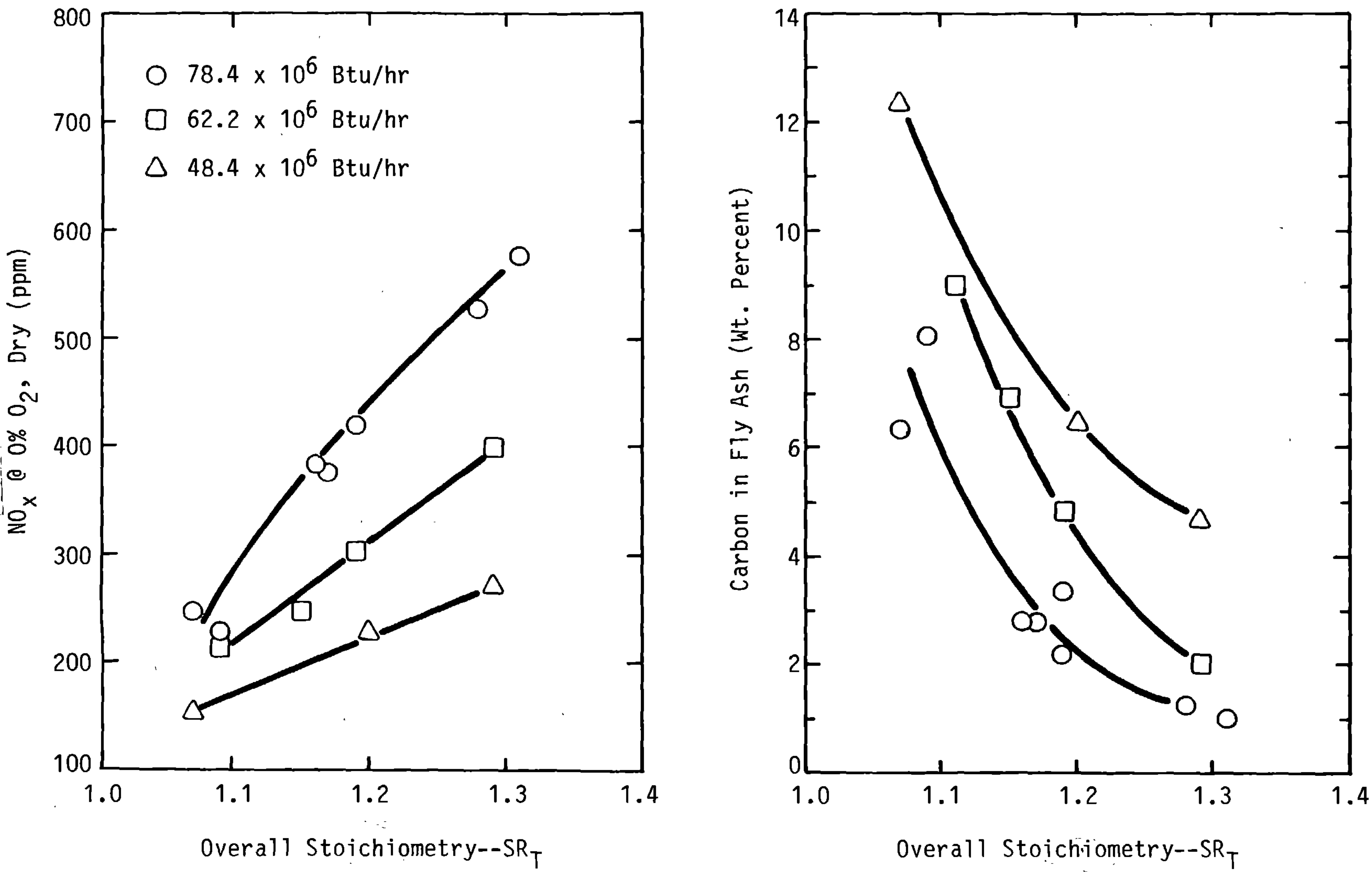


Figure 4-26. Performance of XCL burner with standard coal nozzle, diffuser, and fixed outer vanes firing Pittsburgh #8 coal.

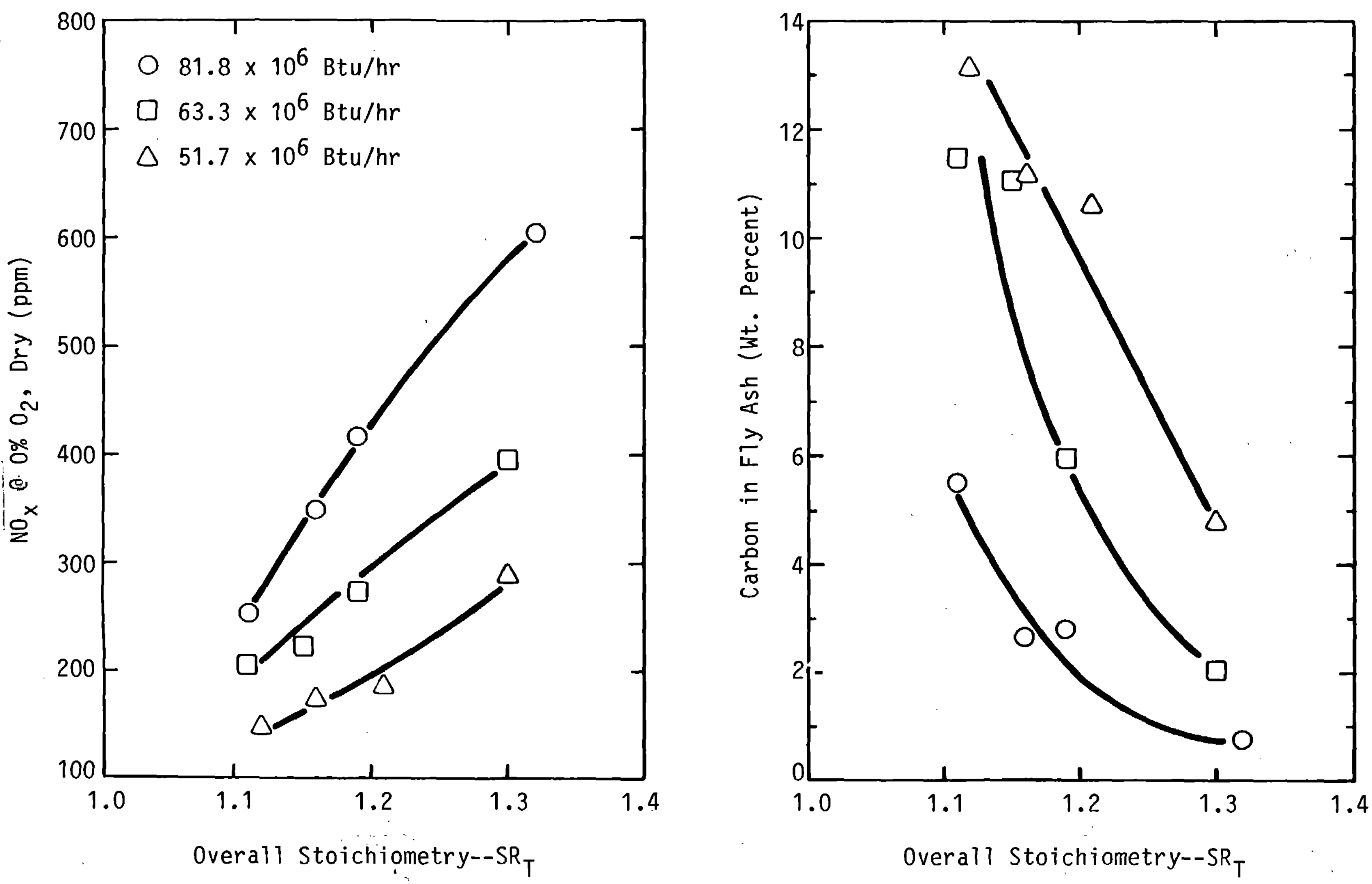


Figure 4-27. Performance of XCL burner with standard coal nozzle, diffuser, and fixed outer vanes firing Utah coal.

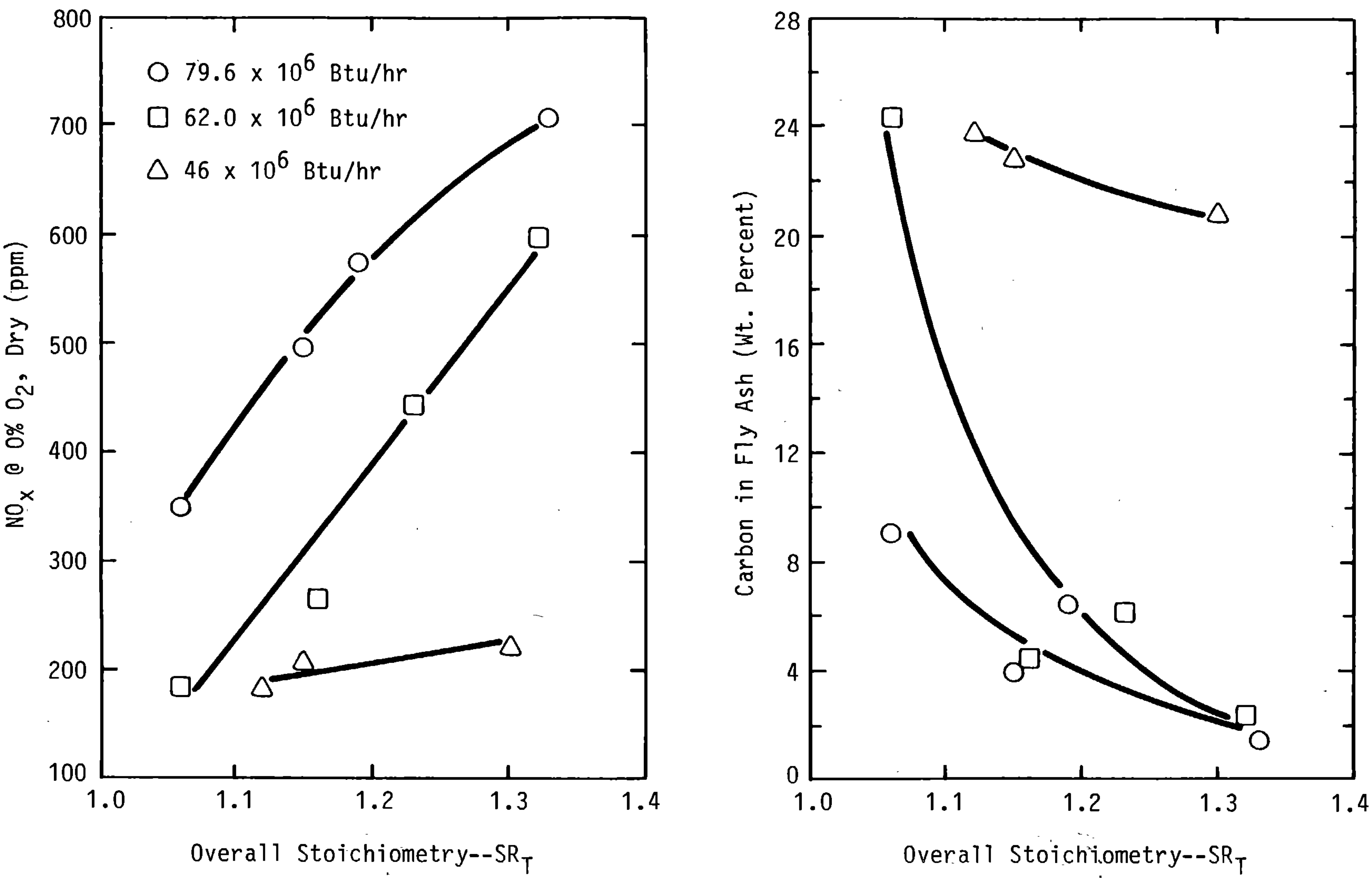


Figure 4-28. Performance of XCL burner with standard coal nozzle, diffuser, and fixed outer vanes firing lower Kittanning coal.

These results are generally consistent with the rankings expected based on the correlation of fuel composition with NO_x discussed in Section 3.5 of this report. Given the level of NO_x, this configuration may be considered somewhere between a staged and radial diffusion flame. Direct comparison of the performance for each fuel is shown in Figure 4-29. The two high-volatile bituminous coals yielded essentially the same NO_x emissions. Much higher NO_x emissions were measured for the medium volatile Lower Kittanning coal. Combustion efficiency, as indicated by fly ash carbon content, was also very similar for the Pittsburgh #8 and Utah coals. The Lower Kittanning coal, however, yielded the highest fly ash carbon levels.

The XCL configuration with the diffuser was characterized using the following burner settings:

Inner Spin Vanes = 30^o CW

Fixed Outer Vanes = 45^o CW

Inner Damper = 75% Open

Outer Damper = 100% Open

This configuration was characterized for three coals at nominal full load; Pittsburgh #8, Lower Kittanning and Comanche. The results are summarized in Figure 4-30. The lowest NO_x emissions were achieved with the subbituminous Comanche coal as expected. The emissions for the other two coals were higher than the Comanche, but very similar to each other. With this very low NO_x configuration, which can be considered aerodynamically staged, the fuel composition-NO_x correlation indicates that the Lower Kittanning and Pittsburgh #8 coals could be expected to produce similar results. Combustion efficiency was substantially different, with the subbituminous coal yielding the lowest unburned carbon levels and the medium volatile bituminous Lower Kittanning coal producing the highest fly ash carbon levels. Flame length for the Pittsburgh #8 and Comanche coals exceeded 22 ft, while the Lower Kittanning coal yielded flames 21-22 ft long.

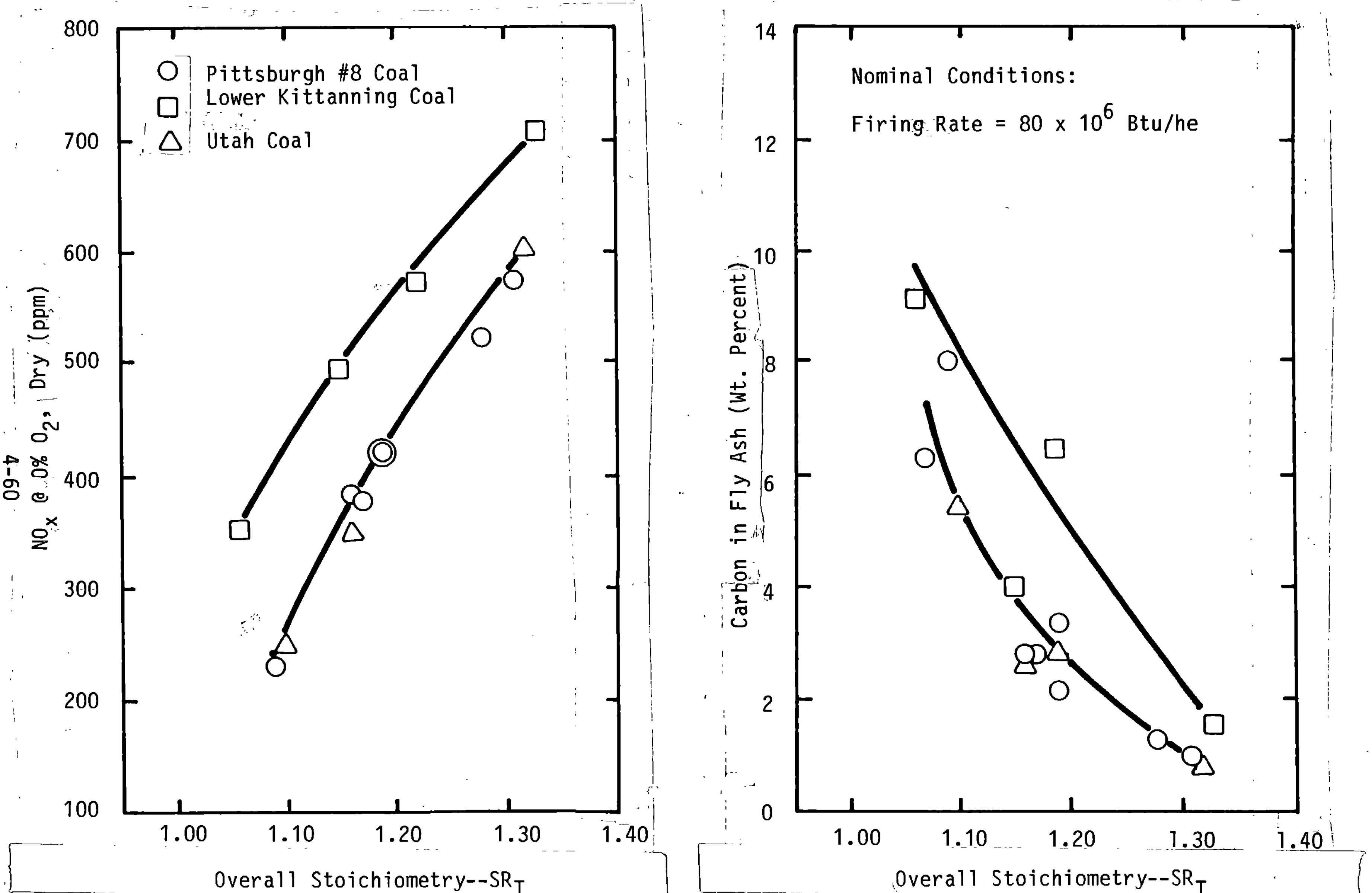


Figure 4-29. Comparison of performance of XCL burner with Standard Coal Nozzle Diffuser, and fixed outervanes for three different coals.

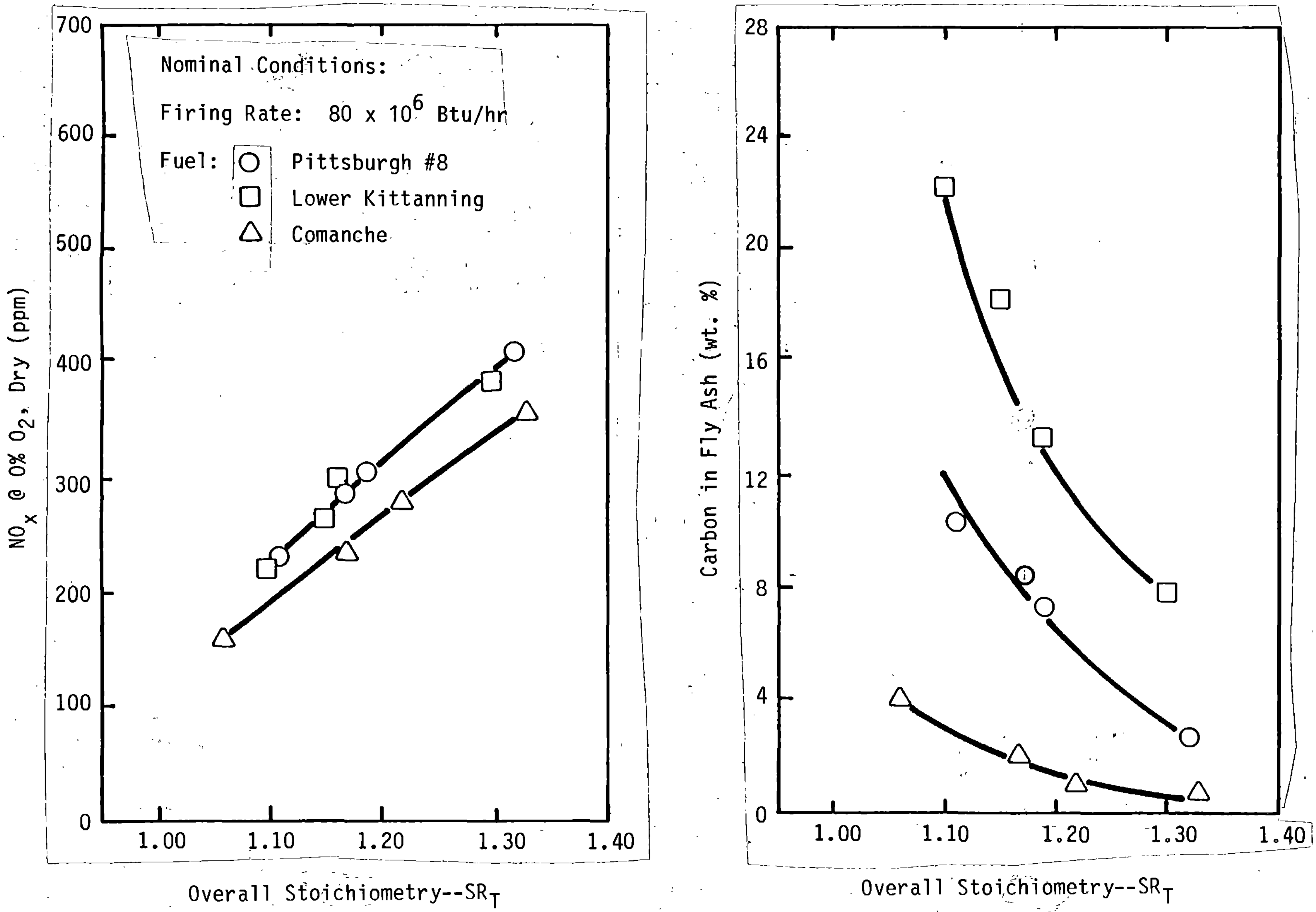


Figure 4-30. Performance of XCL burner with diffuser and fixed outer vanes for three coals.

The performance of the two XCL burner configurations are directly compared in Figure 4-31 for two common coals, Pittsburgh #8 and Lower Kittanning. At nominal full-load conditions with 20 percent excess air, NO_x emissions with the Pittsburgh #8 coal were 420 ppm and 304 ppm for the 30^o impeller and diffuser, respectively. Under similar conditions the difference in NO_x emissions was even greater with the Lower Kittanning coal, namely 573 ppm for the 30^o impeller and 300 ppm with the diffuser.

4.4 Comparison of Burner Performance

Twenty configurations of three basic burner concepts, the Dual Register Burner, Babcock-Hitachi NR burner, and XCL burner, were evaluated as part of this program. In addition, data from five configurations of another DRB design, the Phase V DRB, was available from an analogous test program sponsored by B&W. To facilitate comparison of such a large number of burners, the performance of the burners should be screened with respect to this program's ultimate objective--selection of the second generation low-NO_x burner for retrofit at the EPA limb demonstration site, Edgewater Unit 4. This imposes the following constraints that the selected burner must meet:

- Nominal 78 x 10^6 Btu/hr heat input per burner.
- Flame length less than the firing depth of the boiler, 22 ft 3 in.
- Burner pressure drop within fan limitations, nominally 5 in. W.G.
- Throat diameter no greater than 35 inches.
- Low NO_x emissions, at least 50 percent less than baseline burners.
- High combustion efficiency.
- Mechanical reliability meeting commercial standards.

Each of the burner configurations were designed for firing at 78 x 10^6 Btu/hr with a throat diameter no greater than 35 inches. In addition, B&W incorporated its standard commercial hardware designs thereby ensuring that mechanical reliability will be at least equivalent if not improved, to its

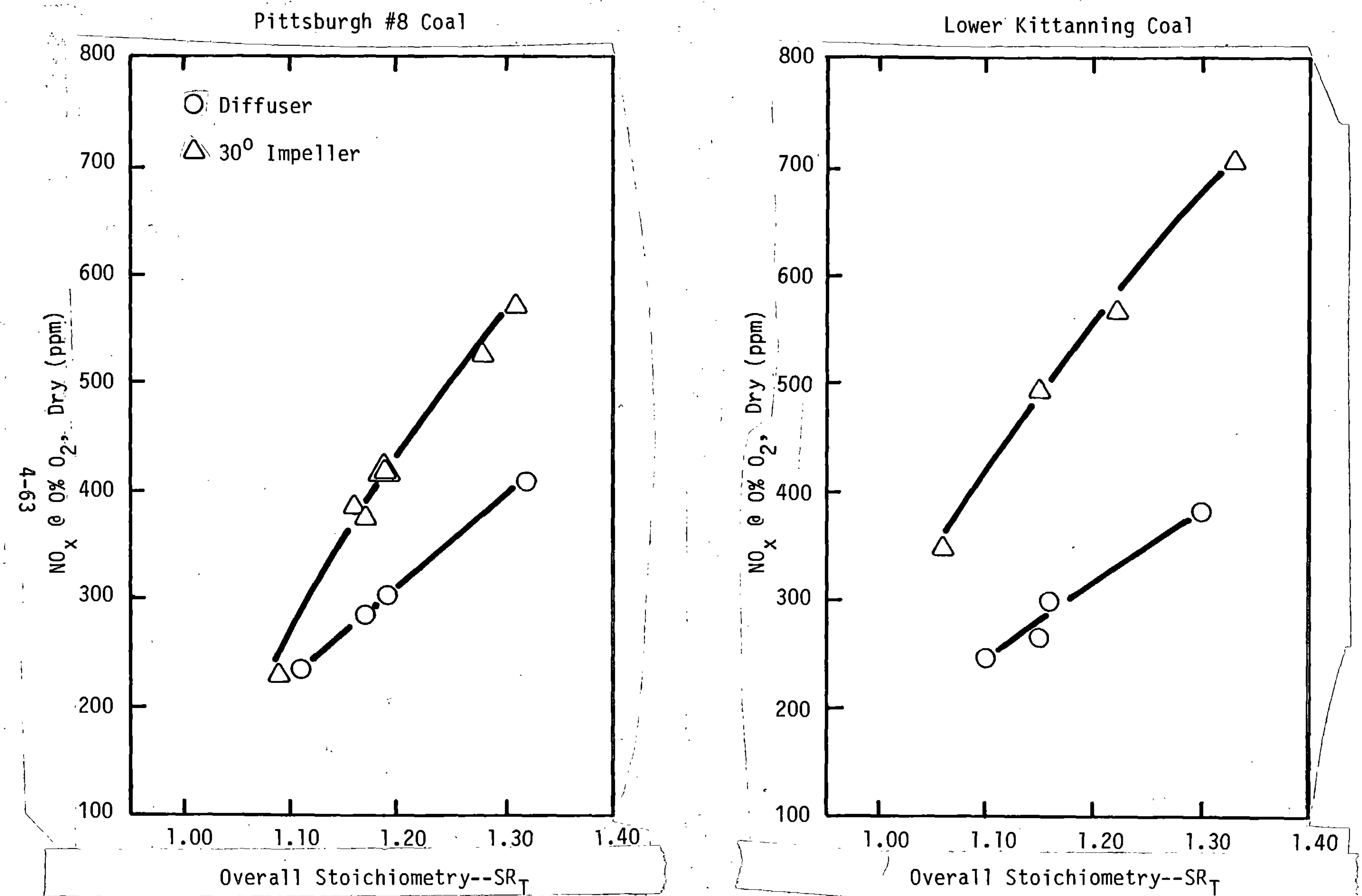


Figure 4-31. Comparison of XCL burner performance with diffuser and 30° impeller--fixed outer vane configuration.

commercial burners. The performance of the burners is therefore the key to proper burner selection.

Of the remaining requirements, flame length imposes the most severe constraint. Data from tests of the Low Velocity DRB, HNR burner, and the initial screening of the XCL burner, presented in Figure 4-32, clearly demonstrate the correlation of NO_x emissions with flame length. At 20 percent excess air and full load conditions, the test data indicate that for a flame less than the firing depth of the LWS, or the Edgewater boiler, NO_x emissions in the range of about 300-400 ppm were achieved by several burner configurations. Using flame length as the initial selection criteria yields 13 candidate burners listed in Table 4-12. From this list, the potential of each burner design for application to the Edgewater boiler can be evaluated.

Only one of the four Low Velocity Dual Register Burner configurations tested met the flame length criteria. The configuration with the 75^o impeller did indeed shorten the flame to 18 ft, but resulted in NO_x emissions of 708 ppm. The 75^o impeller is a design from a high turbulence B&W Circular burner which was not optimized for low emission performance. The impact of this impeller design demonstrates the importance of coal injector design in that, even though the Low Velocity DRB incorporated low-NO_x design characteristics (low combustion air velocity and multiple air zones), the overall burner performance was dominated by the impeller.

Data more representative of DRB performance was collected during the B&W sponsored testing of a Phase V DRB. All five configurations tested could produce a flame 22 ft or less in length. In addition, each configuration achieved emissions less than 372 ppm. However, this could only be achieved with tightly closed inner and outer vanes to produce highly swirling flow. Applying a second requirement, burner pressure drop no more than 5 in. W.G., eliminates all five Phase V DRB configurations from application at Edgewater Unit 4.

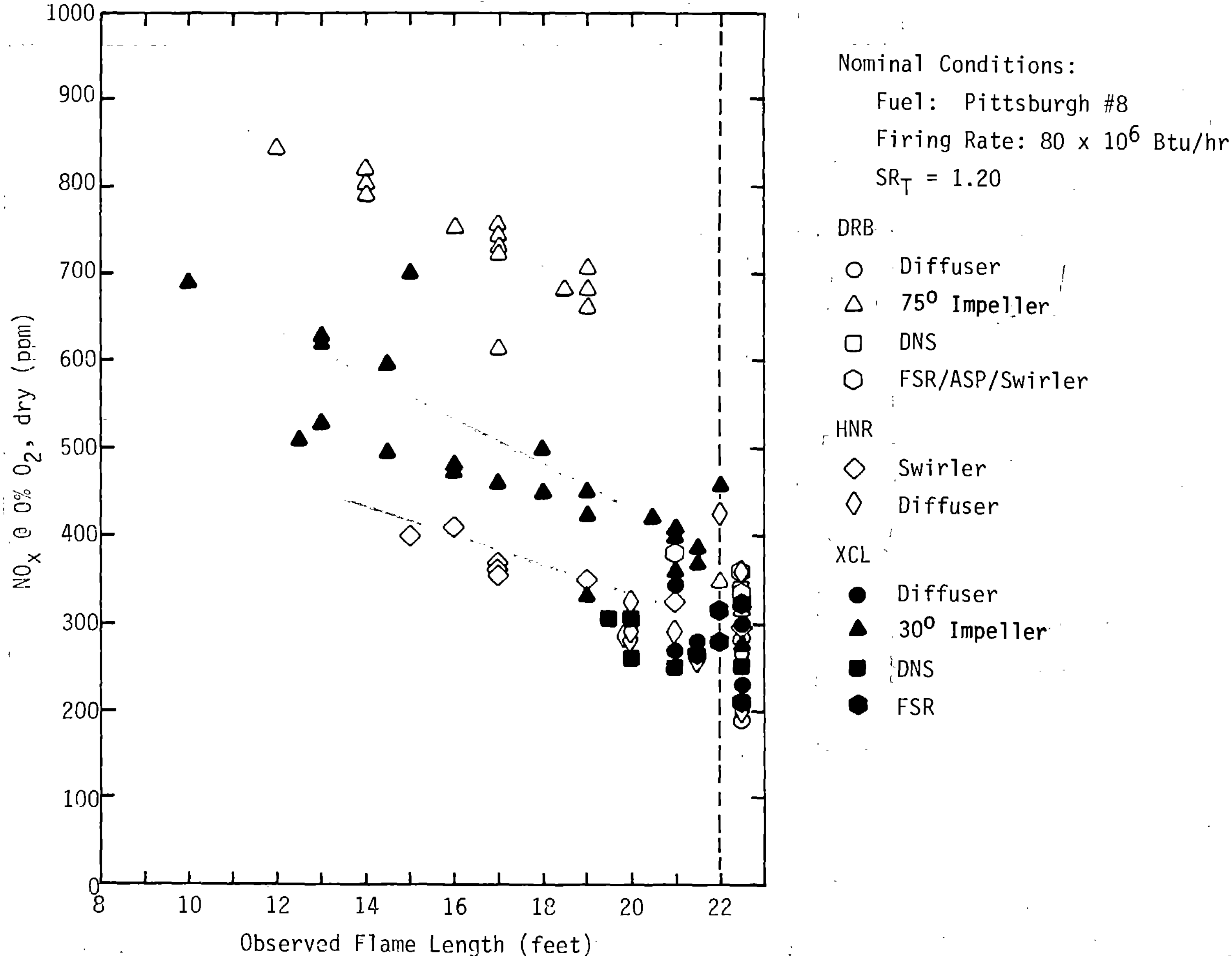


Figure 4-32. Correlation of NO_x emissions with flame length.

TABLE 4-12. SECOND GENERATION LOW NO_x BURNERS WITH FLAMES $\leq$22 FT LONG (78×10^6 Btu/hr, SR_T = 1.20)

Burner	Configuration	NO_x @ 0% O_2 (ppm)	Flame Length (ft)	Fly Ash Carbon (wt.%)	Burner ΔP (in. W.G.)
Low-Velocity DRB	75° Impeller	708	18	7.28	6.0
Phase V DRB	Diffuser	372	20-21	6.12	10.8
	Venturi	350	20-21	6.45	11.0
	Diffuser, ASP	326	22	3.20	6.4
	Diffuser, FSR	292	22	6.96	10.5
	Diffuser, FSR, ASP	328	22	5.16	11.0
HNR	Swirler	348	18-20	N/A	7.20
	Diffuser	289	20	3.34	7.50
XCL	DNS	288	20	N/A	8.20
	30° Impeller, Standard Nozzle	374	20-22	4.42	3.30
	30° Impeller, Expanded Nozzle	546	19-20	1.36	4.30
	20° Impeller, Expanded Nozzle	338	21	4.92*	4.90
	30° Impeller, Standard Nozzle, Fixed Outer Vanes	420	21-22	3.40	4.60

*Data for SR_T = 1.16

The Babcock-Hitachi NR burner had two configurations meeting the flame length requirement while producing NOx emissions less than 350 ppm. To achieve this performance, however, the HNR burner relies on tight burner settings to produce high swirl to shape the flame. These tightly closed burner settings resulted in a burner pressure drop over 7.0 in. W.G., again over the limitation at the LIMB demonstration site.

From the 13 XCL burner configurations tested, five achieved the flame length limitation. The proprietary B&W coal nozzle insert, the $DeNO_x$ Stabilizer, achieved the lowest NO_x emissions of all the configurations with flames less than 22 ft long. However, this performance could only be achieved with a high burner pressure drop, the result of tightly closed, high swirl burner settings. The other four XCL configurations met both the flame length and burner pressure drop constraints. Three of those configurations utilized the 30^o impeller design. The lowest emissions with the 30^o impeller were achieved in the standard coal nozzle, 374 ppm, and the highest emission in the expanded coal nozzle, 546 ppm. An intermediate level of NO_x, 420 ppm, was achieved with the 30^o impeller in the standard coal nozzle and the fixed, 45^o angle outer swirl vanes. The lower emissions for the variable outer spin vane assembly was the result of a lesser degree of swirl at its optimum setting of 50^o. It is likely that with appropriate design, fixed outer vanes should achieve identical performance as that from the variable spin vanes. The final XCL configuration meeting both the flame length requirement and the burner pressure drop limitation utilized the 20^o impeller in the expanded nozzle. This configuration achieved the lowest emissions, 338 ppm, of the four configurations which met both the flame length and pressure drop constraints.

From the thirteen burner configurations meeting the Edgewater boiler flame length requirement, two configurations stand out as the most likely candidates for application: (1) the 30^o impeller in the standard nozzle with appropriate outer vane design, and (2) the 20^o impeller with the expanded coal nozzle tip. Each offer reasonably low emissions, good combustion efficiency, and acceptable flame length and burner pressure drop. In addition, these two configurations offer a very effective "handle" with which to adjust flame length to suit the application--the variable position of the coal impeller. For both impeller designs, flame length and NO_x emissions can be varied simply by moving the impeller a matter of inches. This adjustment can be done on-line, while the boiler is in operation. Since the impeller is a coal nozzle device, it does not affect the pressure drop across the burner registers and spin vanes. The impeller adjustment can thus be used to tune the burner for maximum NO_x reduction within the constraints of available firing depth.

5.0 SO_2 REDUCTION POTENTIAL WITH SORBENT INJECTION

The technology demonstration at Edgewater Unit 4 will utilize the injection of dry sorbents into the furnace for SO_2 control in addition to the installation of low-NO_x burners, hence the term "LIMB" from Limestone Injection Multistage Burner. As part of the initial screening tests, a brief series of sorbent injection tests were conducted for the Low Velocity DRB, Babcock-Hitachi NR burner, and XCL burner to determine the effect of burner design on potential for SO_2 reduction. The operating variables evaluated included:

- Sorbent composition
- Sorbent feed rate
- Injection location

These tests were not intended to be comprehensive, only screening tests to evaluate possible burner differences with established injection locations.

5.1 Injection Configurations

The three burner configurations evaluated with sorbent injection are listed in Table 5-1. Nominal test conditions during all the sorbent injection tests were:

Firing Rate = 78 x 10^6 Btu/hr

SR_P = 0.18

SR_T = 1.20

Primary Air Temperature = 150°F

Combustion Air Temperature = 550°F

Four different injection locations were considered:

- With the pulverized coal

- Two upper furnace locations
- Around the periphery of the burner exit

Injection of sorbent with the coal and through upper furnace penetrations is done as standard procedure to screen for SO_2 control in the LWS facility, including the tests described in Part I, Section 6 of this report. These two locations are illustrated in Figure 5-1. Sorbent is injected into the pulverized coal stream just downstream of the pulverizer, allowing thorough mixing through the length of transport pipe to the burner. For these tests, only the Vicron 45-3 limestone was injected with the coal.

The two locations in the upper furnace evaluated were 8 ft and 19 ft above burner centerline. The 8 ft level, which corresponds to a furnace gas temperature of 2500°F, had two 3-in. injection nozzles. Velocity of the sorbent jet at the nozzle exit at this level was nominally 45 ft/s. Both the Vicron 45-3 limestone and Colton hydrated lime were injected at the 8-ft level. Four 2-in. ID ports were used at the 19 ft level, corresponding to a gas temperature of about 2150°F. Nominal sorbent jet velocity through these four ports was 50 ft/s. Only the Colton Hydrated lime was injected at this uppermost level.

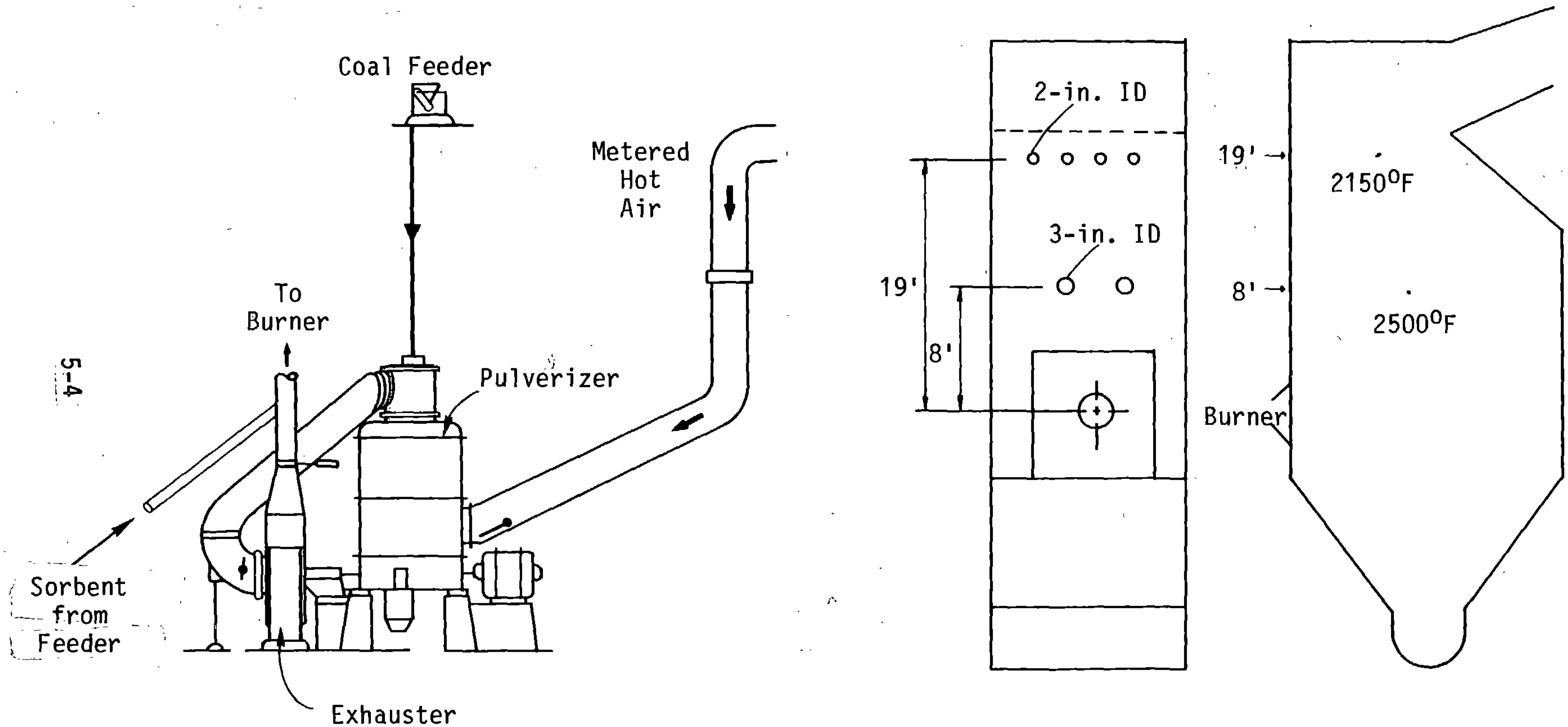
Based on general interest in near-burner injection alternatives, Vicron 45-3 limestone was also injected through four 1-in. ID nozzles equally spaced in the burner exit. This configuration is illustrated in Figure 5-2. The nozzles were positioned to follow the divergence of the burner exit with the nozzle tip flush with the burner exit. The nominal sorbent jet velocity through these burner nozzles was 200 ft/s.

5.2 Test Results

Figure 5-3 compares the results of all three burners tested with "near" burner injection of the Vicron 45-3 limestone. There was little difference in SO_2 capture with the limestone injected with the coal for the three burners, with 28-32 percent capture at Ca/S molar ratio of 2. There was a

TABLE 5-1. BURNER CONFIGURATIONS FOR SORBENT INJECTION TESTS

Burner	Configuration	Impeller Position (in.)	Inner Vanes	Outer Vanes	Inner Damper	Outer Damper
Low Velocity DRB	75° Impeller	0.0	20°CCW	15°CW	50% Open	N/A
HNR	Diffuser, Modified Outer Vanes	N/A	10°CW	20°CW	25% Open	N/A
XCL	Diffuser, Standard Coal Nozzle	N/A	30°CW	40°CW	75% Open	100% Open



Sorbent Injection with Coal

Upper Furnace Locations

Figure 5-1. Sorbent injection locations--with coal and upper furance.

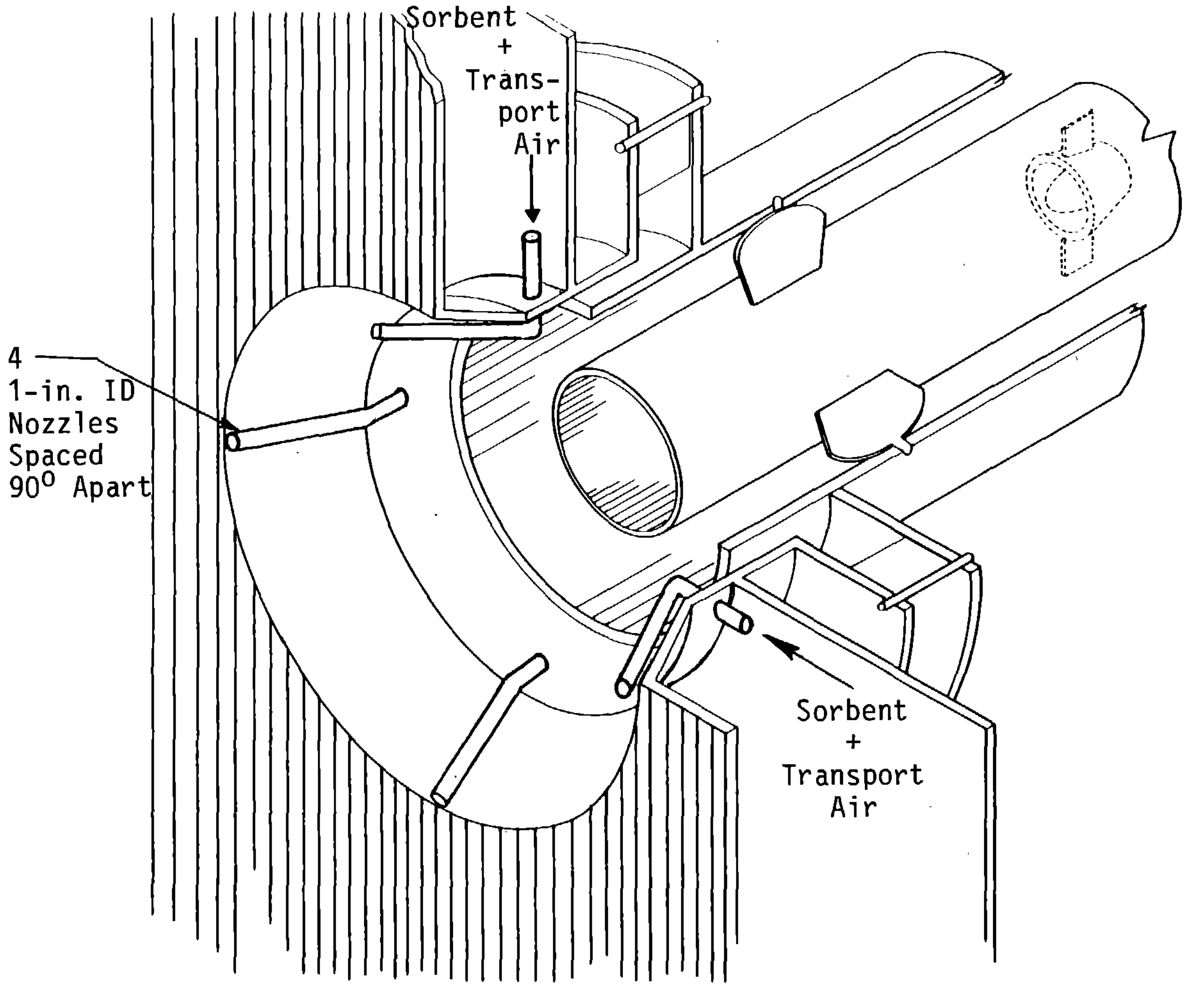


Figure 5-2. Burner exit sorbent injection nozzle configuration.

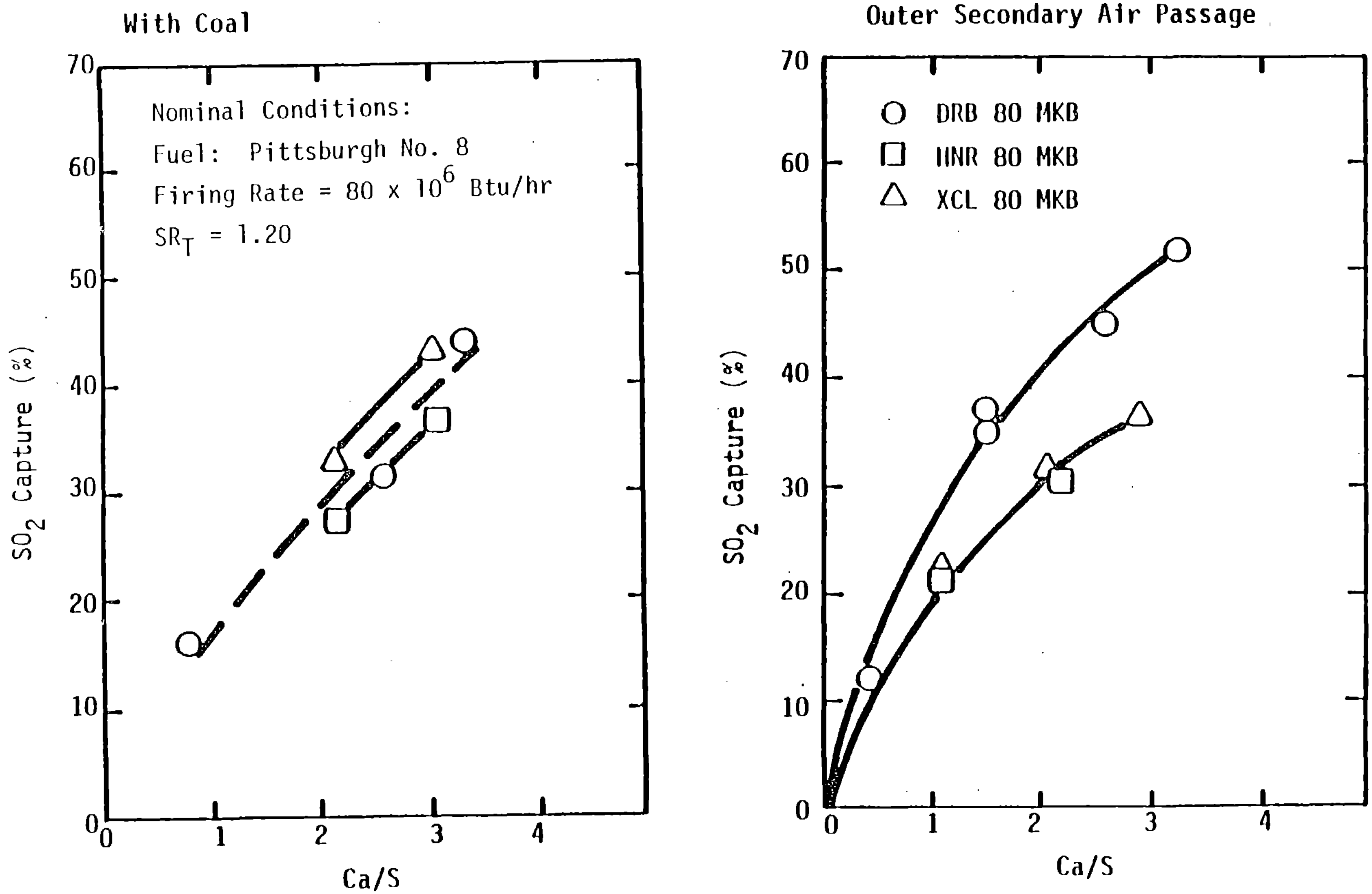


Figure 5-3. Summary of SO_2 capture with near-burner injection of Vicron 45-3.

significant difference in capture for the outer secondary air injection location. The capture was highest for the DRB with a coal impeller, the only burner without the air separation plate and the only configuration with an impeller. The DRB yielded about 40 percent capture at Ca/S of 2, compared to only about 30 percent for the other two burners.

A summary of the hydrated lime injection results with all three burners is presented in Figure 5-4. There was no significant difference in capture for either above burner location for the three burner designs. The 8 ft level yielded 36 percent SO_2 capture Ca/S = 2, while 38 percent reduction was achieved at the 19 ft level. These furnace elevations corresponded to temperatures of about 2500 and 2150^{o}F for the 8-ft and 19-ft levels, respectively. A comparison of hydrated lime and limestone injection at the 8 ft level is made in Figure 5-5 for all three burners. Again, there is no difference among the burners. The hydrated lime achieves only slightly higher SO_2 capture, about 36 percent at Ca/S = 2, than the limestone, about 33 percent at Ca/S = 2, for the similar operating conditions.

This brief series of sorbent injection tests indicates that for upper furnace injection, burner design does not affect SO_2 capture. This is as would be expected. While the burner design may dominate near-field gas flows and temperatures, these factors are mitigated downstream of the burners such as in the upper furnace near the furnace arch. Burner design only appeared to affect SO_2 capture when sorbent was injected through the nozzles in the burner exit. Highest capture using that injection location was achieved with the burner producing the shortest, widest flame, and the highest NO_x--emissions--the DRB equipped with the 75^{o} impeller. This DRB configuration differed from the HNR and XCL burners by not having an Air Separation Plate and by using an impeller to disperse the coal instead of a diffuser or Flame Stabilizing Ring. While it might be expected that the slower mixing, lower NO_x flames from the HNR and SCL burner would yield higher SO_2 capture, the high-velocity sorbent jets may have a better chance to bypass the main flame zone of the shorter DRB flame.

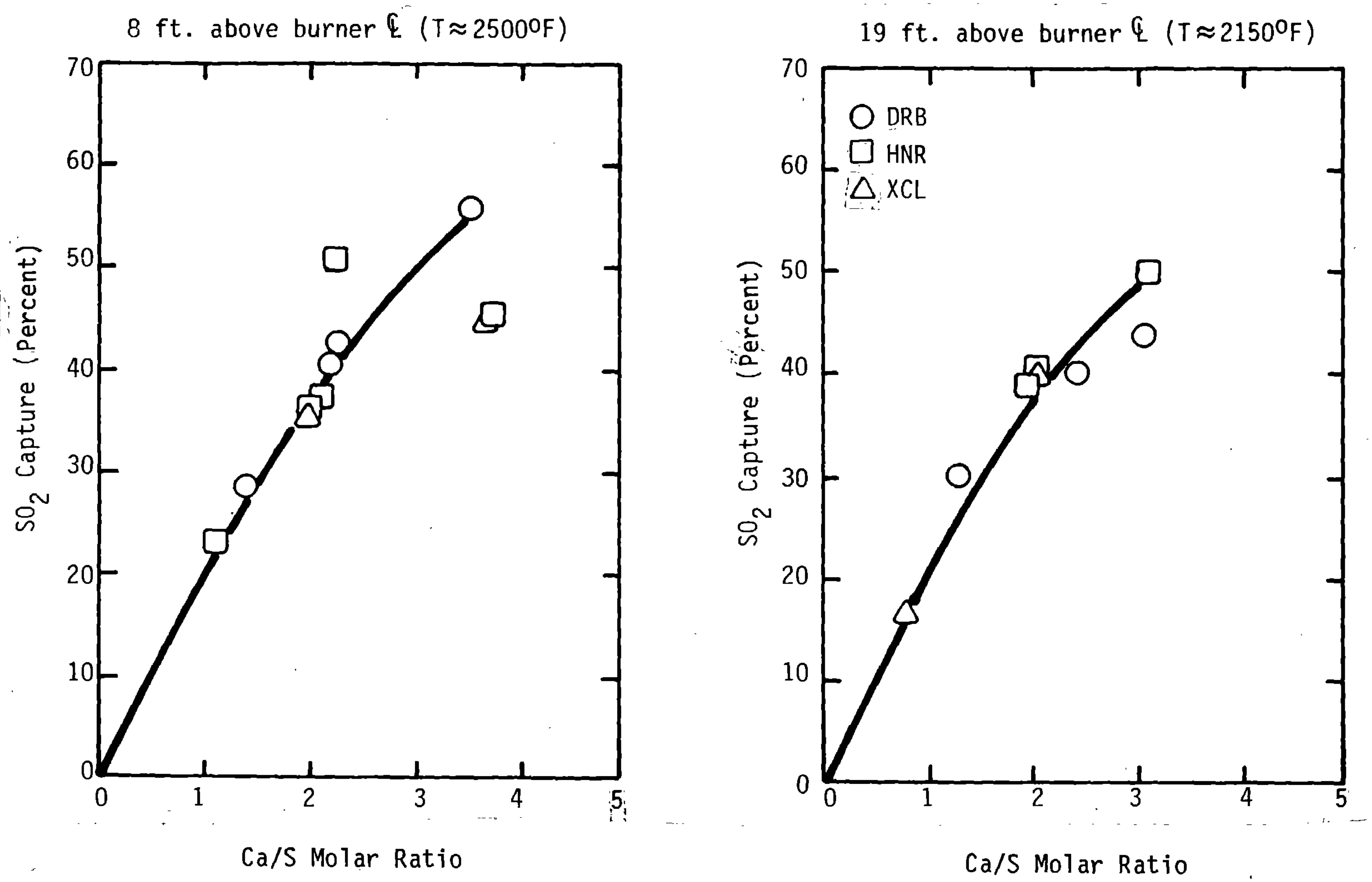


Figure 5-4. Summary of SO_2 capture with Colton hydrated lime injection.

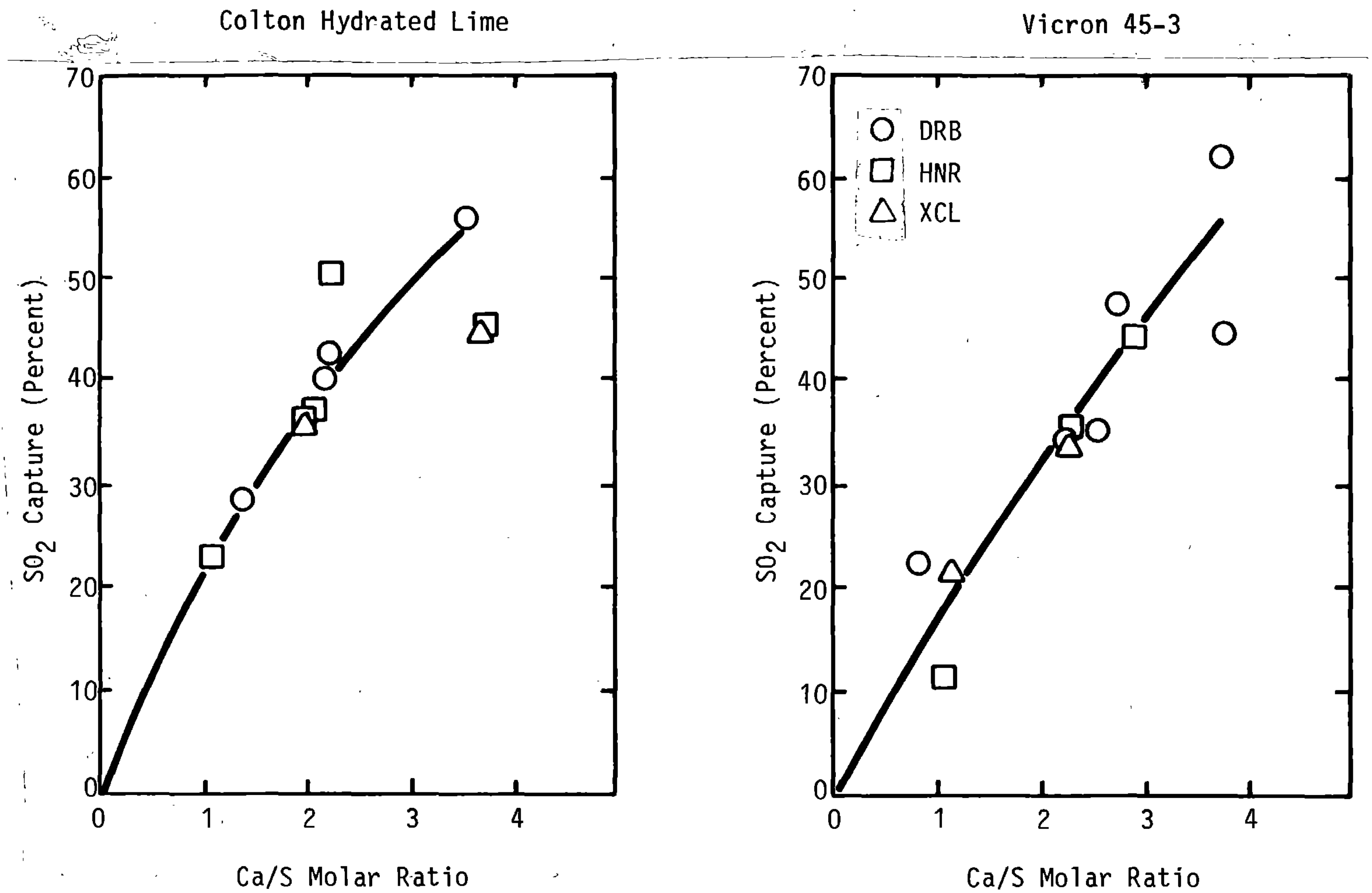


Figure 5-5. Effect of sorbent type on SO_2 capture with injection at $2500^{o}F$.

6.0 CONCLUSIONS

Three B&W Second Generation Low-NO_x burner designs were evaluated for applicability to the EPA LIMB demonstration site, Edgewater Unit 4. This evaluation consisted of testing three full-size, 78 x 10^6 Btu/hr capacity burners in the EPA LWS to optimize their performance and meet the Edgewater boiler requirements. The three basic designs were the Dual Register burner, Babcock-Hitachi NO_x Reducing burner, and the XCL burner. Twenty different configurations of these three basic designs were tested firing Pittsburgh #8 coal, the coal to be used during the LIMB demonstration. The different configurations represent trials of various burner hardware components to optimize the burner geometry for low-emission, high-efficiency, and acceptable flame length. From the screening of the 20 configurations, the optimum burner, an XCL configuration, was characterized with 3 distinctly different coals to broaden the range of application. In addition, a brief series of sorbent injection tests were conduced for a selected configuration of each basic burner design to determine the effect of burner design on SO_2 capture potential.

6.1 Burner Performance and NO_x Emissions

The three basic burner designs, the DRB, HNR, and XCL burners, represent an evolution of development. Each incorporates the common design features of a central, cylindrical coal nozzle surrounded by two concentric annular secondary combustion air passages. The optimization tests screened available burner adjustments as well as the various burner component configurations for each design. The three basic components of each burner, the coal injector, inner secondary air zone, and outer secondary air zone, were evaluated in these screening tests. The results from these tests can be easily generalized for all three low-NO_x burners with respect to importance to performance. In each case, the coal injector was the dominant factor that determined the key performance characteristics of NO_x, flame length, and carbon burnout. Both the design of the coal injector and the available adjustments, such as impeller position, could produce up to about 67 percent reduction in NO_x. The outer secondary air zone, the degree of swirl generated, and the air flow rate through the outer passage, was second in importance to burner performance. The inner air zone factors of swirl and air flow rate generally had the least affect on burner performance.

Consistent and recurring throughout the screening tests of all three burners was the close correlation of NO_x emissions with flame length--low-NO_x emissions were achieved with long flames while short flames were associated with high NO_x. Given the physical constraints of a practical application, such as the Edgewater boiler, the minimum level of NO_x emissions achievable will be limited by the furnace depth (about 22 ft at Edgewater Unit 4).

Specific results for the three burner designs are summarized below.

Dual Register Burner. The Low Velocity DRB designed to fit within the same exit as the other two candidate burners, the HNR and XCL, produced excessively long flames for three of the four configurations. Only a non-optimized 75° impeller design produced a flame less than the 22 ft furnace firing depth. NO_x emissions for the three configurations which produced flames over 22 ft long were low, ranging from 264 ppm to 386 ppm. The 75° impeller-equipped configuration produced 708 ppm with an 18 ft long flame. Available data from a B&W sponsored test program suggest that the performance of this Low Velocity DRB is not representative of the current standard Phase V DRB. Flames less than 22 ft long could be achieved by the Phase V DRB with its slightly higher velocities, albeit with slightly higher NO_x emissions (292-372 ppm). To achieve that performance, however, required tightly closed burner settings which produced burner pressure drops over 6 in. W.G.

Babcock-Hitachi NR Burner. The Babcock-Hitachi NR burner relies on biasing the secondary combustion air to the outer zone coupled with a very high degree of swirl for flame shaping and NO_x control. Minimum NO_x emissions were 222 ppm with a flame over 22 ft long using burner settings typical of Babcock-Hitachi practice. The two other configurations evaluated produced higher NO_x emissions, 289-348 ppm, but with correspondingly shorter flames, 18-20 ft long. In each case, however, burner pressure drop was about 7 in. W.G.

XCL Burner. The XCL burner, which represents the latest development in the B&W Dual Register Burner evaluation, was tested in 13 configurations during 2 series of tests. This burner design demonstrated the most potential to meet the LIMB demonstration because of its inherent flexibility. NO_x emissions ranged from 194-700 ppm with flames from 12 to over 22 ft long. Only 5 configurations yielded flames less than 22 ft long, with NO_x emissions from 288 to 546 ppm. The unique B&W $DeNO_x$ stabilizer achieved the lowest emissions but required burner settings producing a burner pressure drop of 8.20 in. W.G. The other configurations were based on either a 20^o or 30^o coal impeller design. The impeller equipped XCL configurations could achieve a wide range of NO_x and flame length by the adjustment of the impeller position, all with burner pressure drop less than 5 in. W.G. At optimum conditions, the 20^o impeller in an expanded coal nozzle gave 338 ppm NO_x while the 30^o impeller in the standard coal nozzle gave 374 ppm.

From these numerous burner configurations, two stand out as suitable for application for the LIMB demonstration. All configurations tested met the requirements of a firing capacity of 78×10^6 Btu/hr per burner, a throat diameter no greater than 35 inches, and mechanical reliability meeting commercial standards. The Edgewater boiler also imposed the constraint on flame length, 22 ft, and on maximum tolerable burner pressure drop, about 5 in. W.G. In addition, the burners had to produce a stable flame with low emissions but high combustion efficiency. The two configurations meeting all those conditions were:

- XCL burner with 30^o impeller in the standard coal nozzle with appropriate outer vane design.

- XCL burner with 20^o impeller in an expanded coal nozzle.

Performance of these two configurations is summarized in Table 6-1. In addition to meeting all Edgewater boiler requirements the two impeller-equipped XCL burner configurations offer a very effective handle to optimize performance to suit the application. This control is the adjustable position

TABLE 6-1. OPTIMUM BURNER CONFIGURATIONS FOR EDGEWATER UNIT 4 (78×10^6 Btu/hr $SR_T = 1.20$)

Burner	NO_x @ 0% O_2 (ppm)	Flame Length (ft)	Fly Ash Carbon (wt %)	Burner ΔP (in. W.G.)
XCL w/30° Impeller, Standard Coal Nozzle	374	20-22	4.42	3.30
XCL w/20° Impeller, Expanded Coal Nozzle	338	21	4.92	4.90

of the coal impeller. For both designs, flame length and NO_x emissions can be varied simply by moving the impeller a matter of inches. The impeller adjustment can thus be used to tune the burner for maximum NO_x reduction within the constraints of available firing depth.

In application to the Edgewater Unit #4 boiler, NO_x emissions are expected to be somewhat higher than those recorded in the LWS furnace. This is because of the multiple burner configuration and the resulting more confined, hotter thermal environment of the boiler unit. A parameter often used to describe firing density, and to correlate NO_x emissions in different boilers is the burner zone heat liberation, which relates thermal input at the burners to the area of cooled wall surface in the burner zone. This parameter takes value of 175 x 10^3 Btu/hr.ft^2 for the LWS furnace, and 245 x 10^3 Btu/hr.ft^2 for the Edgewater boiler. This difference is expected to yield an increase of approximately 60 ppm in NO_x emissions from the boiler for comparable burner operating conditions in the LWS. Optimum burner configurations referenced in Table 6-1 are therefore expected to give approximately 435 ppm and 400 ppm NO_x, respectively, in the Edgewater boiler.

6.2 SO_2 Reduction Potential

A brief series of sorbent injection tests was performed for a selected configuration of each burner design, DRB, HNR, and XCL burners. Two near burner locations and two upper furnace locations were evaluated at nominal full load conditions. Vicron 45-3 limestone was injected through the three locations closest the burner and Colton hydrated lime was injected through the two upper furnace locations. At the lower level of ports, with a gas temperature of about 2500^oF, limestone achieved 33 percent capture at Ca/S molar ratio of 2 while the hydrated lime achieved 36 percent capture. At the uppermost level, associated with a gas temperature of 2150^oF, the hydrated lime achieved 38 percent capture at Ca/S molar ratio of 2.

The two near burner locations considered were with the coal and through four high-velocity nozzles in the outer secondary air passage. Limestone injected with the coal achieved only 28-32 percent capture at Ca/S molar ratio of 2 for all three burners. The injection of limestone through the outer secondary air passage yielded higher SO_2 capture for the DRB equipped with the 75^{o} impeller (40 percent at Ca/S molar ratio of 2) than for the HNR and SCL burners (30 percent). The difference in results is not fully understood, but appears to be associated with the near burner flow field as suggested by flame shape.

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