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

VOLUME I

Distributed Mixing Burner Evaluation

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NOTICE

ABSTRACT

This report describes the results of a study in which NO_x emissions and general combustion performance characteristics of four burners were evaluated under experimental furnace conditions. Of primary interest was the performance of a low-NO_x Distributed Mixing Burner (DMB), which was tested in a nominal full-scale (120×10^6 Btu/hr or 35 MW) version and in a corresponding half-scale version. Performance was compared against a half-scale commercial low-NO_x Dual Register Burner (DRB) and a 120×10^6 Btu/hr (35 MW) commercial Circular Burner. The report documents the performance of each burner type over a wide range of firing conditions and for different bituminous and subbituminous coal types.

Additional goals of the test program were to provide information relating to the effects of burner design, burner scale and thermal environment on NO_x emission performance. Full- and half-scale DMB performance was compared under equivalent thermal conditions; the DMB was tested under two levels of furnace insulation; results from the DRB and Circular Burners were compared to field data from two utility boilers operating with corresponding burner designs and coal types. A burner zone heat liberation rate parameter was used to compare the relative performance of the different burners under the various firing conditions.

Limited additional testing was conducted to evaluate SO_2 removal performance by injected sorbent materials for the different burner designs and firing conditions. Limestone, hydrated lime, and dolomitic pressure-hydrated sorbents were injected through various burner passages, and at various elevations above the burners. Results indicate a strong sensitivity to injection temperature and the furnace thermal profile.

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1.0 SUMMARY

The objective of this program was to demonstrate the performance of the Distributed Mixing Burner (DMB) on a multi-burner utility boiler. This involved integrating the DMB concept with Babcock & Wilcox (B&W) burner components to produce a prototype burner meeting commercial standards. In the original program plan, the demonstration was to include a full-scale utility boiler retrofit with Distributed Mixing Burners. 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 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 can be extrapolated to utility boilers with some confidence.

1.1 Program Plan

In the original program plan, differences in performance with the DMB were to be determined by direct comparison of the original equipment burners. The elimination of the field installation precluded this comparison and required dependence on research furnace test results. As part of the revised program, the performance of the prototype DMB in the LWS research facility had to be demonstrated to be similar to the performance in a field operating boiler. This objective was achieved by: (1) translating developmental DMB design criteria into practical prototype burners: (2) verifying and optimizing the performance of the prototype B&W DMBs in the LWS; (3)

evaluating the performance of two commercial burners in both utility boilers and the LWS; and (4) from that data base extrapolating the prototype DMB performance to operating utility boilers.

Four different burners were tested:

- 120×10^6 Btu/hr Circular Burner
- 60×10^6 Btu/hr Dual Register Burner
- 60×10^6 Btu/hr Distributed Mixing Burner
- 120×10^6 Btu/hr Distributed Mixing Burner

The first two burners listed represent B&W commercial designs currently in use in utility boilers. The Circular burner, the B&W pre-NSPS design, was tested at full scale. The test matrix and measurements bracketed those used in the field test so that the LWS and field burner performance may be directly compared. This allowed direct evaluation of furnace environment effects.

The DRB is the current commercial low-NO_x burner design offered by B&W. Since a full-scale 120×10^6 Btu/hr DRB would be expected to produce flames about 30-35 ft long and the LWS firing depth is 22 ft, the DRB was tested at reduced scale, 60×10^6. B&W estimated that a one-half scale DRB would produce a flame short enough to avoid flame impingement in the LWS. Reducing the firing rate by a factor of two from full-scale also reduced the heat release per unit cooled surface area by a factor of two. This reduced scale DRB was also tested with additional insulation added to the LWS to more closely match the thermal environment at full load. This provided a direct evaluation of the effects of thermal environment independent of burner scaling. The tests of the DRB similar to the Circular burner tests were conducted to evaluate burner performance in the LWS.

The full-scale, 120×10^6 Btu/hr Distributed Mixing Burner was the key to the evaluation of the DMB concept. The test furnace imposed severe constraints to flame shape and size for a low-NO_x burner. Low-NO_x burners, which rely on controlled, delayed mixing of fuel with air, generally produce longer flames than conventional burners. In fact, to produce a flame less than the furnace depth under staged conditions required more than optimization of available burner controls. Iterative modifications were made to selected burner components, primarily the coal injector, to achieve acceptable flame dimensions.

Three configurations of the half-scale, 60 x 10^6 Btu/hr prototype DMB were evaluated. The two initial configurations considered coal injectors to produce short vs. long flames. The short flame DMB incorporated a coal impeller at the end of the coal pipe similar to that used in the Circular burner. This impeller induces good mixing, producing a relatively short flame. This DMB design would be appropriate for pre-NSPS boilers with restricted firing depths. The long flame DMB used a coal diffuser device like that used in the Dual Register Burner located well back of the burner exit. It functions to produce a uniform distribution of coal at the exit and would be expected to result in a long flame similar to that from a DRB. Based on the developmental tests, long flame DMBs can be optimized to produce somewhat lower NO_x than short flame DMBs. The long flame design would probably be suitable for retrofit in post-NSPS B&W units equipped with DRBs and new boilers with increased firing depth.

During analysis of data from tests with the initial half-scale DMB, the outer secondary passage was determined to be improperly designed resulting in unusually high velocities. Following optimization of the full-sized DMB, the half-scale (60 x 10^6 Btu/hr) burner was modified to match its design parameters. This provided data to determine the effect of burner scaling on performance to assist interpretation and extrapolation of DMB performance to utility boilers.

To further aid extrapolation of the LWS test results, four different fuels were used. The key fuels were obtained from suppliers of the two host boilers. Data for each burner were obtained for different fuels with the primary objective being to directly link the two host sites, eliminating questions of fuel composition on scaling.

1.2 Fuels and Sorbents

Four different coals were used for the purpose of this test program: Utah coal, Illinois coal, (high in sulfur), and one coal from each host boiler site. Data from tests with a fifth coal, Pittsburgh #8, are also included to broaden the interpretation of results, through the link to the LIMB/2nd generation burner program. The compositions of these coals are listed in Table 1-1. The Utah coal has been used as the base fuel at EER in the development of low-emission, high-efficiency burners. It is a high-volatile B bituminous coal from the Western United States with a low sulfur content. The high-sulfur coal used is an Illinois #6 coal. This is a high-volatile C bituminous coal selected to provide data which would be applicable to eastern U.S. boilers burning high-sulfur fuels. The Illinois coal has been tested at EER during previous studies in the LWS, and thus, will permit comparisons with this program. The Wyodak coal is from the DRB host site, Wyodak Plant. This is a subbituminous B coal from Wyoming. Testing the DRB with the Wyodak coal will establish a link to data from an operating boiler. Similarly, testing the coal from the Circular burner host site, Comanche Unit 2, provides a second link to operating boiler data.

Three sorbents were used during this program to evaluate the potential of SO_2 reduction with in-furnace injection. Vicron 45-3 limestone and Colton hydrated lime have been used at EER as examples of each type of material in the development of LIMB technology. In addition, a third sorbent was evaluated for general interest because of its highly reactive nature--pressure hydrated dolomitic lime. Vicron 45-3 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. The pressure hydrated dolomitic lime is a much finer material, with a mass median diameter of only 1.4 μm, in addition to containing a significant amount of magnesium oxide.

1.3 Burner Performance and NO_x Emissions

Two commercial B&W designs, the pre-NSPS Circular burner and the low-NO_x Dual Register Burner, were tested in the LWS to provide a basis with which to

TABLE 1-1. COMPOSITION OF TEST COALS

Coal	Utah		Illinois		Wyodak		Comanche		Pittsburgh #8	
Reporting Basis	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry
Proximate (wt. %)										
Moisture	6.11	0.00	15.26	0.00	23.85	0.00	22.44	0.00	3.50	0.00
Ash	8.02	8.55	8.09	9.54	7.17	9.41	5.00	6.45	12.92	13.40
Volatile	41.26	43.96	34.60	40.84	33.70	44.22	36.12	44.87	33.75	34.98
Fixed C	44.60	46.73	42.06	49.64	35.29	46.37	37.72	48.68	49.83	51.62
Heating Value										
Btu/lb	12,288	13,088	10,710	12,638	8,945	11,753	9,325	12,026	12,177	12,618
MMF Btu/lb		14,440		14,209		13,085		12,939		14,876
MAF Btu/lb		14,311		14,088		12,963		12,855		14,626
Ultimate (wt. %)										
Moisture	6.11	0.00	15.26	0.00	23.85	0.00	22.44	0.00	3.50	0.00
Carbon	68.58	71.86	59.45	70.14	50.93	66.89	54.25	69.97	68.13	70.54
Hydrogen	5.16	5.49	4.28	5.05	3.65	4.81	3.80	4.91	4.63	4.79
Nitrogen	1.28	1.36	1.07	1.27	0.75	0.98	0.76	0.98	1.21	1.26
Sulfur	0.60	0.64	3.23	3.81	0.43	0.57	0.43	0.56	3.22	3.30
Ash	8.02	8.55	8.09	9.54	7.17	9.41	5.00	6.45	12.42	13.40
Oxygen*	10.24	10.91	8.64	10.21	13.23	17.34	13.32	17.14	6.41	6.63
Forms of Sulfur (wt. %)										
Sulfate	0.01	0.01	0.18	0.21	0.01	0.01	0.02	0.02	0.22	0.23
Puritic	0.13	0.13	0.95	1.11	0.06	0.09	0.09	0.12	1.62	1.65
Organic	0.46	0.50	2.11	2.49	0.36	0.47	0.32	0.42	1.38	1.42

*Oxygen determined by difference.

judge DMB performance. This comparative evaluation verified safe, efficient operation of the prototype DMB providing confidence for field application. Limited sorbent injection tests evaluated the effect of burner design on SO_2 reduction potential for both near burner and upper furnace locations.

The full-scale 120 x 10^6 Btu/hr Distributed Mixing Burner was the key to this demonstration program. The LWS test furnace imposed severe constraints to flame shape and size for a low-NO_x burner. Low-NO_x burners, like the DMB, rely on controlled, delayed mixing of the fuel with air. This delayed mixing generally produces a long flame which may cause operational problems in a boiler. Although equipped with adjustable inner and outer secondary air control as well as the tertiary air ports, the dominant factor in determining ultimate performance (NO_x/flame length) was the coal injector configuration. Iterative modifications were made to the coal injector to yield the optimum performance for the LWS. There was a direct tradeoff between NO_x emissions and flame length.

The final design selected resulted in unstaged flames about 16 ft long. Under staged conditions, with a burner zone stoichiometric ratio (SR_B) of 0.70, the flame length increased to approximately 22 ft. The optimum configuration for the 120 x 10^6 Btu/hr DMB was determined to be:

- Spreader design = 4-inch support pipe with four 8-inch blades at a 30^o angle from axial.
- Inner Spin Vanes = 35^o Open CW.
- Outer Register = 10^o Open CW (clockwise).
- Spreader = 3-in. retracted inner/outer secondary air distribution--50/50.

NO_x emissions for the DMB at these optimum settings at nominal full-load conditions with a burner zone stoichiometry of 0.70 and 20 percent excess air were 300, 340, 298, and 273 ppm (corrected to 0% O_2) for Utah, Illinois, Comanche, and Wyodak coals, respectively. This performance compares favorably with the two commercial B&W burners tested, as seen in Table 1-2.

1.4 SO_2 Reduction Potential

The potential for SO_2 control combined with NO_x reduction was evaluated in a series of sorbent injection trials. A total of six different injection locations were considered. Three sorbents were used: Vicron 45-3 limestone, Colton hydrated lime, and a limited number of tests with a pressure hydrated dolomitic lime. Thermal environment was the key factor determining SO_2 capture efficiency. The sensitivity of SO_2 capture to thermal environment is summarized in Figure 1-1. Upper furnace locations where gas temperatures were about 2200°F yielded the highest captures. Near burner injection, either with the coal or through tertiary air ports generally gave the poorest SO_2 capture. The pressure hydrated dolomitic lime was the most effective of three sorbents on a Ca/S molar ratio basis, however, the advantage disappears when considered on a mass basis because of the additional magnesium component.

TABLE 1-2. COMPARISON OF BURNER PERFORMANCE IN THE LWS FIRING UTAH COAL (SR_T = 1.20)

	DMB		DRB	Circular
	Full Scale	Half Scale	Half Scale	Full Scale
Firing Rate (10^6 Btu/hr)	120	60	60	120
SR_B	0.70	0.70	1.20	1.20
FEGT (°F)	1792	1776	1776	1828
NO_x (ppm @ 0% O_2)	300	350	390	380
Flame Length (ft)	22	18	18	>22

SR_B = Burner Zone Stoichiometric Ratio

FEGT = Furnace Exit Gas Temperature

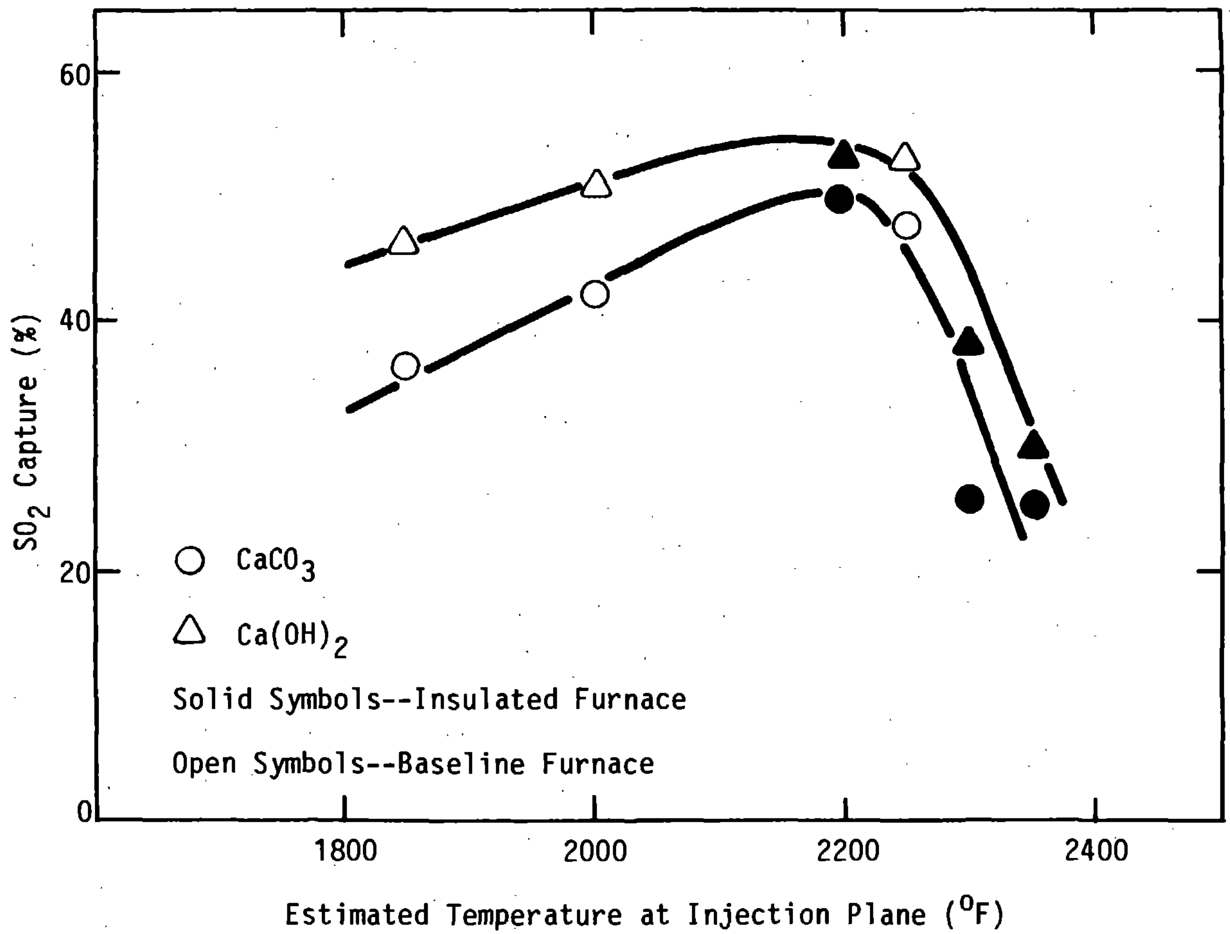


Figure 1-1. Estimated relationship between injection temperature and SO_2 capture--60 x 10^6 Btu/hr DMB, Illinois coal.

2.0 INTRODUCTION

NO_x emissions from pulverized coal combustion are typically higher than from the combustion of liquid or gaseous fossil fuels because coal contains substantial quantities of nitrogen compounds. During combustion, these compounds decompose to liberate HCN and NH_3 which react readily with oxygen to form NO_x. Up to 80 percent of the total NO_x emissions from the combustion of coal is due to fuel nitrogen oxidation.[1]

One of the most effective techniques for reducing NO_x emissions from high-nitrogen fuels is staged combustion. This involves firing the fuel under oxygen deficient conditions initially, followed by secondary air addition to complete combustion. In the fuel-rich primary zone, the bound nitrogen compounds are preferentially reduced to N_2 prior to the addition of the secondary air. The effectiveness of this type of staging in reducing NO_x emissions depends on the combustion conditions, particularly in the initial fuel-rich zone. The optimum stoichiometry in the fuel-rich zone for NO_x abatement is about 0.7, or 70 percent of theoretical air required for stoichiometric combustion. Staging has been demonstrated to be effective in reducing NO_x emissions on full scale wall-fired boilers through the use of overfire air ports.[2] However, in boiler retrofit applications of overfire air for staging, the stoichiometry in the initial zone around the burners is preferably maintained above stoichiometric conditions (100 percent theoretical air) to minimize slagging and corrosion in the lower furnace and to achieve acceptable char burnout. This limits the effectiveness of overfire air ports for NO_x control.

For several years, Energy and Environmental Research Corporation (EER) has been working with the U.S. Environmental Protection agency (EPA) in the development of a low-NO_x pulverized coal burner for wall-fired applications. The Distributed Mixing Burner (DMB) approach involves staging the combustion process with discrete air ports around each circular burner. The DMB allows a fuel-rich primary zone, with stoichiometry near the optimum range, to be established adjacent to the burner while maintaining an overall oxidizing atmosphere in the furnace around the burners, minimizing slagging, corrosion, and char burnout problems. In the development process, NO_x emissions less than 0.15 lb/10^6 Btu were achieved with test burners in research facilities.[3]

The objective of this program was to demonstrate the performance of the DMB on a multi-burner utility boiler. This involved integrating the DMB concept with Babcock & Wilcox (B&W) burner components to produce a burner meeting commercial standards. Performance of such a prototype B&W DMB was to be verified in the EPA Large Watertube Simulator (LWS) test facility, followed by full retrofit and testing in a utility boiler.

2.1 DMB Concept and Development

The DMB concept involves staging the combustion process to minimize NO_x emissions while maintaining an overall oxidizing atmosphere in the furnace to minimize slagging and corrosion. NO_x production from fuel nitrogen compounds is minimized by driving a majority of the compounds into the gas phase under fuel-rich conditions and providing a stoichiometry/time-temperature history which maximizes the decay of the evolved nitrogen compounds to N_2. Thermal NO_x production is minimized by heat loss from the fuel-rich zone which reduces peak temperatures.

A schematic representation illustrating how the DMB design stages the fuel/air mixing sequentially is shown in Figure 2-1. The combustion process occurs in three zones. In the first zone pulverized coal transported by the primary air combines with the inner secondary air to form a very fuel-rich (30 to 50 percent theoretical air) recirculation zone which provides flame stability. The coal devolatizes and fuel nitrogen compounds are released to the gas phase. Outer secondary air is added in the second "burner zone" where the stoichiometry increase up to about 70 percent theoretical air. This is the optimum range for reduction of bound nitrogen compounds to N_2. Air to complete the combustion processes is supplied through tertiary ports located outside the burner throat. This allows substantial residence time in the burner zone for decay of bound nitrogen compounds to N_2 and radiative heat transfer to reduce peak temperatures. The tertiary ports surround the

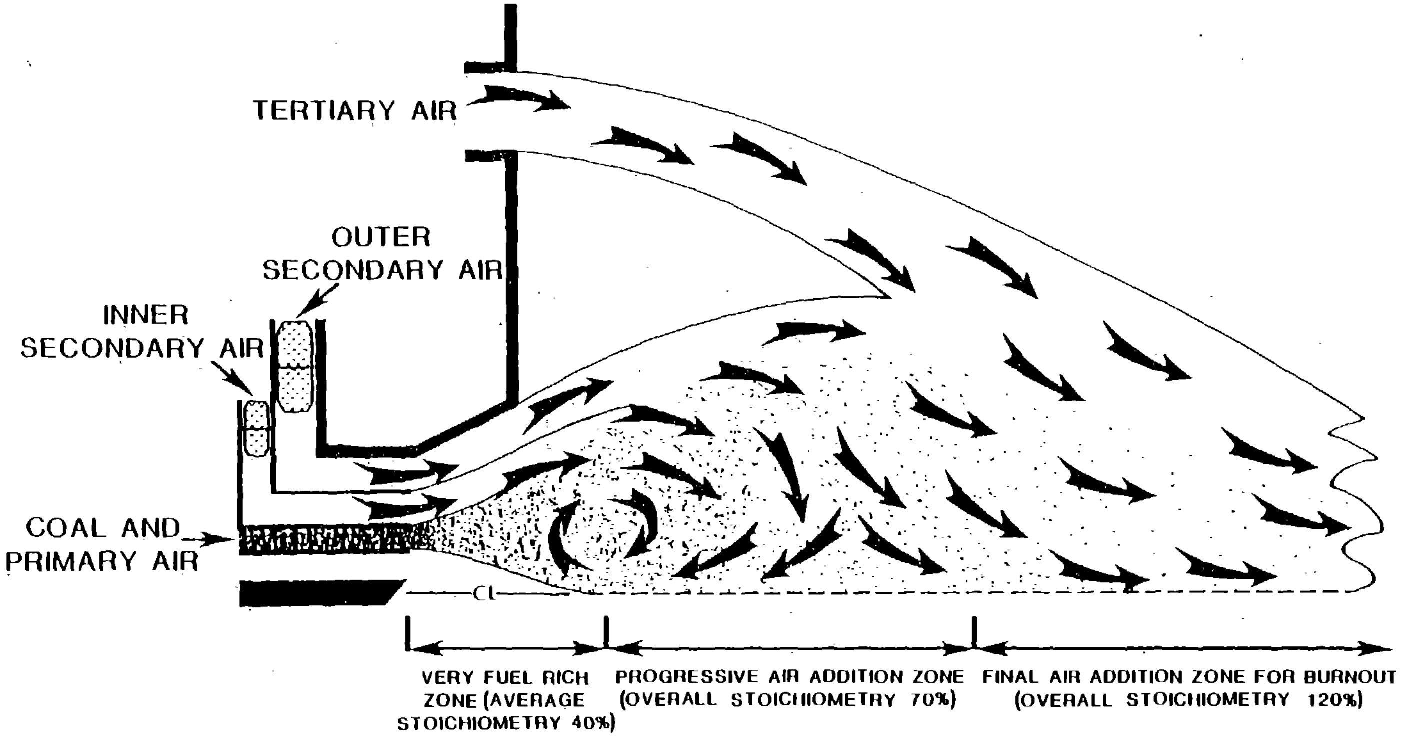


Figure 2-1. DMB concept.

burner throat providing an overall oxidizing atmosphere and minimize interactions between adjacent burners.

Components for a typical, fully commercial DMB design would include:

- Four independently controlled air streams:
  - Primary air for pneumatic transport of coal from pulverizer to burner.
  - Two concentric annular secondary air streams around the primary jet.
  - Tertiary air through four outboard ports.
- Fuel injector design to produce a uniform coal distribution and initiate mixing with secondary combustion air streams to stabilize the flame.
- Adjustable assemblies for each secondary air stream to control air flow rate distribution and degree of swirl.
- Commercial ignition and flame scanner system for start-up and safety.

The key components for the DMB are the outboard staged air ports closely coupled to each burner in a multi-burner installation.

The development history of the DMB is summarized in Figure 2-2. Initial development of the DMB concept was carried out at the International Flame Research Foundation (IFRF) under EPA Contract 68-02-0202. This included proof-of-concept tests in a research furnace firing at 8.5 x 10^6 Btu/hr. Additional development and scale-up tests were conducted at EER under EPA Contract 68-02-1488. To provide a standard means of evaluating burner performance, two large-scale test facilities were constructed: the Small

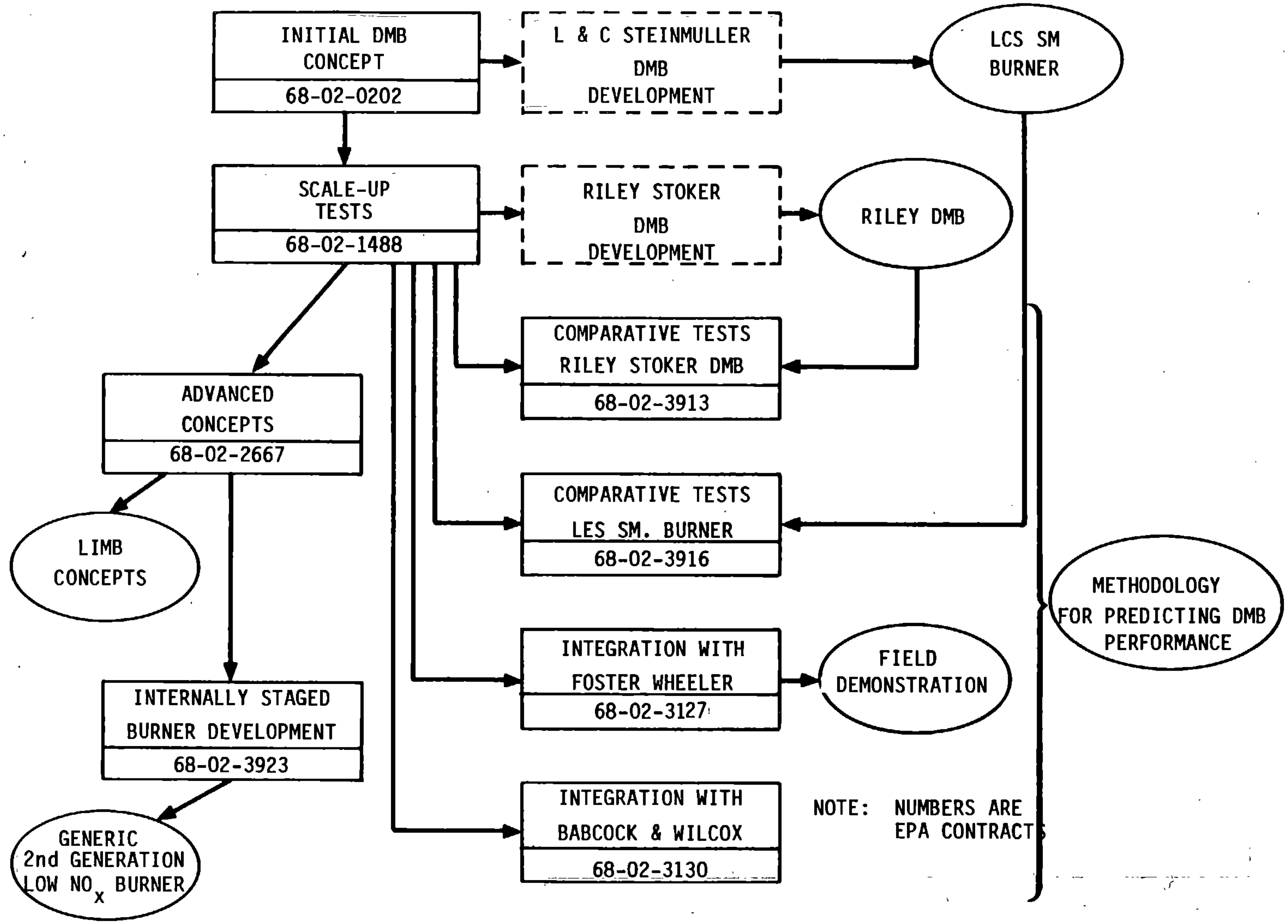


Figure 2-2. Development history of the distributed mixing burner.

Watertube Simulator (SWS) and the Large Watertube Simulator. The SWS was designed to simulate the thermal environment of a small watertube boiler. It had a capacity of 10 x 10^6 Btu/hr and provided a means of testing burners at moderate scale so that the effects of parametric variations could be evaluated at low cost. The LWS was designed to simulate a large industrial or small utility watertube boiler. The furnace shape was similar to commercial boilers with a hopper bottom, a nose, and provision for front-wall firing. The firing capacity of the LWS was 150 x 10^6 Btu/hr which allowed full-scale burners to be evaluated under conditions simulating large commercial systems.

Six experimental DMB configurations were designed and tested. The designs covered a firing rate range of 10 to 100 x 10^6 Btu/hr as single burners and also as a four-burner array. The DMBs were research designs with flexible parameters so that the effects of burner design variations on NO_x emissions, flame stability and combustion efficiency could be evaluated. Minimum NO_x emissions for each burner were in the range of 0.1 - 0.2 lb/10^6 Btu. The results of the tests were compiled into a set of design criteria which could be used to apply the DMB concept to commercial burners.

At this point, the development divided into two parallel efforts. One focused on advanced concepts of NO_x and SO_x control. In EPA Contract 68-02-2667 the DMB concept was integrated with sorbent injection for SO_x control. The resulting process was termed "Limestone Injected Multi-Stage Burner" (LIMB). In EPA Contract 68-02-3923 advanced burner concepts were developed to achieve staging without the need for the outboard tertiary air ports of the DMB.

The other effort focused on the further development and commercialization of the DMB. Two EPA demonstration programs were established. This project, EPA Contract 68-02-3130, was to demonstrate the application of DMB technology to large utility boilers with B&W burner hardware. In a parallel project (EPA Contract 68-02-3127) the DMB concept was integrated with Foster Wheeler (FW) components to be demonstrated in a small utility boiler in the range of 100 to 500 x 10^3 lb/hr.

In parallel with this EPA development, two other burner manufacturers elected to develop DMBs for commercial offerings. Based on the results of the initial IFRF tests, L&C Steinmuller (LCS), a German burner/boiler manufacturer, developed the Staged Mixing (SM) burner based on the DMB concept. LCS installed the SM burners in a 700 MW German boiler and demonstrated a 50 percent reduction in NO_x emissions.[4] The SM burner is now the standard commercial burner offering for LCS. Riley Stoker developed a DMB based on the design criteria developed in EPA Contract 68-02-1488 in conjunction with EER. The Riley Stoker DMB was tested in research facilities at EER. The results of these independent developments were integrated with the EPA work in EPA Contracts 68-02-3916 and 68-02-3913 which included tests of the LCS and Riley Stoker DMBs, respectively, in the LWS test facility.

2.2 Program Objectives and History

The objective of this program was to evaluate the performance of the EPA Distributed Mixing Burner, incorporating B&W burner hardware, in a utility boiler. The original plan to achieve this objective after contract initiation on September 30, 1978 involved four key elements:

1. A field test of the host boiler with the original burners to establish the "baseline" burner/boiler performance.

2. A test of the original, "baseline" burner in the LWS research furnace to calibrate the furnace against the corresponding host boiler.

3. Evaluation and optimization of a prototype DMB with B&W components in the LWS to verify performance prior to installation at the host site.

4. Long-term field evaluation of the DMB in the host boiler.

Babcock & Wilcox held the prime contract with the EPA to achieve these goals. EER was subcontracted to support the B&W effort. The EER effort included:

- Engineering assistance throughout the program as required, such as DMB design input, definition of program plan and measurement plan, data analysis, and reporting.
- All LWS testing of the original baseline burner and the prototype DMB.
- Field testing support during both the baseline and low-NO_x test phases.

Progress on this plan was delayed because of difficulties in finding a suitable host boiler. The selection of the host site was the key to the entire project. The host site defined boiler specific burner design requirements, including firing capacity, burner and tertiary air port spacing, fuel characteristics, nominal operating conditions and duty cycle, furnace dimensions, and flame confinement. In about May 1981, a final effort to secure a host failed. A proposed Ohio Edison boiler was found to be unacceptable by the EPA due to high projected cost to complete this project. Costs to fully retrofit a utility boiler with Distributed Mixing Burners had escalated beyond available funding. From that point, the effort focused on restructuring the program to achieve the program goals without a costly field demonstration. Negotiations among the participants, B&W, EER, and EPA, reached initial agreement on a revised program about December 1981. The revised program scope was finalized in February 1983, with the cost breakdown agreed to in November 1983. The revised program scope addressed two distinct issues. The major portion of the program still focused on the evaluation of the Distributed Mixing Burner for utility boiler application. The second area of interest added to the scope of this project was an evaluation of alternate concepts for low-NO_x emissions coupled with high levels of particulate removal and possible SO_x control. These alternate concepts, detailed in Volume IV of this report, considered fuel-rich, high-temperature prechambers, such as cyclone furnaces. This alternate concept program was structured to: (1) compile and synthesize existing data on coal-fired precombustion systems; (2) conduct initial pilot scale tests at 1 x 10^6 But/hr to identify the key parameters affecting NO_x and SO_x reduction potential, and (3) a second phase of more fundamental testing structured to investigate a broader range of SO_x control issues in smaller, well-controlled experiments to generate a more complete set of basic precombustor design data.

The evaluation of the DMB for utility boiler application was restructured to achieve the program objective without a field installation. In the original program plan, differences in performance with the DMB were to be determined by direct comparison of the original equipment burners. The elimination of the field installation precluded this comparison and required dependence on research furnace test results. As part of the revised program, the performance of the prototype DMB in the LWS research facility had to be demonstrated to be similar to the performance in a field operating boiler. This objective was achieved by: (1) translating developmental DMB design criteria into practical prototype burners; (2) verifying and optimizing the performance of the prototype B&W DMBs in the LWS; (3) evaluating the performance of two commercial burners in both utility boilers and the LWS; and (4) from that data base extrapolating the prototype DMB performance to operating utility boilers.

Work began in earnest on the revised program scope for the DMB evaluation in May 1984 with the preparation of a detailed test plan. Actual testing for this program was initiated in September 1984 and was completed in June 1986. During that time frame, the scope of the DMB evaluation program was expanded further. The expanded scope was an opportunity presented by the initiation of another EPA demonstration project to directly participate in full-scale application of low-emission burners to an operating boiler.

The EPA demonstration of LIMB (Limestone Injection Multistage Burner) technology had the objective of reducing both NO_x and SO_2 emissions by 50 percent. The NO_x reduction was to be achieved by retrofitting existing burners at Ohio Edison's Edgewater Unit 4 boiler with second generation low-

NO_x burners. Because of the constraints at this boiler, evaluation of three candidate B&W burners prior to selection was essential.

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. Burners sized at 78 x 10^6 Btu/hr, the same size as the Edgewater burners, were tested in the LWS, minimizing scale-up questions. 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 these tests, the influence of adjustable burner parameters (e.g. swirl level, air distribution) and of changes to burner hardware components (e.g. coal nozzle) was determined. For each of the three basic burner designs one configuration was selected for sorbent injection testing, to determine the effect 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 applicability of this new burner. These tests were conducted in two phases, with the initial screening tests from August through October 1985 and the final optimization tests from February through March 1986.

2.3 Guide to the Report

The broad scope of this program can be separated into four distinct parts: (1) the evaluation of prototype DMBs for application to utility boilers; (2) field tests of baseline burners at two host boilers to support the extrapolation of prototype DMB performance to field applications; (3) evaluation of three B&W second generation low-NO_x burners to be selected for use in the EPA LIMB demonstration; and (4) alternate concepts for NO_x and SO_x control in precombustors. Each of these represents a distinct element of the program. This report is, therefore, organized to fully address each element.

Volume I--Distributed Mixing Burner Evaluation. This volume of the report, Part I, presents the results from the prototype burner evaluations in the LWS, the principal element to achieve the original program objectives. This part describes the methodology employed to evaluate the DMBs without a field retrofit, linking research furnace results to operating boilers. The experimental systems, including test burners, fuels, the test facility itself, and testing procedures, are fully detailed. Burner performance for each test burner are discussed. The key to interpretation of the results is the link of the LWS test results to operating utility boilers achieved with tests of commercial B&W burners in the LWS and field test results of the same burner design in utility boilers. This link allows extrapolation of prototype DMB performance from the LWS to the field. A summary of sorbent injection trials for SO_2 control is also included in Volume I to broaden the existing data base and experience with LIMB technology.

Volume II--Second Generation Low-NO_x Burners. Volume II summarizes the LWS trials of the three B&W low-NO_x burners considered for the EPA LIMB demonstration program at Edgewater Station Unit 4. The three burners included: the Dual Register burner (DRB), Babcock-Hitachi NR burner (HNR), and the B&W XCL burner. The burners and each configuration tested are described, along with the fuels and test facility configuration used throughout these tests. The optimization of the various configurations of each basic burner design is described with respect to the key performance criteria of NO_x emissions, flame length, combustion efficiency, and burner pressure drop. The performance of each optimized configuration is compared to the LIMB demonstration site requirements and recommendations for burner selection are made. Finally, a brief series of sorbent injection tests was conducted for a selected configuration of each burner design. These tests were performed to determine any possible effect of burner design on SO_2 capture potential with sorbent injection.

Volume III--Field Evaluations. Volume III details the field tests performed in conjunction with the DMB evaluation. The field tests were performed at two different utility boilers, generally similar in design and size except for the burner equipment. Comanche Unit 2 of Colorado Public

Service was equipped with B&W Circular burners, the pre-NSPS (New Source Performance Standard) burner design. The Wyodak Plant of Black Hills Power was equipped with Dual Register Burners. Test results of emissions and boiler performance are presented for each unit. Key performance aspects from these two boilers are used in interpretation of LWS tests of the Circular burner and Dual Register burner.

Volume IV--Alternate Concepts. Precombustor studies for NO_x and SO_2 control are described in Part IV of this report. This work represents alternate concepts considered as a result of the program's reorganization. Part IV stresses the fundamental design considerations for precombustor control of SO_2 emissions with a brief summary of pilot scale, 1 x 10^6 Btu/hr tests for NO_x control. The various experimental apparatus and test procedures for this fundamental work are described. Results from entrained flow sulfidation tests and slag sulfur chemistry are fully detailed.

Volume V--Burner Evaluation Data Appendices. Volume V of this report documents the Quality Assurance program for the LWS tests of the DMB evaluation and the Second Generation Low NO_x burner selection. In addition, computer listings of all valid data reported in Volumes I and II are included for reference.

3.0 DMB EVALUATION METHODOLOGY

In the original program plan, differences in performance achieved with the DMB were to be determined by direct comparison of the original equipment burners and the DMBs in one representative operating utility boiler. The elimination of the field installation of the DMB precludes this comparison and requires dependence on research furnace test results. As part of the program, it must be verified that the performance of burners tested in the LWS is similar to, or may be extrapolated to, the performance of burners installed in a utility boiler. Two factors which can influence this extrapolation are burner scaling and furnace environment. The revised program plan provided an evaluation of the scaling and furnace environment effects through two field tests of utilities equipped with conventional B&W burners and tests of five burners in the EPA LWS at EER. The revised program organization is shown in Figure 3-1.

Two host boilers were selected. These boilers were hosts in the sense that they were field tested and the commercial burners tested in the LWS were designed to match the specific host boiler characteristics. The sites for the host boilers were:

1. Wyodak Plant. This unit is a B&W opposed wall-fired boiler equipped with 30 Dual Register Burners (DRB). The plant is rated at 330 MW_e with a nominal maximum capacity of 350 MW_e. The plant is located near Gillette, Wyoming, and is operated by Pacific Power and Light Company and Black Hills Power & Light Company.

2. Comanche Station #2. This unit is equipped with 32 B&W Circular burners in an opposed wall-fired arrangement. The plant, owned and operated by Colorado Public Service Company, has a generating capacity of 350 MW_e.

Ideally, the burner tests in the LWS would be conducted at full-scale so that burner scaling methods need not be considered. However, the flame length from a full-scale, 120 x 10^6 Btu/hr B&W DRB was expected to exceed the

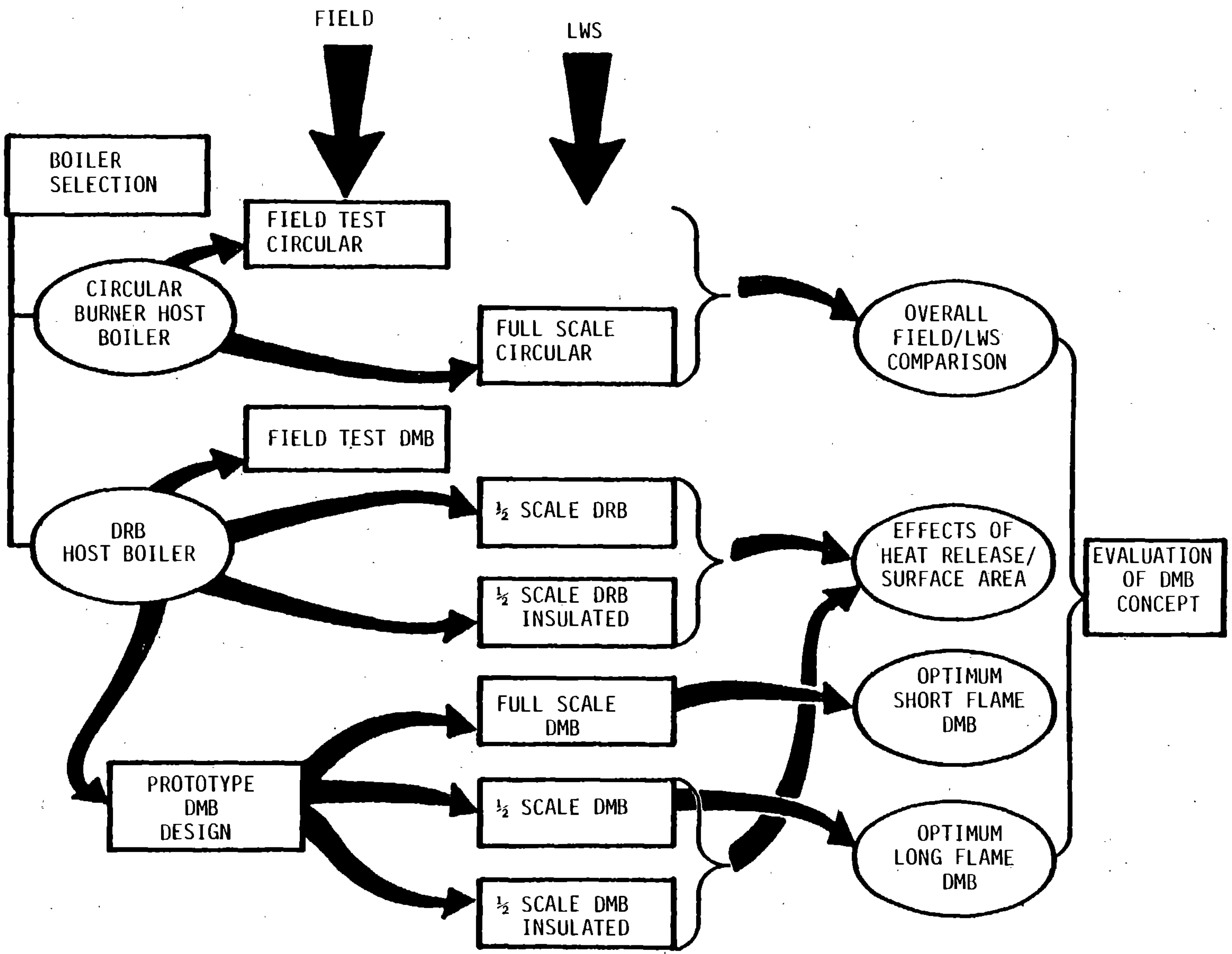


Figure 3-1. Revised program organization.

firing depth of the LWS. Consequently, the DMB tests were performed at 120 x 10^6 Btu/hr and 60 x 10^6 Btu/hr in order to better understand scaling effects, and to tie all aspects of the test program together, i.e. scaling within the LWS and scaling from LWS to field. Burner scaling, however, was not well understood at the time.

In previous developmental DMB tests, burner scaling was based on constant velocities and geometrical similarity. Results from these tests suggest that this type of scaling results in increasing NO_x emissions with firing rate. From a phenomenological viewpoint, scaling the velocities with the linear dimensions should be used to maintain constant flame residence times. Practical considerations, such as maximum acceptable pressure drop and minimum velocities to maintain pneumatic pulverized coal transport, limit the application of this scaling method. This program therefore included tests to confirm that the scaling method employed gives satisfactory results.

It is well known that furnace environment can affect burner performance. The important variables include furnace geometry, flame interaction, furnace surface area and volume, and furnace heat extraction. The burner/boiler manufacturers, including B&W, have found that NO_x emissions from burners of their design can be correlated with the furnace heat release per unit cooled surface area. The definitions of the cooled surface area and the shapes of the correlations differ among the manufacturers. The program included tests to evaluate the effects of the specific LWS furnace environment on burner performance and to compare these effects with those of full-scale utility boilers.

3.1 Large Watertube Simulator Tests

The evaluation of the DMB for utility boiler application was restructured to achieve the program objective without a field installation. In the original program plan, differences in performance with the DMB were to be determined by direct comparison of the original equipment burners. The elimination of the field installation precluded this comparison and required dependence on research furnace test results. As part of the revised program, the performance of the prototype DMB in the LWS research facility had to be demonstrated to be similar to the performance in a field operating boiler. This objective was achieved by: (1) translating developmental DMB design criteria into practical prototype burners; (2) verifying and optimizing the performance of the prototype B&W DMBs in the LWS; (3) evaluating the performance of two commercial burners in both utility boilers and the LWS; and (4) from that data base extrapolating the prototype DMB performance to operating utility boilers.

Four different burners were tested:

- 120 x 10^6 Btu/hr Circular Burner
- 60 x 10^6 Btu/hr Dual Register Burner
- 60 x 10^6 Btu/hr Distributed Mixing Burner
- 120 x 10^6 Btu/hr Distributed Mixing Burner

The first two burners listed represent B&W commercial designs currently in use in utility boilers. Due to the characteristic short flame, the Circular burner, the B&W pre-NSPS design, was tested at full scale. The test matrix and measurements bracketed those used in the field test so that the LWS and field burner performance may be directly compared. This allowed direct evaluation of furnace environment effects.

The DRB is the current commercial low-NO_x burner design offered by B&W. Since a full-scale 120 x 10^6 Btu/hr DRB would be expected to produce flames about 30-35 ft long and the LWS firing depth is 22 ft, the DRB will be tested at reduced scale, 60 x 10^6 Btu/hr. B&W estimated that a one-half scale DRB would produce a flame short enough to avoid flame impingement in the LWS. Reducing the firing rate by a factor of two from full-scale also reduced the heat release per unit cooled surface area by a factor of two. Therefore, the reduced scale DRB was also tested with additional insulation added to the LWS to more closely match the thermal environment at full load. This provided a direct evaluation of the effects of thermal environment independent of burner scaling. The tests of the DRB, similar to the Circular burner tests, were conducted to evaluate burner performance in the LWS.

For the full-scale, 120 x 10^6 Btu/hr Distributed Mixing Burner, (DMB) the test furnace imposed severe constraints with regard to flame shape and size. Low-NO_x burners, generally produce longer flames than conventional burners, and the available firing depth in the LWS is considered to be comparatively small for burners of this capacity. Iterative modifications were made to selected burner components, primarily the coal injector, were therefore necessary in order to achieve acceptable flame dimensions with the 120 x 10^6 Btu/hr DMB.

Three configurations of the half-scale, 60 x 10^6 Btu/hr prototype DMB were evaluated. The two initial configurations considered coal injectors to produce short vs. long flames. The short flame DMB incorporated a coal impeller at the end of the coal pipe similar to that used in the Circular burner. This impeller induces good mixing, producing a relatively short flame. This DMB design would be appropriate for pre-NSPS boilers with restricted firing depths. The long-flame DMB used a coal diffuser like that used with the Dual Register Burner, located well back from the burner exit. It functions to produce a uniform distribution of coal at the exit and would be expected to result in a long-flame similar to that from a DRB. Based on the developmental tests, long flame DMBs can be optimized to produce somewhat lower NO_x than short-flame DMBs. The long-flame design would probably be suitable for retrofit in post-NSPS B&W units equipped with DRBs and new boilers with increased firing depth.

During analysis of data from tests with the initial half-scale DMBs, the outer secondary passage was determined to be improperly designed resulting in unusually high velocities. Following optimization of the full-sized DMB, the half-scale 60 x 10^6 Btu/hr burner was modified to match its design parameters. This provided data to determine the effect of burner scaling on performance to assist interpretation and extrapolation of DMB performance to utility boilers.

To further aid extrapolation of the LWS test results, four different fuels were used. The key fuels were obtained from suppliers of the two host boilers. Data for each burner were obtained for different fuels with the primary objective being to directly link the two host sites to tests performed in the LWS, eliminating questions of fuel composition on scaling.

3.2 Utility Boiler Field Tests

Table 3-1 shows the characteristics of the two boilers tested. Both boilers fire subbituminous coal and use a front and rear wall firing configuration. The front and rear wall burners at the Comanche boiler are directly opposed with four rows of four burners each. The front and rear burners at Wyodak are offset to avoid flame interactions and are arranged in five rows of three burners each. The boilers have comparable furnace cross-sectional dimensions, but the Wyodak boiler has a taller furnace to accommodate the five burner rows. Thus, the Wyodak furnace has a lower ratio of firing rate to cooled surface area.

During testing, the boilers were generally operated in a normal fashion by the operators without interference from EER. Thus, the burner settings, load, and excess air were controlled by plant personnel. The overfire NO_x ports were closed during the day at the Comanche boiler at the request of EER, and returned to their normal open position of 18 percent at night. Table 3-2 shows the typical burner settings and flame characteristics during the tests. Both the Circular and Dual Register burners operated satisfactorily during the tests. Exact flame lengths could not be determined with the available observation ports. Both burners showed a high combustion efficiency and large imbalances of fuel or air distribution were not observed.

Both boilers operated over a narrow excess O_2 range, 2.5 to 3.5 percent at Comanche and 3.8 to 4.0 percent at Wyodak. Thus the data were not sufficient to establish NO_x emissions with excess O_2. Figure 3-2 shows NO_x emissions at the two boilers as a function of load. Both correlations show a similar slope, with lower NO_x emissions for the Dual Register burner at Wyodak. Nominal NO_x emissions with the Circular burner at Comanche were 550 ppm at 0% O_2 (0.64 lbs/10^6 Btu). Full load emissions at Wyodak with all mills in service were 395 ppm at 0% O_2 (0.46 lbs/10^6 Btu). More detailed results are presented in Part III.

TABLE 3-1. BOILER DESCRIPTIONS

<table>
<tr><th>UNIT</th><th>COMANCHE UNIT 2</th><th>WYODAK UNIT 1</th></tr>
<tr><td>UTILITY</td><td>COLORADO PUBLIC SERVICE</td><td>PACIFIC POWER & LIGHT
BLACK HILLS POWER & LIGHT</td></tr>
<tr><td>BOILER MANUFACTURER</td><td>B&W</td><td>B&W</td></tr>
<tr><td>YEAR OF INITIAL OPERATION</td><td>1976</td><td>1978</td></tr>
<tr><td>GROSS GENERATING CAPACITY</td><td>350 MW_E</td><td>350 MW_E</td></tr>
<tr><td>TYPE OF BURNER</td><td>B&W CIRCULAR</td><td>B&W DUAL REGISTER</td></tr>
<tr><td>NO. OF BURNERS</td><td>32</td><td>30</td></tr>
<tr><td>NO. OF MILLS</td><td>4</td><td>5</td></tr>
<tr><td>BURNER ARRANGEMENT</td><td>4W x 4H ON
FRONT & REAR WALLS</td><td>3W x 5H ON
FRONT & REAR WALLS</td></tr>
<tr><td>FURNACE DIMENSIONS</td><td>43'W x 45'D x 161'H</td><td>46'W x 45'D x 180'H</td></tr>
<tr><td>COAL TYPE</td><td>SUB BITUMINOUS</td><td>SUB BITUMINOUS</td></tr>
<tr><td rowspan="2">ADDITIONAL FEATURES</td><td>8 NO_X PORTS</td><td>SEALED NO_X PORTS
OPPOSING BURNERS OFFSET</td></tr>
<tr><td colspan="2">COMPARTMENTED WINDBOXES</td></tr>
</table>

TABLE 3-2. BURNER OPERATING CHARACTERISTICS

UNIT	COMANCHE	WYODAK
BURNER TYPE	CIRCULAR	DUAL REGISTER
TYPICAL BURNER SETTINGS	BOTTOM BURNERS-REGISTERS 50% OPEN TOP BURNERS -REGISTERS 100% OPEN	OUTER REGISTERS 50% OPEN INNER REGISTERS 25-50% OPEN SWIRL VANES 10% OPEN
FLAME CHARACTERISTICS	LONG AND NARROW 0-2 FT STANDOFF	LONG AND NARROW 35 - 44 FT LONG 0.5-3 FT STANDOFF

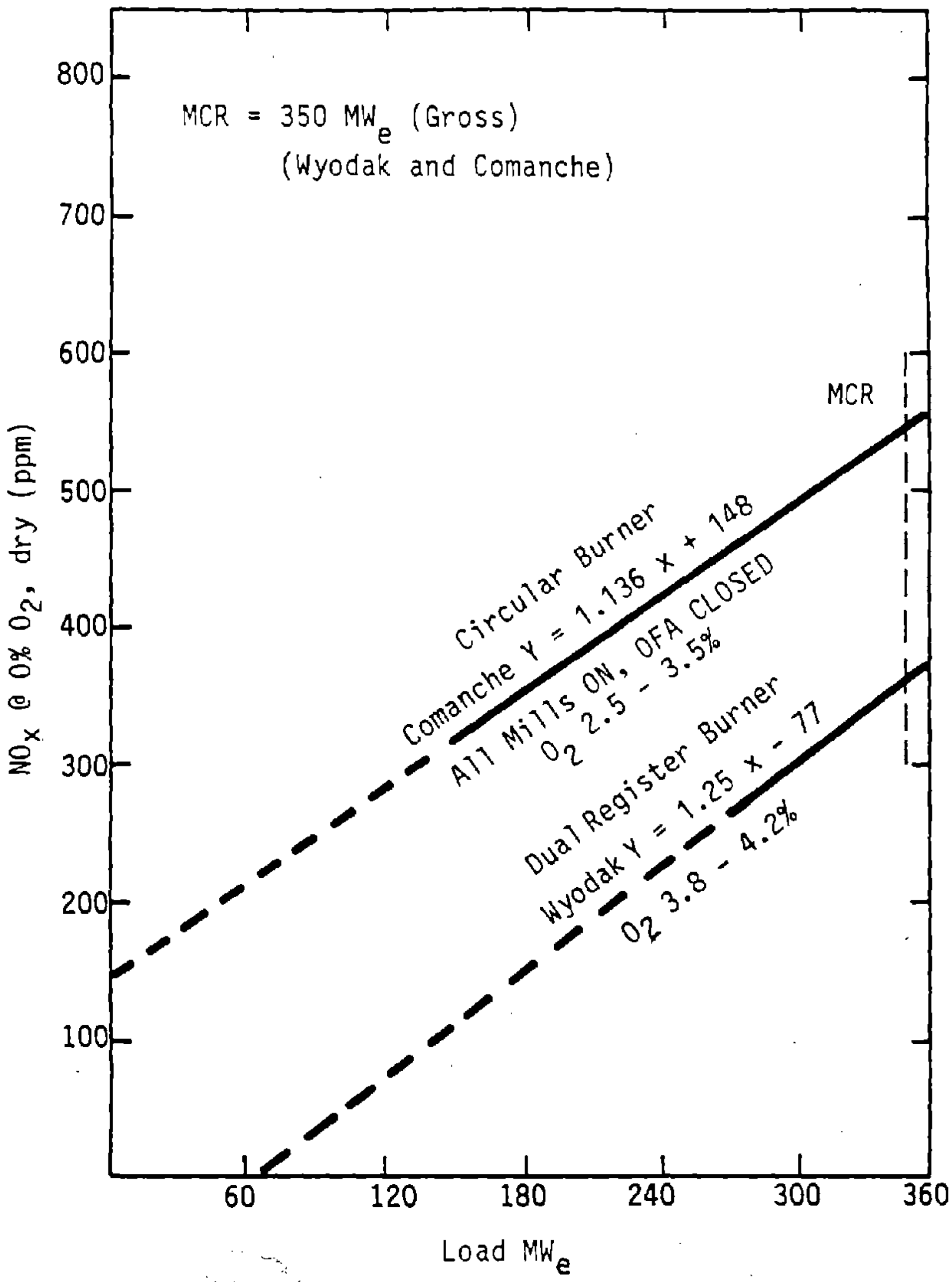


Figure 3-2. NO_x emissions vs. boiler load.

4.0 EXPERIMENTAL SYSTEMS

Four different burners were tested in the EPA Large Watertube Simulator to facilitate evaluation of the Distributed Mixing Burner for utility boiler application without a costly retrofit installation. The burners tested included:

- 120 x 10^6 Btu/hr B&W Circular Burner
- 60 x 10^6 Btu/hr B&W Dual Register Burner
- 60 x 10^6 Btu/hr Distributed Mixing Burner
- 120 x 10^6 Btu/hr Distributed Mixing Burner

The Circular burner and the Dual Register burner are both B&W commercial burner designs currently installed in utility boilers. Characterizing the performance of these two commercial designs in the LWS essentially calibrates the test furnace, establishing the basis with which to extrapolate the performance of the prototype Distributed Mixing Burner to operating boilers. The Distributed Mixing Burner was evaluated at two scales to develop scale-up criteria for burner performance from the test facility to an operating boiler.

Evaluation of these test burners was conducted in the EPA Large Watertube Simulator at the El Toro, California, test site of EER. To determine effect of furnace thermal environment on performance and resulting scale-up criteria, two insulation configurations were established for selected burner trials. Burner performance was evaluated using four principal coals: a base development fuel, a high sulfur coal for SO_2 control considerations, and two coals from the host boiler sites of the commercial burners. In addition to burner performance and NO_x emission optimization, SO_2 reduction potential was evaluated by injection of three sorbent materials through several furnace locations. All tests were conducted in the LWS 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.

4.1 Burner Designs

4.1.1 120×10^6 Btu/hr Circular Burner

The Circular Burner is B&W's pre-NSPS (New Source Performance Standard) burner design. The test burner shown in Figure 4-1, was scaled to match the design criteria of the burners at Comanche Unit 2. The Circular burner is a simple design, with a central coal pipe surrounded by a single concentric annular secondary air passage. The inlet to the coal nozzle is formed by a 90° pipe elbow. An impeller made up of 4 concentric conical rings at a 75° included angle imparts a radial component to the coal/primary air stream to enhance mixing between the coal and secondary air streams. The axial position of the impeller could be varied in relation to the coal nozzle exit using the impeller support pipe. The Circular burner, as well as all the other test burners, utilized a steel throat and exit which were water spray cooled. In actual boiler installations, the burner exit is generally formed by tube bends in the water wall covered by a thin refractory layer.

The secondary air register was a conventional assembly of adjustable radial guide vanes. Varying the position of the vanes generated varying degrees of tangential swirl. A theoretical swirl number can be defined as[5,6]:

$$S = \frac{G_\vartheta}{G_x R} \tag{4-1}$$

where G_ϑ = axial flux of tangential momentum

G_x = axial flux of axial momentum

R = equivalent nozzle radius

The calculation of swirl number using equation 4-1 requires accurate measurements of velocity and static pressure distributions to be made in a cross-section of the swirl jet. However, in the absence of these measurements, the swirl number can be predicted directly from register geometry with reasonable accuracy. For a guided-vane cascade in radial flow such as the

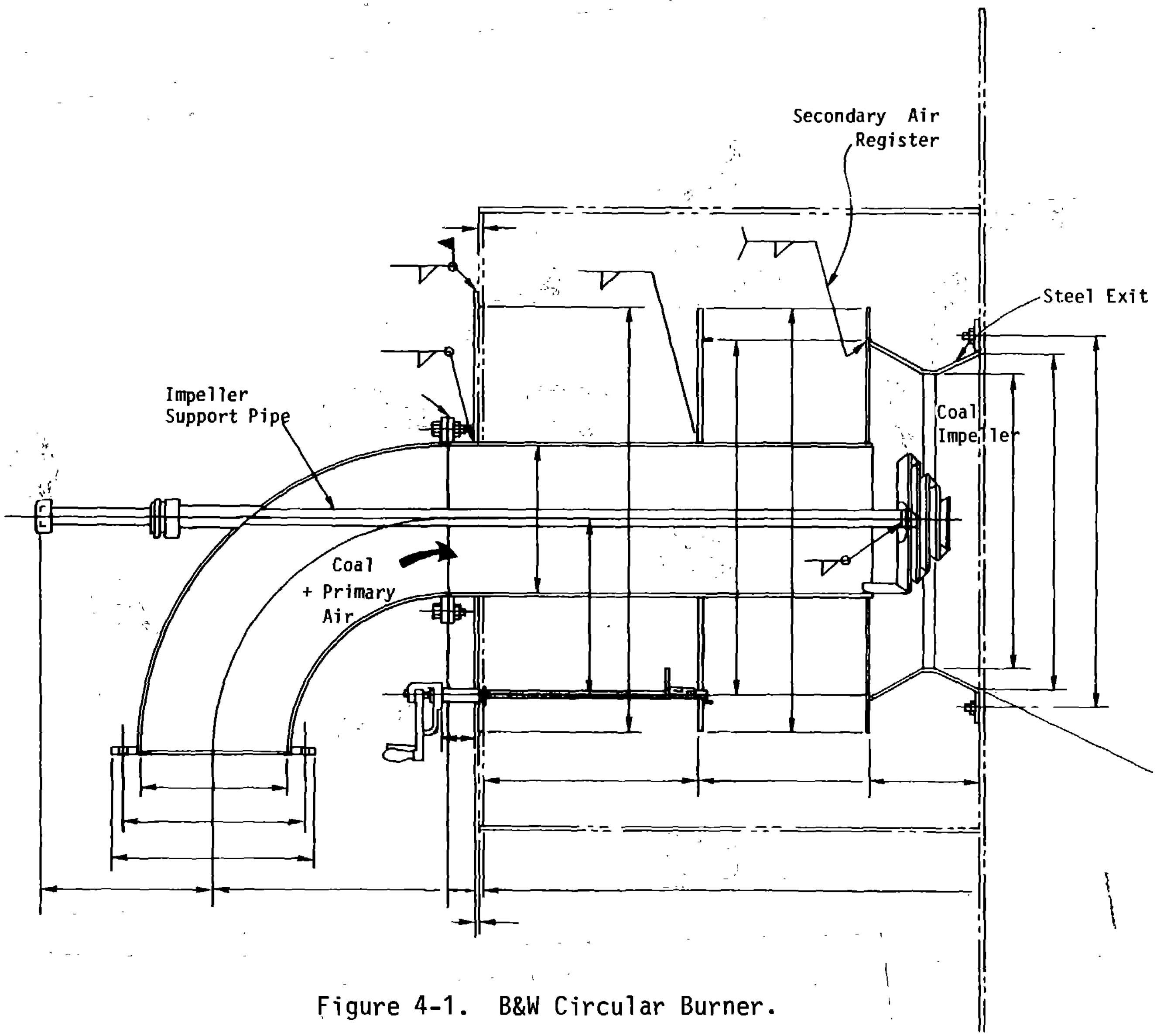


Figure 4-1. B&W Circular Burner.

one used in the Circular burner, the swirl number can be calculated using the following empirical expression:

$$S = \frac{\sigma R}{2B} \tag{4-2}$$

where = ratio of the average tangential and radial velocity components at the swirl exit (R) and is defined as:

$$\sigma = \frac{1}{1 - \Psi} \; \frac{\tan}{1 + \tan\ \alpha \tan\ (\pi/z)} \tag{4-3}$$

B = axial width of the register channel

z = number of vanes in a cascade

α = vane angle

$$\Psi = \text{blockage factor} = \frac{zS}{2\ R_1 \cos \alpha} \tag{4-4}$$

S = finite thickness of the vane

R_1 = swirler exit radius

From these empirical equations, a swirl number can be related to radial vane position for the Circular burner as shown in Figure 4-2.

Burner velocity characteristics at nominal full load of 120 x 10^6 Btu/hr are summarized in Figure 4-3. The Circular burner typically operates with a primary stoichiometry (SR_P) of 0.30 and an overall stoichiometry (SR_T) of 1.15. At these conditions, the primary velocity is 72 f/s and the secondary velocity is 112 f/s.

4.1.2 60 x 10^6 Btu/hr Dual Register Burner

The Dual Register Burner is the current commercial low-NO_x burner design offered by B&W. The test burner was scaled down from the burners in operation at the Wyodak plant. A cross-section of the DRB is shown in Figure 4-4.

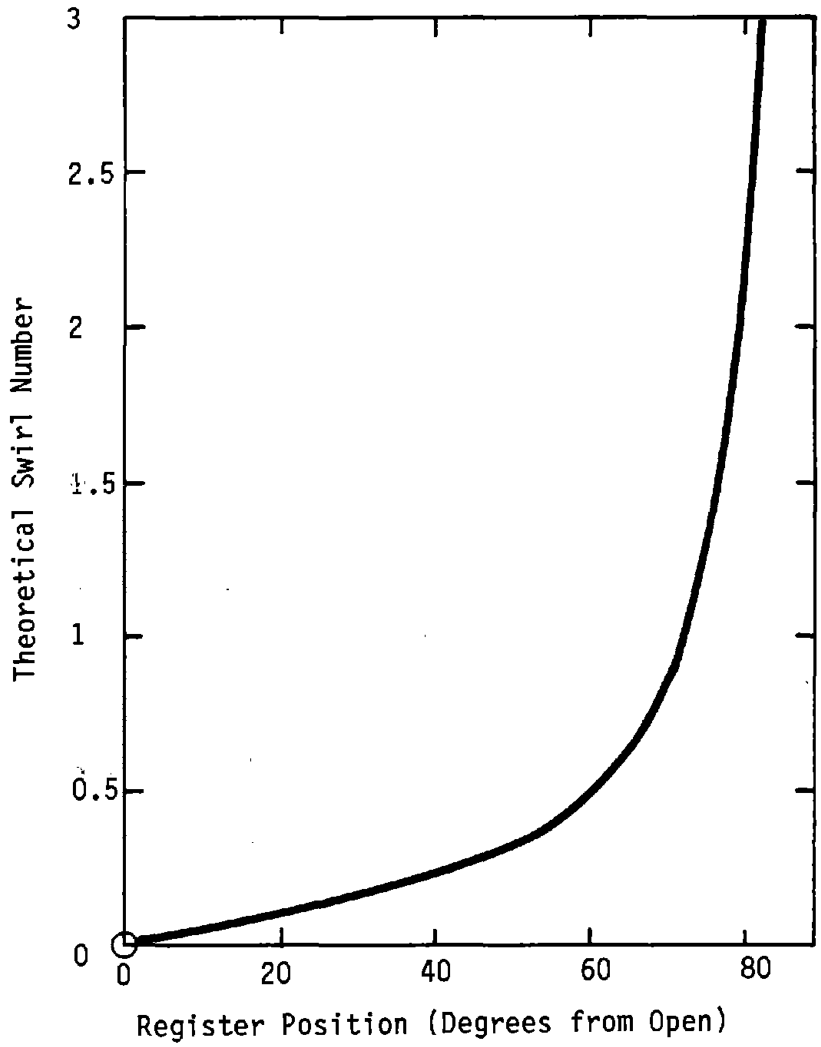


Figure 4-2. Swirl characteristics of 120 x 10^6 Btu/hr circular burner register.

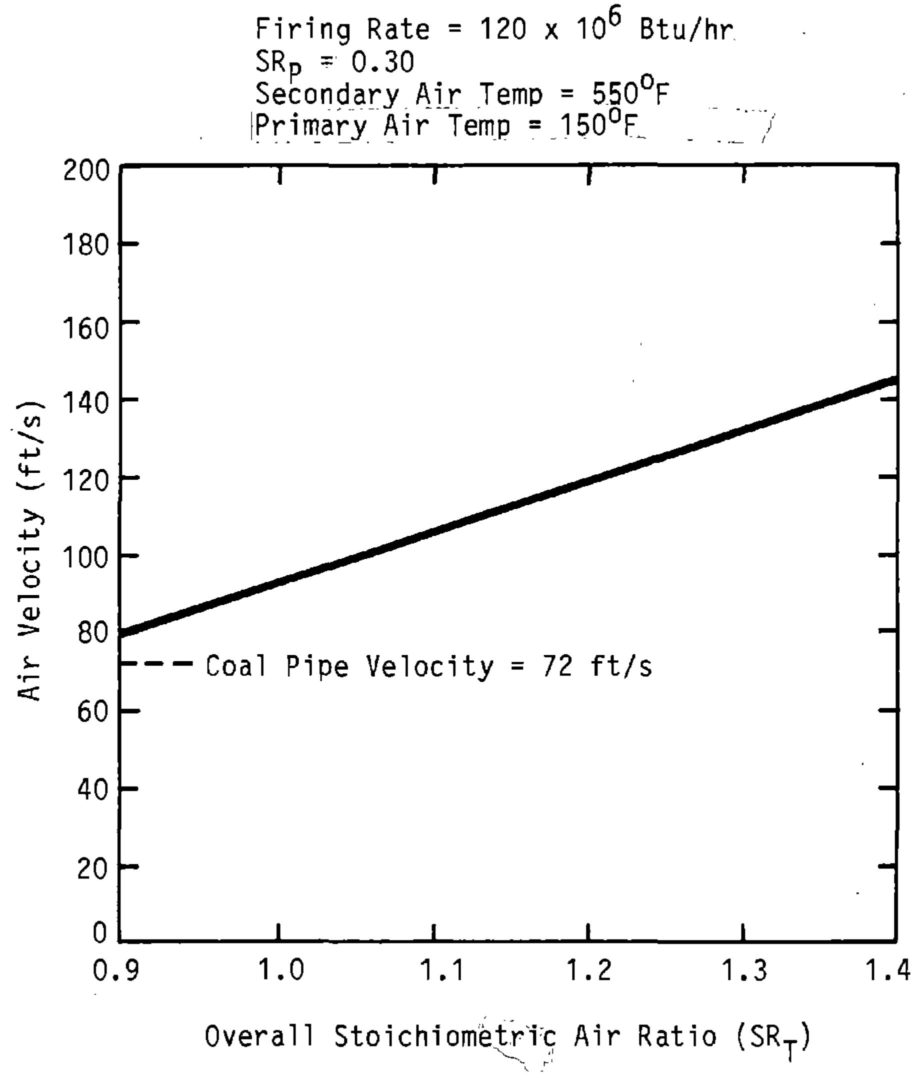


Figure 4-3. Velocity characteristics of 120 x 10^6 Btu/hr Circular Burner.

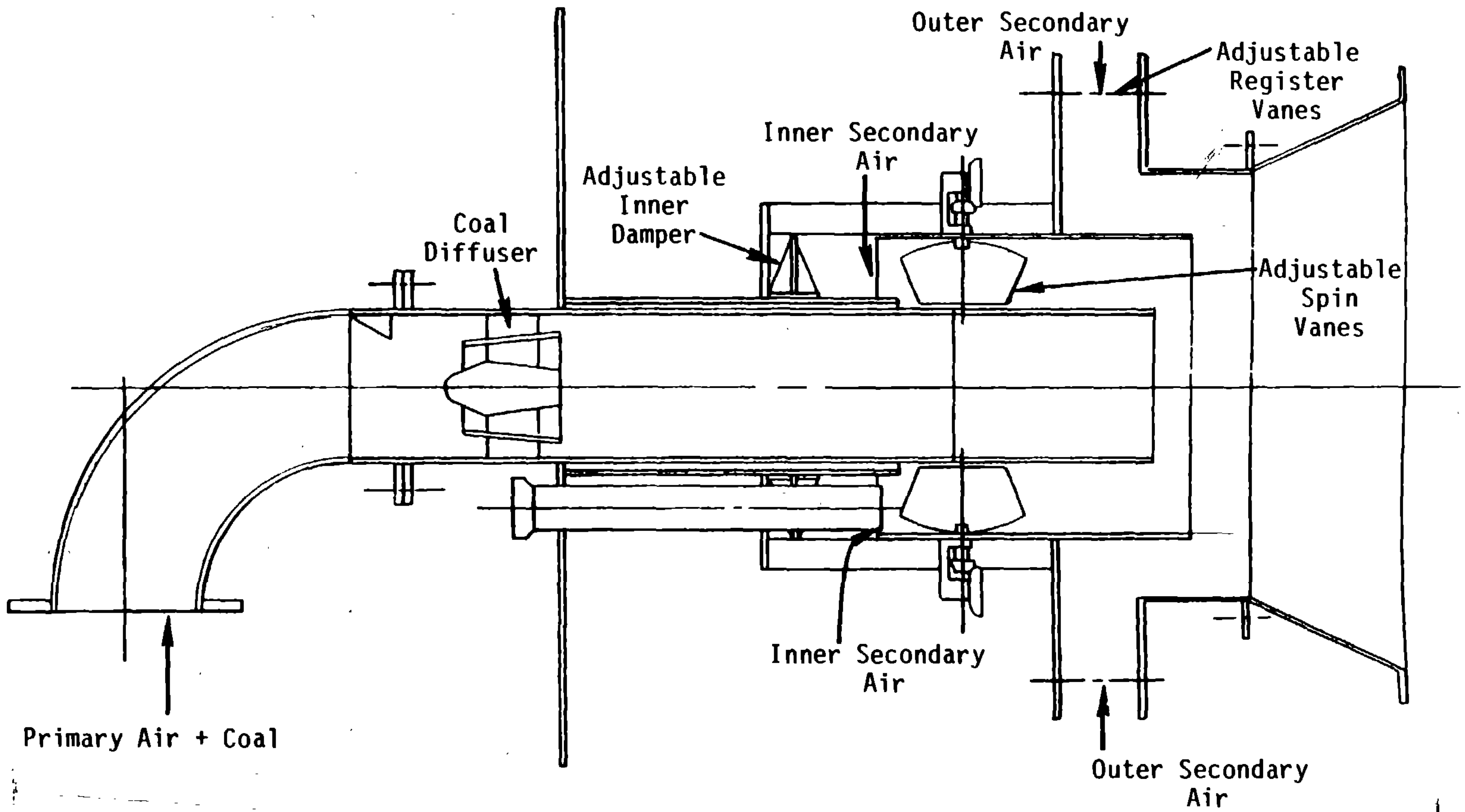


Figure 4-4. B&W Dual Register Burner.

The burner design evolved from the concept of using multiple air zones to allow controlled, delayed mixing of the fuel and combustion air. The DRB 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° elbow. 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 or radial component to the primary air/coal stream. The combustion, or secondary, air is divided between two annular passages. The inner passage is equipped with an adjustable damper, or sleeve, for flow control and a set of adjustable axial spin vanes for swirl control. The outer secondary air passage utilizes adjustable radial register vanes for both flow and swirl control. During these DMB evaluation tests, the DRB and the DMBs were installed in a compartmented windbox so that the air flow to the inner and outer secondary air passages could be metered and controlled independent of burner adjustments.

Swirl characteristics were calculated for both inner and outer zone devices. The outer zone radial vane assembly could be treated like the Circular burner register assembly in equation 4-2. For an axial flow swirl generator such as that used for the inner passage, the following empirical expression can be used to predict the swirl number[5]:

$$\boxed{S = \frac{2}{3}\left[\frac{1-z^3}{1-z^2}\right]\tan\alpha}$$

$$z = Rh/R$$

where R_h = hub radius

R = spin vane radius

= spin vane angle

The swirl characteristics of the Dual Register Burner are summarized in Figure 4-5. Burner velocity characteristics at nominal full load, with an overall stoichiometry of 1.20 and a primary stoichiometry of 0.20, are

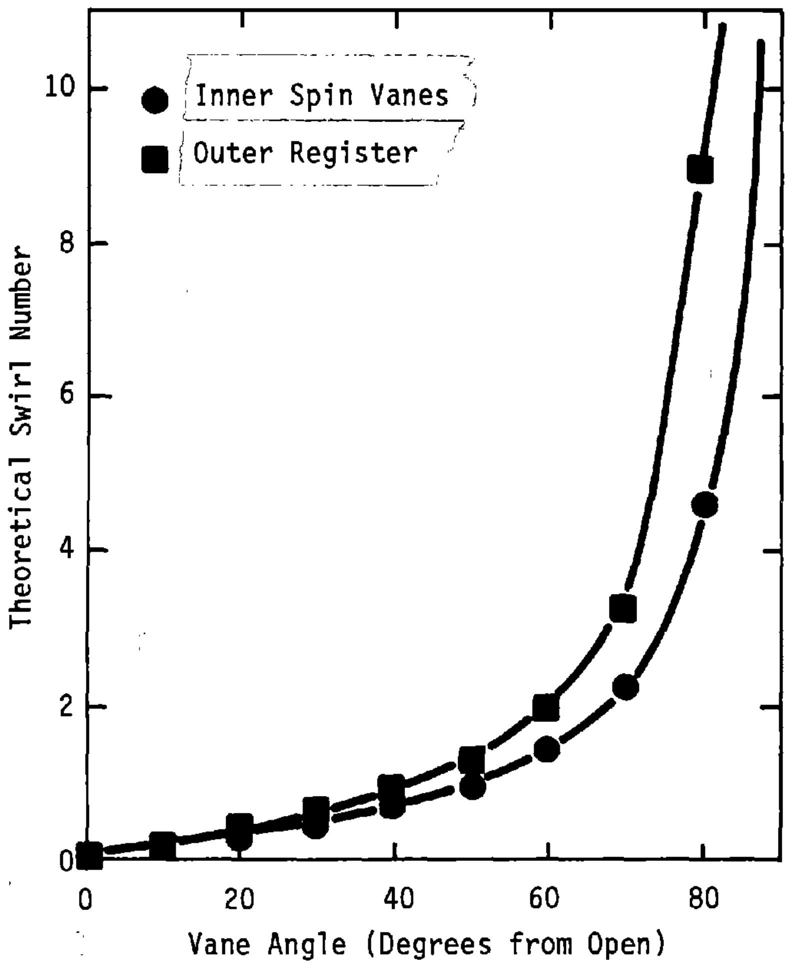


Figure 4-5. Swirl characteristics of 60 x 10^6 Btu/hr dual register burner.

summarized in Figure 4-6. In the general context of swirl characteristics it should be noted that the DRBs employed in Wyodak Unit 1 are an earlier version of this burner design. In this version the inner register assemblies are of the radial inlet design, similar to those employed in the outer air register. Also, the primary air mixing device is a venturi rather than a diffuser. This latter variable was however shown to have only a small impact on mixing/NO_x emissions in testing conducted on an 80 x 10^6 Btu/hr DRB.

4.1.3 60 x 10^6 Btu/hr Distributed Mixing Burners

B&W integrated the basic DMB design criteria with their commercial burner components. This adaptation resulted in an arrangement resembling a Dual Register Burner surrounded by four equally spaced tertiary air ports. The components common to the DRB include a central, cylindrical coal nozzle and two concentric, annular secondary air passages. As for the DRB, pulverized coal with primary air enters the coal nozzle through a 90^o elbow. The inner secondary air passage is equipped with a sliding sleeve damper for flow control and adjustable axial spin vanes for swirl generation. The outer secondary passage is equipped with a register assembly of radial vanes for both flow and swirl control. B&W designed the tertiary air ports with a divergent, cone-type exit for each of the prototype DMBs.

Three configurations of the half-scale, 60 x 10^6 Btu/hr prototype B&W DMB were evaluated. The two configurations initially evaluated are shown in Figure 4-7. One of these initial configurations utilized a 75^o coal impeller similar to that used with the B&W Circular burner. This impeller was expected to produce a "short" flame under staged conditions, thus making their configuration appropriate for retrofit in boilers with shallow firing depths. The other configuration incorporated the Dual Register Burner type coal diffuser. This configuration was expected to produce a longer flame with lower NO_x emissions which could be accommodated in larger, post-NSPS applications. The mounting arrangement on the LWS, common for all three 60 x 10^6 Btu/hr DMB configurations, is shown in Figure 4-8.

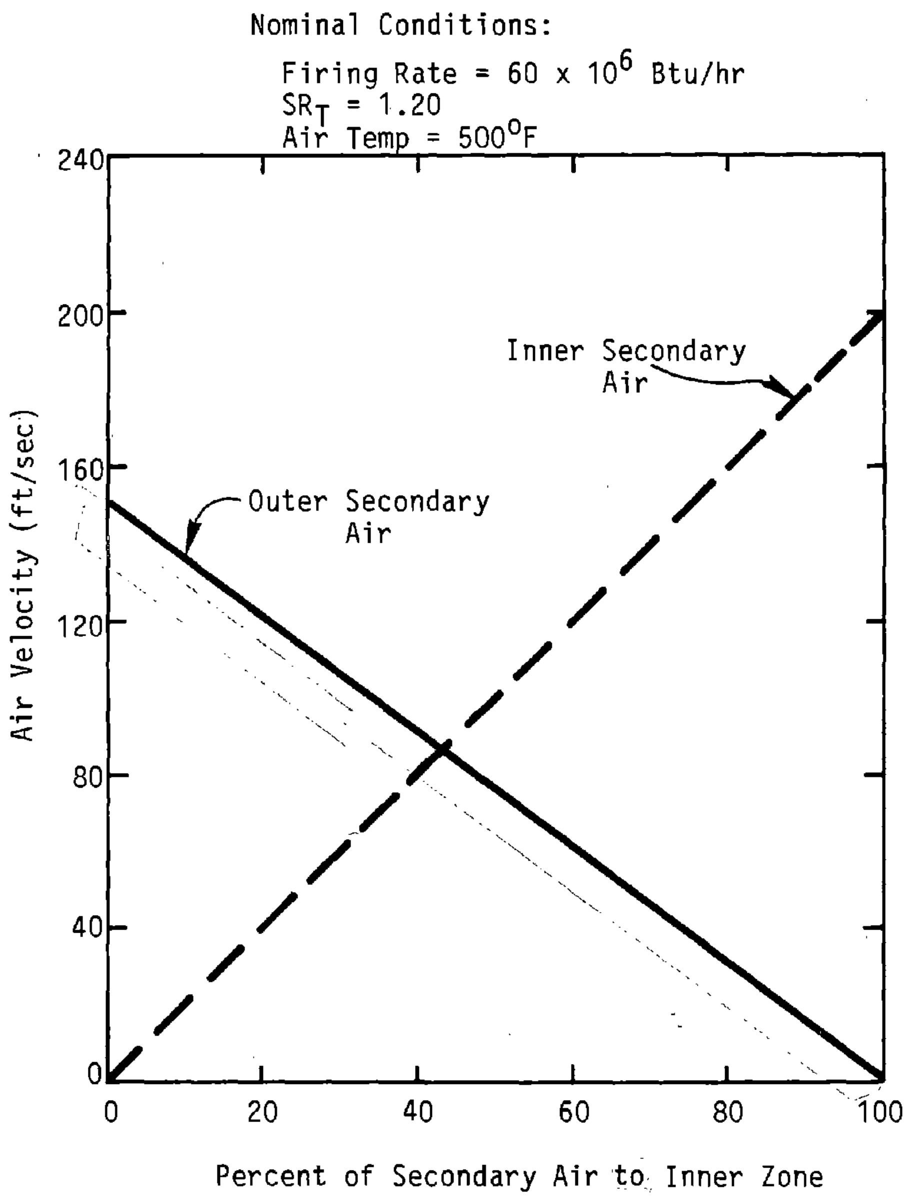
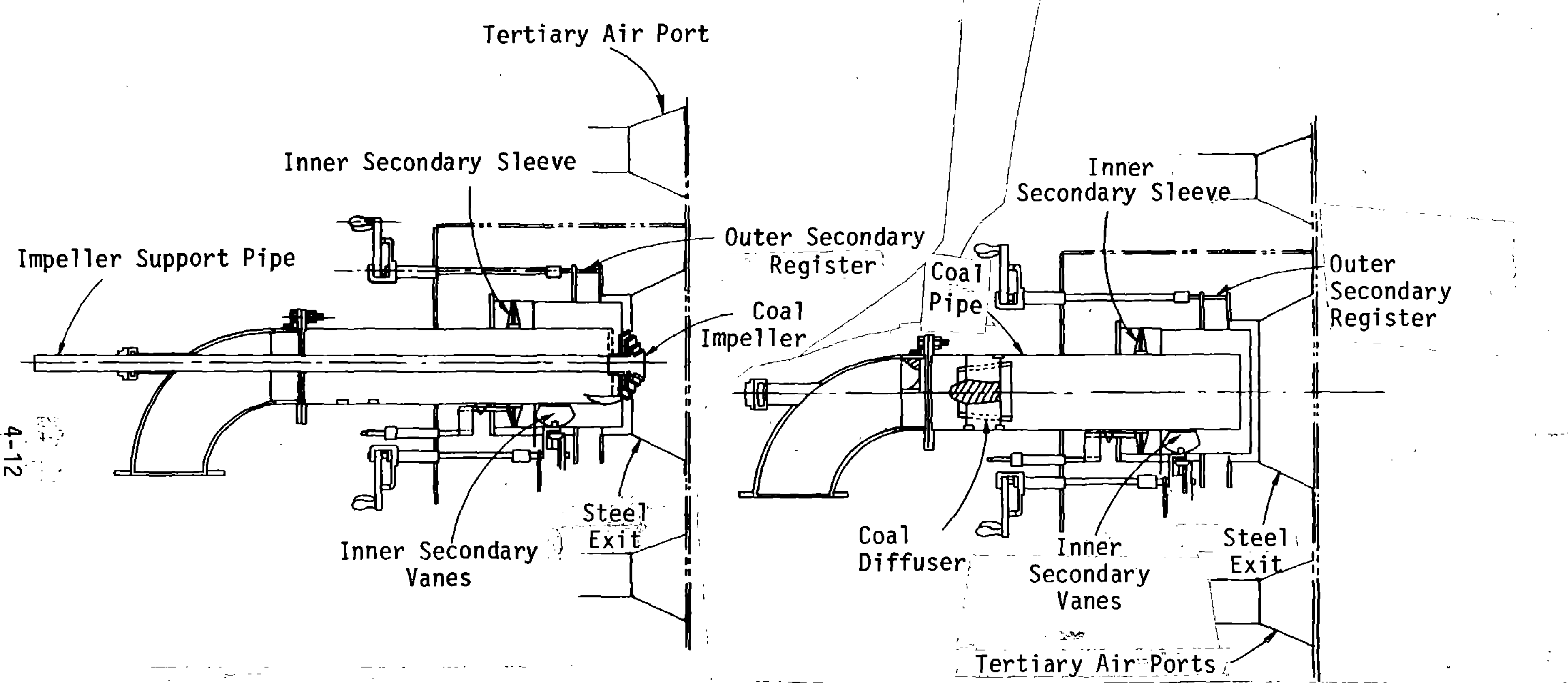


Figure 4-6. 60 x 10^6 Btu/hr Dual Register Burner velocity characteristics.



a) 75^{o} Impeller Configuration

b) Coal Diffuser Configuration

Figure 4-7. Initial 60 x 10^{6} Btu/hr DMB configurations.

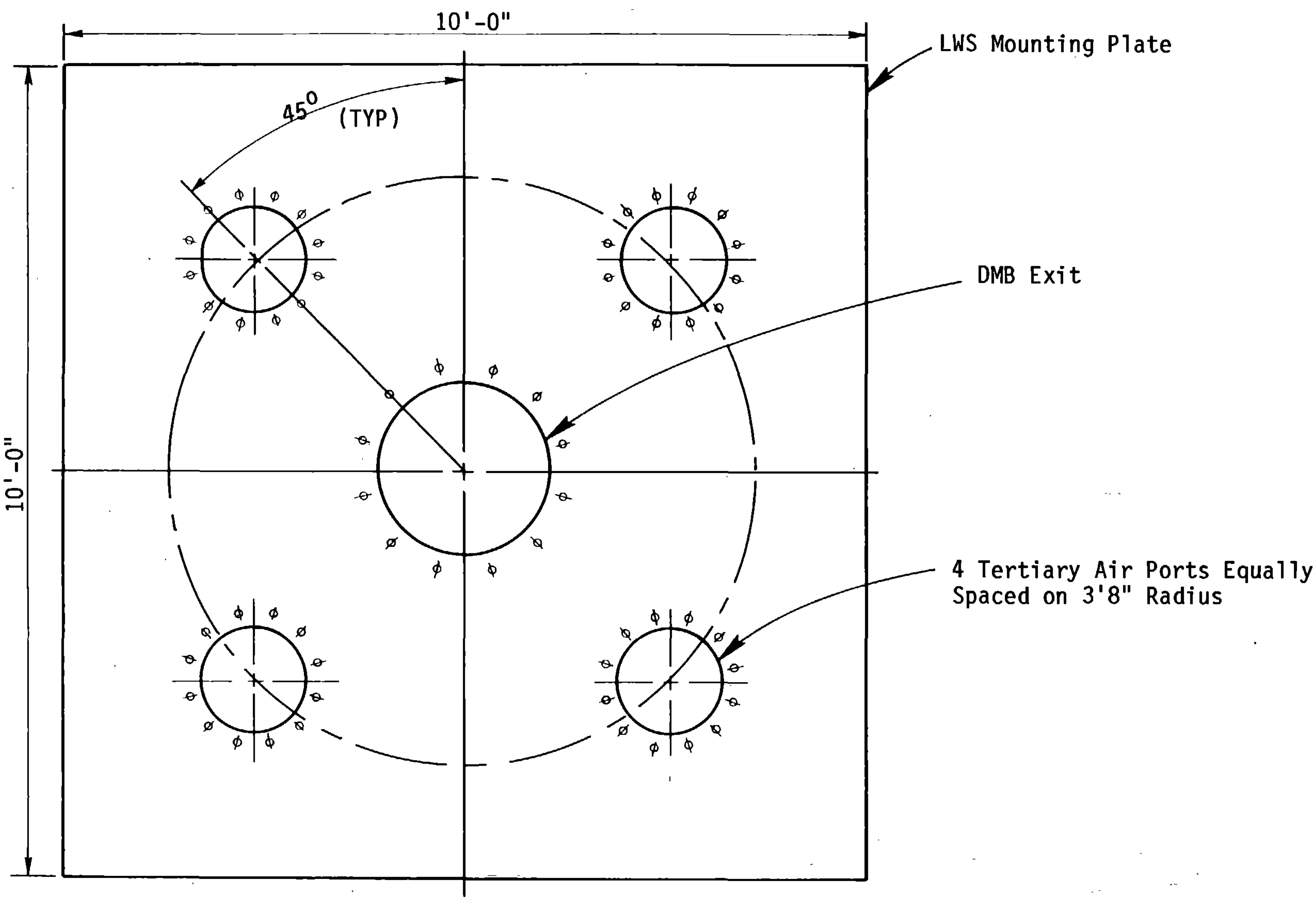


Figure 4-8. Mounting arrangement for 60 x 10^6 Btu/hr DMBs.

During analysis of data from tests with the initial 60 x 10^6 Btu/hr DMB, outer secondary air velocities were determined to be unusually high. Investigation of the design parameters revealed that the outer passage was improperly sized. The velocity characteristics for the initial half-scale DMB, shown in Figure 4-9, show that under staged conditions at a burner zone stoichiometry of 0.70, an equal distribution of air between the inner and outer passages yields an outer secondary velocity of about 240 f/s. This is significantly higher than the DMB design criteria of 60 f/s for secondary air.

Following optimization of the properly sized 120 x 10^6 Btu/hr DMB, the half-scale DMB was modified to match the design of the full scale, 120 x 10^6 Btu/hr DMB. This modified 60 x 10^6 Btu/hr DMB is shown in Figure 4-10. This third half-scale DMB configuration utilized a scaled version of the optimum coal spreader from the 120 x 10^6 Btu/hr DMB tests. This scaled-down version of the coal spreader had the following design characteristics:

Support pipe diameter = 2.875 in. O.D.

Blade Height = 3.0625 in.

Blade Length = 4.4375 in.

Blade Angle = 30^o from axial

This design produced an effective swirl number of 0.415, compared to the full-scale version, described in section 4.1.4, with a swirl number of 0.414. The velocity characteristics of the modified half-scale DMB are shown in Figure 4-11.

The same swirl generators were used in the initial and modified 60 x 10^6 Btu/hr DMBs, only the outer secondary passage outside diameter (i.e. burner throat) was changed. The swirl characteristics were therefore the same. These are summarized in Figure 4-12. As with the Dual Register Burner, the radial vane assembly used for the outer secondary passage is a more effective swirl generation device than the inner passage, axial spin vane assembly.

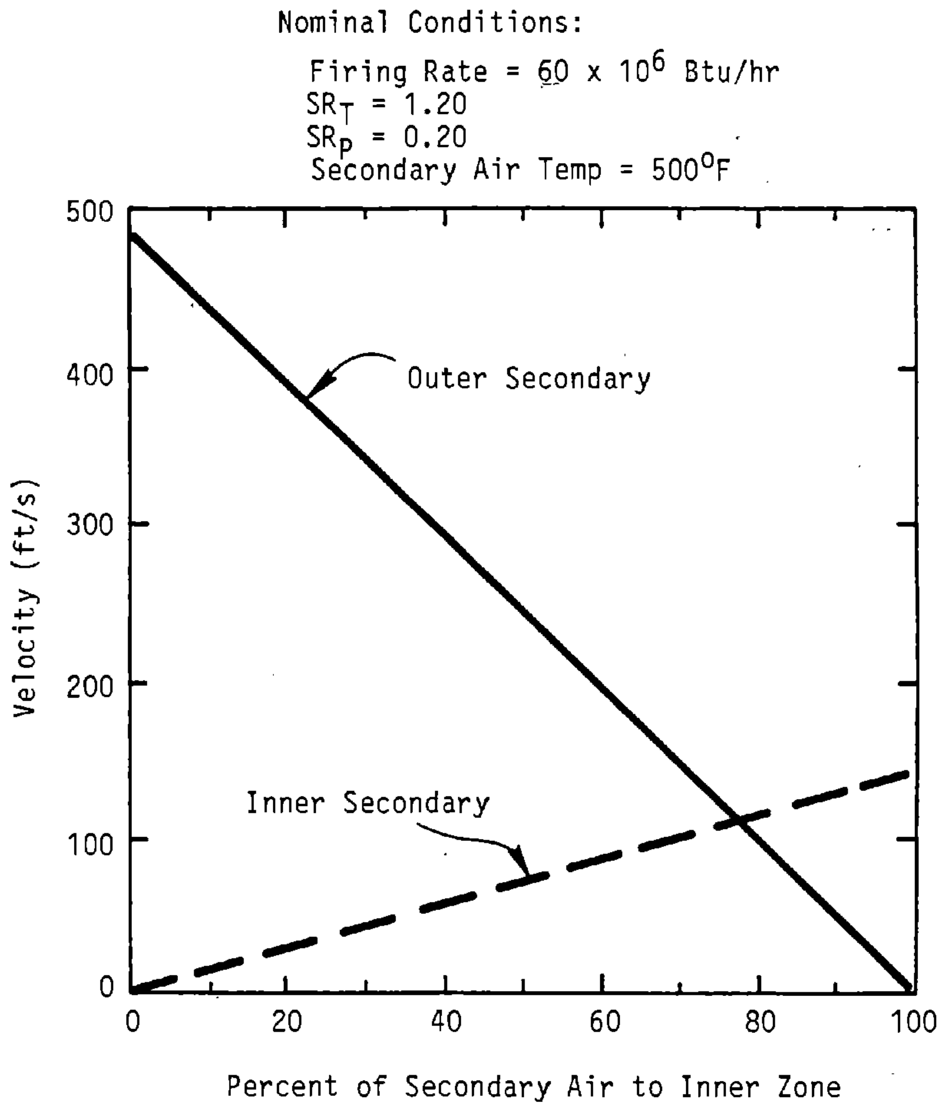
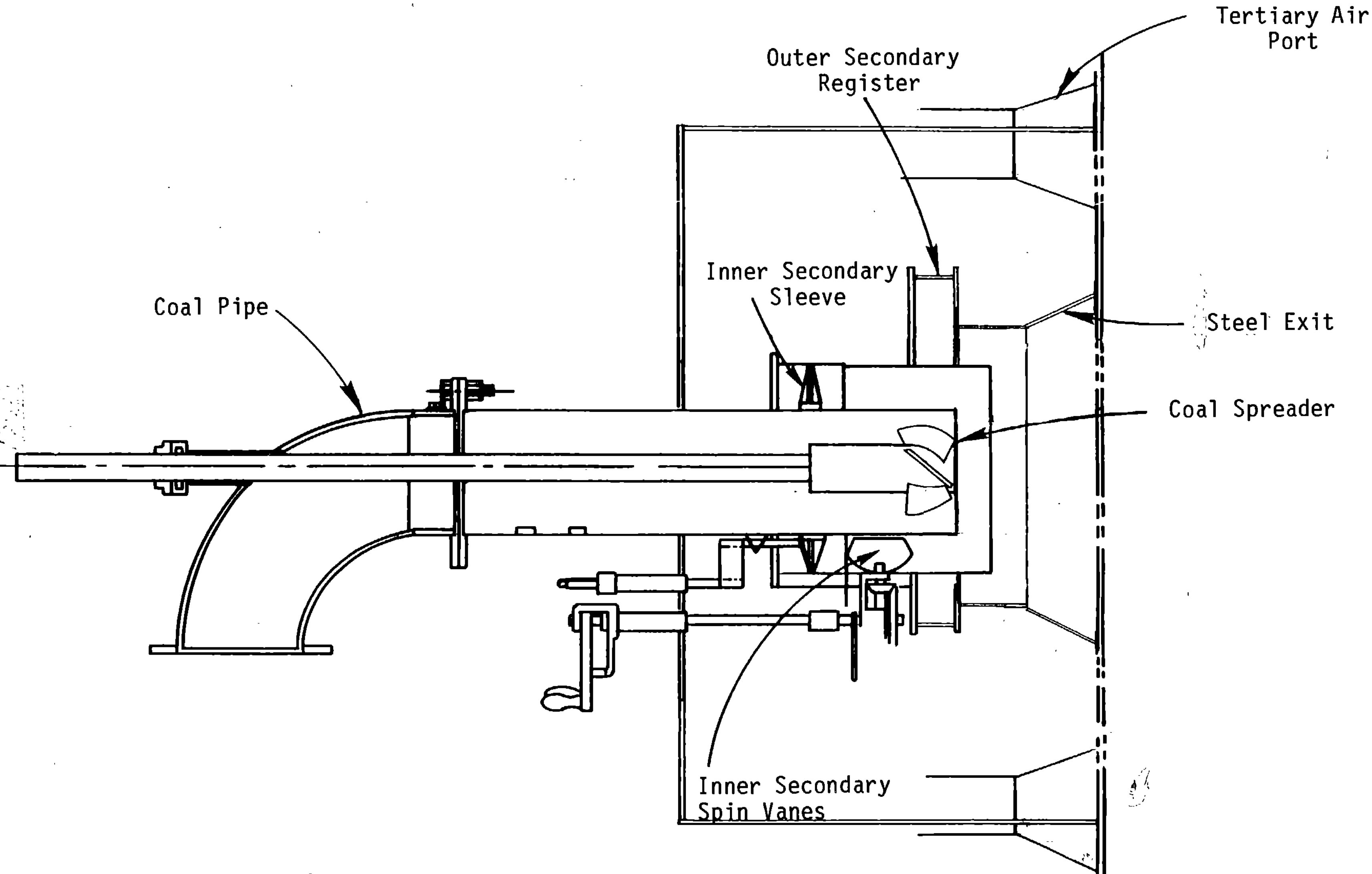


Figure 4-9. Velocity characteristics of initial 60 x 10^6 Btu/hr DMB under staged conditions (SR_B = 0.70).



e 4-10. Modified 60 x 10^6 Btu/hr Distributed Mixing Burner.

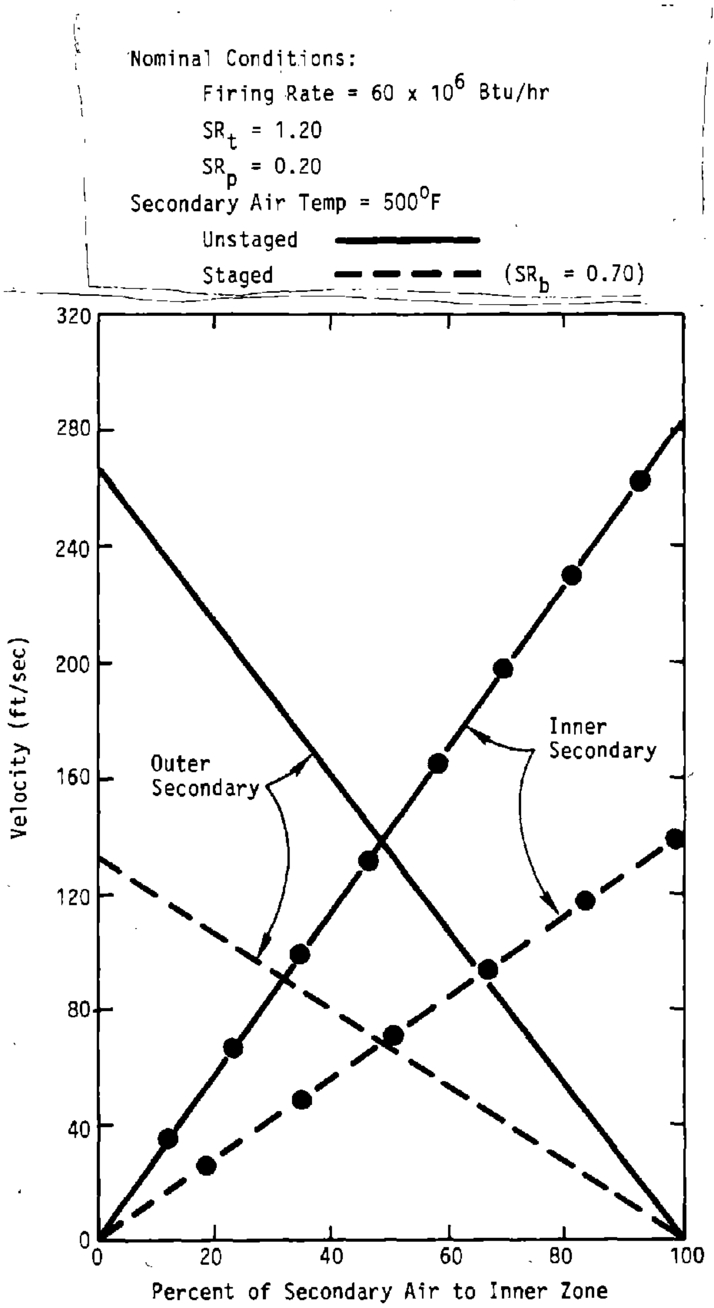


Figure 4-11. Velocity characteristics of modified 60×10^6 Btu/hr DMB.

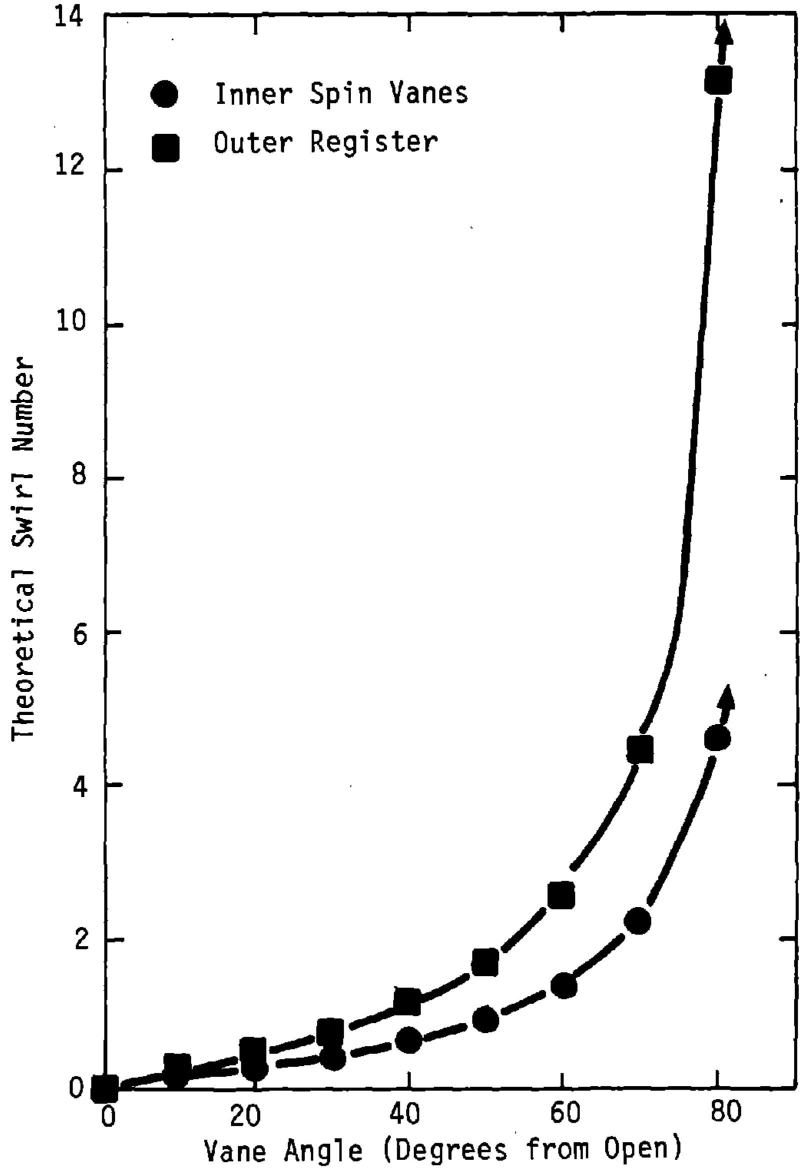


Figure 4-12. Swirl characteristics of 60 x 10^6 Btu/hr DMB.

4.1.4 120×10^6 Btu/hr Distributed Mixing Burner

The full-scale, 120×10^6 Btu/hr Distributed Mixing Burner is shown in Figure 4-13. The principal components were the same as described previously for the half-scale DMBs, with DRB-type hardware and four tertiary air ports with conical divergences. The mounting arrangement onto the LWS test furnace is shown in Figure 4-14. The operational characteristics for this full-scale DMB, burner velocities and swirl, are shown in Figures 4-15 and 4-16, respectively.

With this burner operating in a staged combustion mode it was found necessary to implement a series of modifications to the coal nozzle to produce flame dimensions which could be accommodated within the available firing depth of the LWS. These modifications were developed in an iterative manner, and consisted of seven variations of coal spreader design. Four designs, shown in Figure 4-17, were based on the standard B&W 37° impeller made up of three concentric conical rings around a center cone shaped bluff body. Variations to this basic design included reducing the number of rings and lengthening the ring to cover more coal pipe cross-section, Figure 4-17(b); adding six support vanes, set 25° angle between the center body and conical ring, Figure 4-17(c); and removing the outer ring and using six larger vanes set at a 25° angle.

Since these designs achieved limited success in reducing flame length, the conical impeller-type spreader was abandoned in favor of single swirler designs. The three designs tested are summarized in Figure 4-18. The design which yielded an acceptable flame length had the following design characteristics:

Support Pipe Diameter = 4.0625 in.

Blade Height = 4.375 in.

Blade Length = 8.25 in.

Blade Angle = 30° from axial

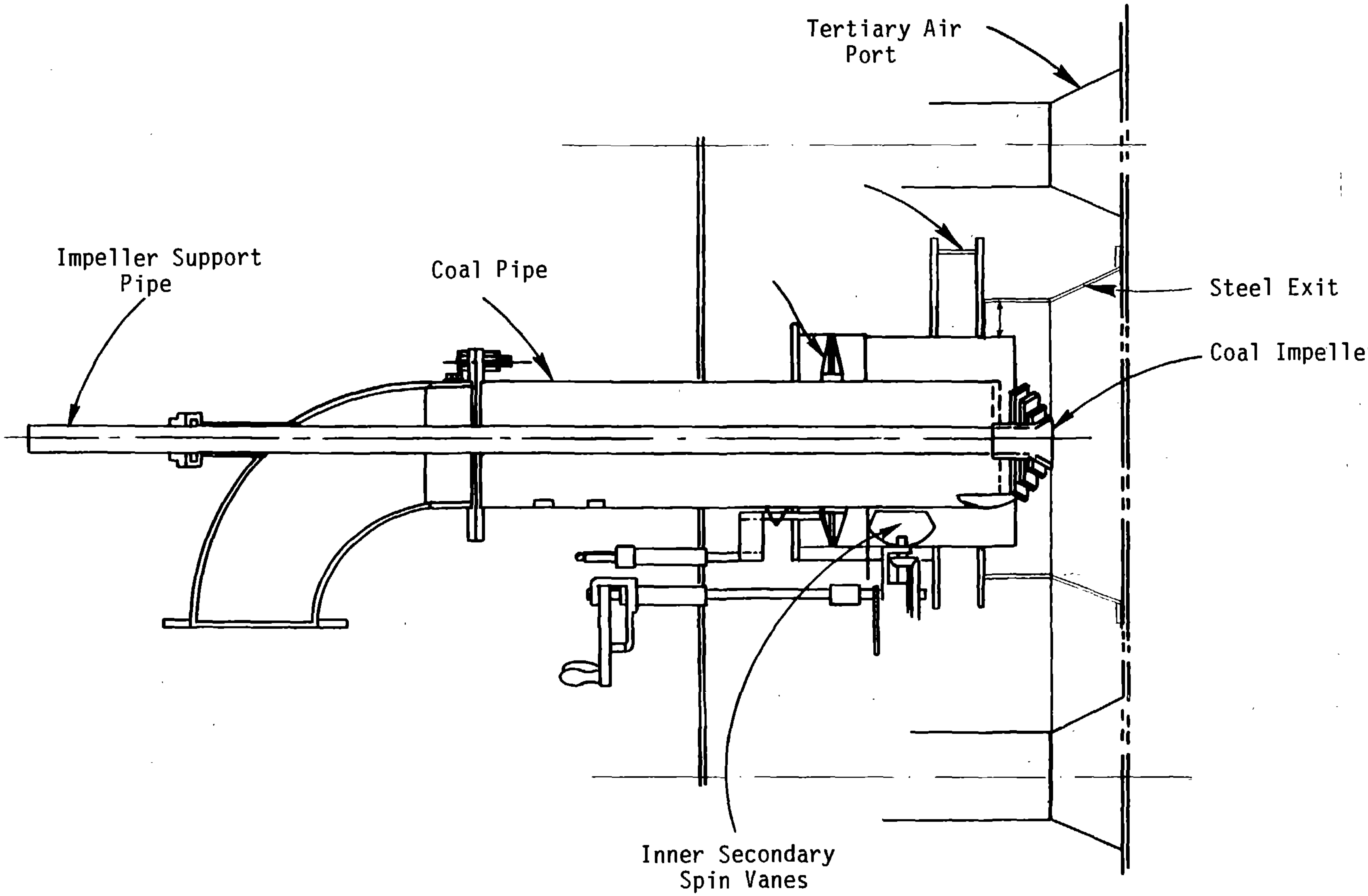


Figure 4-13. 120 x 10^6 Btu/hr Distributed Mixing Burner with standary B&W coal impeller.

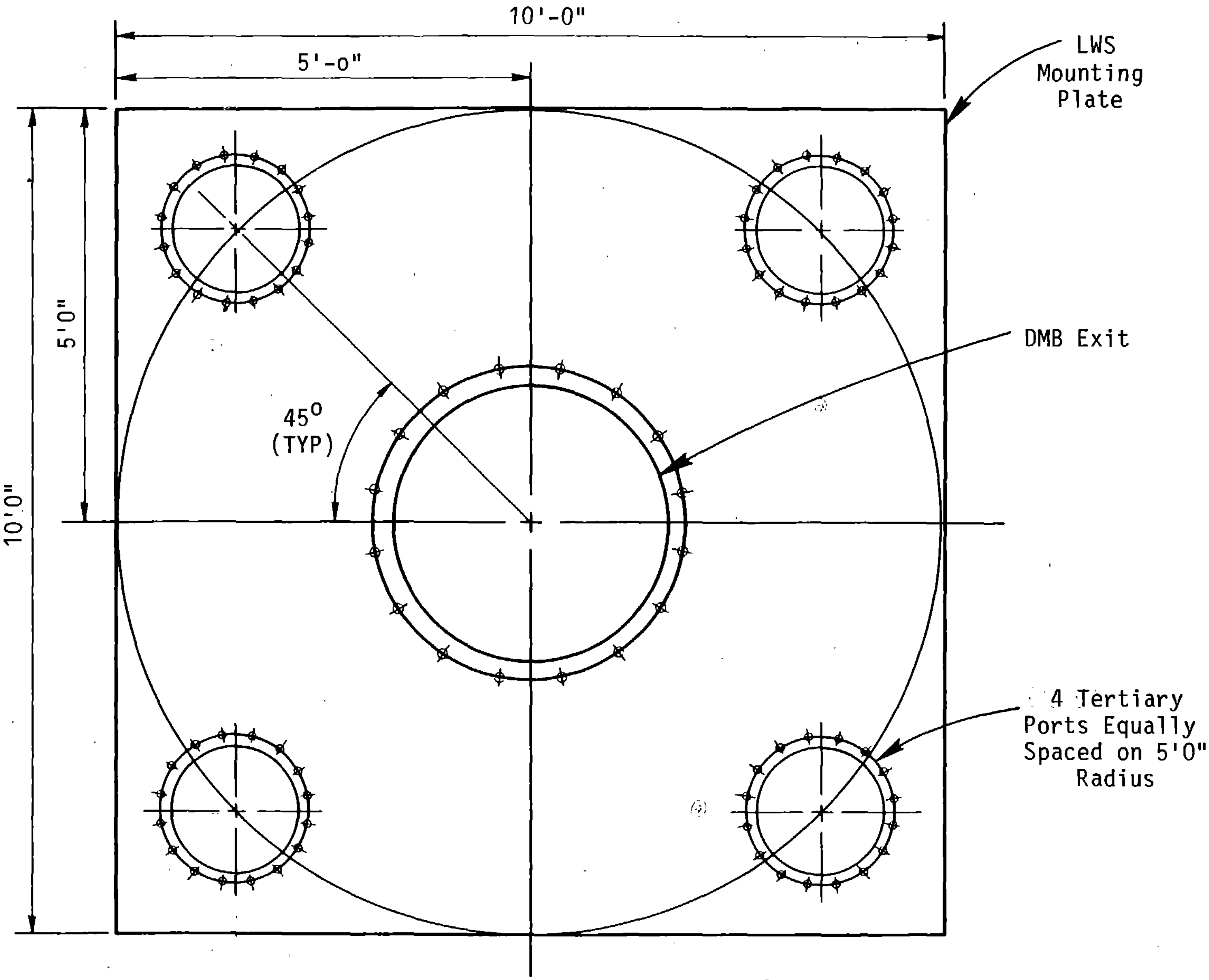


Figure 4-14. Mounting arrangement for 120 x 10^6 Btu/hr DMB.

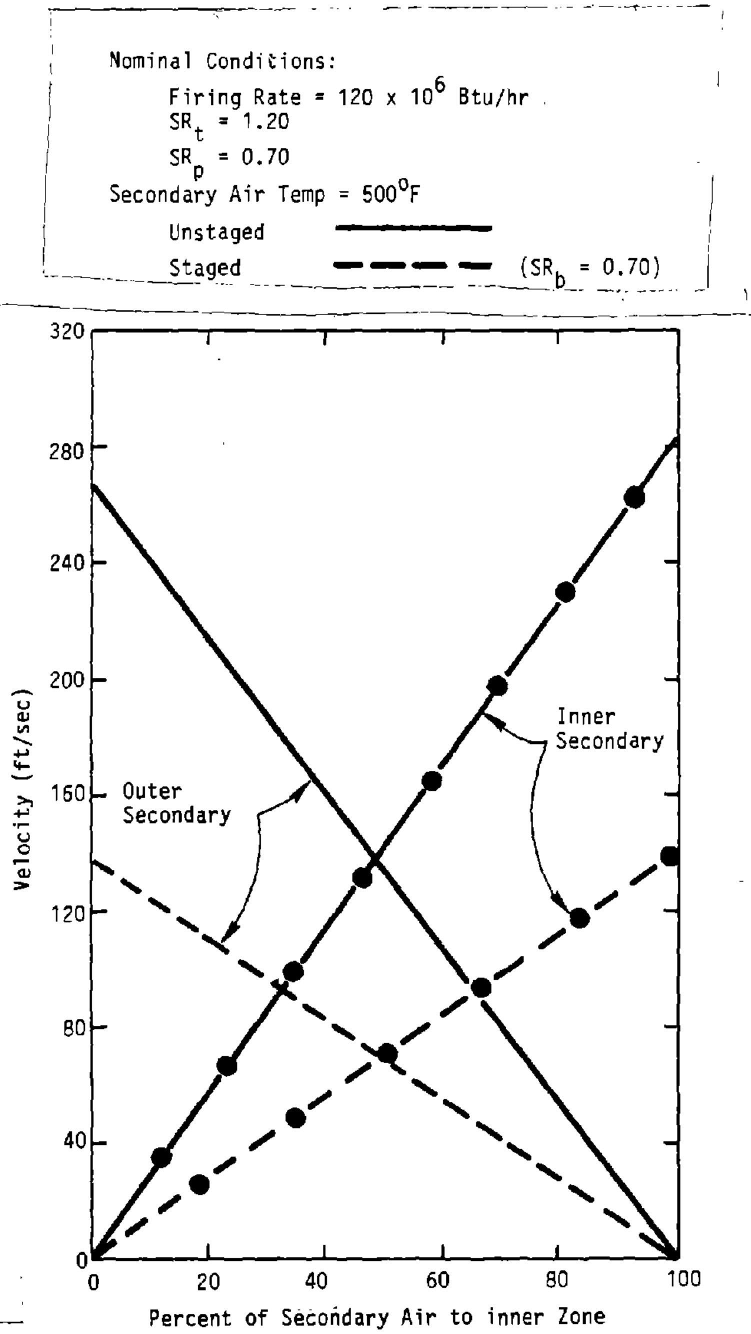


Figure 4-15. Velocity characteristics of 120 x 10^6 Btu/hr DMB.

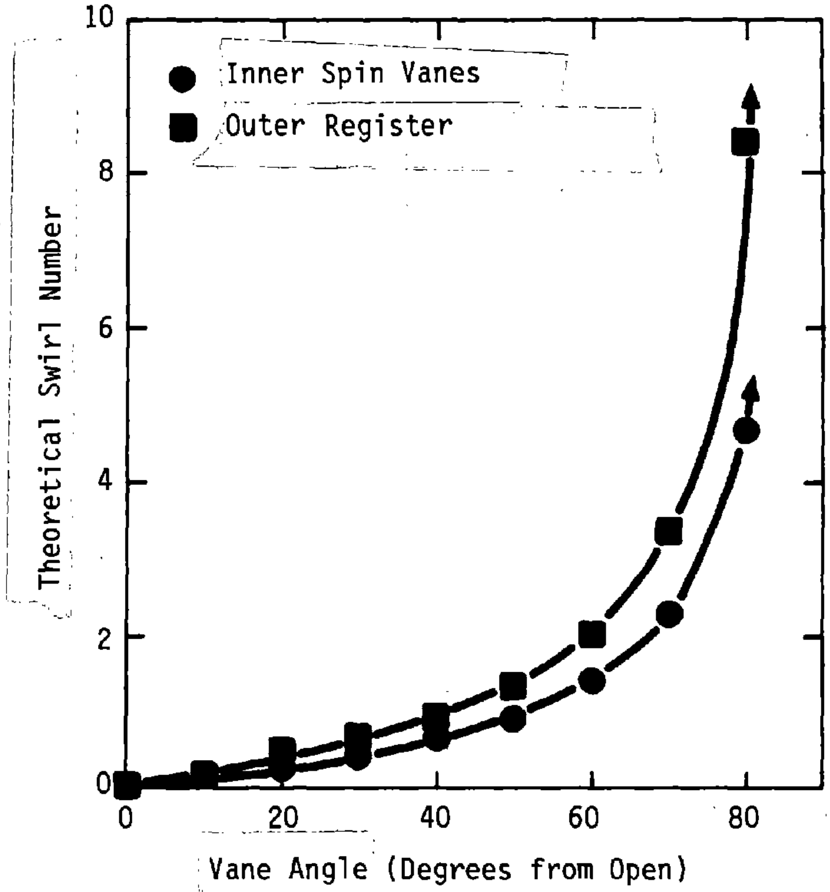
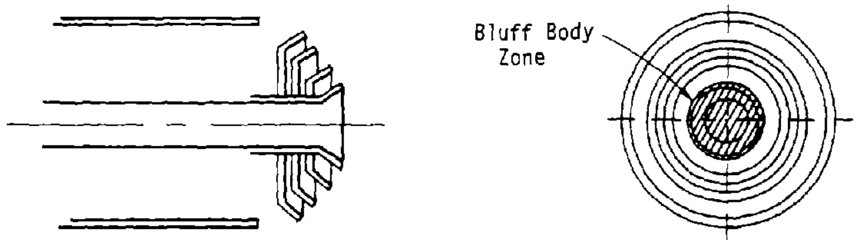
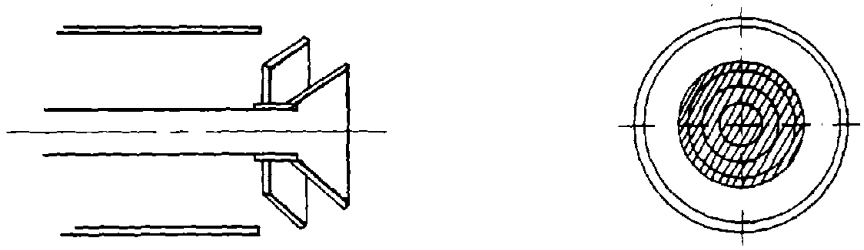


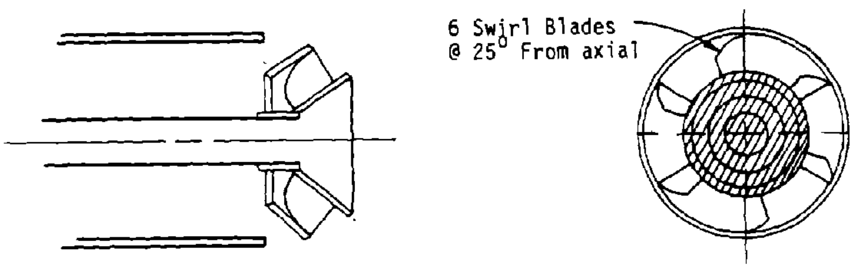
Figure 4-16. Swirl characteristics of 120 x 10^6 Btu/hr DMB.



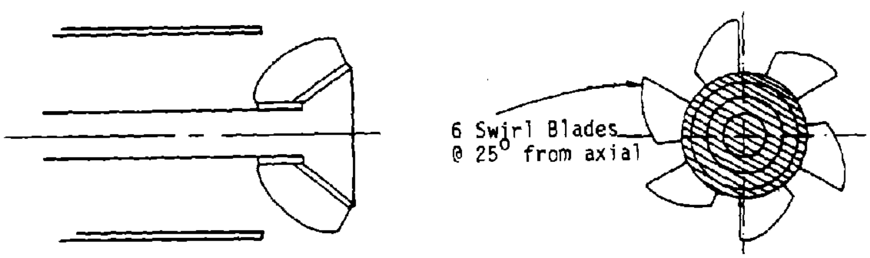
(a) Baseline 37^{o} Impeller



(b) Dual Cone 37^{o} Impeller

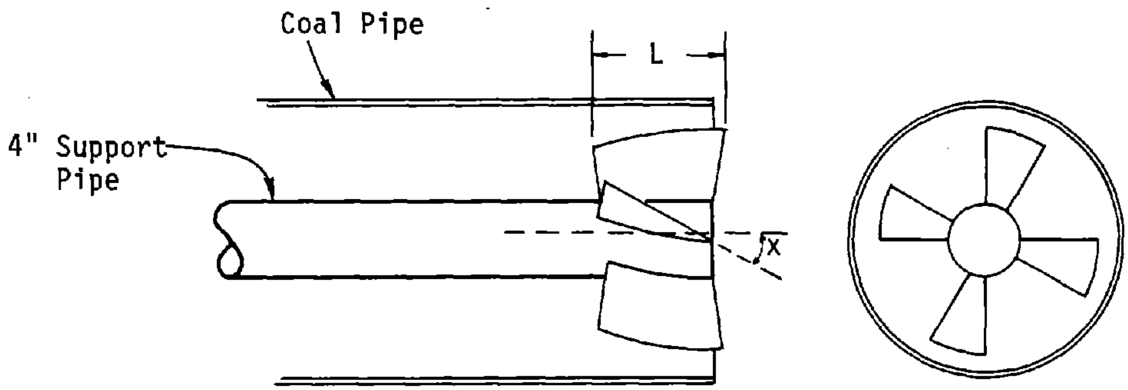


(c) Dual Cone 37^{o} Impeller with 6 - 25^{o} Vanes



(d) Single Cone 37^{o} Impeller with 6 - 25^{o} Vanes

Figure 4-17. Impeller configurations tested with 120 x 10^{6} Btu/hr DMB.



Number of Blades	Blade Angle (X)	Blade Length (L)
4	25	4"
4	30	6"
4	30	8"

Figure 4-18. Swirler designs tested with 120 x 10^6 Btu/hr DMB.

This design produced an effective swirl number of 0.414 and was selected as the final, optimum configuration of the 120 x 10^6 Btu/hr DMB.

4.2 Fuels and Sorbents

Four different coals were used for the purpose of this test program: Utah coal, Illinois coal (high in sulfur), and one coal from each host boiler site. Data from tests with a fifth coal, Pittsburgh #8, in conjunction with the LIMB demonstration program, are also included to broaden the interpretation of results. The compositions of these coals and their respective ashes are again listed in Table 4-1 and 4-2, respectively. The Utah coal has been used as the base fuel at EER in the development of low-emission, high-efficiency burners. It is a high volatile B bituminous coal from the Western United States with a low sulfur content. The high-sulfur coal used is Illinois #6 coal. This is a high-volatile C bituminous coal selected to provide data which would be applicable to eastern U.S. boilers burning high-sulfur fuels. The Illinois coal has been tested at EER during previous studies in the LWS, and thus, will permit comparisons with this program. The Wyodak coal is from the DRB host site, Wyodak Plant. This is a subbituminous B coal from Wyoming. Testing the DRB with the Wyodak coal will establish a link to data from an operating boiler. Similar objectives are gained by testing the coal from the Circular burner host site, Comanche Unit 2. This boiler also uses a Wyoming subbituminous B coal, denoted Comanche for this project. The fifth coal with data presented in Part I of this report is Pittsburgh #8. This high-volatile A bituminous coal was the coal selected for the EPA LIMB demonstration program at Ohio Edison's Edgewater Unit 4 and was used during the second generation low-NO_x burner selection tests, discussed in Part II of this report.

Predictions of NO_x formation and reduction potential 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.[7] Application of these correlations yielded results summarized in Table 4-3. The NO predictions listed include theoretical total conversion of fuel

TABLE 4-1. COMPOSITION OF TEST COALS

Coal	Utah		Illinois		Wyodak		Comanche		Pittsburgh #8	
Reporting Basis	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry
Proximate (wt. %)										
Moisture	6.11	0.00	15.26	0.00	23.85	0.00	22.44	0.00	3.50	0.00
Ash	8.02	8.55	8.09	9.54	7.17	9.41	5.00	6.45	12.92	13.40
Volatile	41.26	43.96	34.60	40.84	33.70	44.22	36.12	44.87	33.75	34.98
Fixed C	44.60	46.73	42.06	49.64	35.29	46.37	37.72	48.68	49.83	51.62
Heating Value										
Btu/lb	12,288	13,088	10,710	12,638	8,945	11,753	9,325	12,026	12,177	12,618
MMF Btu/lb		14,440		14,209		13,085		12,939		14,876
MAF Btu/lb		14,311		14,088		12,963		12,855		14,626
Ultimate (wt. %)										
Moisture	6.11	0.00	15.26	0.00	23.85	0.00	22.44	0.00	3.50	0.00
Carbon	68.58	71.86	59.45	70.14	50.93	66.89	54.25	69.97	68.13	70.54
Hydrogen	5.16	5.49	4.28	5.05	3.65	4.81	3.80	4.91	4.63	4.79
Nitrogen	1.28	1.36	1.07	1.27	0.75	0.98	0.76	0.98	1.21	1.26
Sulfur	0.60	0.64	3.23	3.81	0.43	0.57	0.43	0.56	3.22	3.30
Ash	8.02	8.55	8.09	9.54	7.17	9.41	5.00	6.45	12.42	13.40
Oxygen*	10.24	10.91	8.64	10.21	13.23	17.34	13.32	17.14	6.41	6.63
Forms of Sulfur (wt. %)										
Sulfate	0.01	0.01	0.18	0.21	0.01	0.01	0.02	0.02	0.22	0.23
Puritic	0.13	0.13	0.95	1.11	0.06	0.09	0.09	0.12	1.62	1.65
Organic	0.46	0.50	2.11	2.49	0.36	0.47	0.32	0.42	1.38	1.42

*Oxygen determined by difference.

TABLE 4-2. COAL ASH CHARACTERISTICS

Elemental Ash	Utah	Illinois	Wodak	Comanche	Pittsburgh #8
Elemental Ash (wt. %)					
SiO_2	58.40	49.03	34.48	23.18	48.67
Al_2O_3	19.96	17.71	17.10	13.99	20.19
TiO_2	0.77	0.68	0.78	1.04	0.84
Fe_2O_3	4.18	18.07	5.48	5.07	23.87
CaO	4.56	4.37	19.73	28.42	1.60
MgO	1.05	0.78	5.29	5.15	0.60
Na_2O	1.54	1.02	1.29	1.20	2.00
K_2O	1.06	1.91	0.53	0.29	0.31
P_2O_5	0.51	0.21	1.03	1.41	0.39
SO_3	4.77	4.47	12.62	17.50	1.25
Ash Fusion Temperatures (°F)					
Oxidizing					
IDT	2350	2337	2233	2390	2377
ST	2448	2409	2258	2412	2554
HT	2546	2479	2300	2425	2580
FT	2653	2533	2311	2451	2616
Reducing					
IDT	2297	2041	2163	2316	2171
ST	2388	2135	2203	2342	2298
HT	2502	2310	2214	2351	2459
FT	2621	2339	2272	2383	2498

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

Coal	Utah	Illinois	Wyodak	Comanche	Pittsburgh #8
ASTM D388 Rank	High-Volatile B Bituminous	High-Volatile C Bituminous	Subbituminous B	Subbituminous B	High-Volatile A Bituminous
Composition (wt. % daf)					
Nitrogen	1.49	1.40	1.08	1.05	1.45
Volatile Matter	48.07	45.15	48.81	47.96	40.39
Fixed Carbon	51.10	54.88	51.19	52.04	59.61
NO Predictions (ppm @ 0% O_2)					
Theoretical	2987	2836	2402	2297	2790
Premixed	1188	1082	935	911	1058
Radial Diffusion	876	821	708	694	825
Minimum Staged	275	276	244	242	288

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, the Utah coal would be expected to yield the highest NO_x emissions with a conventional burner, such as the Circular burner while the two subbituminous coals would produce the lowest NO_x levels. However, the Utah coal is most amenable to staging, with 77 percent reduction in NO_x from premixed to staged conditions. Under staged conditions, such as those achieved with a DMB, the two subbituminous coals would again be expected to produce the lowest NO_x and the Pittsburgh #8 coal the highest. However, the correlation indicates that absolute NO_x emission values for the different coals are much closer under staged combustion conditions, compared to premixed conditions where differences can be large.

As-fired pulverized coal samples were obtained on a daily basis throughout the testing period. The pulverized coal was sampled downstream of the pulverizer exhauster following ASME PTC 4-2 procedures. The objective of this sampling was to verify the composition and fineness of the coal. The mean compositions of the different coals, determined from the average values of all daily samples, are summarized in Table 4-4, which shows also the relative standard deviation of the individual components of the ultimate analysis. The Pittsburgh #8 was used briefly during this part of the program and sampled but once, this standard deviation could not be determined. The standard deviation for the four main fuels tested was less than 2 percent, suggesting very consistent coal composition.

Typical particle size distributions for the test coals are shown in Figure 4-19. Daily variations of coal fineness are shown in Table 4-5. Coal fineness was maintained nominally at 70 percent through 200 mesh (75μm), consistent with industry standards. Actual values ranged from 67 percent for the single day of testing with Pittsburgh #8 coal to 74.3 percent for the Wyodak coal.

TABLE 4-4. MEAN COAL COMPOSITION DATA--AVERAGES OF ULTIMATE ANALYSIS PERFORMED ON DAILY COAL SAMPLES

Coal	Utah		Illinois		Wyodak		Comanche		Pittsburgh #8*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Composition (Dry, wt. %)										
Carbon	71.55	1.98	66.81	0.69	64.34	0.77	65.06	1.14	72.00	-
Hydrogen	5.26	0.11	4.67	0.12	4.62	0.11	4.49	0.16	4.73	-
Nitrogen	1.41	0.07	1.26	0.07	1.00	0.03	1.00	0.04	1.39	-
Sulfur	0.63	0.07	3.79	0.08	0.43	0.02	0.55	0.06	3.12	-
Ash	7.86	1.62	9.76	0.46	7.75	0.03	6.52	0.45	10.02	-

*Single day of operation.

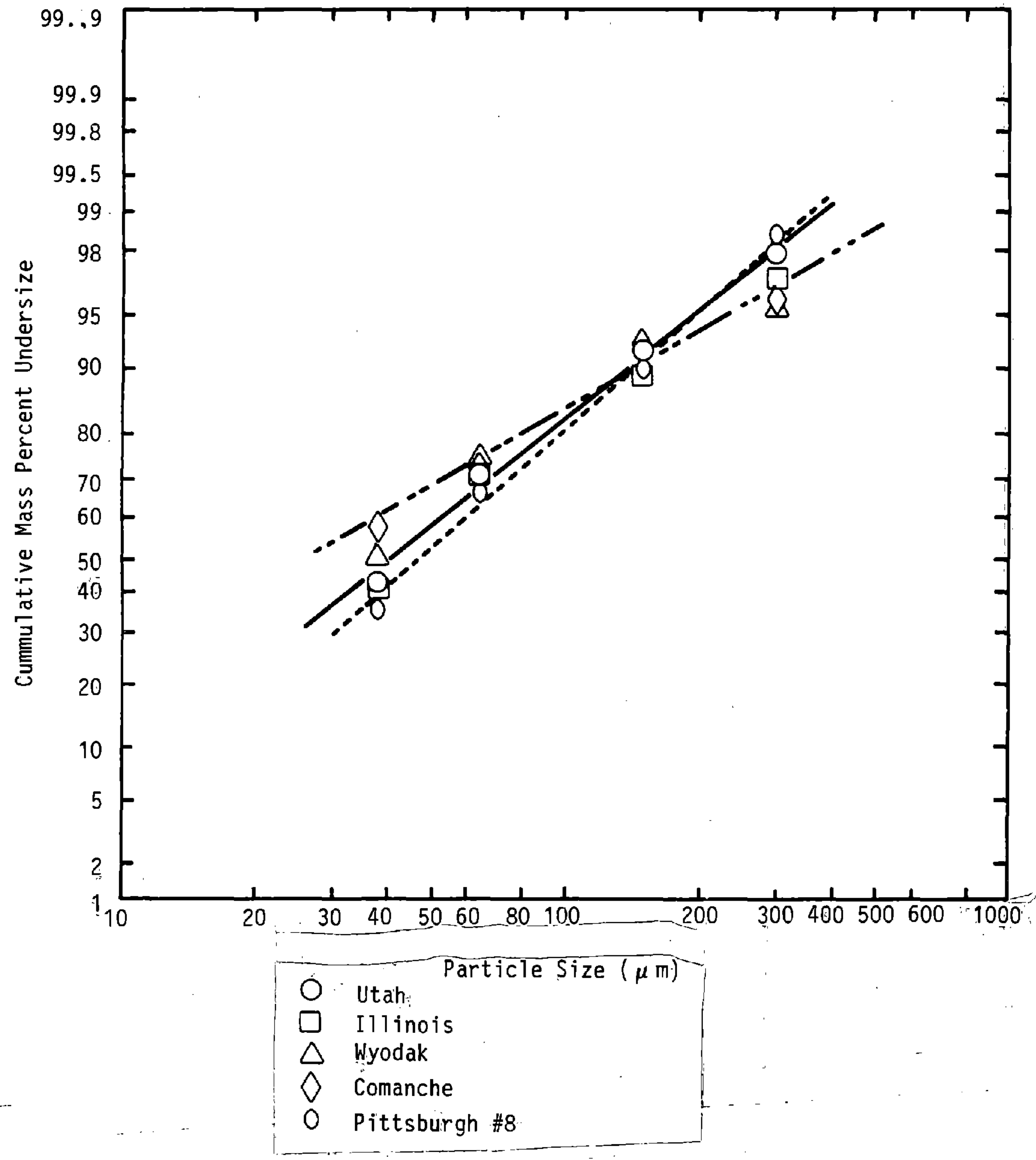


Figure 4-19. Coal particle size distributions.

TABLE 4-5. VARIATION OF COAL FINENESS--WEIGHT PERCENT PASSING 200 MESH SCREEN

Pittsburgh #8*	Mean (wt. %)	Std. Dev. (%)
Utah	70.9	3.96
Illinois	70.6	4.52
Wyodak	74.3	4.41
Comanche	72.4	5.93
Pittsburgh #8*	67.0	-

*Single Day of Testing

Three sorbents were used during this program to evaluate the potential of SO_2 reduction with in-furnace injection. Vicron 45-3 limestone and Colton hydrated lime have been used at EER as examples of each type of material in the development of LIMB technology. In addition, a third sorbent was evaluated for general interest because of its highly reactive nature--pressure hydrated dolomitic lime. The physical and chemical characteristics of these sorbent materials are listed in Table 4-6 and the corresponding size distributions are shown in Figure 4-20. Vicron 45-3 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. The pressure hydrated dolomitic lime is a much finer material, with a mass median diameter of only 1.4 μm, in addition to containing a significant amount of magnesium oxide.

4.3 Test Facility

4.3.1 Large Watertube Simulator

Testing of the burners was conducted in the EPA Large Watertube Simulator (LWS) at the El Toro, California, test site of EER. The LWS has a capacity to accommodate up to 150 x 10^6 Btu/hr input. The furnace is designed to match the size and geometry of a large industrial or small utility single-wall fired furnace. Figure 4-21 shows its general construction and Table 4-7 lists its design parameters and dimensions.

The LWS furnace is 22 ft deep and 16 ft wide. The overall height is 50.5 ft from the hopper to the top. The hopper is located in a concrete-lined pit so that the test burners are positioned at ground level. The furnace is arranged in a front-wall fired configuration with the nose directly above the rear (or target) wall. Single- and four-burner arrays have been fired in this configuration at over 100 x 10^6 Btu/hr. It is also possible to arrange burners for opposed or corner firing.

The shape of the LWS furnace generally matches industrial and utility boiler specifications. For example, the hopper design and nose angle are

TABLE 4-6. PHYSICAL AND CHEMICAL PROPERTIES OF SORBENTS

		Physical Properties			Elemental Ash %)									
Sorbent	Theoretical Characteristics	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	SO_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
Pressure Hydrated Dolomitic Lime	$Ca(OH)_2 \cdot Mg(OH)_2$	1.4	2.289	N.A.	42.42	0.10	0.49	N.A.	26.4	N.A.	0.28	N.A.	N.A.	N.A.

N.A. - No Analyses Available

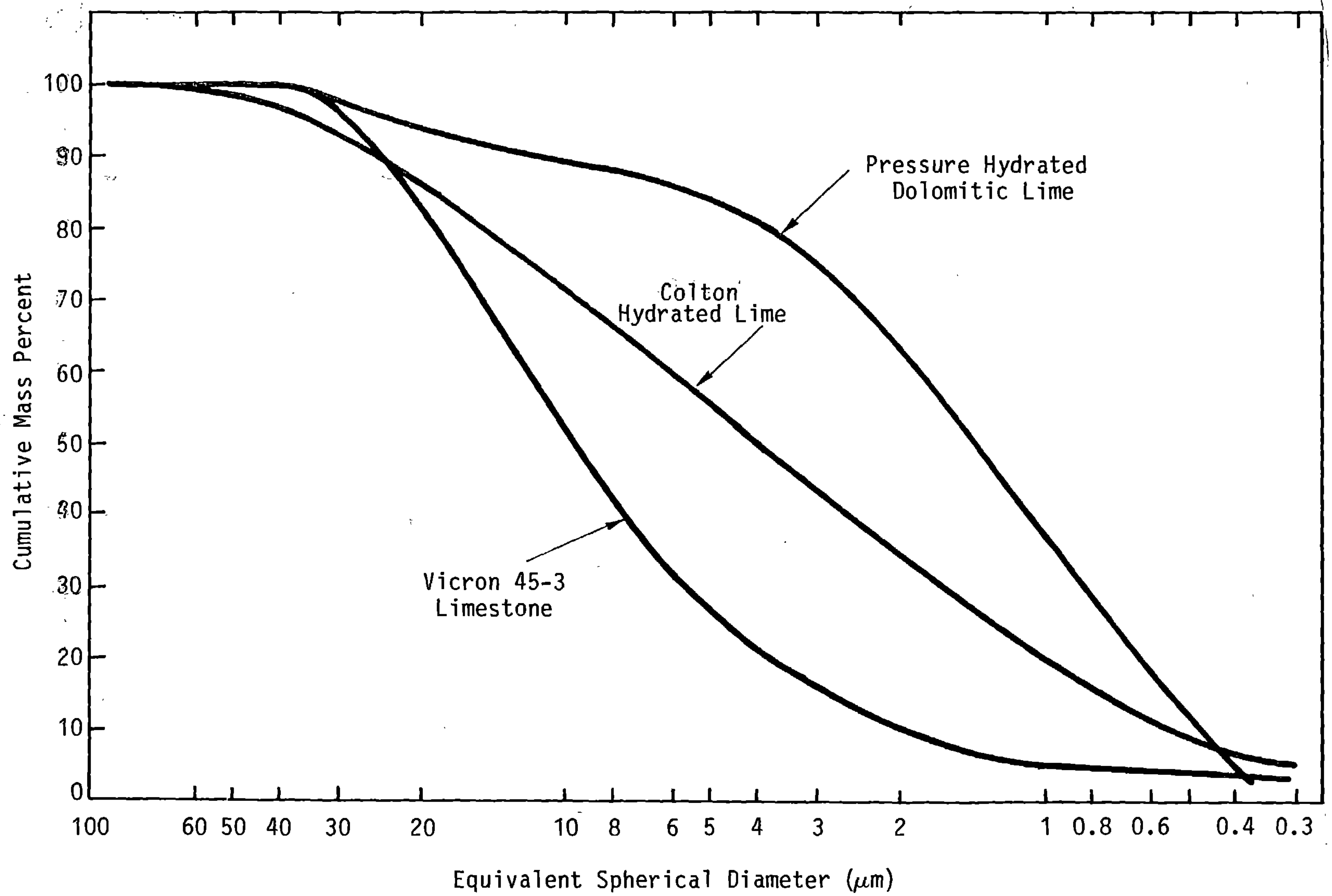


Figure 4-20. Particle size distributions of sorbent materials.

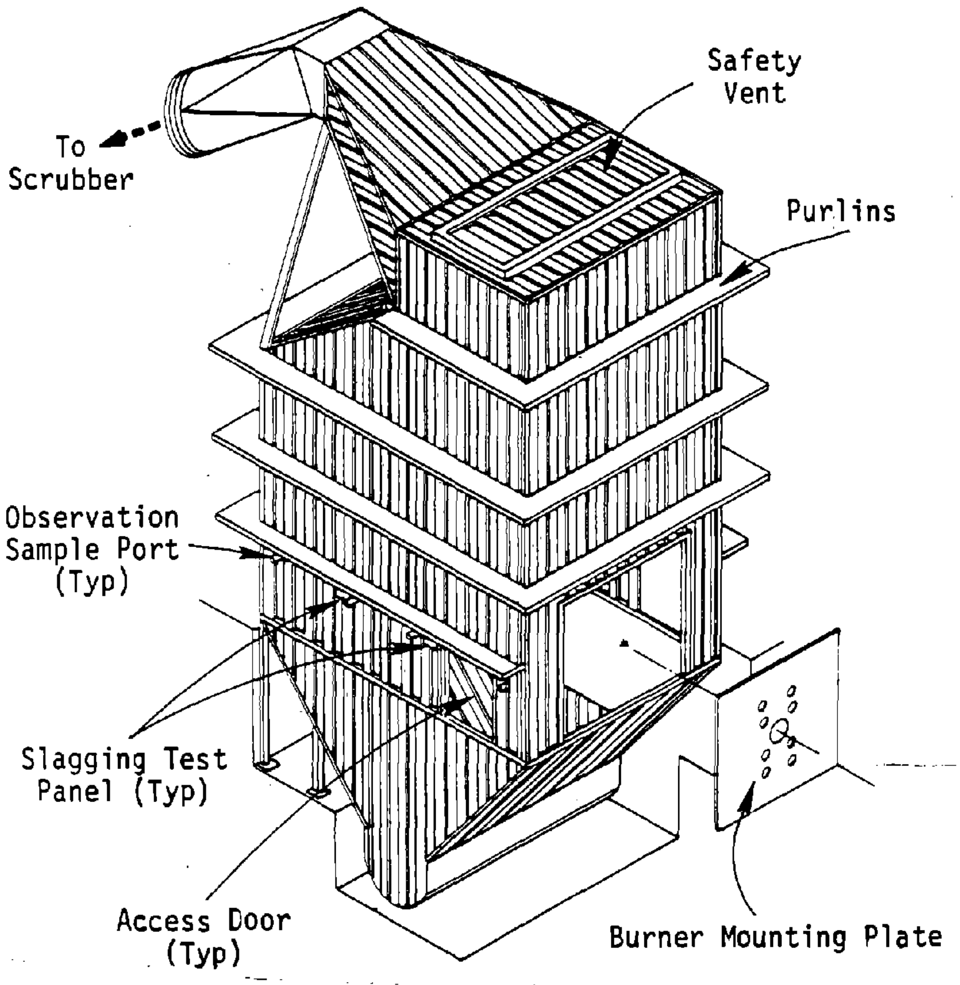


Figure 4-21. General configuration of Large Watertube Simulator, LWS.

TABLE 4-7. LWS FURNACE CHARACTERISTICS

Parameter		Value
Firing		
Configuration	Primary	Single Wall
	Optional	Opposed or Corner
Firing Rate	Minimum	50×10^6 Btu/hr (Practical Limit)
	Maximum	150×10^6 Btu/hr
Dimensions		
Firing Depth		22 ft
Width		16 ft
Rear Wall Height		20 ft
Knuckle-to-Nose Height		27.5 ft
Nose Angle		37^o (From Horizontal)
Hopper Angle		52^o (From Horizontal)
Height Above Ground Level		35.7 ft
Total Vertical Height		50.5 ft (Pit-to-Top)
Cooled Surface Area		
Burner Zone		804 ft^2
Total Furnace		1951 ft^2
Volume		
Burner Zone		3520 ft^3
Total Furnace		11,544 ft^3 (to Nose)
Insulation		All Sidewalls Knuckle-Up 16 ft
Cooling		Spray-Cooled on All Surfaces

identical to those used for field operating equipment. The area above the nose would normally contain superheater tubes in a field installation. In the LWS, this area is empty. However, the area has been sized so that if the convective tubes are installed, the tube size, spacing, and gas velocity will approximate typical field-operating boiler specifications.

The LWS furnace is externally spray-cooled with water to absorb the heat of combustion and control furnace wall temperatures. The vertical walls of the furnace in the vicinity of the burner are insulated with refractory so that furnace internal temperatures are similar to those of field operating boilers. The four sidewalls are insulated with 2 inches of Kaiser I-R-C refractory from the hopper knuckle up to 16 ft. The front and back slope of the hopper are insulated across the width of the furnace and 8 feet down the hopper slopes with one 2.5-inch layer of G-26 firebrick. The heat liberation/cooled surface area is also similar to field-operating boilers at nominal full load.

An overall view of the LWS system is presented schematically in Figure 4-22. Combustion air supplied by a forced-draft blower passes through a tubular heat exchanger and into a manifold. The combustion air flow rate is measured and controlled by multiple venturis and dampers. For burners equipped with a common windbox, several venturis can be connected in parallel. The use of multiple venturis allows accurate flow rate measurement over a wide flow rate range. The other side of the heat exchanger is supplied with hot exhaust from a separate oil-fired combustion chamber. This allows the combustion air preheat temperature to be controlled independently of the performance of the burner firing in the research furnace.

The fuel supply system can handle liquid and solid fuels. Underground tanks and pumps can be used to fire a wide range of liquid fuels. Compressed air and steam are available for atomization. Two Raymond bowl pulverizers are available for firing pulverized coal directly. Alternatively, coal may be pulverized and removed from the primary coal/air stream in a baghouse. The pulverized coal is stored in hopper bottom bins and can be utilized to form coal/oil or coal/water mixtures if desired.

1. Coal Storage
2. Main Coal Hopper
3. Crusher
4. Coal Feeder
5. Pulverizer
6. P.A. Exhauster
7. Main Combustion Air Fan
8. Tubular Air Heater
9. P.A. Trim Heater
10. P.A. Venturi
11. Oil/Gas Fired Preheater
12. Air Plenum
13. Combustion Air Venturis
14. Burner
15. Windbox
16. LWS
17. Exhaust Duct
18. Spray Tower Scrubber

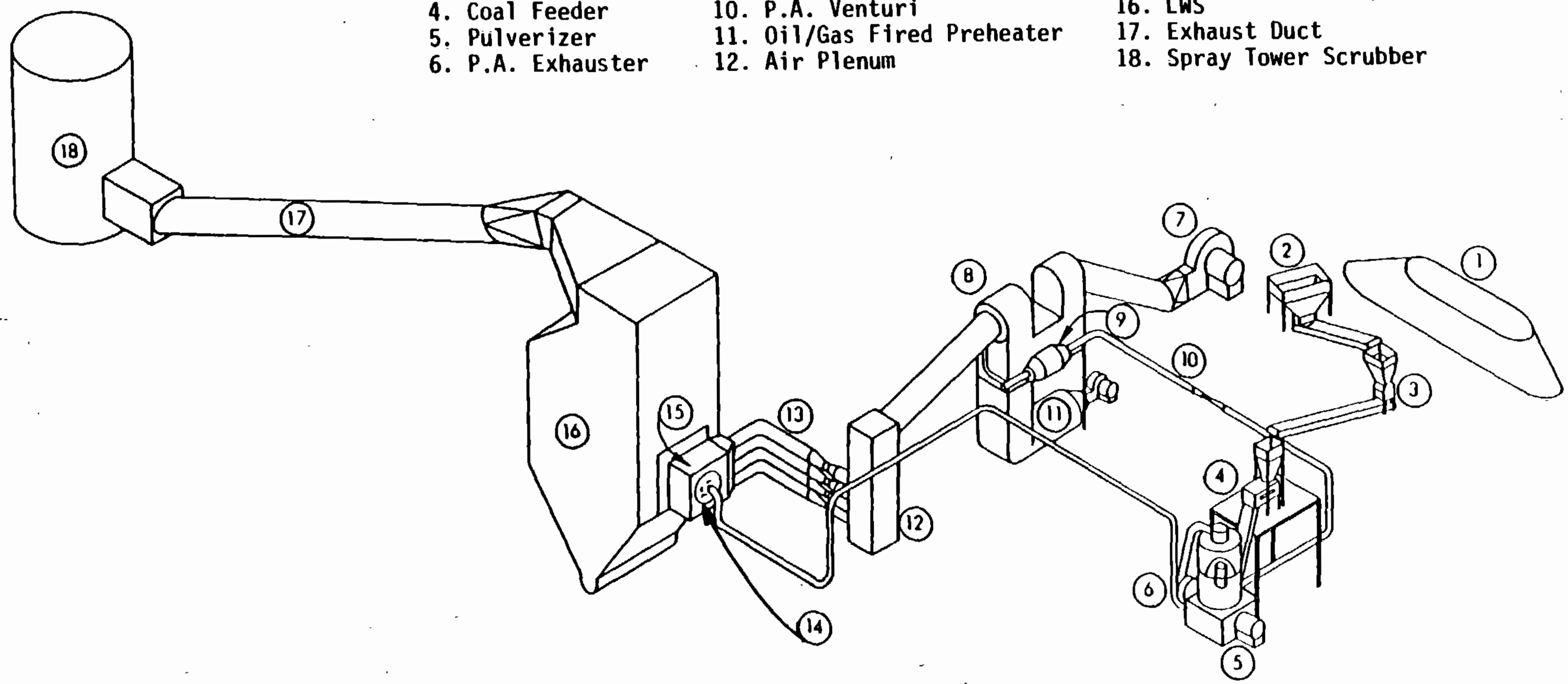


Figure 4-22. Large Watertube Boiler Simulator facility.

The furnace exhaust system was designed to permit a wide range of emission measurements. The sampling location is near the end of a long straight duct meeting EPA specifications for the minimum number of sampling points. Since there is no convective section, the temperature at the sampling point is about 1200°F. The exhaust duct is externally spray-cooled like the furnace. Downstream of the sampling location, the exhaust passes into a calcium carbonate scrubber which controls SO_x and particulate emissions. This system meets all applicable air pollution control regulations.

4.3.2 Test Configuration

One of the key aspects of this restructured program was to evaluate the effects of furnace environment on burner performance and to compare these effects with those of a full-scale utility boiler. Since the LWS geometry is fixed, the criteria used to modify the furnace environment was to match the mean furnace exit temperature at 120 x 10^6 Btu/hr while firing the reduced scale 60 x 10^6 Btu/hr burners through the use of additional insulation. The insulation requirements were evaluated by EER using the Richter furnace heat transfer model.

Several iterative trials were run for selected insulating configurations. Additional insulation in the distribution shown in Figure 4-23 was considered. Results from the modeling work indicated that by covering the area with a ceramic-board type of insulation, exit temperatures for 60 x 10^6 Btu/hr input could match the exit temperatures with the baseline insulation configuration fired at 120 x 10^6 Btu/hr.

The success of this insulation and thermal furnace exit temperature match is summarized in Table 4-8. Furnace exit gas temperatures measured with suction pyrometers, or high velocity thermocouples shows the effectiveness of the insulation pattern. At 120 x 10^6 Btu/hr, the average furnace exit temperature was 1810°F with no insulation. Firing at 60 x 10^6 Btu/hr, the exit gas temperature in the uninsulated furnace was 250°F lower,

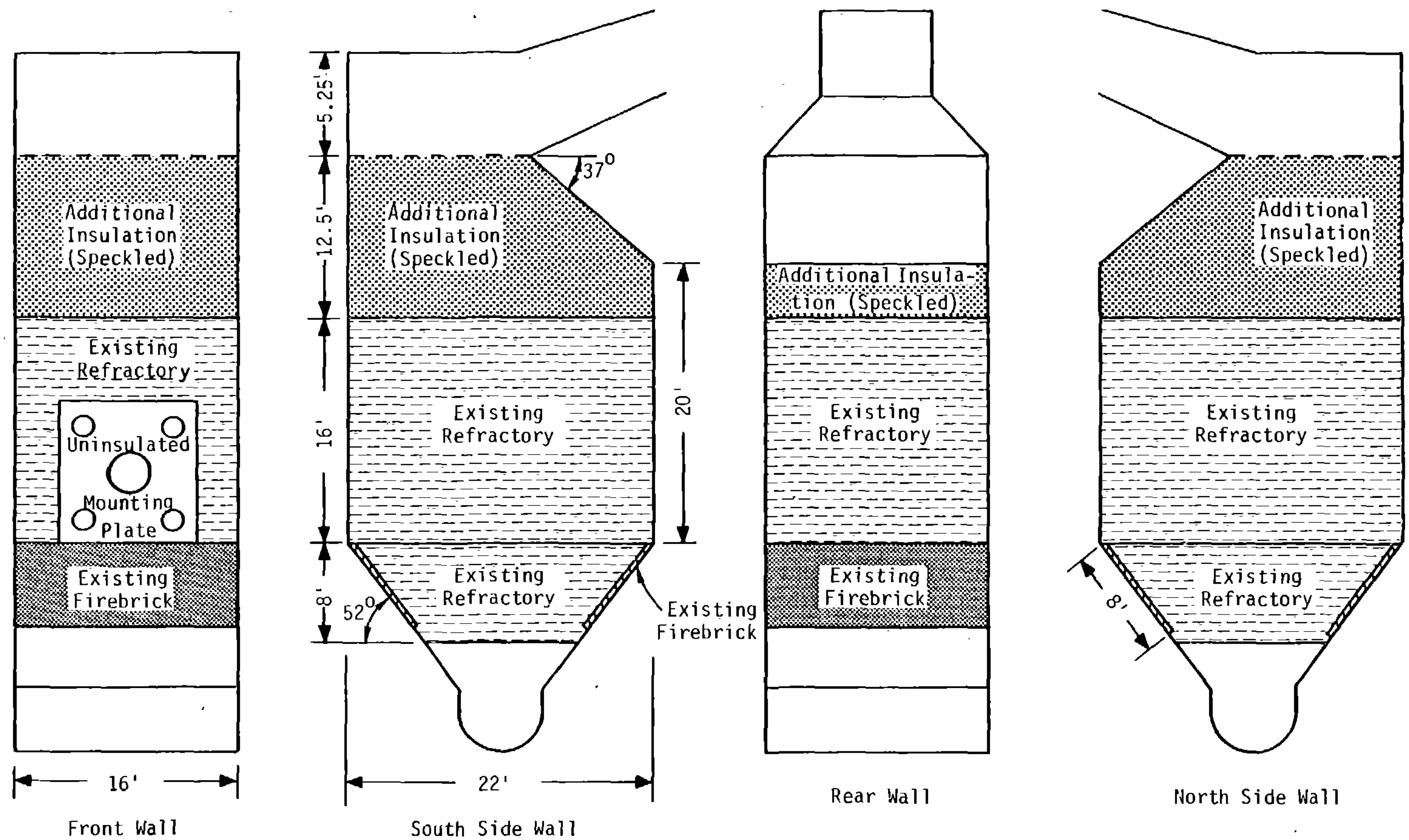


Figure 4-23. Insulation pattern in the LWS for operation at 60 x 10^6 Btu/hr.

TABLE 4-8. LWS FURNACE EXIT GAS TEMPERATURES

BURNER	FURNACE CONFIGURATION	EXIT TEMPERATURE (°F)	
		AVERAGE	RANGE
120×10^6 Btu/hr DMB	Uninsulated	1792	1723-1878
120×10^6 Btu/hr Circular	Uninsulated	1828	1770-1912
60×10^6 Btu/hr DMB (Initial Design)	Uninsulated	1562	1484-1640
60×10^6 Btu/hr DMB (Initial Design)	Insulated	1776	1732-1819
60×10^6 Btu/hr DMB (Modified)	Insulated	1776	1657-1828

with the insulation pattern shown in Figure 4-23, the average furnace exit gas temperature was 1776°F, within 35°F or 2 percent of a perfect match.

4.4 Test Procedures

Established test procedures were utilized during the evaluation of the DMB concept in the LWS. The test procedures were in accordance with guidelines set by previous EPA Quality Assurance Project Plans and described in the Burner Evaluation Test Plan submitted June 1984. Specific quality assurance activities for these tests are documented in Part V, Appendix A of this report. A routine set of input/output measurements was completed for all test conditions. These measurements document all input parameters which specified the test conditions and monitored the key overall performance parameters including flame stability and emissions. These standard measurements are listed in Table 4-9. Most of the measurements were made continuously and results were processed into engineering units in real-time by a microcomputer. Those parameters which must be recorded manually were entered into the computer separately so that the computer generated data record is a complete listing of all parameters. These computer listed raw data are included in Part V, Appendix B.

The sampling train utilized for the continuous emission monitoring of the flue gas is shown in Figure 4-24. All materials in contact with the sample are glass, 316 stainless steel or Teflon. These materials are nonreactive with NO at low temperatures. The stainless steel sampling probes are water cooled, and small cyclones adjacent to the probe remove particulate matter and condensed water. The sample is then transported to the control room through a Teflon line where it is filtered and dried. The sample pump is Teflon lined and the sample flow rate is maintained at several times the instrument's requirements to minimize response time. Excess sample flow is bypassed to a vent. Commercial gas analyzers are used for measurements of O_2, CO_2, CO, NO/NO_x, and SO_2 and are listed in Table 4-10. The accuracy of each instrument is maintained by frequent calibration with zero and certified calibration gases.

TABLE 4-9. STANDARD INPUT/OUTPUT MEASUREMENTS

Parameter	Measurement Method	Record	Frequency
Burner Settings	Observation	Manual	Each Test
Fuel Flow Rate	Weigh-Belt Feeder and by Oxygen Balance Calculations	Computer	Continuous
Fuel Fineness	ASME PTC 4.2	Manual	Once/Day as Required
Fuel Composition	Samples Obtained Prox. & Ult. Analysis	Manual Manual	Once/Day Selected Tests
Combustion Air Flow Rate	Calibrated Venturi	Computer	Continuous
Combustion Air Temperature	Thermocouples	Computer	Continuous
Flame Characteristics	Direct Inspection Color Video	Manual Monitor/Tape	Once/Test Continuous
Exhaust Composition	Analyzers O_2--Paramagnetic CO--NDIR CO_2--NDIR NO_x--Chemiluminescence	Strip Chart and Computer	Continuous
Furnace Exit Temperature	Suction Pyrometer	Manual	Selected Tests

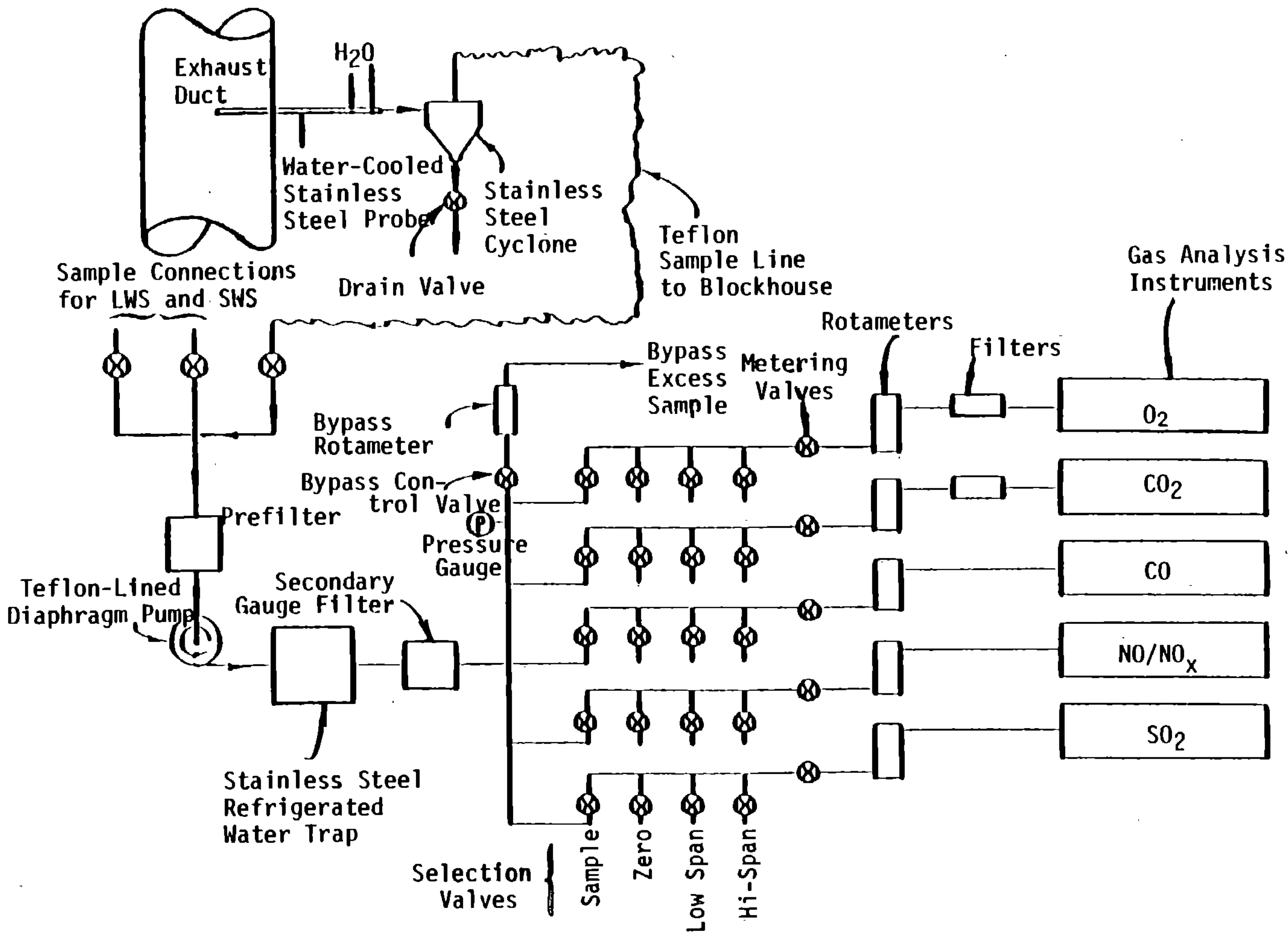


Figure 4-24. Flue gas sample train schematic.

TABLE 4-10. GAS PHASE SPECIES INSTRUMENTATION

Species	Operating Principle	Instrument	Model No.
O_2	Paramagnetic	Beckman	755
CO_2	Nondispersive Infrared	Anarad	AR-600
CO	Nondispersive Infrared	Anarad	AR-500R
NO/NO_x	Chemiluminescence	Teco	10R
SO_2	UV Absorption	DuPont	400

For selected test conditions, fly ash samples to determine the extent of unburned carbon were collected. Figure 4-25 shows the system used for this purpose. The system consists of a 3-inch I.D. nozzle, insulated stainless steel cyclone, orifice flowmeter, and an induced draft fan. A large 8-inch x 10-inch glass fiber filter holder also can be connected in series or in parallel with the cyclone. For normal conditions, the cyclone collects the fly ash at a rate of approximately 50 grams in 5 minutes sampling time. The cyclone itself is designed with a cutoff diameter (D_{50}) of about 3 microns.

For selected conditions, additional measurements were made to more fully characterize burner operating conditions and burner performance. These additional measurements are listed in Table 4-11.

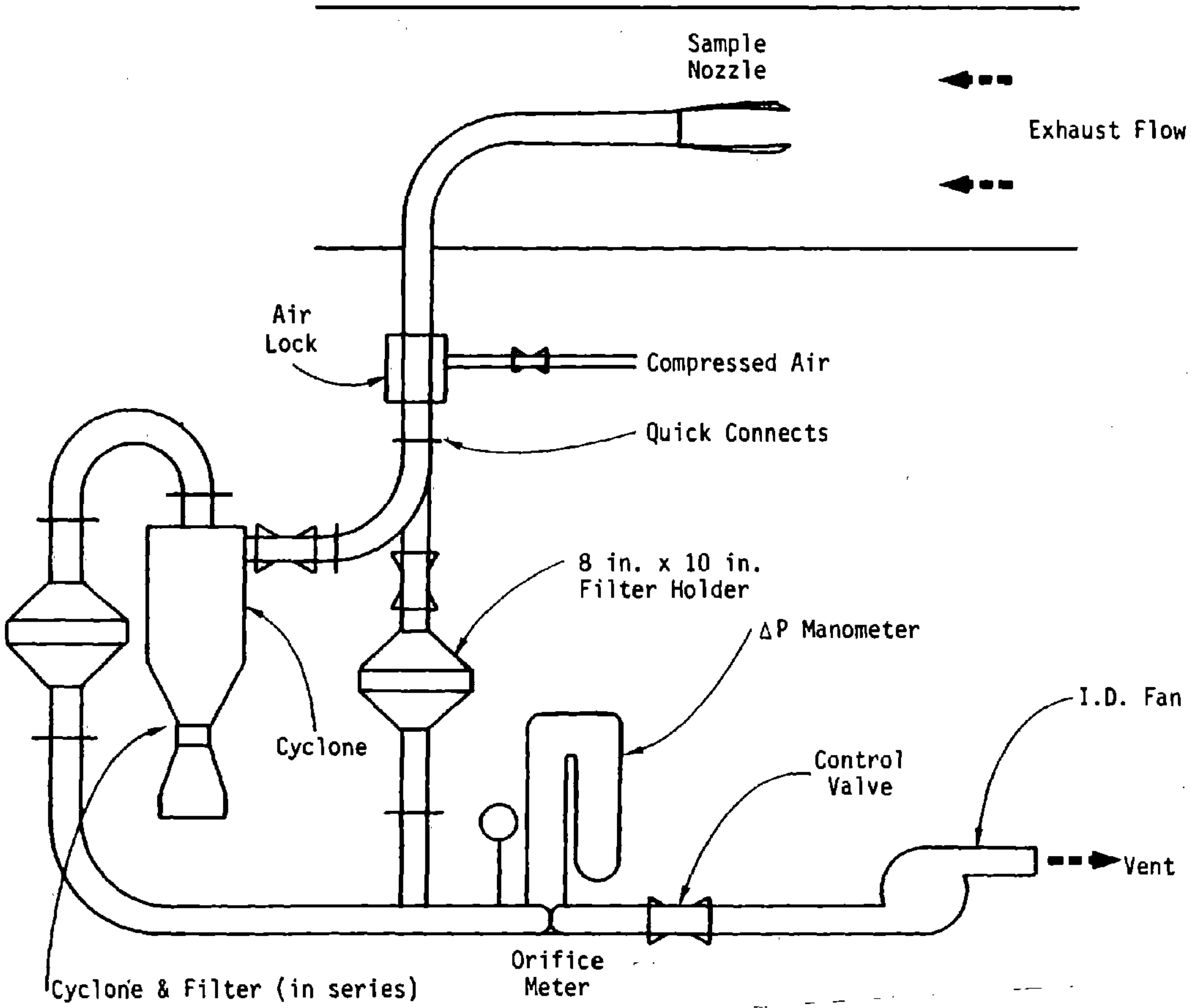


Figure 4-25. High volume isokinetic particulate sampling system.

TABLE 4-11. DETAILED MEASUREMENT FORMAT

Inputs		Outputs	
Parameter	Method	Parameter	Method
Coal Composition	Ultimate and Proximate Analysis--ASTM	Particulate Matter: Total Mass	EPA Method 5
		Composition	Ultimate Analysis--ASTM
Coal Size Distribution	ASTM Method D197	Combustion Efficiency:	
Sorbent Composition	ASTM Methods	CO, CO_2	Standard Measurement Format
Sorbent Size Distribution	SediGraph Particle Size Analyzer	Particulate	Ultimate Analysis
		Calcium Utilization:	
		SO_2	Continuous Monitor UV and/or EPA Method 6
		SO_3	Controlled Condensation and EPA Method 8
		Particulate	Ultimate Analysis
		Slagging Characteristics	Water-Cooled Slagging Panels
		Fouling Characteristics	Fouling Probes

5.0 BURNER PERFORMANCE AND NO_x EMISSIONS

5.1 Circular Burner

The 120 x 10^6 Circular Burner was initially tested using Utah coal. The baseline settings were based on the information supplied by B&W for design point operation. The resulting flame was very long (>22 feet) and wide (>16 feet) with correspondingly low NO_x emissions, which was uncharacteristic of the expected Circular Burner performance. Parametric adjustments were made to the available burner controls, including: decreasing the primary air velocity, retraction of the impeller, and adjustments to the secondary air register. These adjustments did not produce any significant effects on the flame shape or emissions. In addition baffles were installed in the windbox to create an air flow distribution in the windbox similar to field installation. This also had negligible effect on burner performance. Since these attempts to alter burner performance had little or no effect, the approximate design point operating conditions as shown below, were utilized for all the remaining tests. These tests were conducted after verification that the excessive flame length would not damage the structure of the LWS.

AIR VELOCITIES (ft/sec)		BURNER SETTINGS	
Primary	Secondary	Impeller	Secondary Air Register
70	110	-1 inch (from zero position)	15^o Open

The effects of excess air on the Circular Burner NO_x and CO emission characteristics are summarized in Figure 5-1 for both full and 55 percent firing capacities. At full load, NO_x emissions decreased 6 ppm/percent excess air over the range tested. The flame was stable with no detachment, with lengths > 22 feet and widths > 16 feet for all conditions. At the design point overall stoichiometry (SR_T) of 1.15, NO_x emissions were about

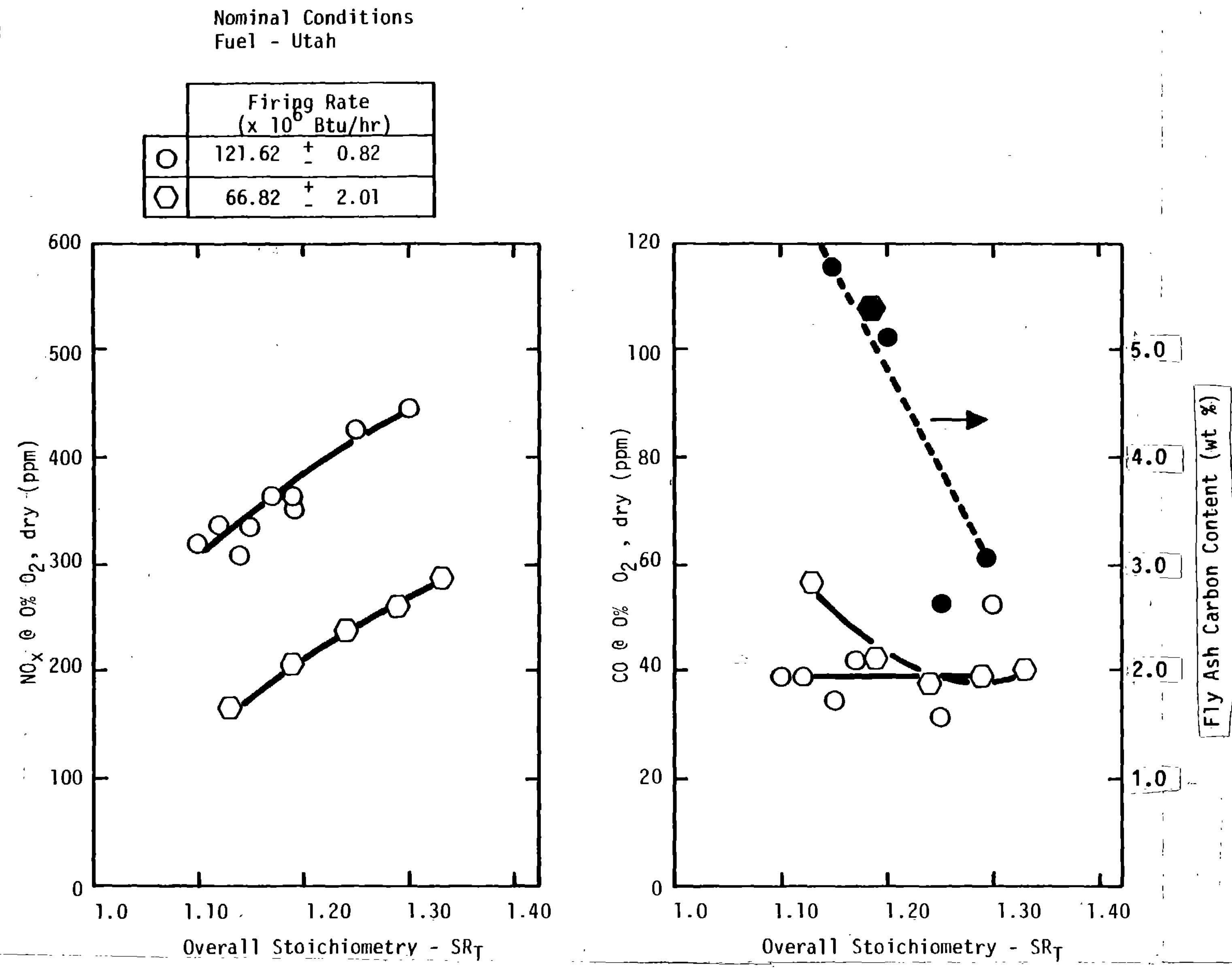


Figure 5-1. Summary of 120 x 10^6 Btu/hr Circular Burner with Utah coal.

350 ppm.* CO was generally stable throughout the range tested at 40 ppm. Excess air had similar effects at reduced load (67×10^6 Btu/hr), with a decrease in NO_x of 6 ppm/percent excess air. The flame was slightly less stable at this reduced firing rate and shorter (18-22 feet). At $SR_T = 1.15$, NO_x emissions were 175 ppm resulting in a 50 percent reduction from full load operation. CO emissions were about 40 ppm down to an excess air level of 19 percent increasing to 57 ppm at 13 percent excess air.

The effect of excess air on the Circular burner firing Illinois coal is summarized in Figure 5-2 for two firing capacities. At normal full load (120×10^6 Btu/hr) NO_x emissions decreased by 4 ppm/percent excess air, with a baseline of 370 ppm. The flame was similar to that of Utah, with lengths > 22 feet and widths > 16 feet. CO emissions were stable at 35 ppm over the range tested. Reduction of firing rate to 67×10^6 Btu/hr resulted in approximately a 36 percent decrease in NO_x emissions at baseline conditions to 235 ppm with a slight increase in CO to about 42 ppm.

A series of tests were conducted firing the Comanche Coal that is used at the Comanche Unit Generating Station, which is equipped with B&W circular burners, in order to provide a direct comparison between the burner performance on the LWS test facility and a field installation. Figure 5-3 summarizes the effect of excess air at two firing capacities with Comanche coal. At full capacity, NO_x emissions decreased 11 ppm/percent excess air with a design point ($SR_T = 1.15$) of 375 ppm. CO was stable at about 35 ppm down to an excess air level of 10 percent with a rapid increase beyond that level. The flame was more characteristic of the Circular burners operating in the field with lengths of 16-20 feet and widths of 10-12 feet over the range tested. At reduced load of 70×10^6 Btu/hr excess air. Reduction in firing rate by 42 percent resulted in a decrease in NO_x emissions of approximately 30 percent down to 260 ppm at $SR_T = 1.15$ with no significant change in CO emissions.

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*Unless otherwise stated, emission values referenced in the text are reported as corrected to 0% 02, dry.

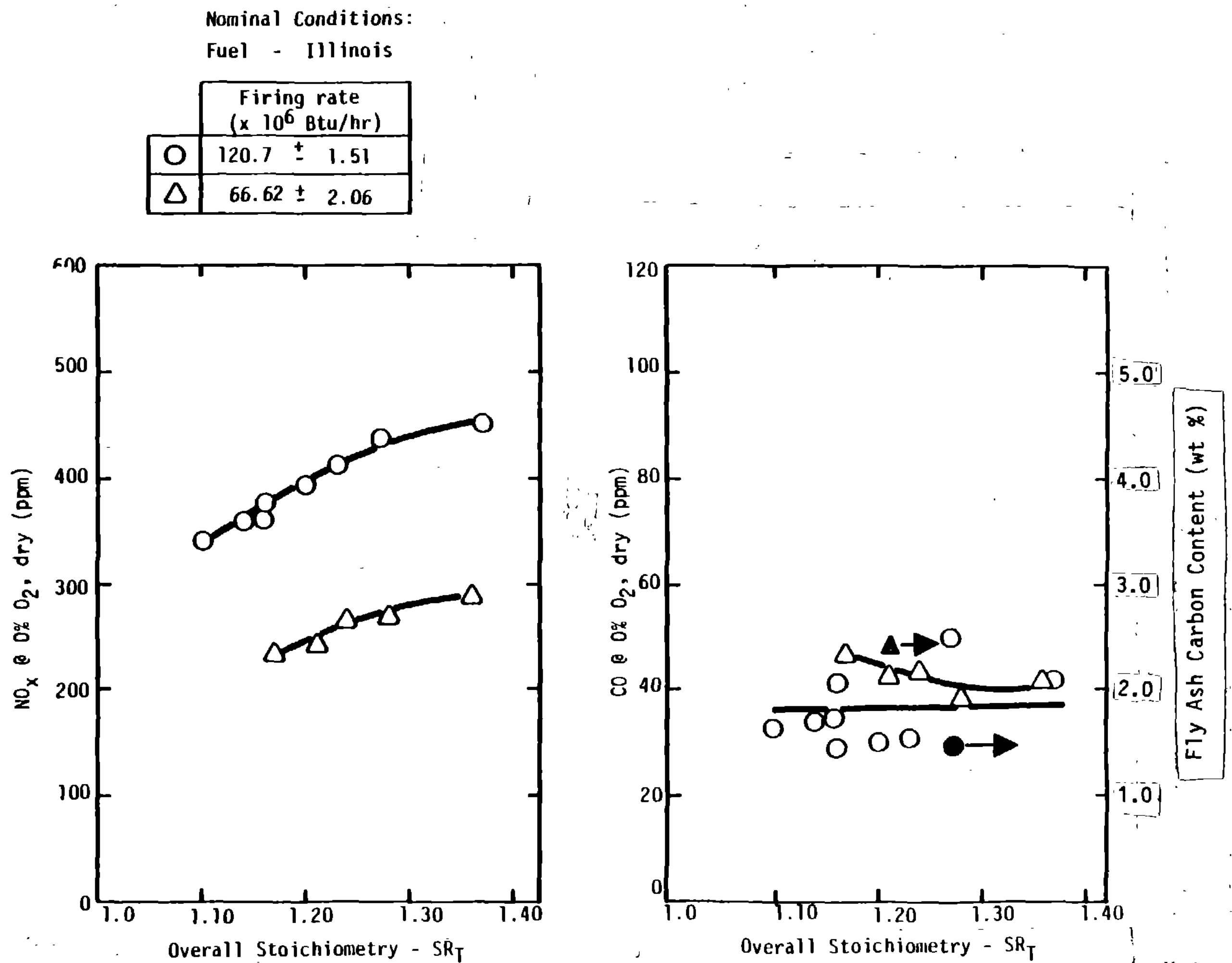


Figure 5-2. Summary of Circular Burner performance with Illinois coal.

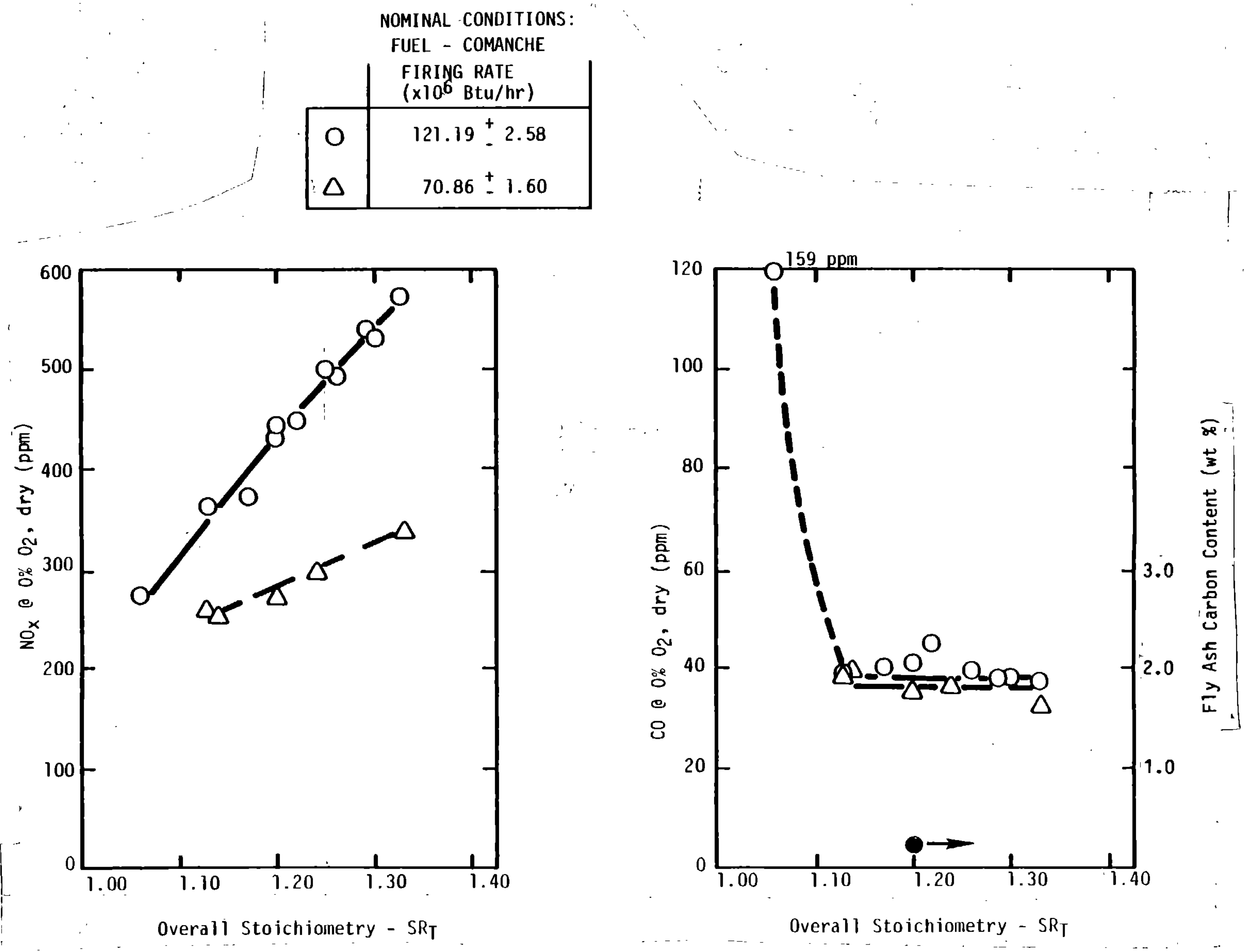


Figure 5-3. Summary of Circular Burner performance with Comanche coal.

Thus, while Circular Burner performance with Utah and Illinois coals is comparable, with the subbituminous Comanche coal the visible flame was much more compact, and NO_x emissions were much more sensitive to increasing excess air. This behavior is believed to be due to the higher inherent reactivity of the subbituminous coal, which leads to earlier and more intense heat release. Consequently, under nonstaged conditions, this leads to better fuel-nitrogen/oxygen contacting in the early stages of combustion, compared to the less reactive bituminous coals.

At the Comanche Generating Station, normal operation includes a percentage of the combustion air going through NO_x ports (overfire air ports) located above the burners. Therefore, to quantify the effect of this overfire air on burner performance, a brief test was conducted using overfire air. A percentage of the total combustion air was diverted through four overfire air ports located 19 feet above the burner centerline. Figure 5-4 summarizes the results. NO_x emissions decreased by 7 ppm/percent stoichiometric air diverted through the overfire air ports from about 450 ppm to 346 ppm with no change in CO emissions. Flame length increased from about 18 feet at baseline to 22 feet at the maximum overfire air level (15 percent).

5.2 Dual Register Burner

A major objective of the tests with the 60 x 10^6 Btu/hr Dual Register burner was to obtain performance data in the LWS for comparison to field data from a DRB-equipped boiler, the Wyodak Plant in Wyoming. This data would be used to extrapolate LWS burner performance to practical applications. For these tests the LWS was insulated to provide a thermal environment comparable to DMB and Circular burner tests at 120 x 10^6 Btu/hr. The tests of the 60 x 10^6 Btu/hr DRB included a brief series of burner adjustments to verify normal operating ranges while firing Utah coal at full load, followed by characterization of the DRB over load and excess air variation with Utah, Wyodak, and Pittsburgh #8 coals.

Nominal Conditions
Fuel - Comanche
Firing Rate = 120.6 ± 1.18 x 10^6 Btu/hr
SR_T = 1.20

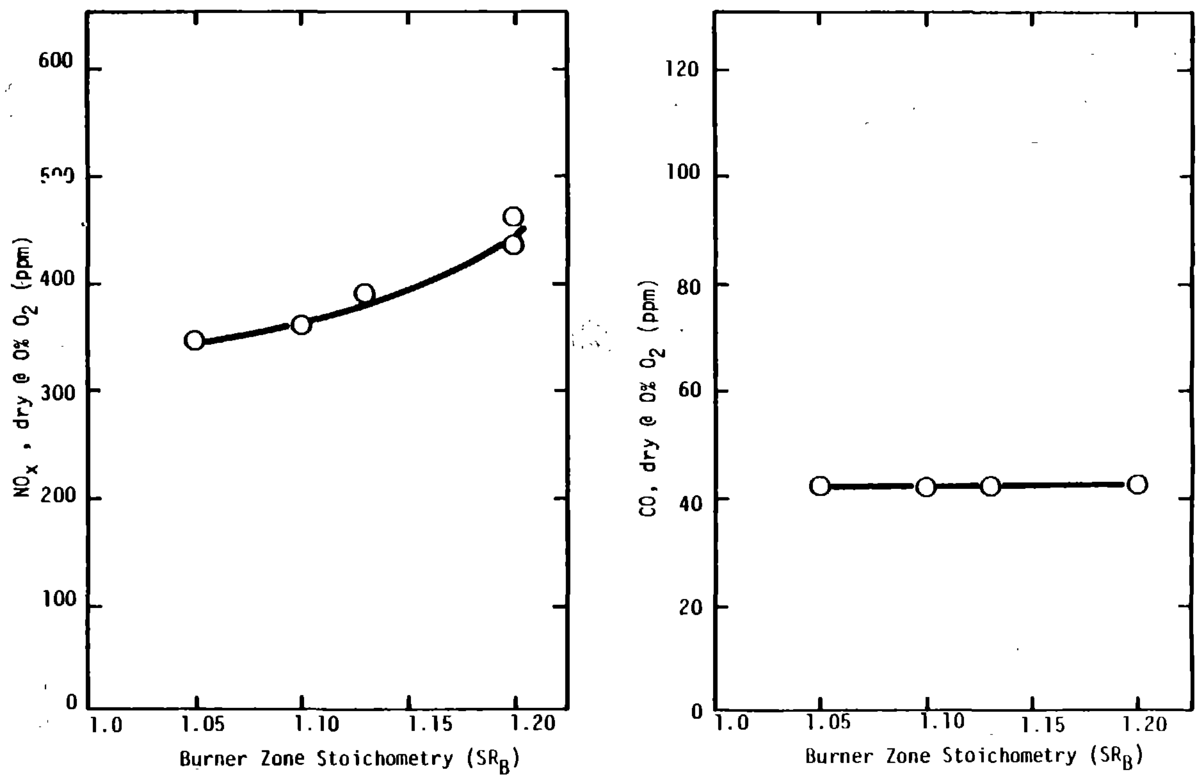


Figure 5-4. Effect of OFA on Circular Burner performance.

The main burner adjustments available for the DRB were inner spin vane position and outer register position. At full load with Utah coal and an overall stoichiometry of 1.20, NO_x emissions ranged from 253 to 392 ppm (on a dry basis, corrected to 0 percent O_2) with corresponding flame lengths of over 22 feet to about 16 feet. For this burner, NO_x emissions were found to be most sensitive to the setting of the inner spin vane position. Varying this setting from 40°CCW to 40°CW resulted in NO_x emissions ranging from 253 to 392 ppm. For a fixed inner vane setting of 30°CW, changing the outer register setting from 50°CW to 20°CW was found to reduce the NO_x emission from 392 to only 370 ppm. This behavior is different from that observed with the 78 x 10^6 Btu/hr DRB tested in Phase V of the program, where outer register adjustment was found to be dominant. The reasons for this difference in behavior are not apparent from aspects of burner design or operation.

The burner settings chosen for characterization with the different coals were:

- Inner spin vane = 30° CW
- Outer register = 40° CW

These settings were selected since they are representative of the burner settings employed at the Wyodak Plant.

The effect of excess air on DRB performance at full load for the three subject coals is summarized in Figure 5-5. Lowest NO_x emissions were measured for the subbituminous Wyodak coal and the highest for the high volatile bituminous Pittsburgh #8 coal. NO_x emissions at an overall stoichiometry of 1.20 were 290, 390 and 415 ppm for Wyodak, Utah, and Pittsburgh #8 coals, respectively.

For the bituminous coals, unburned carbon in the fly ash was considered to be acceptable at nominal operating conditions, but was observed to increase strongly as excess air was reduced, as shown in Figure 5-5. For the Wyodak coal, however, the carbon in ash was exceptionally low at nominal

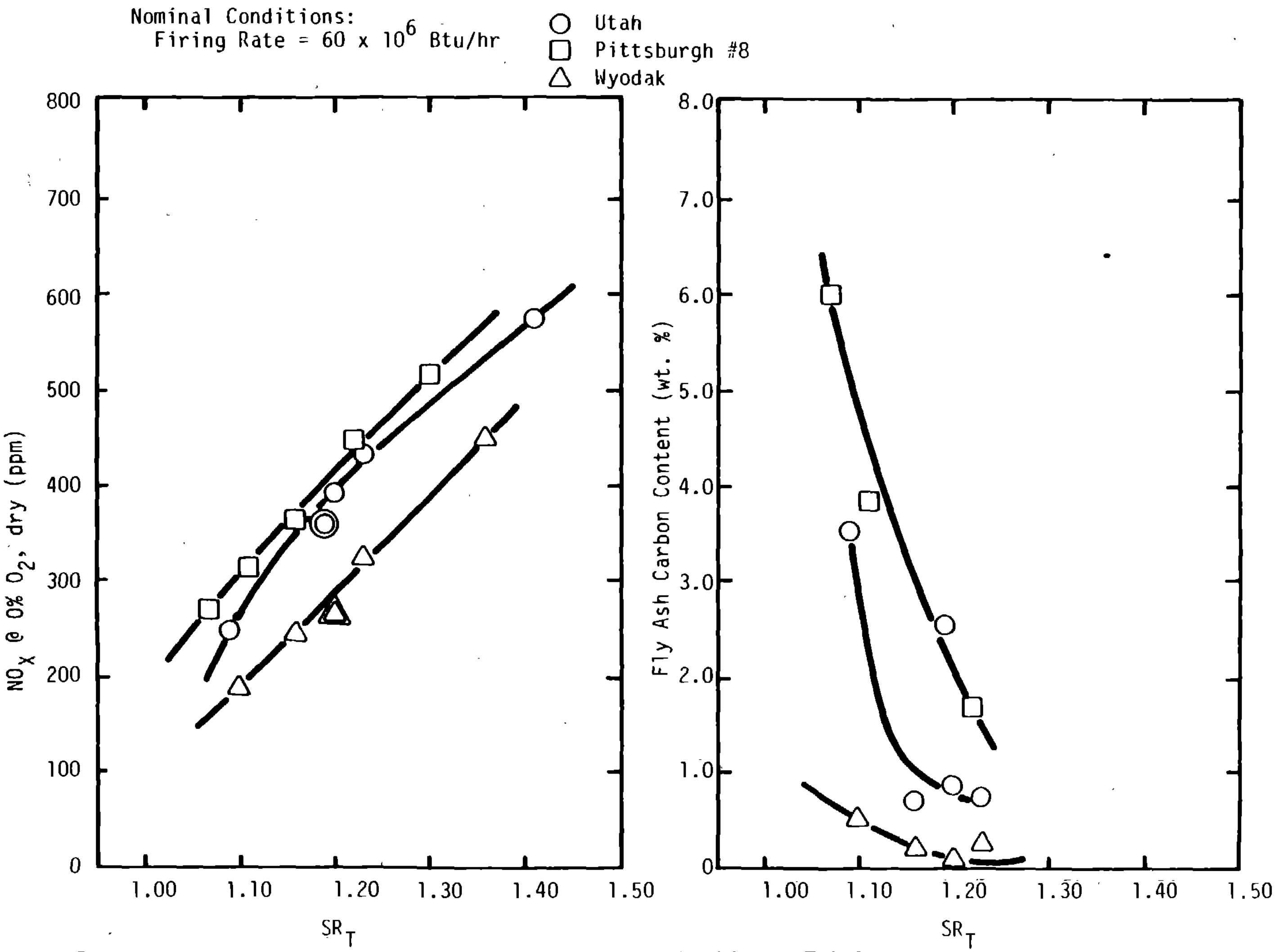


Figure 5-5. Effect of excess air on 60 x 10^6 Btu/hr Dual Register Burner performance at full load.

excess air levels, and generally commensurate with values measured at the Wyodak boiler (approximately 0.2 percent).

The performance of the 60 x 10^6 Btu/hr DRB at 75 percent load is summarized in Figure 5-6 for Utah and Wyodak coals. At this load, NO_x emissions were virtually identical for the two coals. NO_x emissions were about 200 ppm at an overall stoichiometry of 1.20 for both coals. Again, the Wyodak coal yielded low levels of carbon in the fly ash even down to an overall stoichiometry of 1.01. Unburned carbon in the Utah coal ash was higher at this reduced load condition than that for full load operation.

Additional Dual Register Burner test data in the LWS was collected during tests of 78 x 10^6 Btu/hr second generation low NO_x burners, as described in Volume II of the report on this project. Data representative of typical DRB performance was collected during B&W sponsored testing (B&W P.O. 635-0A008408DM) of a 78 x 10^6 Btu/hr Phase V DRB. These tests were conducted in the LWS with additional insulation, yielding an average flue gas exit temperature of 1855°F. Results from five configurations of the Phase V DRB tested with Pittsburgh #8 coal are shown in Figure 5-7. Two of the configurations were representative of commercial applications, the coal diffuser and the coal pipe venturi. With burner settings representative of field use, as in the Wyodak boiler, the diffuser configuration produced 293 ppm NO_x with a flame over 22 feet long while the venturi produced 350 ppm NO_x with a 20-21 feet flame. At similar flame lengths, the NO_x difference was less pronounced, showing approximately 12 percent higher NO_x for the venturi configurations opposed to the diffuser.

5.3 120 x 10^6 Btu/hr Distributed Mixing Burner

The primary focus of initial screening tests conducted with this burner was to develop an impeller and/or burner operating parameters that resulted in a flame that was capable of being staged without severe flame impingement on the furnace rear wall. The initial burner settings were determined from the DMB 60 x 10^6 Btu/hr burner tests with the inner register and outer registers set at 30° and 10° open, respectively, which produced counter

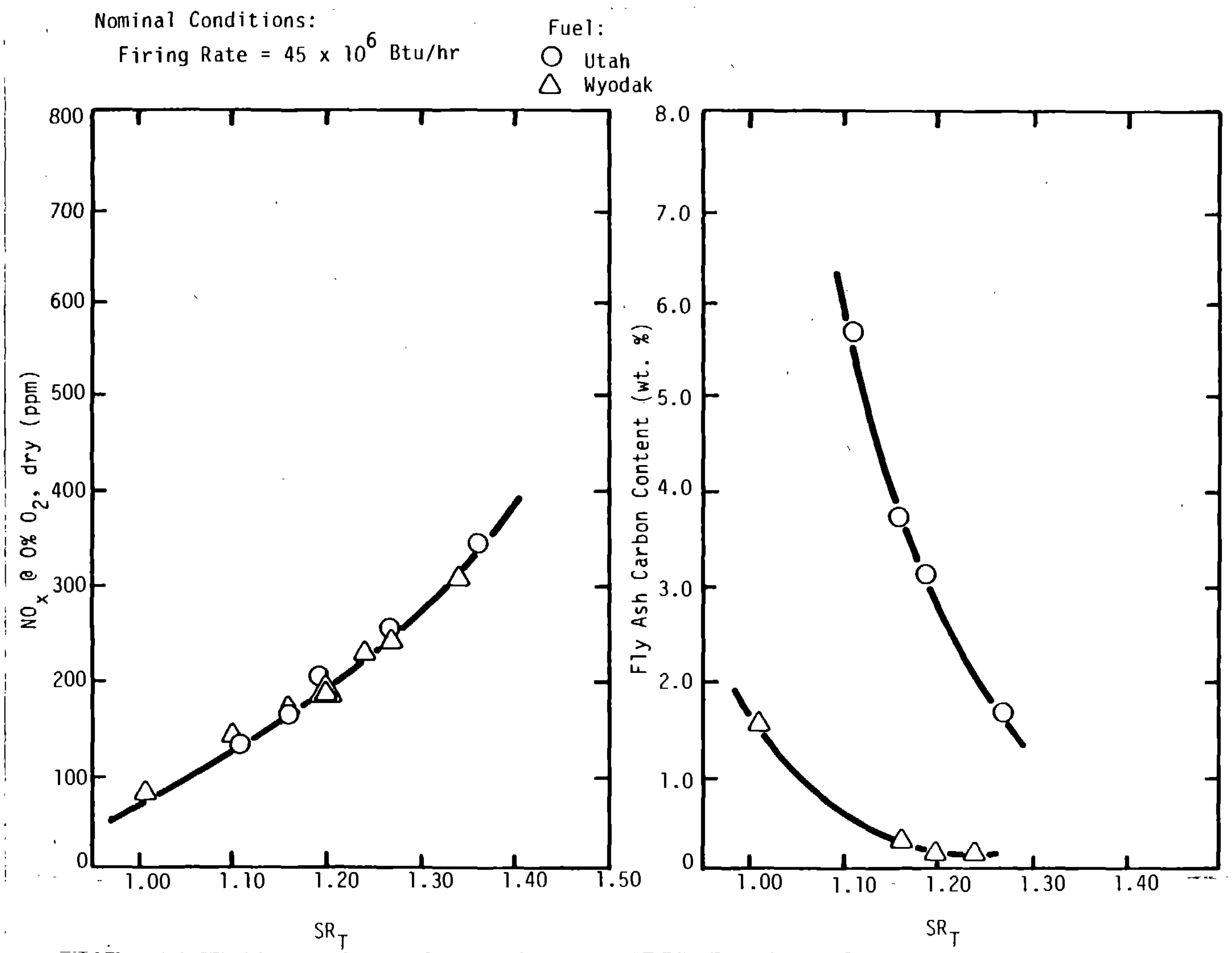


Figure 5-6. Effect of excess air on 60 x 10^6 Btu/hr Dual Register burner performance at 75 percent of full load.

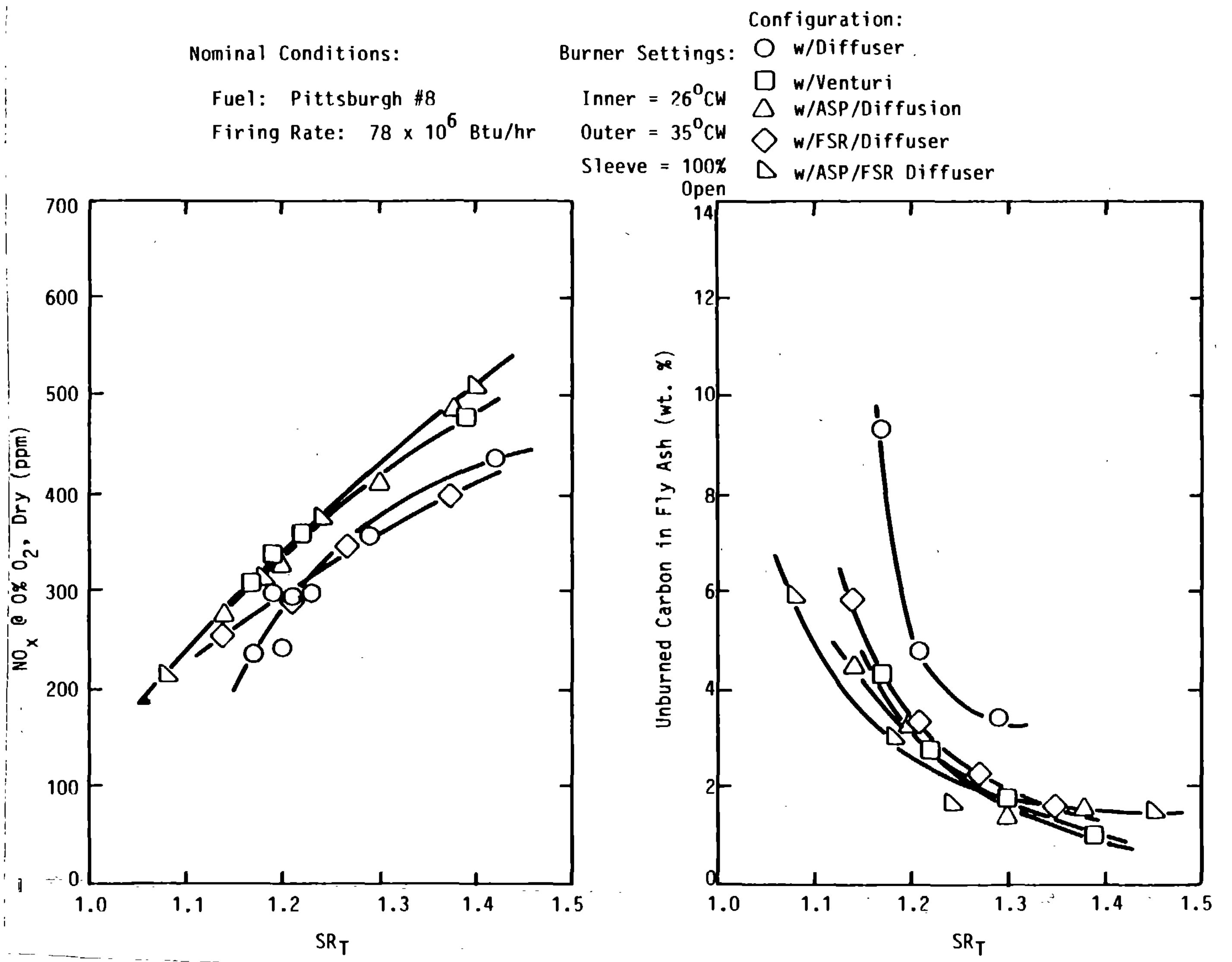


Figure 5-7. Effect of excess air on Phase V DRB configurations' performance.

current flows. The outer register generally had the greatest effect on flame length with a tightly closed setting resulting in a decreased flame length. All the impellers were tested at the B&W zero or baseline position and adjustments were made in both directions to determine the effects on flame length. The following iterative modifications were made to the impeller to obtain a reasonable flame length.

1. B&W Baseline Impeller (@ 37^{o}).
2. Dual cone design with no swirl blades.
3. Dual cone design with 6 blades @ 25^{o}.
4. Large single cone with 6 blades @25^{o}.
5. 4" support pipe with four 4" blades @25^{o}.
6. 4" support pipe with four 6" blades @ 30^{o}.
7. 4" support pipe with four 8" blades @ 30^{o} with an effective twist.

The final design resulted in unstaged flames of about 16 feet in length. At staged conditions (SR_B = 0.70) the flame length increased to approximately 22 feet. These resultant lengths were acceptable for continued operation.

The final optimization test involved changing the direction of spin on the inner register. Due to high windbox pressures of about 10 and 5 inches of H_2O respectively on the inner and outer secondary passages, it was not possible to make register adjustments while running the burner. Therefore, since flame length was the major concern, two alternate positions were tried to determine the optimum performance.

The optimum configuration of the 120 x 10^6 Btu/hr DMB was determined to be:

- Spreader Design = 4 inch support pipe with four 8 inch blades at a 30^{o} angle from axial.

- Burner Settings: Inner Spin Vanes = 35^{o} Open clockwise

Outer Register = 10^{o} Open Clockwise
Spreader Position = 3 in. Retracted

These settings were utilized for all the 120 x 10^6 Btu/hr DMB performance characterization tests.

A series of tests was conducted with the two primary fuels, Utah coal and Illinois coal to determine the effects of excess air at unstaged operating conditions. The results are summarized in Figure 5-8. The effect of excess air is similar for both coals, with the Utah coal resulting in a reduction in NO_x of 12 ppm/percent excess air compared to 10 ppm/percent excess air for Illinois coal. Design point conditions at an overall stoichiometry (SR_T) = 1.20 yielded 640 ppm and about 625 ppm NO_x for Utah and Illinois coals, respectively. Illinois coal produced slightly higher CO emissions, approximately 43 ppm compared to about 36 ppm with Utah coal.

Figure 5-9 indicates the effect of staging on the DMB emissions. NO_x is reduced by approximately 58 percent at SR_B = 0.61. However, staging also increased the flame length from about 16-17 feet at unstaged conditions, to over 22 feet at SR_B = 0.61. Since this flame length is unacceptable for continued operation in the LWS, staging was decreased to SR_B = 0.70. This condition resulted in a 53 percent NO_x reduction with acceptable flame lengths of 21-22 feet. CO emissions were generally unaffected by staging. The baseline values at optimum conditions (SR_B = 0.70, SR_T = 1.20) were 300 ppm and 44 ppm for NO_x and CO, respectively. The effect of excess air at staged conditions was also evaluated, and results are shown in Figure 5-10. NO_x emissions were reduced by about 4 ppm/percent excess air with no significant change in CO emissions. However, carbon in ash was measured to increase from 2.8 percent unstaged to approximately 5.5 percent at SR_B = 0.7.

The DMB performance was also evaluated with two host coals, Comanche and Wyodak, and with Illinois coal. Figure 5-11 summarizes the effect of staging with these coals. The greatest effect was with the Wyodak coal, with a 55 percent decrease in NO_x as a result of staging to SR_B = 0.71, with no significant increase in CO. At SR_B = 0.71, flame lengths were 22 feet,

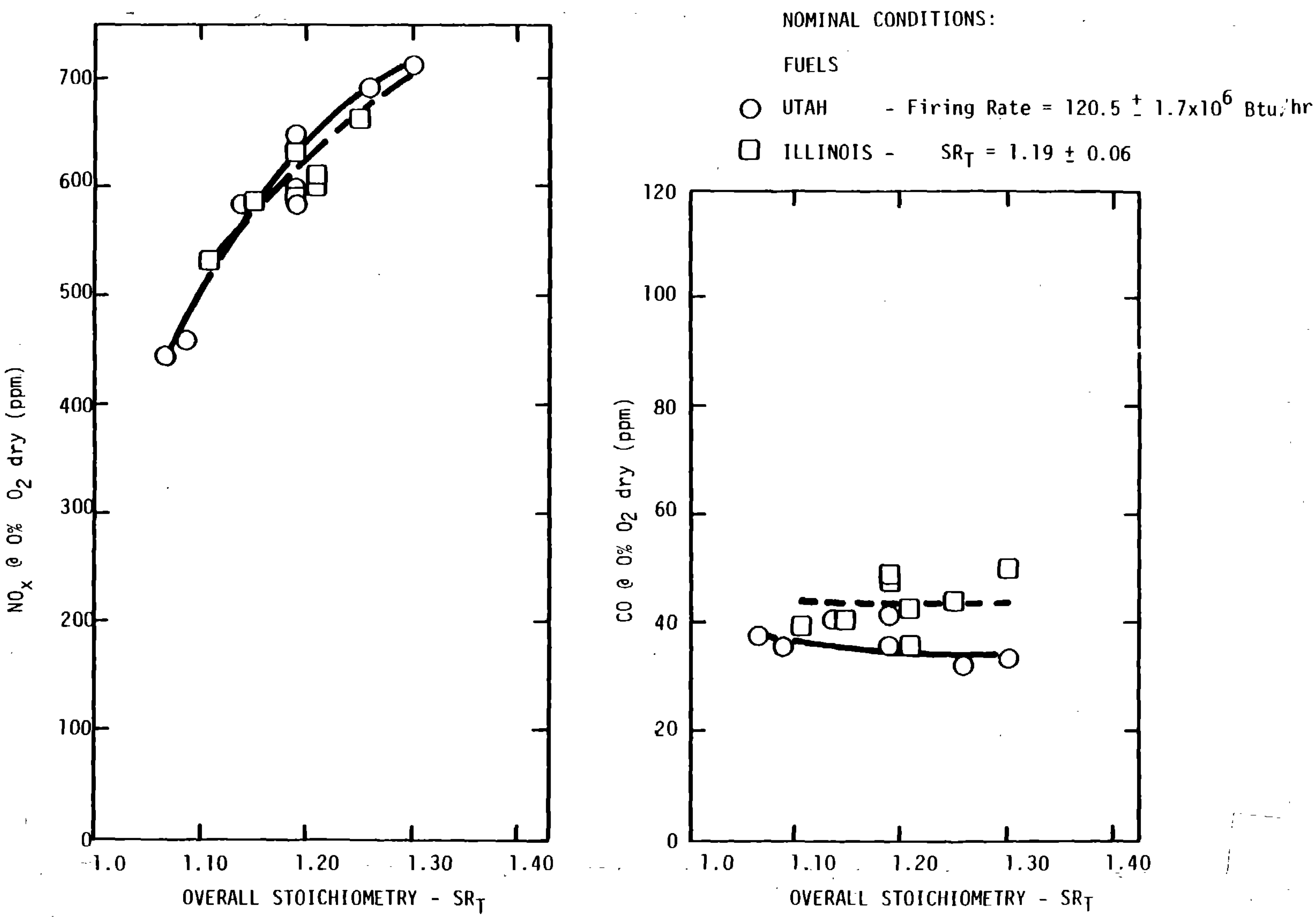


Figure 5-8. Summary of 120 x 10^6 Btu/hr DMB unstaged operation.

NOMINAL CONDITIONS
FUEL - UTAH
FIRING RATE = 122.0 ± 1.3 x 10^6 Btu/hr
SR_T = 1.20 ± 0.01

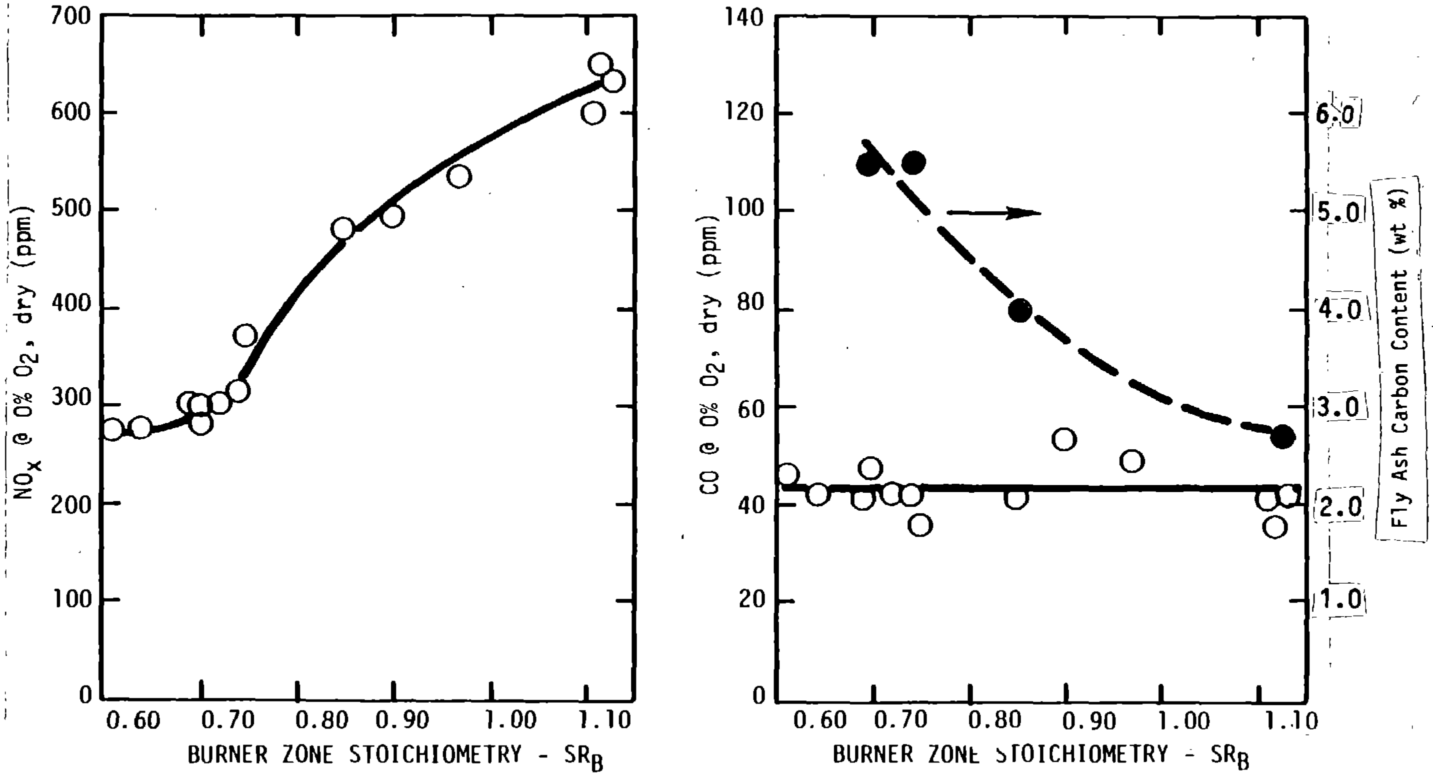


Figure 5-9. Effect of staging on 120 x 10^6 Btu/hr DMB with Utah coal.

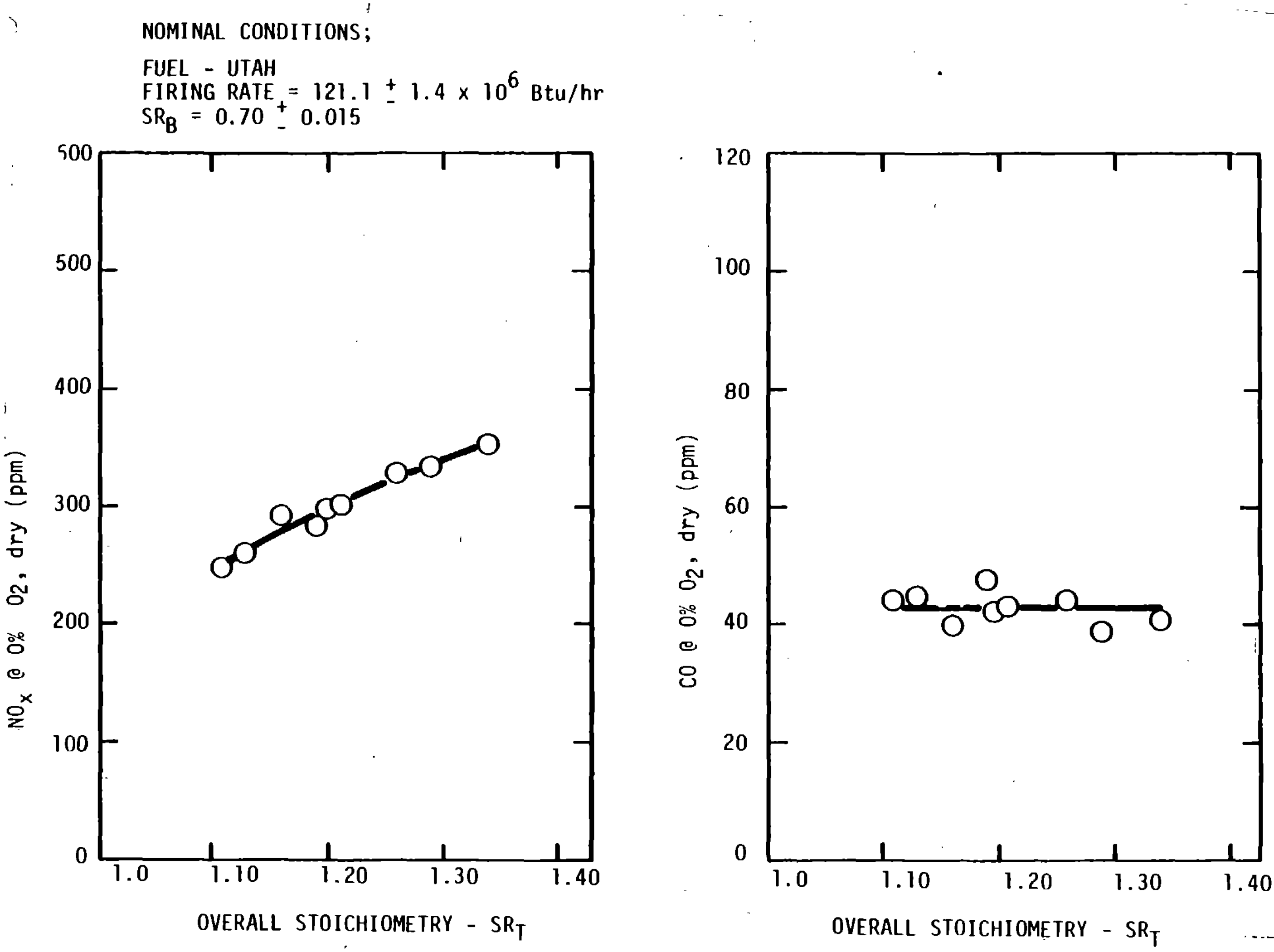


Figure 5-10. Effect of excess air on 120 x 10^6 Btu/hr DMB with Utah coal.

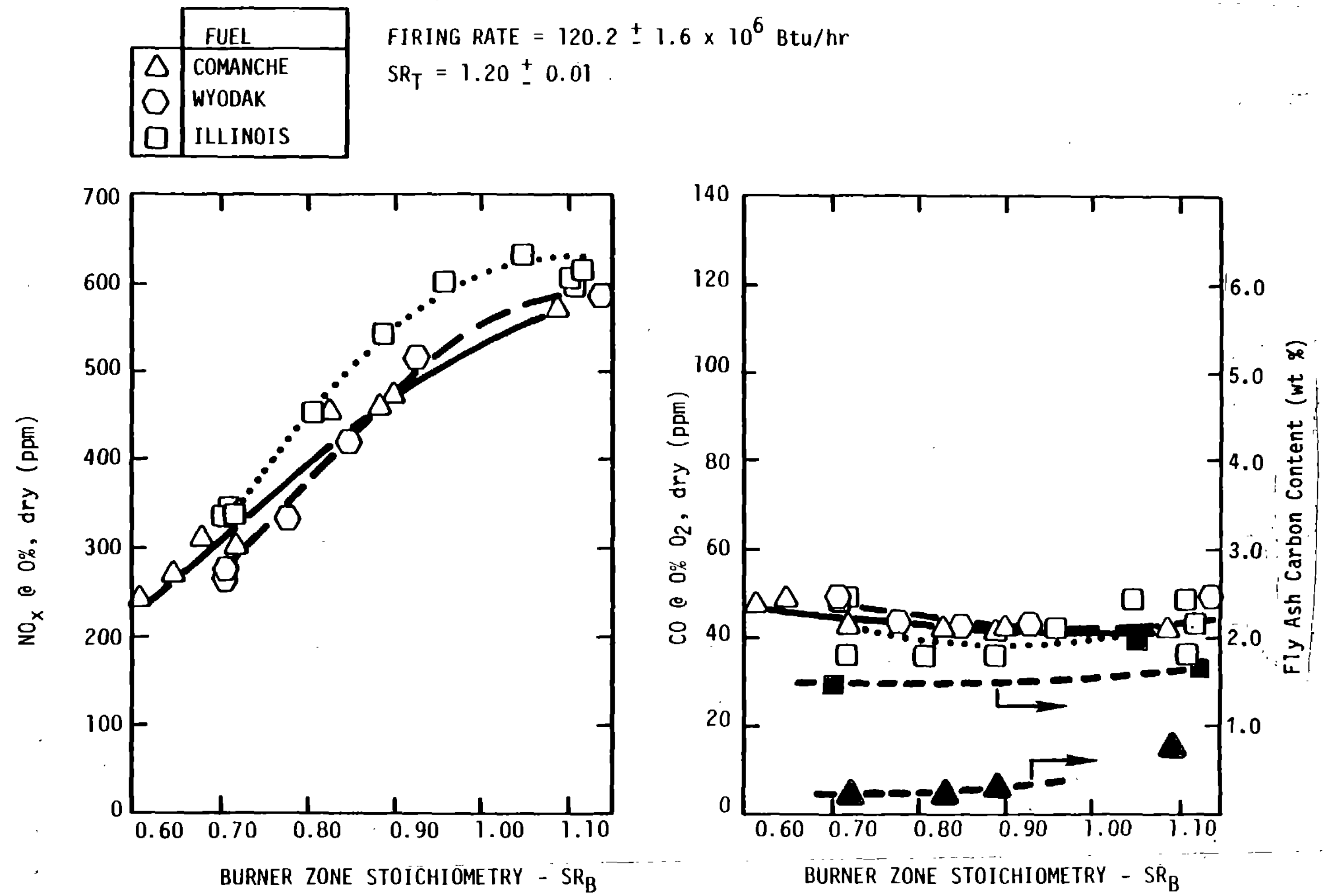


Figure 5-11. Effect of staging on 120 x 10^6 Btu/hr DMB with alternate host fuels.

therefore, no further staging was attempted. Overall NO_x emissions were lowest using the Wyodak coal under optimum conditions, with NO_x = 270 ppm and about 48 ppm CO.

With Comanche coal, NO_x emissions were decreased by 53 percent as a result of staging to SR_B = 0.65 with only a slight increase in CO emissions. Below SR_B = 0.65, the flame increased to over 22 feet and NO_x was reduced by approximately 3 percent. At design point SR_B = 0.70 and SR_T = 1.20, emissions were 300 ppm NO_x and 45 ppm CO. NO_x emissions were similar to Utah coal emissions, and about 30 ppm higher than achieved with the Wyodak coal. With Comanche coal the carbon in ash remained at low levels throughout the staging range.

Staging had the least effect on Illinois coal resulting in a 44 percent reduction to SR_B = 0.71 with no increase in CO emissions. At optimum conditions, NO_x emissions were highest with Illinois coal at 340 ppm. This is 40 ppm higher than Utah and Comanche coals and about 70 ppm higher than Wyodak fuel.

Figure 5-12 summarizes the effect of excess air for operation on the alternate fuels under staged conditions. The greatest effect was with Illinois coal with a 4 ppm/percent excess air reduction in NO_x with a slight increase (less than 10 ppm) in CO. The effect of excess air with Comanche and Wyodak coals were similar but less pronounced than Illinois or Utah coals, with about a 3 ppm/percent excess air reduction in NO_x and no increase in CO emissions.

Further tests were conducted to determine the turndown capabilities of the 120 x 10^6 Btu/hr DMB, and Figure 5-13 shows the effect of load reduction on unstaged operation with Utah and Illinois coals. Results are similar, with a reduction in NO_x of about 21 percent for both fuels with no increase in CO emissions. With Utah coal, the minimum firing rate was 72 x 10^6 Btu/hr, which represents a turndown capability of about 40 percent. The flame was stable and decreased in length to about 14 feet with NO_x emissions of 454 ppm. With Illinois coal, the minimum firing rate was 65 x 10^6 Btu/hr or

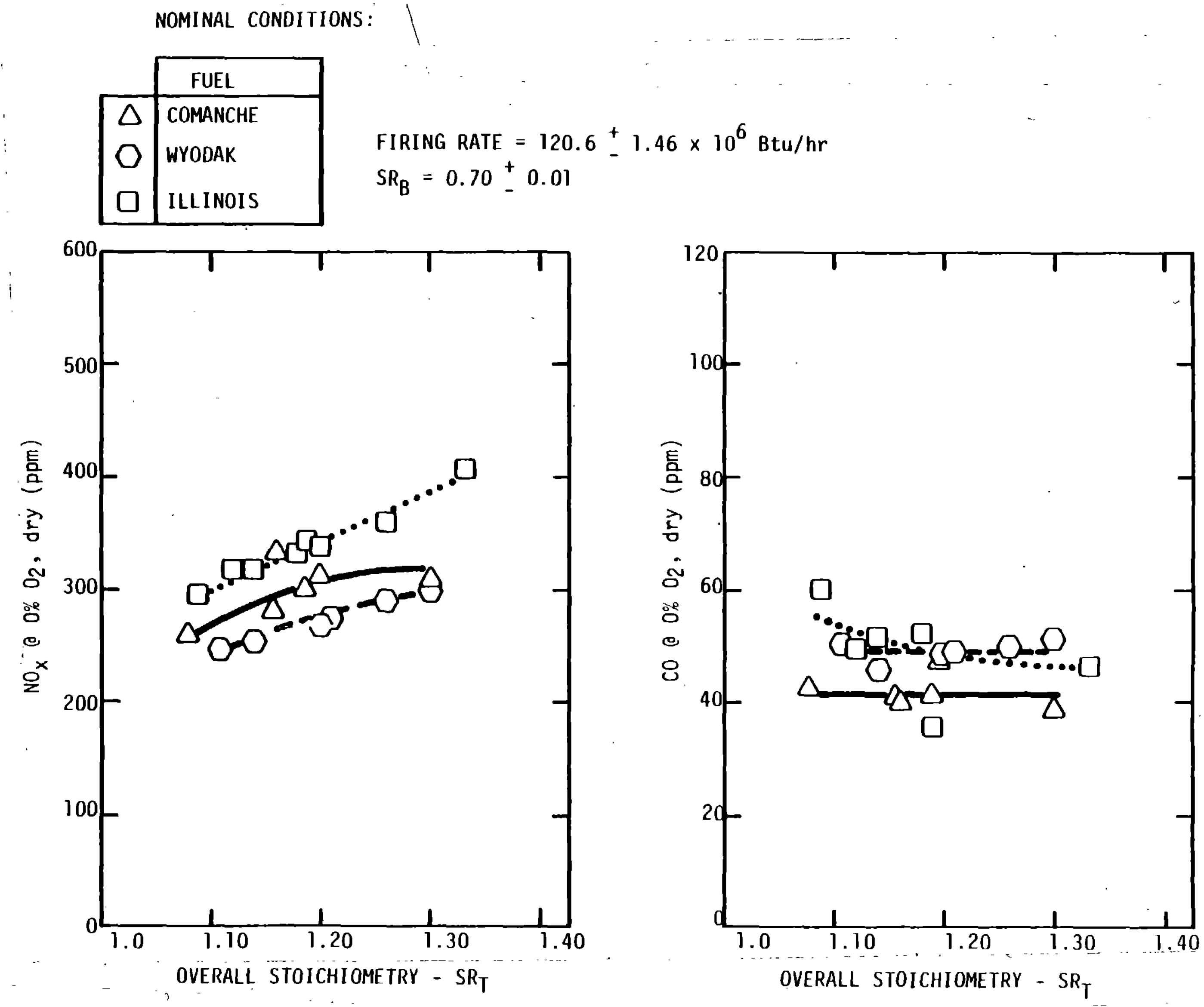


Figure 5-12. Effect of excess air on 120 x 10^6 Btu/hr DMB staged operation with alternate host fuels.

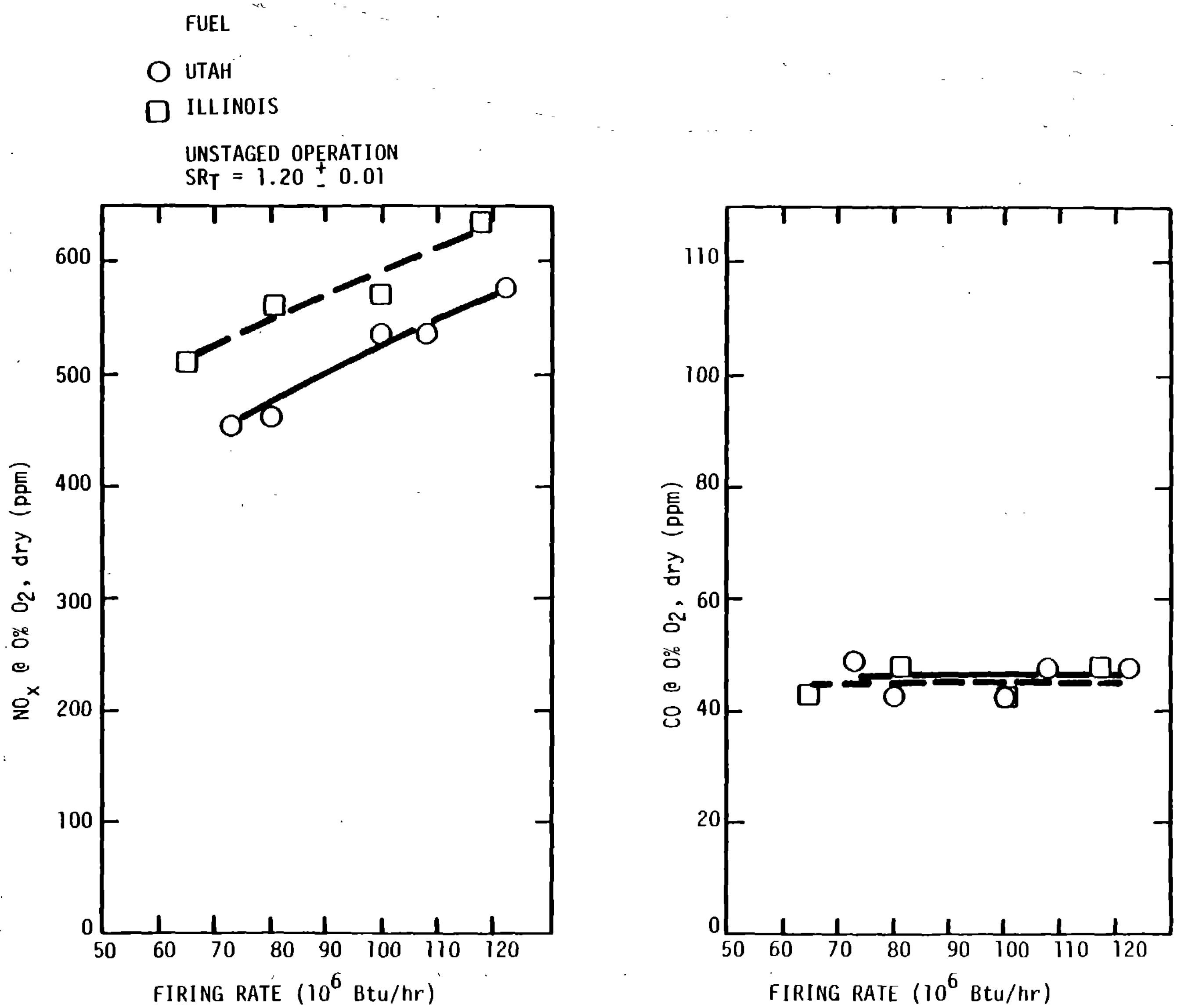


Figure 5-13. Effect of firing rate on DMB 120 x 10^6 Btu/hr DMB unstaged operation.

a 45 percent turndown capability. The resulting flame was stable with a shorter flame of 10-12 feet and NO_x emission of 510 ppm. Burner operation at firing rates below those referenced above was found to result in a deterioration in flame stability performance.

A more detailed evaluation of reduced load operation was conducted with Illinois coal and is summarized in Figures 5-14 and 5-15. Figure 5-14 shows the effect of staging with reduced load. NO_x is decreased by 30.2 percent as staging is increased to SR_B = 0.71. This is significantly less than the full load effect. However, at SR_B = 0.7, NO_x emissions are similar at both full and reduced load operation with at about 340 ppm. CO emissions are slightly higher at reduced load, approximately 50 ppm. The effect of excess air at reduced load is slightly greater when compared to full load, with a 7 ppm/percent excess air decrease in NO_x and a 15 ppm increase in CO emission as shown in Figure 5-15. At baseline staged conditions, the resulting flame was stable and approximately 16-17 feet long.

5.4 60 x 10^6 Btu/hr DMB in Baseline LWS

The 60 x 10^6 Btu/hr DMB was initially tested in the "improper" high velocity outer secondary configuration. The so called short flame version used a coal impeller similar in design to the device used in the pre-NSPS Circular burner. A long flame arrangement, using a coal diffuser instead of impeller, was also tested. The tests of the two initial 60 x 10^6 Btu/hr DMBs were conducted in the baseline LWS.

5.4.1 Evaluation of Initial DMB with Impeller

The 60 x 10^6 Btu/hr DMB was initially tested with the coal impeller at its baseline position in the coal nozzle as defined by B&W. A series of tests were conducted with Utah Coal to determine the effect of register adjustments on unstaged performance. For unstaged operation, the registers effectively acted as flow control devices. Due to the increased pressure drop through each secondary passage as the registers were closed, it was not possible to operate at unstaged conditions with the registers at more than

NOMINAL CONDITIONS:
FUEL - ILLINOIS
FIRING RATE = 64.9 $\pm$ 1.4 x 10^6 Btu/hr
SR_T = 1.20 $\pm$ 0.01

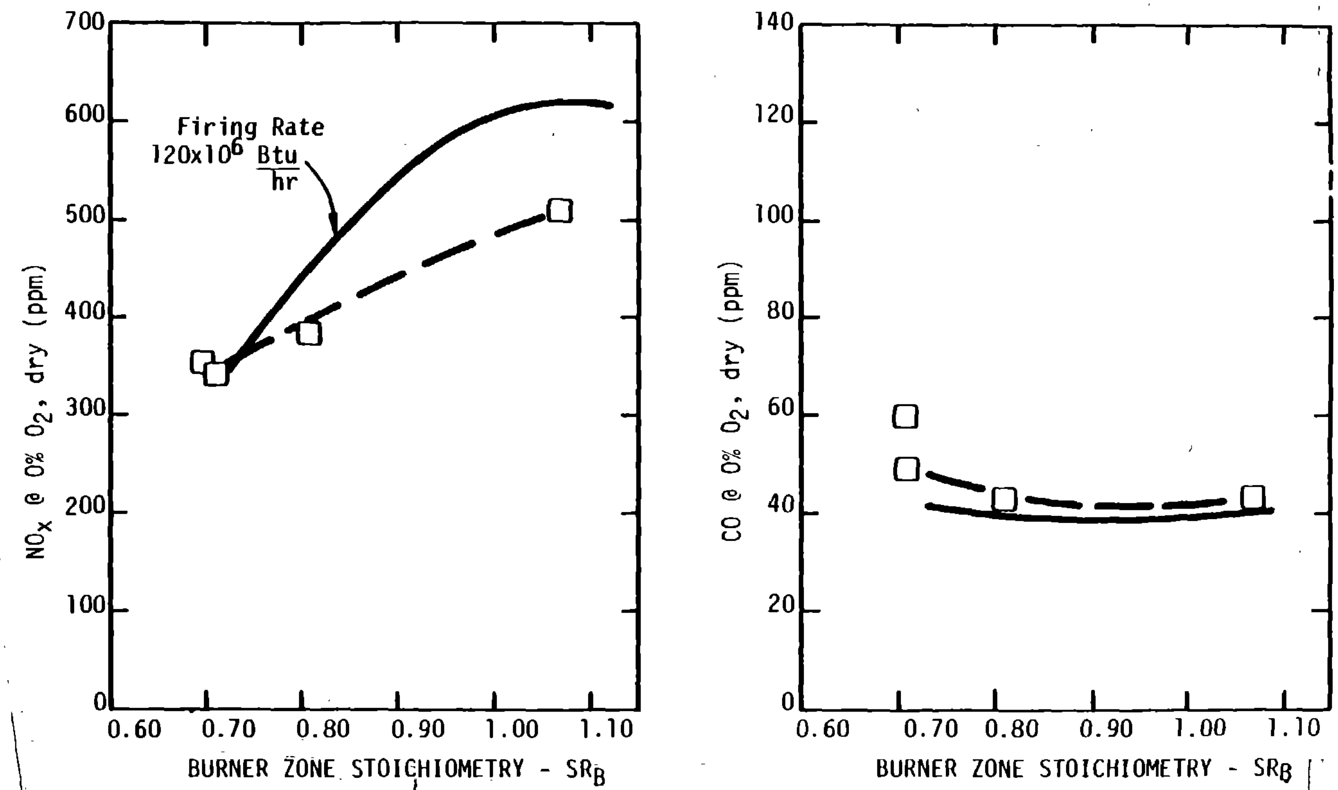


Figure 5-14. Effect of staging on 120 x 10^6 Btu/hr DMB at reduced load.

NOMINAL CONDITIONS:

FUEL - ILLINOIS
FIRING RATE = 65.4 ± 1.8 x 10^6 Btu/hr
SR_B = 0.71 ± 0.01

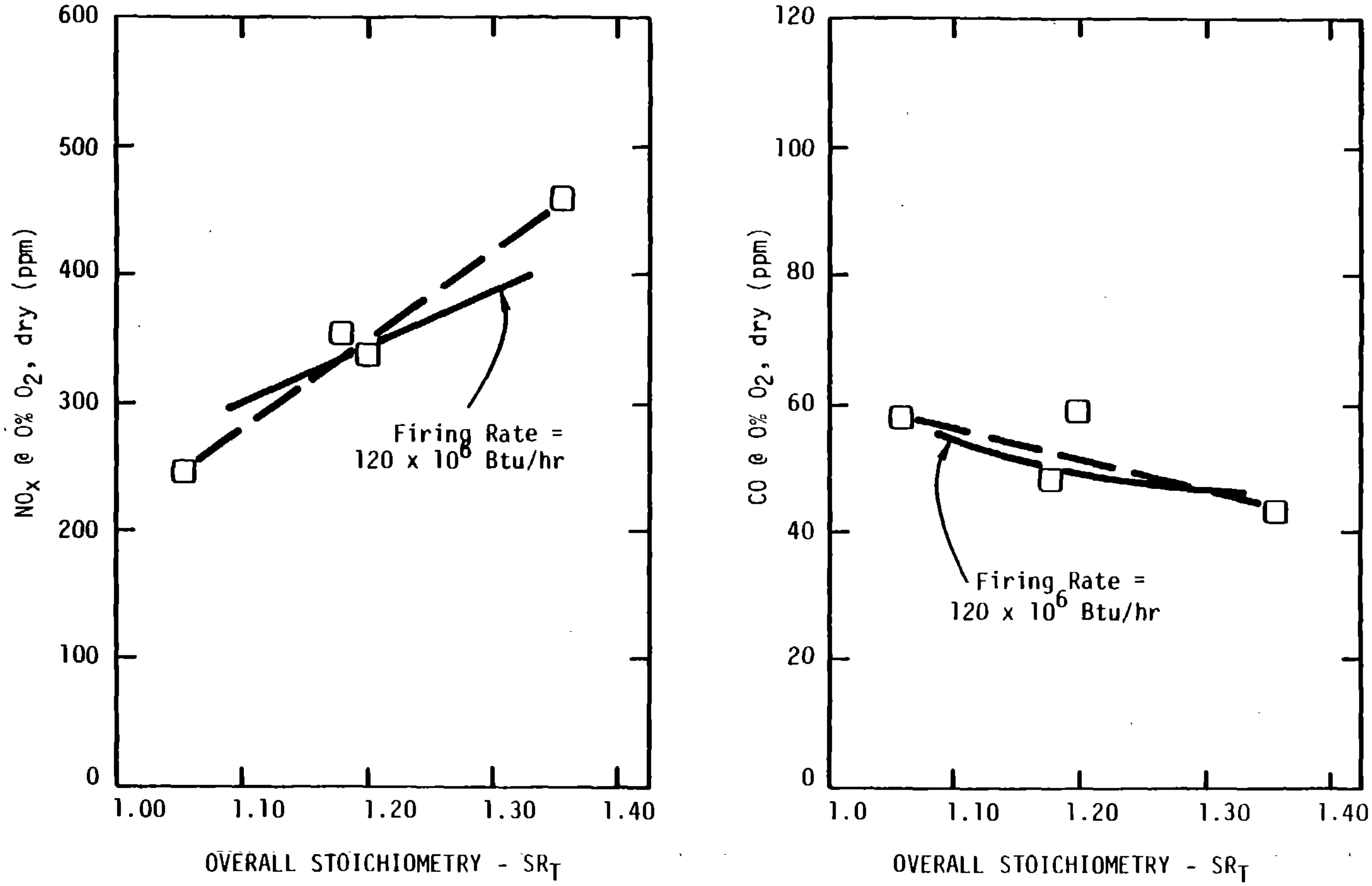


Figure 5-15. Effect of excess air on 120 x 10^6 Btu/hr DMB at reduced firing rate.

40^o and 30^o closed on the inner and outer registers, respectively. Figure 5-16 shows the effect of excess air on unstaged performance at these burner settings. NO_x emissions decreased by about 10 ppm/percent theoretical air. CO emissions were minimum 65 ppm, at an overall stoichiometry (SR_T) of about 1.18. Either a reduction or an increase in total air from this point resulted in an increase in CO emissions. The flame was stable throughout the range tested with resulting flame lengths of about 14-16 feet.

An extensive test series was conducted to determine the optimum burner settings for the 60 x 10^6 Btu/hr DMB at staged conditions. Figures 5-17 and 5-18 show the effects of register adjustment on emissions and flame length. Optimum settings were 20^o open counter clockwise and 10^o open on the inner and outer registers, respectively. These settings resulted in a reversed flow pattern with counter-clockwise flow through the inner passage and clockwise flow through the outer passage. The flame was stable throughout the range of adjustment with lengths ranging from 16-20 feet.

The effect of staging by diverting air through the tertiary ports is shown in Figure 5-19. To more fully characterize the effect of staging, two different burner settings were used, since the above optimum register settings precluded operation of the burner unstaged. By opening the inner register to 40^o (CCW) a wider range of staging was achievable. Generally, the results are comparable with both settings. Staging the burner resulted in a decrease of NO_x emissions of 10 ppm/percent decrease in burner zone stoichiometry (SR_B) with no effect on CO emissions. At design point, SR_B =0.70 NO_x was 390 ppm and CO was 60 ppm. The flame was stable, rooted within the burner exit, with the main body of the flame about 16-17 feet in length. However, the flame was not well-defined with combustion appearing to occur throughout the entire length of the furnace with evidence of flame licking the rear wall. Figure 5-20 summarizes the effects of excess air on burner performance. NO_x was reduced by approximately 8 ppm/percent excess air. CO emissions were not significantly effected by excess air, remaining stable at about 75 ppm down to an excess air level of 7 percent. Compared to the 120 x 10^6 DMB performance, unburned carbon was found to be high and ranged between 8 percent and 12 percent for optimum staged conditions. A

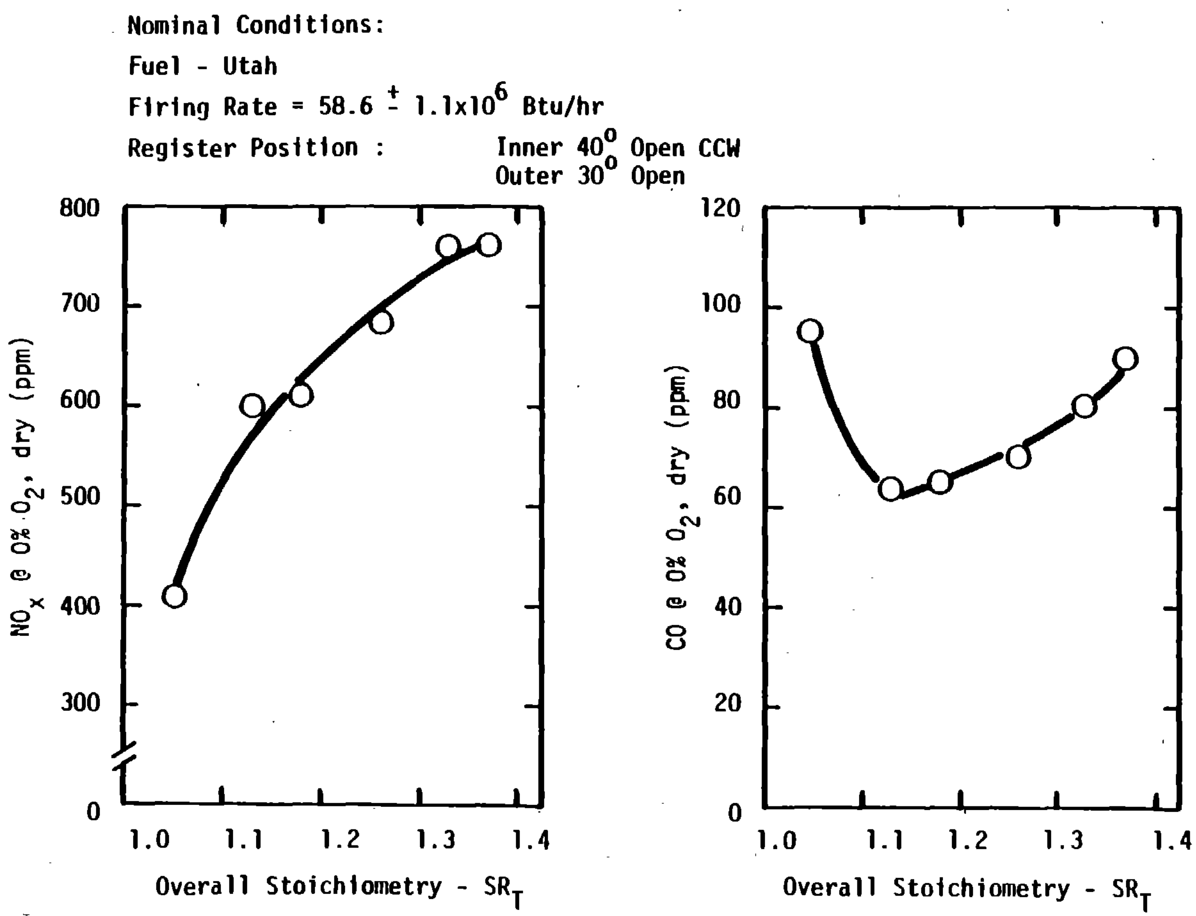


Figure 5-16. Effect of excess air on unstaged 60 x 10^6 Btu/hr DMB performance.

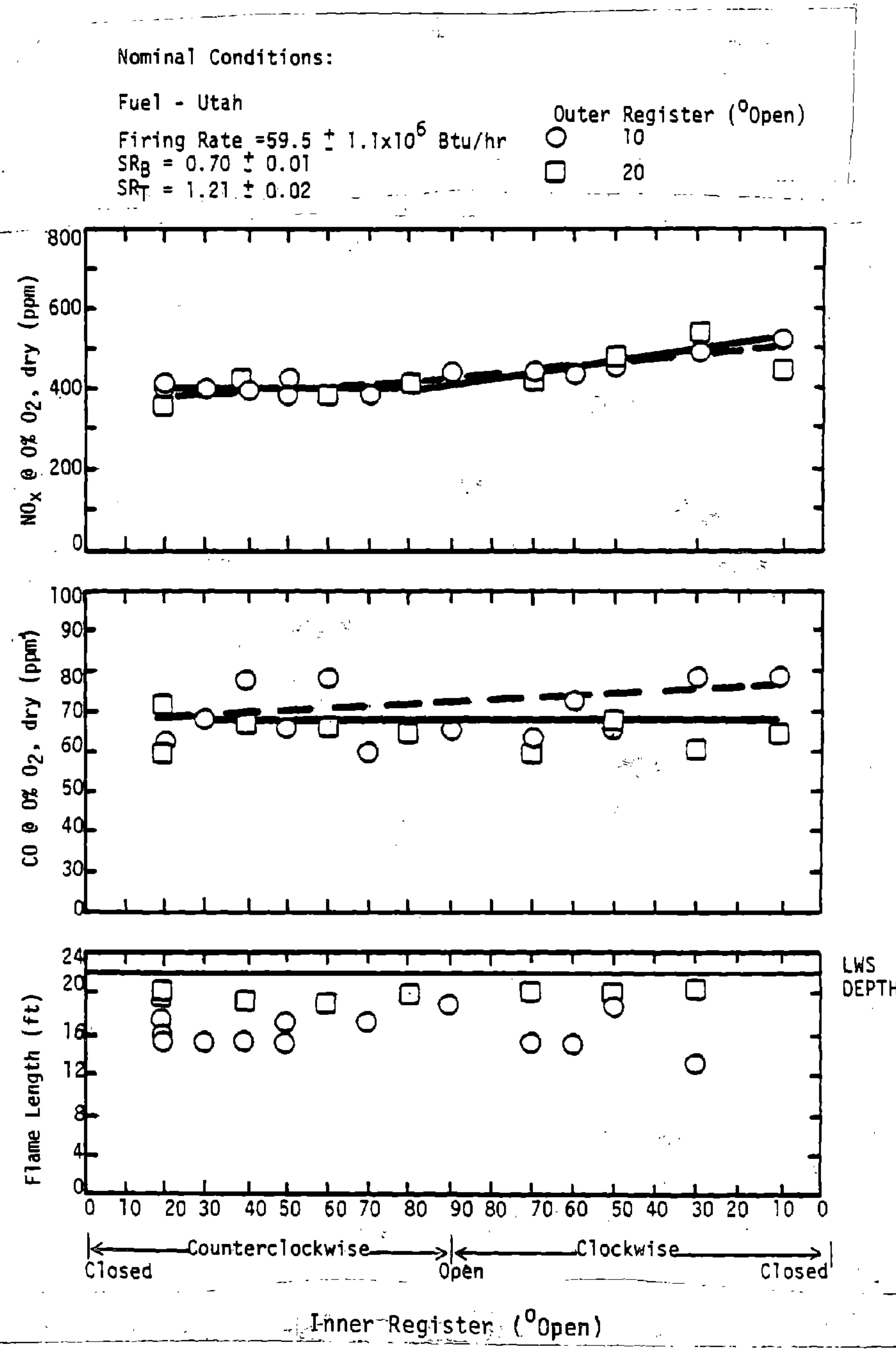


Figure 5-17. Effect of inner register on 60 x 10^6 Btu/hr DMB staged performance.

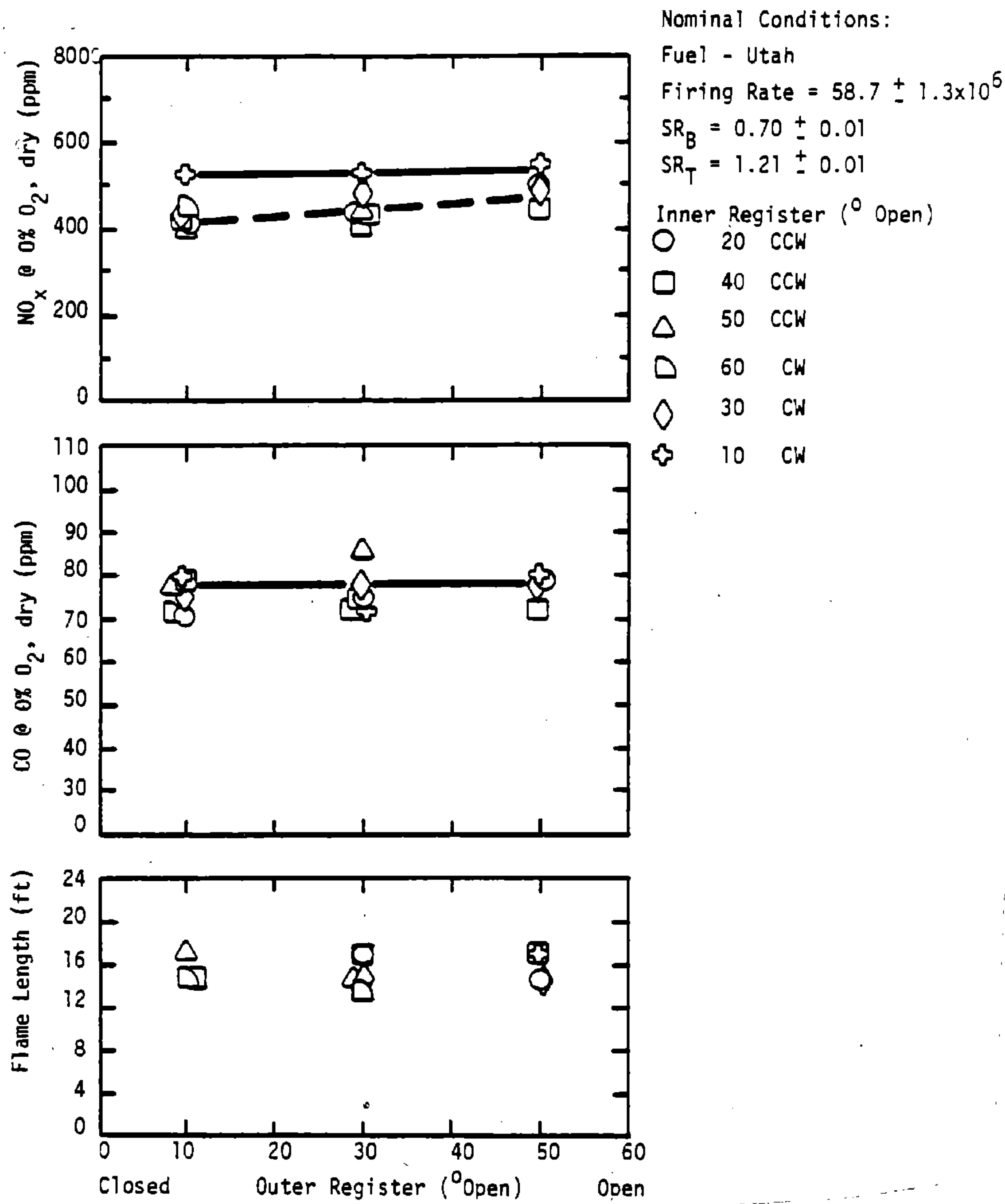


Figure 5-18. Effect of outer register on 60 x 10^6 Btu/hr DMB staged performance.

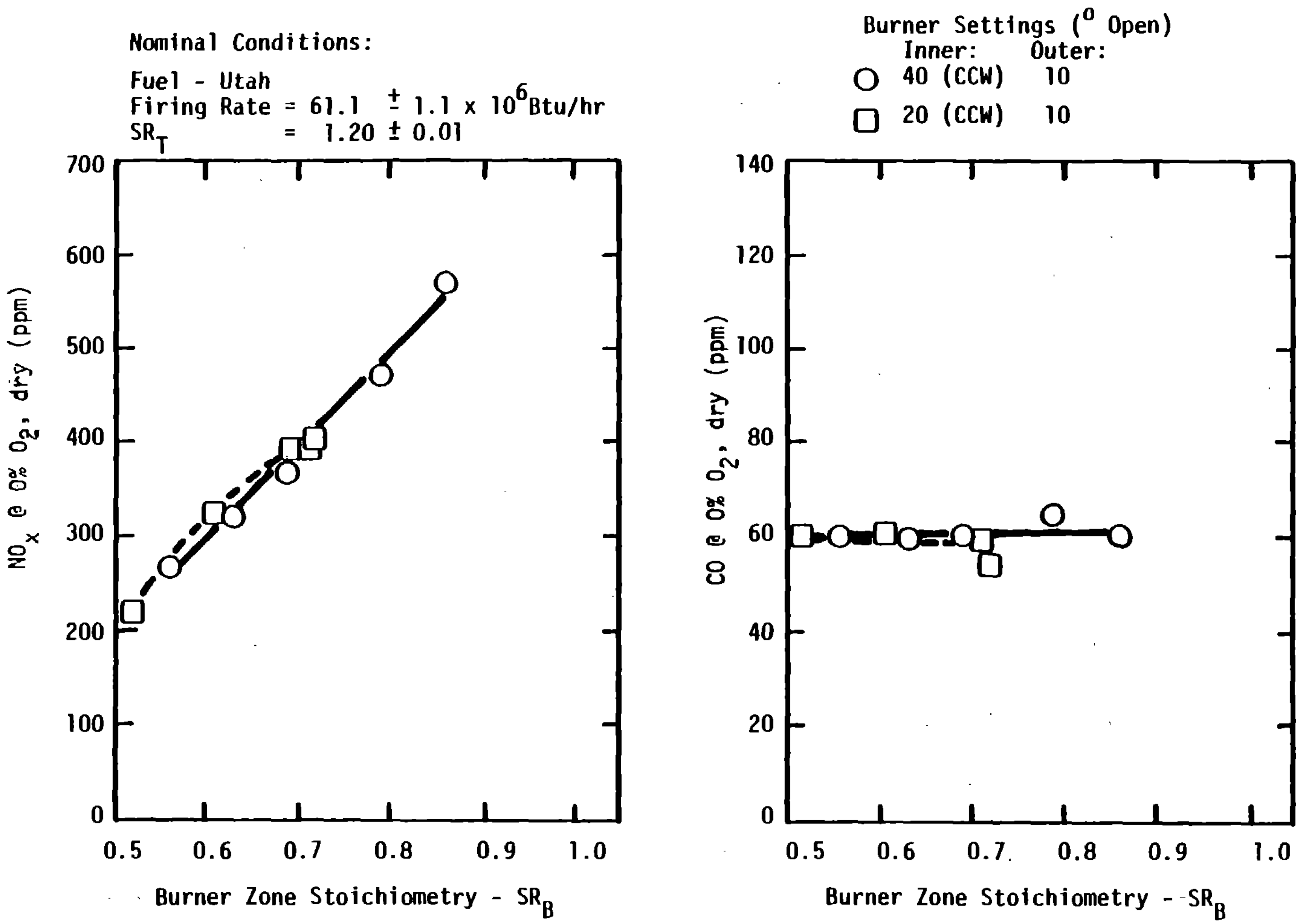


Figure 5-19. Effect of staging on 60 x 10^6 Btu/hr DMB performance.

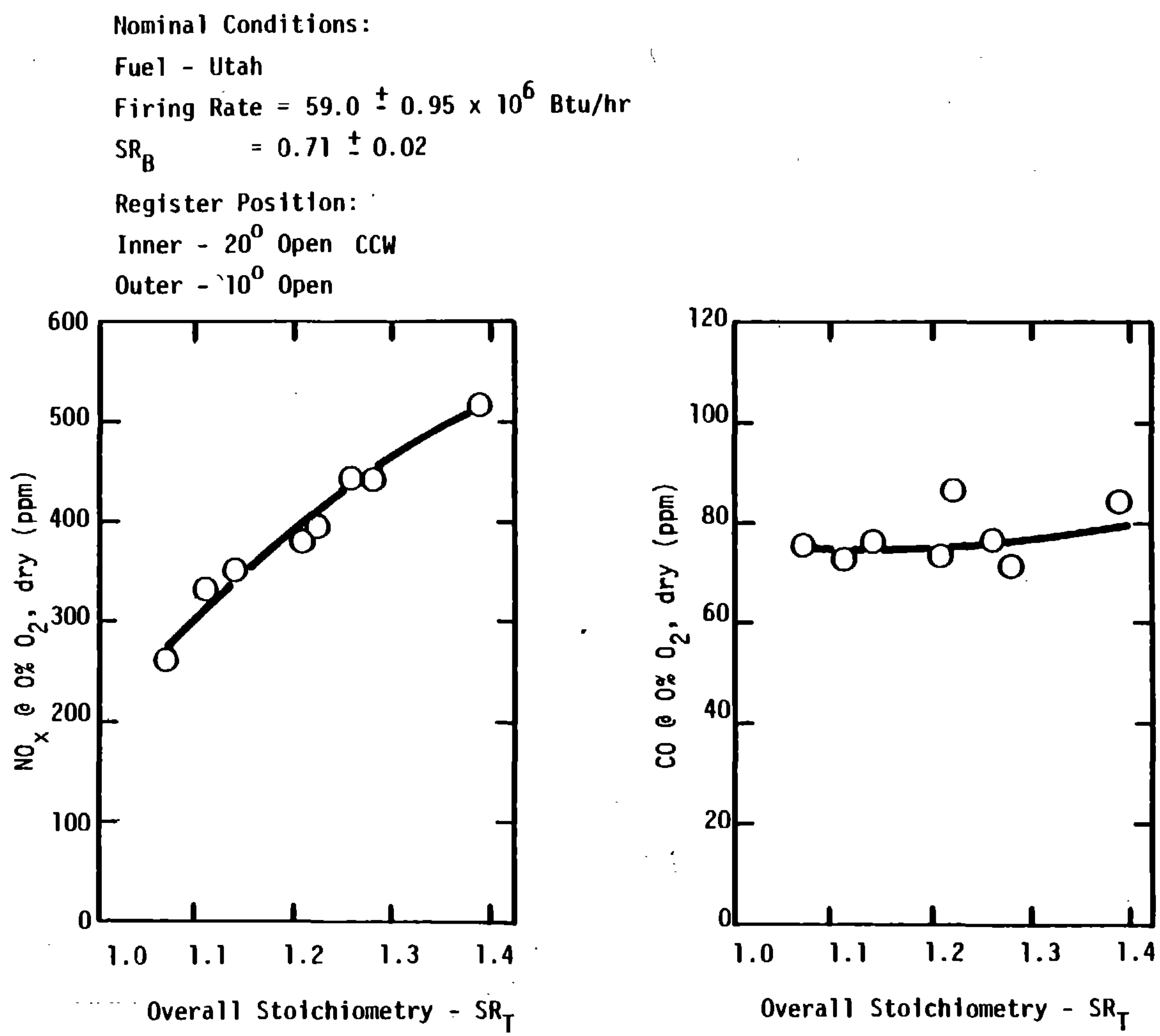


Figure 5-20. Effect of excess air on 60 x 10^6 Btu/hr DMB performance.

contributory factor here is believed to be the relatively cold furnace environment.

The 60 x 10^6 Btu/hr DMB performance with two host coals, Comanche and Wyodak, and with Illinois Coal was also evaluated. Figure 5-21 summarizes the significant effect of staging with the Comanche Coal. Increasing staging from SR_B = 0.82 to SR_B = 0.65 reduced NO_x emissions by about 19 ppm/percent theoretical air. At design point operation (SR_B = 0.70 NO_x was 420 ppm, approximately 30 ppm higher than with Utah Coal. The CO emissions for the Comanche Coal were low at 43 ppm throughout the range tested, significantly lower than the corresponding emissions with Utah coal. The flame length was shorter (13-14 feet), but lacked the intensity of the Utah flame.

Initial tests with the Wyodak Coal presented problems in flame stability and operational difficulties. At optimum conditions, the flame was detached about 10-12 feet from the burner exit. The flame could not be retracted with the burner adjustments available. A second attempt to fire the Wyodak Coal was made at a later date, with the furnace heated by previous tests with another coal. With these furnace conditions, it was possible to maintain a flame stabilized within the burner exit. The reasons for this change in performance are not clear, but are probably due to the characteristics of the subbituminous Wyodak Coal and the furnace thermal environment. Decreased primary air flow, resulting from increased mass flow of coal to achieve design firing capacity limited operating range to an SR_B of 0.65. (A similar but less severe problem was also encountered with the Comanche coal.) At these conditions NO_x and CO emissions were 445 and 49 ppm, respectively. The flame was dull in color and approximately 14-15 feet in length.

Since the two host sites utilize low sulfur coals and the baseline Utah coal is also low in sulfur, high sulfur Illinois Coal was evaluated to provide data which would be applicable to eastern U.S. boilers burning high sulfur fuels. Figure 5-22 summarizes the effect of staging with the Illinois coal. NO_x emissions were reduced by 12 ppm/percent decrease in SR_B. Optimum conditions at an SR_B of 0.65 resulted in NO_x and CO emissions of 350 ppm and

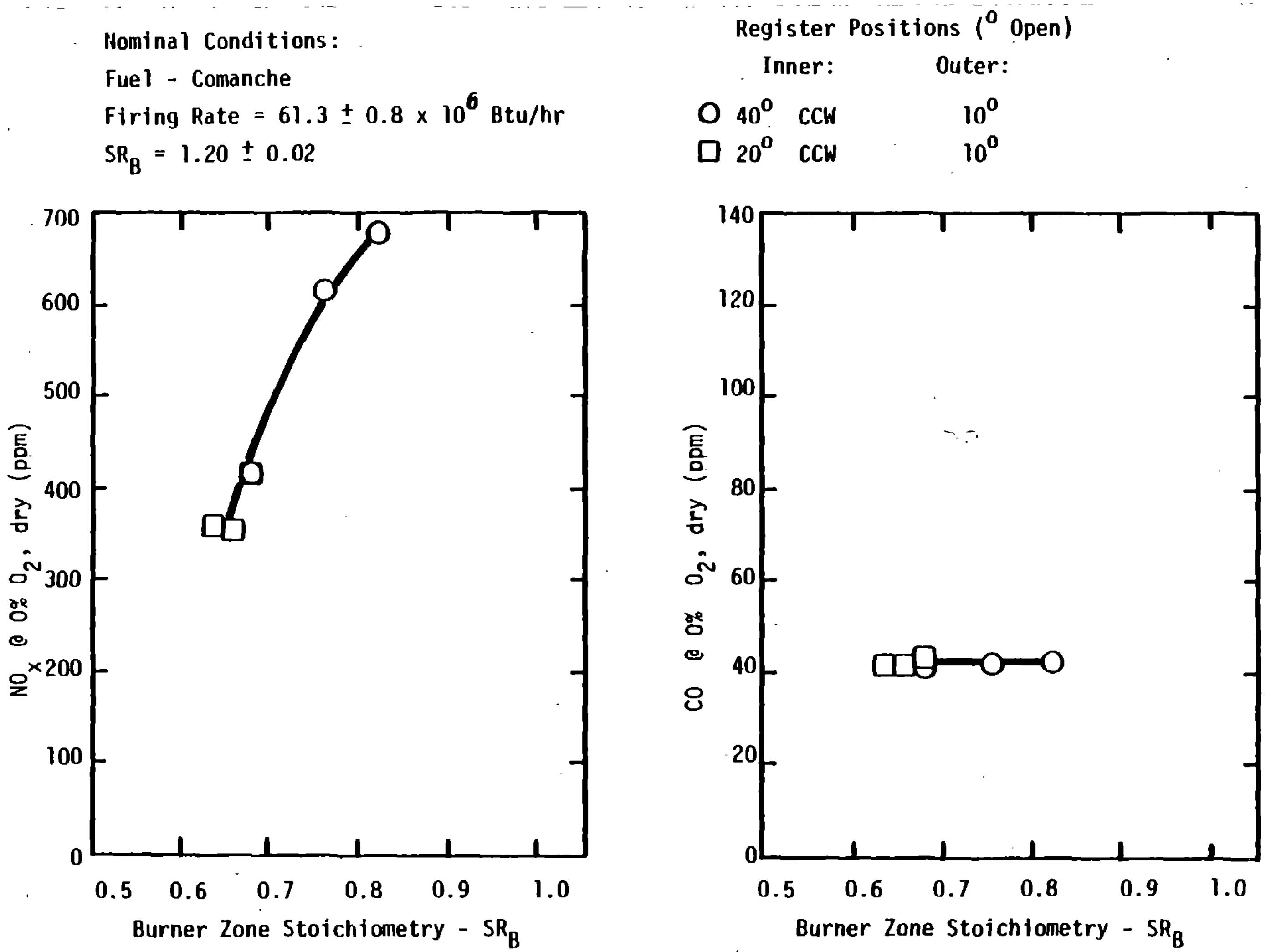


Figure 5-21. Effect of staging on 60 x 10^6 Btu/hr DMB with Comanche coal.

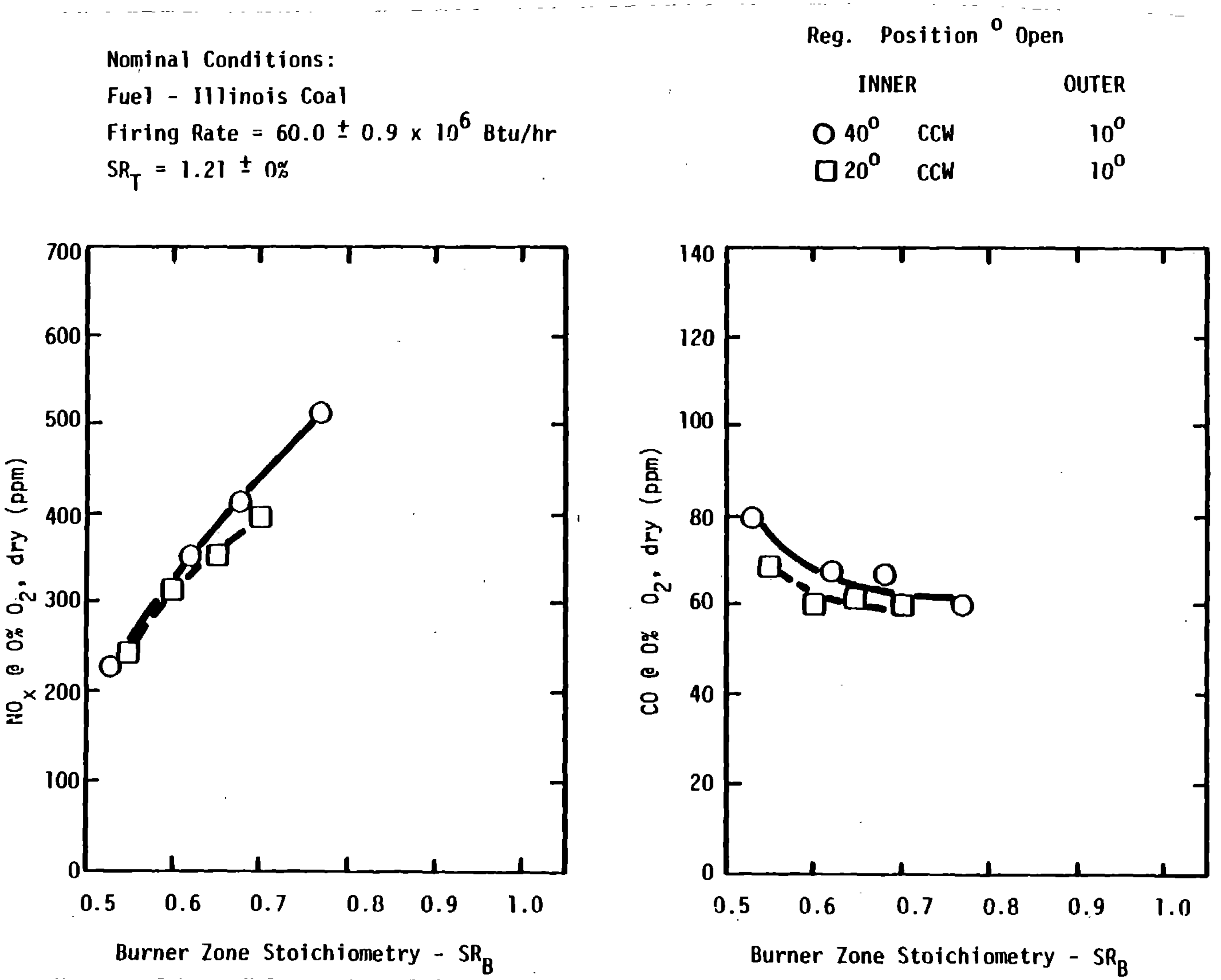


Figure 5-22. Effect of staging on 60 x 10^6 Btu/hr with Illinois coal.

61 ppm, respectively. The flame was stable throughout the range tested with length of approximately 19-21 feet.

The effect of excess air on the alternate fuels is summarized in Figure 5-23. Excess air had a similar effect on Illinois and Comanche Coal with a reduction in NO_x emissions of approximately 9 ppm/percent excess air. NO_x emissions for Wyodak were about 80 ppm higher than with Illinois, but as excess air was reduced, the difference in emissions was less than 15 ppm. The highest CO emissions of 65 ppm resulted for the Illinois Coal, with the characteristic CO "knee" at $SR_1 = 1.13$. The host coals showed considerably lower CO levels, typically less than 50 ppm, and good carbon burnout.

Key results at optimum conditions for the impeller equipped 60×10^6 Btu/hr DMB are summarized in Table 5-1.

5.4.2 Evaluation of Initial DMB with Coal Diffuser

The long flame configuration of the 60×10^6 Btu/hr DMB was achieved by installing a coal diffuser back in the coal pipe near the coal inlet of the burner in place of the impeller used for the short flame design. Long flame developmental DMBs were found to produce lower NO_x emissions than DMBs which produced shorter flames. However, long flame burner designs could only be used in installations which could accommodate the long flames, such as boilers which utilize opposed-fired B&W Dual Register Burners (DRBs). A brief series of tests was conducted with Utah coal to optimize burner performance with regard to emissions and flame characteristics.

The effect of register adjustment on staged burner performance is summarized in Figure 5-24. The flame was over 22 feet long, the firing depth of LWS, and 6-8 feet wide throughout the entire range of register adjustment. The tests of the short flame DMB 60 indicated that flame length was most sensitive to outer register position. The flame could be shortened by closing the outer register and this decreased the degree of swirl. With this long flame configuration, however, even register settings of only 20° and 10° open produced excessive flame length. Attempts to shorten the flame by

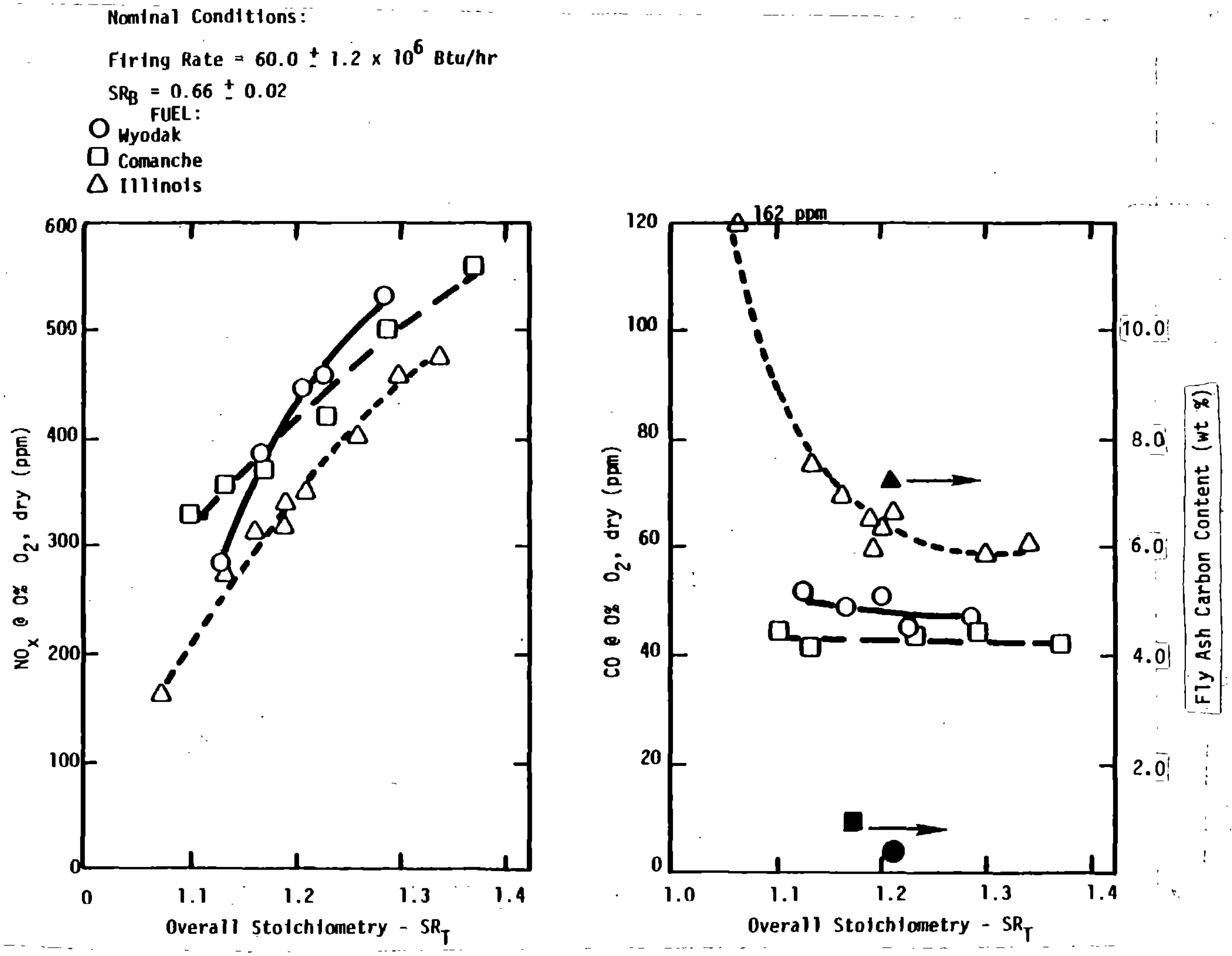


Figure 5-23. Summary of effect of excess air on 60 x 10^6 Btu/hr DMB staged performance.

TABLE 5-1. SUMMARY OF THE 60 x 10^6 Btu/hr DMB SHORT FLAME BURNER OPTIMUM CONDITIONS

Test No.	Fuel	Firing Rate (10^6 Btu/hr)	SR_B	SR_T	NO_x, ppm (0% O_2)	CO, ppm (0% O_2)	Flame Length (ft)
3.10	Utah	61.1	0.69	1.19	390	60	16-17
9.02	Wyodak	59.4	0.66	1.21	449	49	13-14
4.02	Comanche	61.1	0.68	1.23	420	43	12-14
6.07	Illinois	59.8	0.65	1.21	348	61	19-21

Note: OPTIMUM BURNER CONDITIONS:

Inner Register - 20^{o} Open CCW

Outer Register - 10^{o} Open CW

Spreader - 0

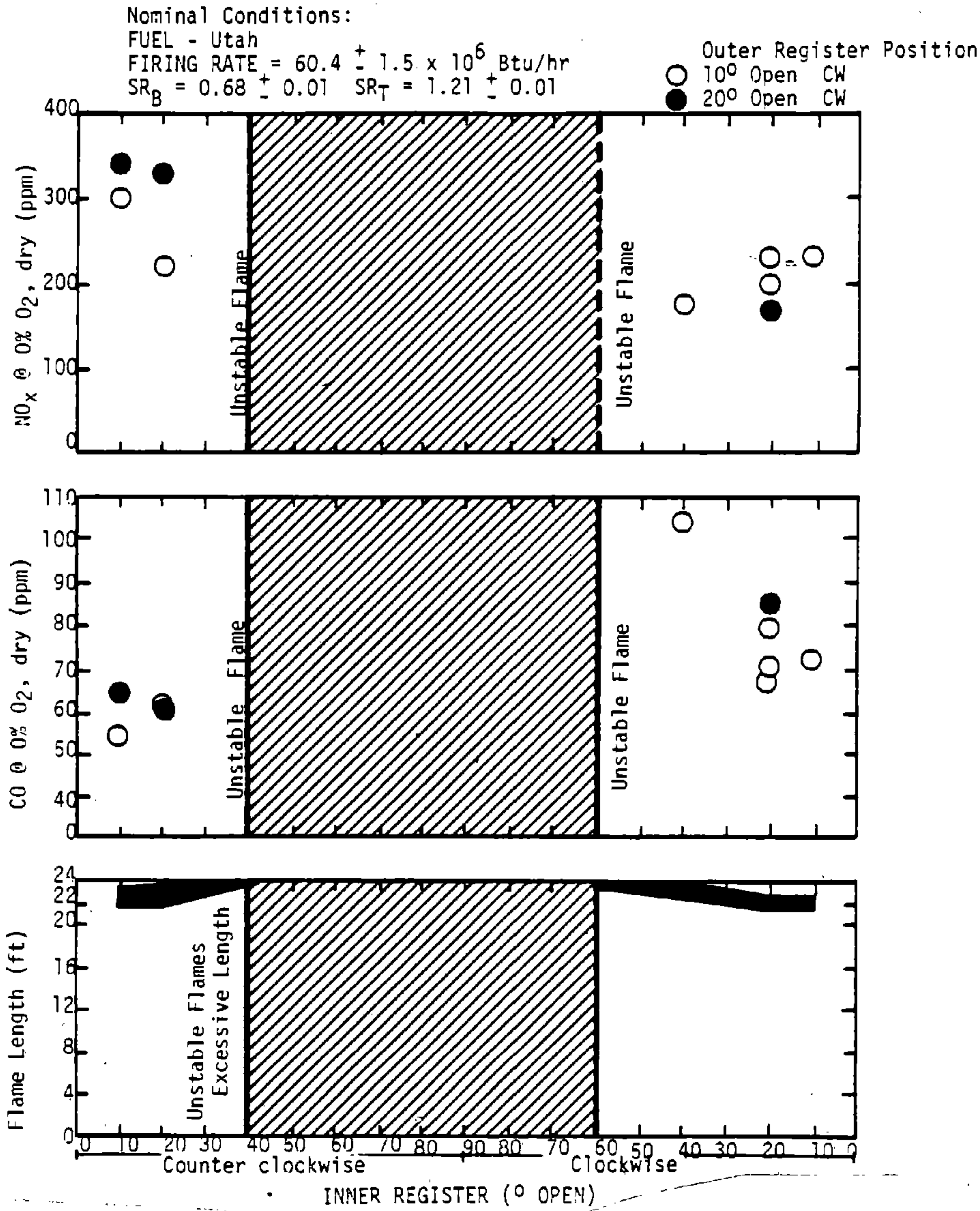


Figure 5-24. Effect of register adjustment on diffuser equipped DMB performance.

creating counter flow between the two secondary air passages were not successful. Opening the inner register to a position of 40^{o} open ore more resulted in unstable flames of even greater length. The best overall performance was achieved with the inner register set to 20^{o} open clockwise and the outer register at 10^{o} open. However, even these settings produced a flame which impinged on the rear wall of the LWS.

To avoid potential damage to the facility, the tests were abbreviated and only Utah coal was evaluated. The effect of staging on emissions from the long flame 60 x 10^6 Btu/hr DMB is shown in Figure 5-25. NO_x emissions decreased by 13 ppm/percent theoretical air as staging was increased from SR_B = 0.86 to SR_B = 0.61. The CO emissions increased by approximately 30 ppm over the same range of staging. The flame was stable throughout the range tested with the minimum length of 21-22 feet at SR^B = 0.86. At design point conditions SR_B = 0.70 NO_x and CO emissions were 230 ppm and 63 ppm respectively. This long flame design resulted in a 41 percent reduction in NO_x emissions from the short flame configuration with no significant change in CO emissions.

Figure 5-26 shows the effect of excess air on the long flame DMB 60. NO_x emissions decreased at about 6 ppm/percent excess air. The CO emissions were minimum at the design point SR_T = 1.2, at about 62 ppm.

5.5 60 x 10^6 Btu/hr DMB in Insulated LWS

5.5.1 Characterization of Initial DMB with Impeller

Additional insulation was installed above the baseline refractory up to the nose of the LWS to produce a thermal environment at 60 x 10^6 Btu/hr input similar to that produced in the baseline configuration at full load, 120 x 10^6 Btu/hr. After the installation of the ceramic board insulation, the short flame 60 x 10^6 Btu/hr DMB was retested to evaluate the effects of thermal environment on its performance. The initial tests were conducted with Utah coal. The burner conditions determined to be optimum in the baseline LWS were maintained during these tests to provide a direct

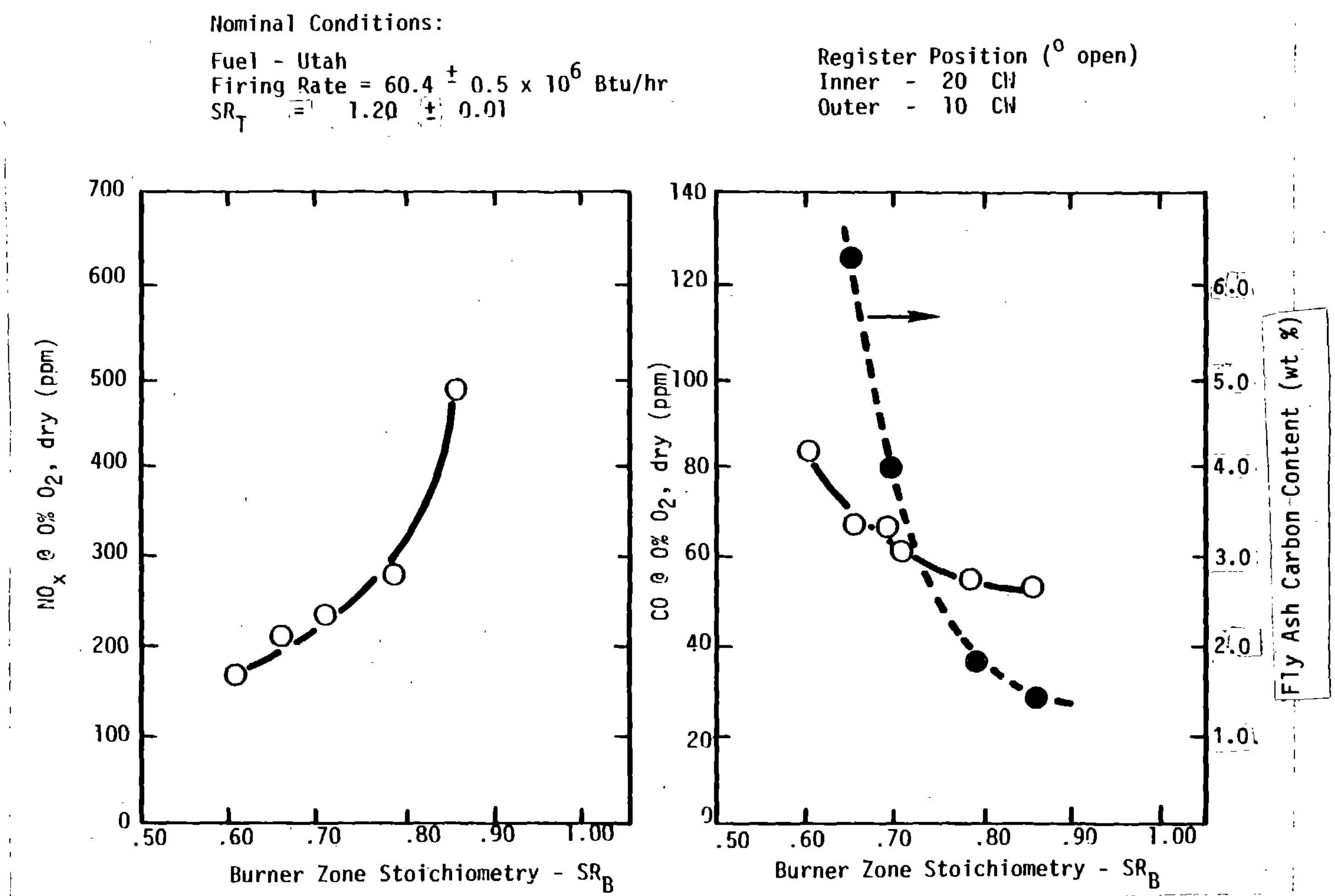


Figure 5-25. Effect of staging on diffuser equipped DMB performance.

NOMINAL CONDITIONS:

FUEL - UTAH
FIRING RATE = 60.7 $\pm$ 0.55 x 10^6 Btu/hr
SB_B = 0.69 $\pm$ 0.01

REGISTER POSITIONS (^{o} Open)
INNER - 20 CW
OUTER - 10 CW

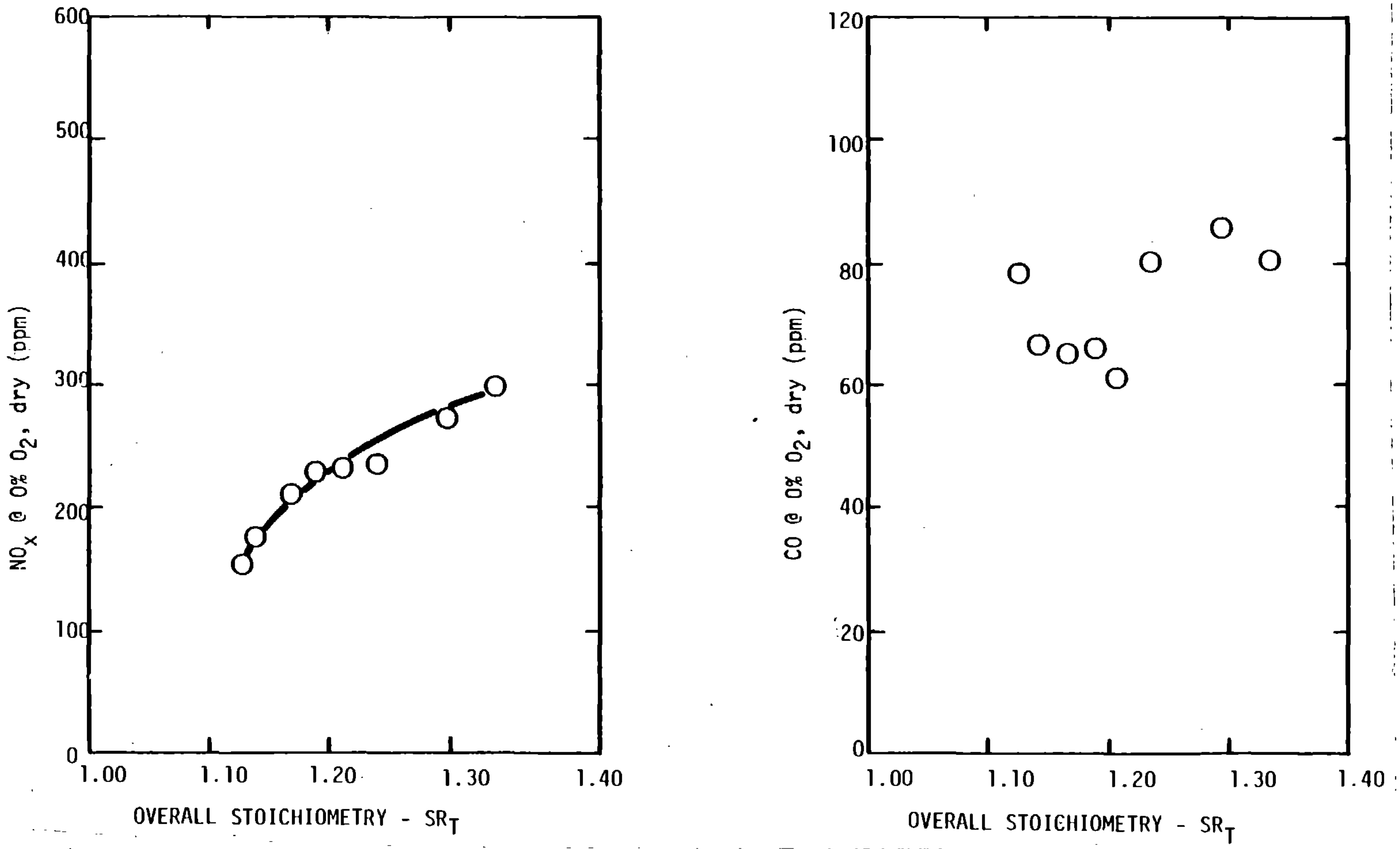


Figure 5-26. Effect of excess air on diffuser equipped DMB performance.

comparison. An array of six Type K thermocouples were utilized in the exit of the LWS to evaluate temperature differences. In addition, a suction pyrometer was positioned adjacent to one of the thermocouples to provide a calibration of radiation induced errors in temperature measurement. Another suction pyrometer was installed in the middle of the furnace about 8 feet above the burner centerline. Table 5-2 summarizes these temperature measurements. Variations in these temperatures are generally due to the change in ash and slag build up over time in the furnace. The insulation increased furnace temperatures on the average approximately 200°F.

The effect of staging and excess air on emissions from the short flame 60×10^6 Btu/hr DMB in the insulated LWS are shown in Figures 5-27 and 5-28, respectively. NO_x decreased at a rate of about 14 ppm/percent theoretical air as staging increased, compared to about 10 ppm/percent theoretical air in the baseline LWS. Overall, NO_x emissions with the Utah coal were higher in the insulated furnace. At a nominal burner zone stoichiometry of 0.7, NO_x emissions were 540 ppm compared to only 390 ppm in the baseline LWS. CO emissions, an indication of combustion efficiency, were lower in the insulated furnace, 51 ppm compared to 60 ppm and measurements indicated that carbon in ash was considerably reduced (to 2.5 percent) compared to the cold furnace. The flame was stable over the range of staging tested, with lengths of 20-22 feet. NO_x emissions were much more sensitive to excess air in the insulated furnace than for the baseline configuration, with rates of change in NO_x of 14 and 8 ppm/percent excess air, respectively. This data suggests the enhancement of thermal NO_x formation and the resulting increased sensitivity to combustion stoichiometry.

The 60×10^6 Btu/hr DMB performance with two host coals, Comanche and Wyodak, and with Illinois Coal was also evaluated in the insulated LWS. Figure 5-29 summarizes the effect of staging of the alternate fuels. Increasing staging yielded similar results for each coal with NO_x increasing at approximately 10 ppm/percent increase in theoretical air. At $SR_B = 0.7$, NO_x was 446 ppm for Comanche which is about 25 ppm higher than in the baseline furnace. There was no significant change in CO emissions at about 38 ppm. The flame length was about 16-18 feet over the range tested and

TABLE 5-2. SUMMARY OF LWS FURNACE TEMPERATURES DURING 60 x 10^6 BTU/HR DMB TESTS

Furnace Configuration	Exit Temperature (Bare Type K), °F	Exit Suction Pyrometer, °F	OFA Suction Pyrometer °F
Baseline	1374-1547	1484-1640	1818
Insulated	1590-1682	1732-1819	2095

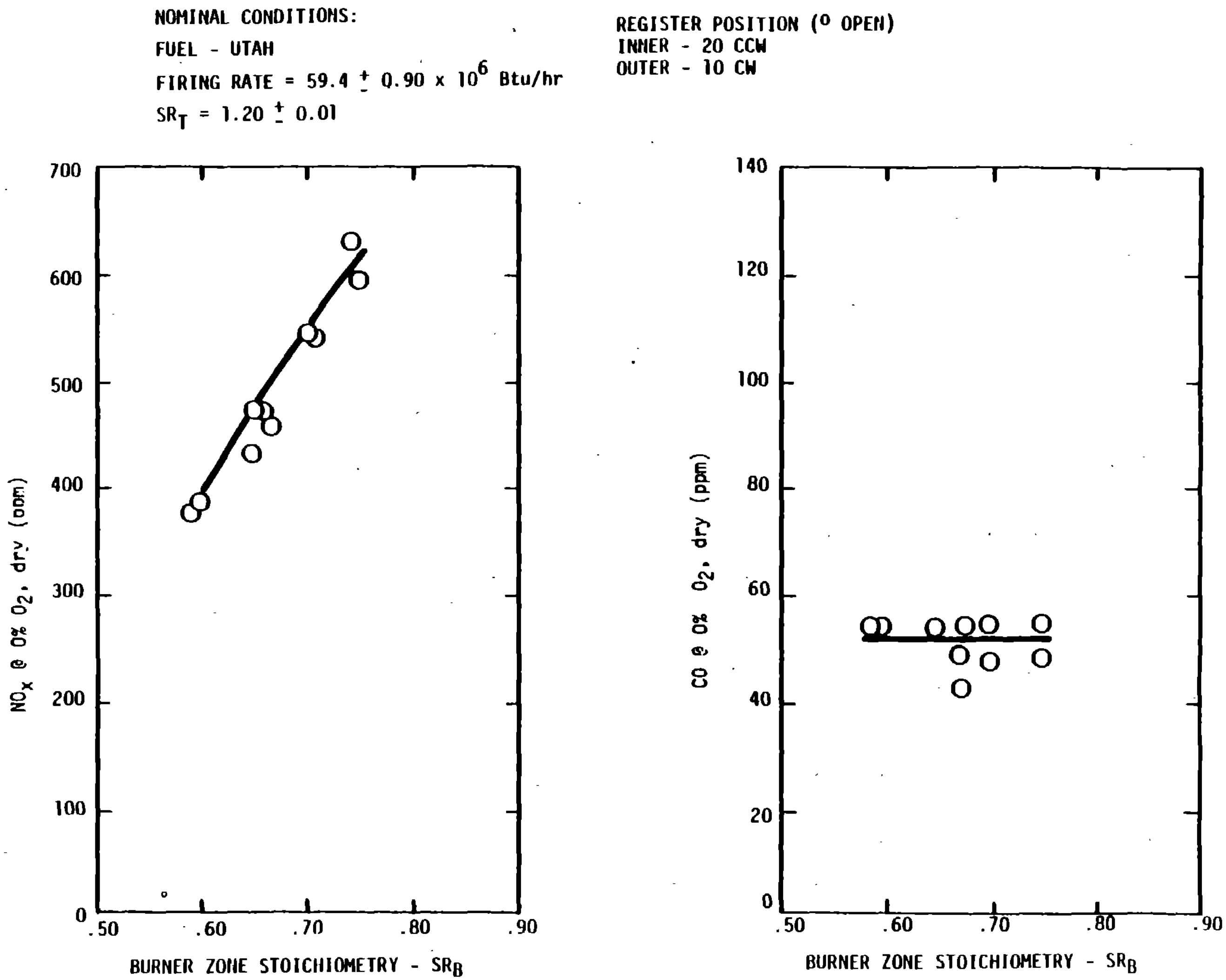


Figure 5-27. Effect of staging on 60 x 10^6 Btu/hr DMB performance in insulated LWS.

NOMINAL CONDITIONS:
FUEL = UTAH
FIRING RATE = $62.2 \pm 23 \times 10^6$ Btu/hr
$SR_B = 0.65 \pm 0.03$
REGISTER POSITION (^{o} OPEN)
INNER - 20 CCW
OUTER - 10 CW

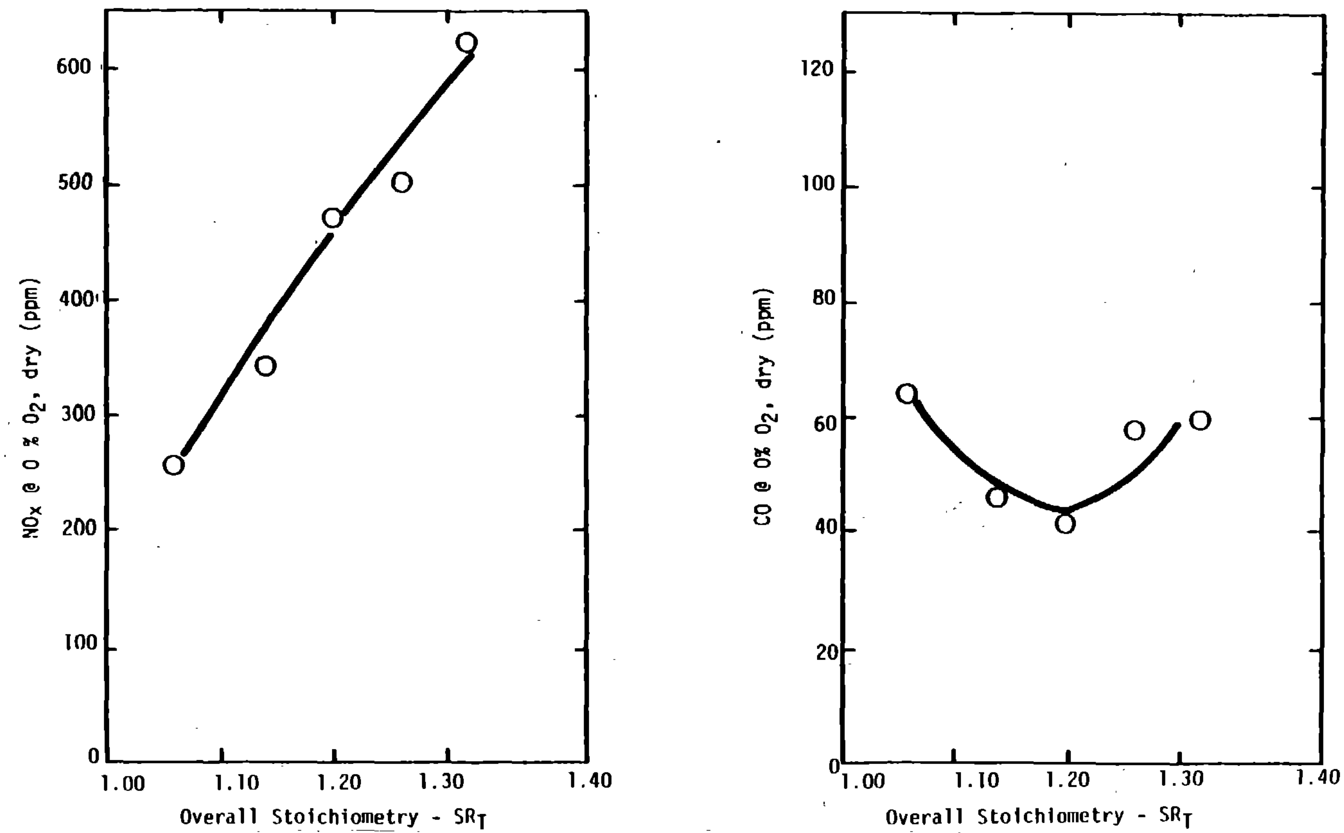


Figure 5-28. Effect of excess air on 60×10^6 Btu/hr DMB performance in insulated LWS.

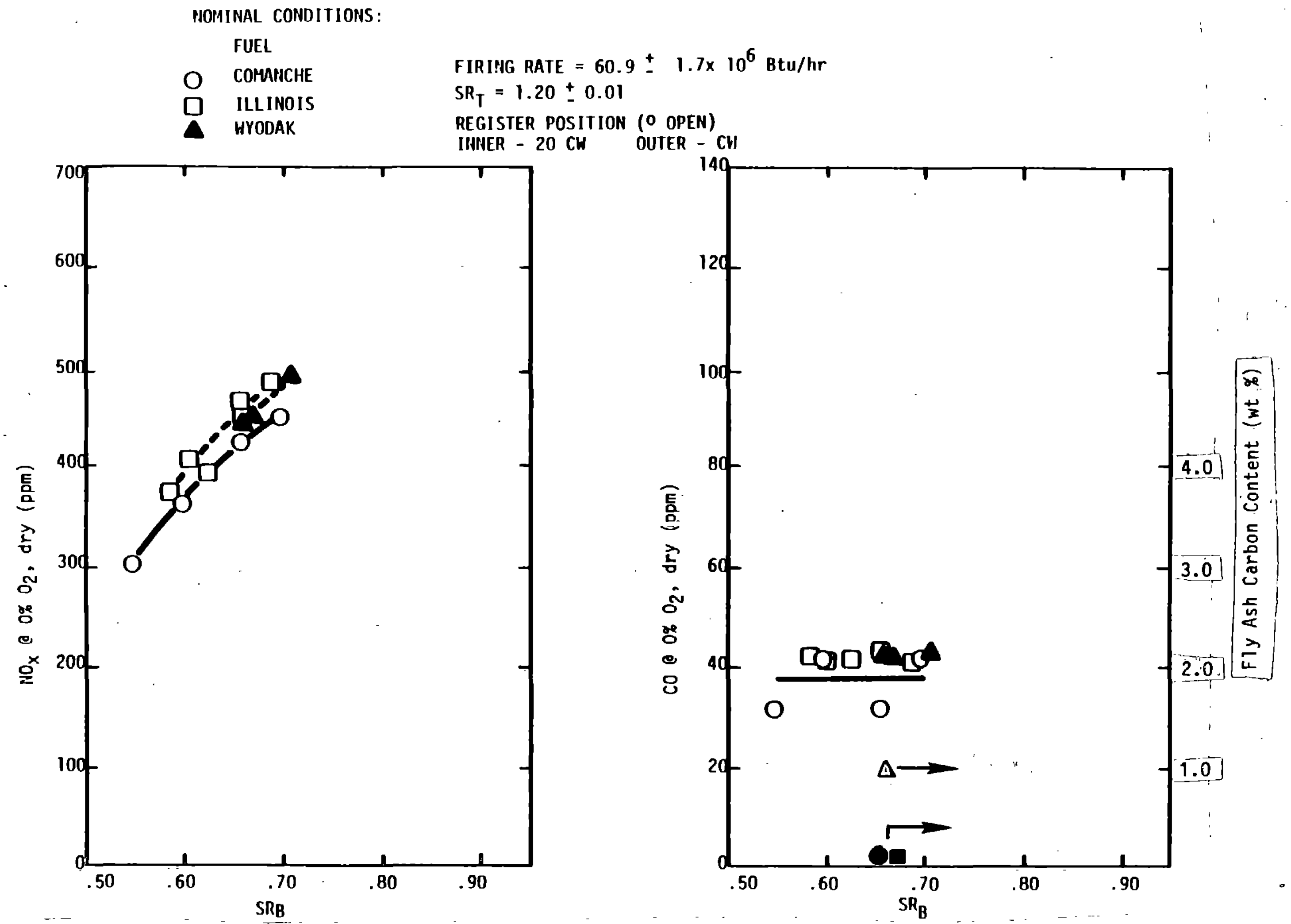


Figure 5-29. Effect of staging on 60 x 10^6 Btu/hr DMB with alternate fuels and insulated LWS.

again lacked the intensity of the Utah flame. As in the previous tests with Wyodak coal, decreased primary air flow, resulting from increased mass flow of coal to achieve design firing capacity, limited the operating range of staging to SR_B = 0.65. CO emissions were slightly lower with 43 ppm. The flame was stable, but dull in color with a length of about 17-20 feet. High sulfur Illinois coal was evaluated to provide data which would be applicable to U.S. boilers burning eastern high sulfur fuels. Optimum conditions at SR_B = 0.65 resulted in NO_x emissions of about 456 ppm which is 100 ppm higher than in the uninsulated configuration. CO emissions were substantially lower at 43 ppm compared to 61 ppm. The flame was stable throughout the range tested with lengths of about 20-22 feet.

The effect of excess air on 60 x 10^6 Btu/hr DMB performance with Comanche and Illinois coals is shown in Figure 5-30. Overall combustion stoichiometry had a similar effect on NO_x for the two coals, decreasing 8 ppm/percent excess air. This slope is similar to that measured in the baseline furnace. Both fuels resulted in similar NO_x emissions for the excess air range tested, with slightly lower CO produced by the Comanche coal.

The effect of excess air on the 60 x 10^6 Btu/hr DMB in the insulated LWS with Wyodak Coal is summarized in Figure 5-31. NO_x emissions decreased 8 ppm/percent excess air over the range tested. The flame was stable, but with slight detachment of about 6-12 inches from the burner throat and was about 16-18 feet in length. At baseline conditions SR_B = 0.70 and SR_T = 1.20 NO_x emissions were approximately 500 ppm. Also shown is the effect of excess air in the uninsulated LWS. NO_x emissions are generally 50 ppm lower in the uninsulated LWS over the range tested. CO emissions were not significantly different (5 ppm) between the two furnace thermal configurations.

5.5.2 Evaluation of Modified DMB

The initial 60 x 10^6 Btu/hr DMB had been incorrectly scaled, resulting in very high secondary air velocities. The modified DMB evaluated incorporated design parameters which matched the 120 x 10^6 Btu/hr DMB. In

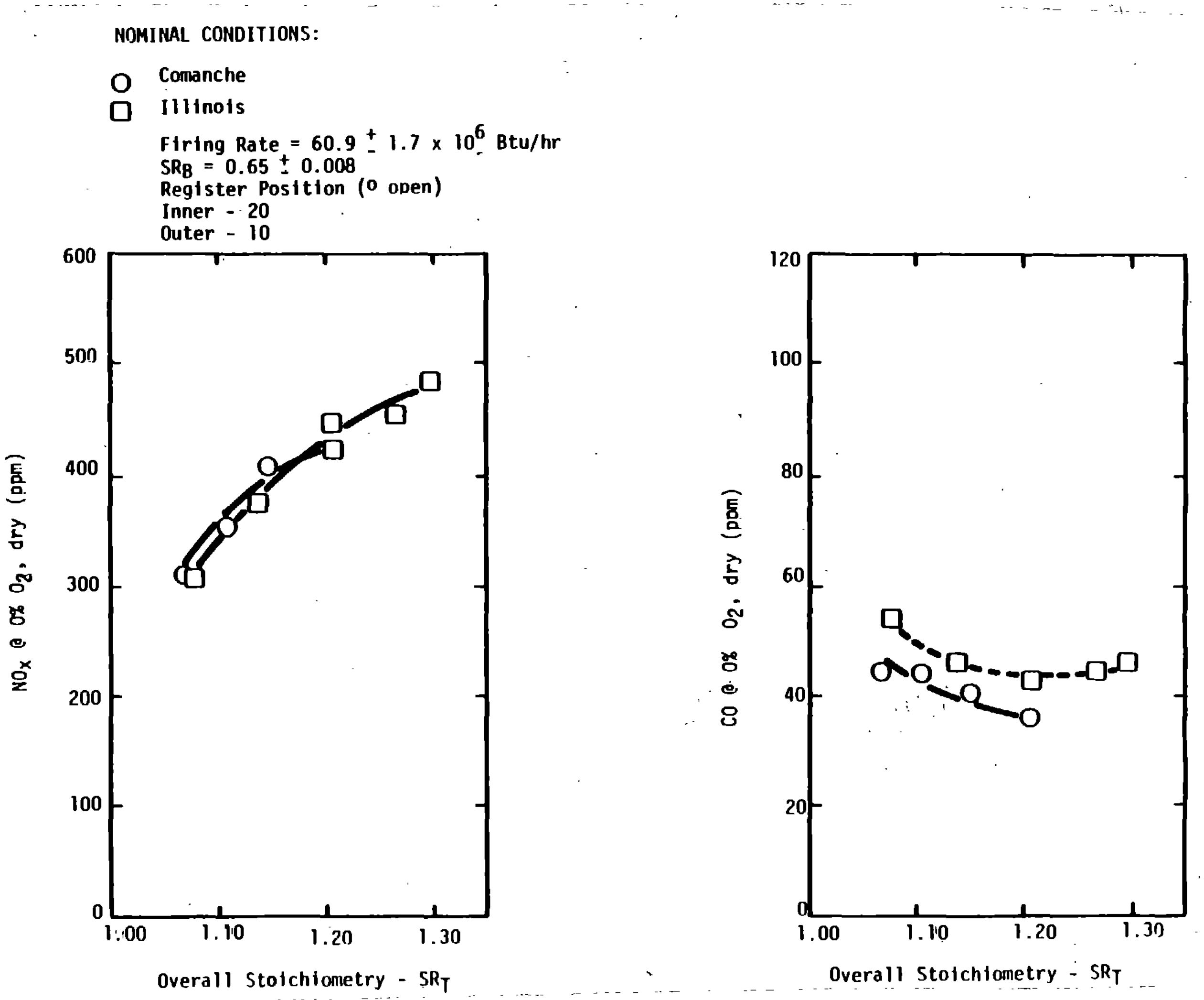


Figure 5-30. Effect of excess air on 60 x 10^6 Btu/hr DMB with alternate fuels and insulated LWS.

NOMINAL CONDITIONS:

FUEL WYODAK
FIRING RATE = 59.6 ± 0.50 x 10^6 Btu/hr
SR_B = 0.69 ± 0.01

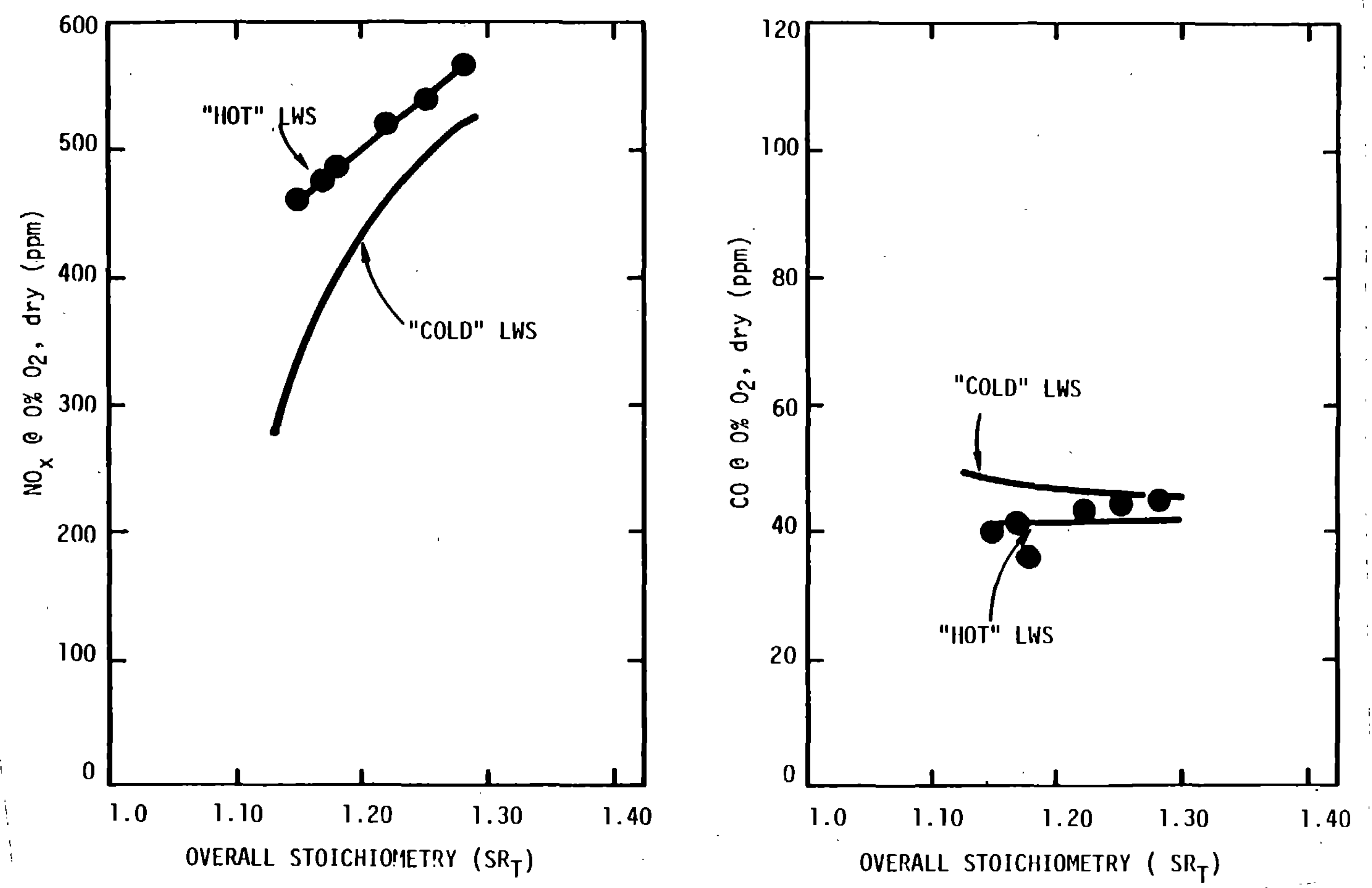


Figure 5-31. Summary of 60 x 10^6 Btu/hr DMB burner performance with Wyodak coal.

addition to adjusted burner velocities, the optimum coal spreader from the 120×10^6 Btu/hr DMB was scaled down for this redesigned 60×10^6 Btu/hr DMB. Thus, the redesigned small DMB matched the larger scale 120×10^6 Btu/hr DMB.

Parametric optimization of the redesigned 60×10^6 Btu/hr DMB was conducted using Utah coal fired at nominal full load. The burner was operated at nominal design point air flows throughout these optimization tests, with primary stoichiometry of 0.20, burner zone stoichiometry of 0.70, and overall stoichiometry of 1.20. The secondary air was divided equally between the inner and outer passages. Since the DMB design had been optimized with the larger-scale 120×10^6 DMB, the parametric optimization for this small DMB was limited to the following adjustable burner parameters:

- Coal spreader position
- Outer register vane position
- Inner spin vane position
- Secondary air distribution

The effect of these parameters are briefly described below:

Coal spreader position. The reference or zero, position of the spreader was defined with the leading edge of spreader flush with the end of the coal nozzle. With the coal spreader advanced 2 inches beyond the coal nozzle into the furnace, NO_x emissions were measured as 372 ppm (at 0 percent O_2 dry). As the coal spreader was retracted to the zero position NO_x emissions decreased to 348 ppm, and then increased to 382 ppm as the spreader was further retracted to a position 3 inches inside the coal nozzle. The flame length varied between 18 and 20 feet for this entire range of adjustment.

Outer register vane position. The outer register vanes were varied over a range from 10^o open to 50^o open in a clockwise direction. NO_x emissions were lowest (336 ppm) at the more open, lower swirl position of 50^o with a flame length of 20-22 feet. At a position of 10^o, which matches the optimum setting for the 120 x 10^6 Btu/hr DMB, NO_x emissions were about 367 ppm with 18-20 foot flames.

Inner spin vane position. The spin vanes were adjusted from the 25° clockwise to the 20° counter clockwise positions. Over this range of adjustment, NO_x emissions varied from 322 to 459 ppm with flame lengths from 12 to 21 feet. The best performance was achieved at 55° clockwise with 372 ppm and flames about 13 feet long. The corresponding outer register setting was 10°CW.

Secondary air distribution. Secondary air distribution was varied from 10 percent to 60 percent biased toward the inner passage.

From these parametric tests, the burner parameters which yielded the best performance for the 60 x 10^6 Btu/hr DMB were:

Coal spreader position	= 0 inches
Inner spin vanes	= 55° CW
Outer register	= 10° CW
Secondary air distribution	= 50% inner/ 50% outer

The staged performance of the 60 x 10^6 Btu/hr DMB was characterized at the above listed optimum settings for Utah, Wyodak, and Comanche coals. The effect of staging for each coal is shown in Figure 5-32. NO_x emissions were lowest for the Utah coal. At the design point burner zone stoichiometry of 0.70, NO_x emissions were 340, 440, and 525 ppm for Utah, Comanche, and Wyodak coals, respectively. The carbon content of fly ash samples were less than 0.5 percent for the two subbituminous coals, Comanche and Wyodak, and 1.5 percent for the Utah coal at design point conditions.

With many low-NO_x burners, an increase in carbon-in-ash is normally expected as staged combustion is applied. For the 60 x 10^6 Btu/hr DMB burner, however, the results of Figure 5-32 indicate that there is no deterioration in carbon burnout for the two subbituminous coals, and only a marginal charge for Utah coal, even though substantial reductions in NO_x

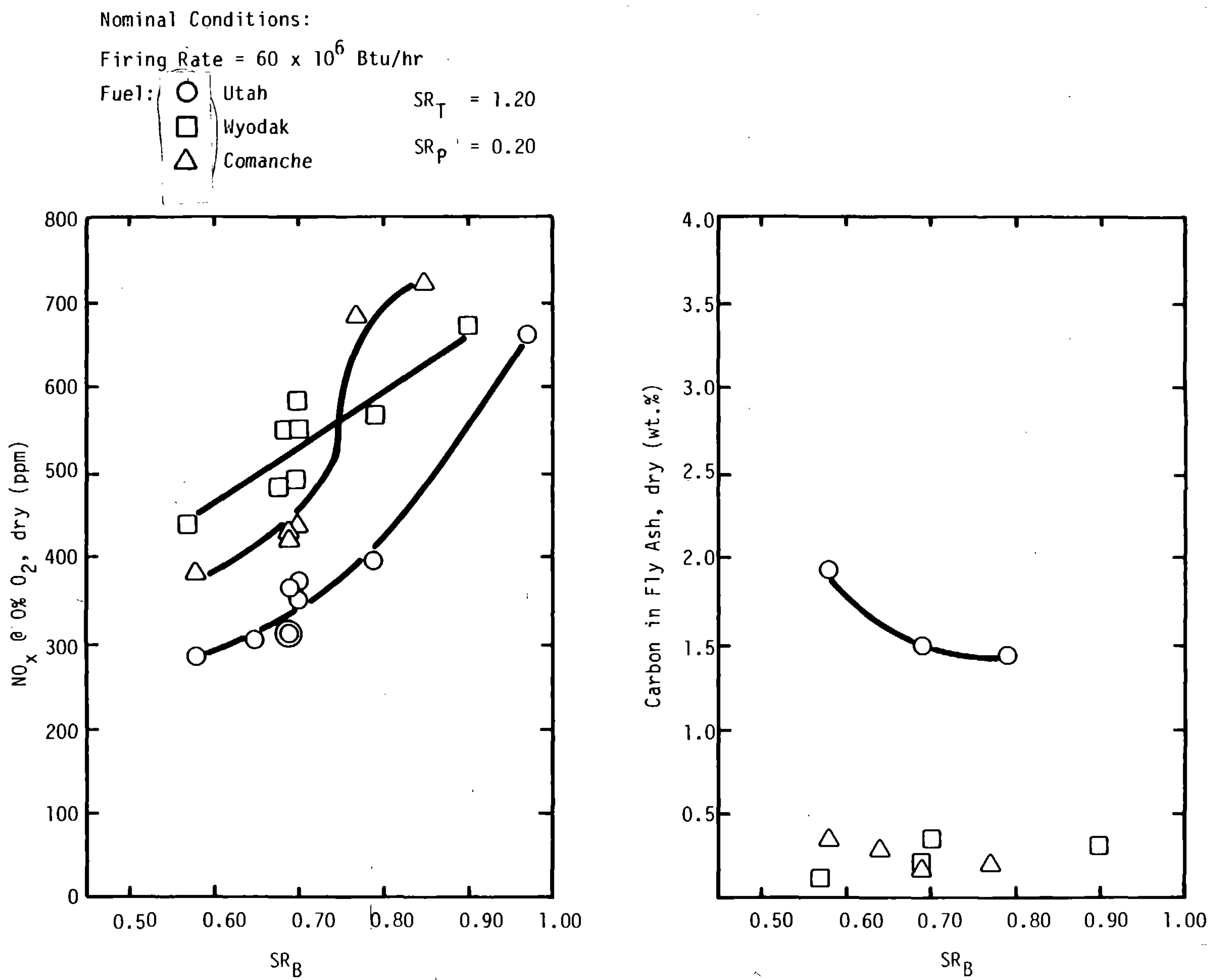


Figure 5-32. Effect of staging on modified 60 x 10^6 Btu/hr DMB performance.

emissions are achieved. This is believed to be due in part to the low firing rate which provides long residence times for burnout to occur. Previous results for the 120 x 10^6 Btu/hr DMB have shown a much stronger effect of staging on carbon burnout for the Utah coal. Burnout with the subbituminous coals was found to be consistently good and relatively insensitive to staging. This may be associated with the higher reactivity of these fuels.

The effect of excess air at staged conditions, with a burner zone stoichiometry of 0.70, is shown in Figure 5-33 for all three coals. Again, NO_x emissions were lowest for Utah coal and highest for the Wyodak coal over the range of excess air evaluated. Again, unburned carbon levels were exceptionally low, less the 0.5 percent carbon, for the subbituminous coals. Combustion efficiency was more sensitive for the small DMB with the Utah coal, with up to about 3.2 percent carbon in the fly ash at an overall stoichiometry of 1.10.

The 60 x 10^6 Btu/hr DMB was also evaluated briefly unstaged with all three coals. The results are shown in Figure 5-34. Flame lengths under these unstaged conditions ranged from 10 to 13 feet for the subbituminous coals and about 17-18 feet for the Utah coal. NO_x emissions were lowest for the Utah coal with 775 ppm at an overall stoichiometry of 1.20. NO_x emissions at the same excess air level were 850 and 900 ppm for the Wyodak and Comanche coals, respectively. As with staged conditions, carbon in fly ash was less than 0.5 percent for the subbituminous coals. Again, the combustion efficiency of the DMB was more sensitive when firing Utah coal, although the level of carbon in the fly ash was still very low (less than 2.5 percent).

5.6 Discussion of Results and Extrapolation to Full Scale

The preceding sections have presented NO_x emission and burner performance data for the four major burner designs which were the subject of this program. While this discussion has provided information on individual burner performance the overall burner test program was structured to provide data to address the performance scale-up issues of:

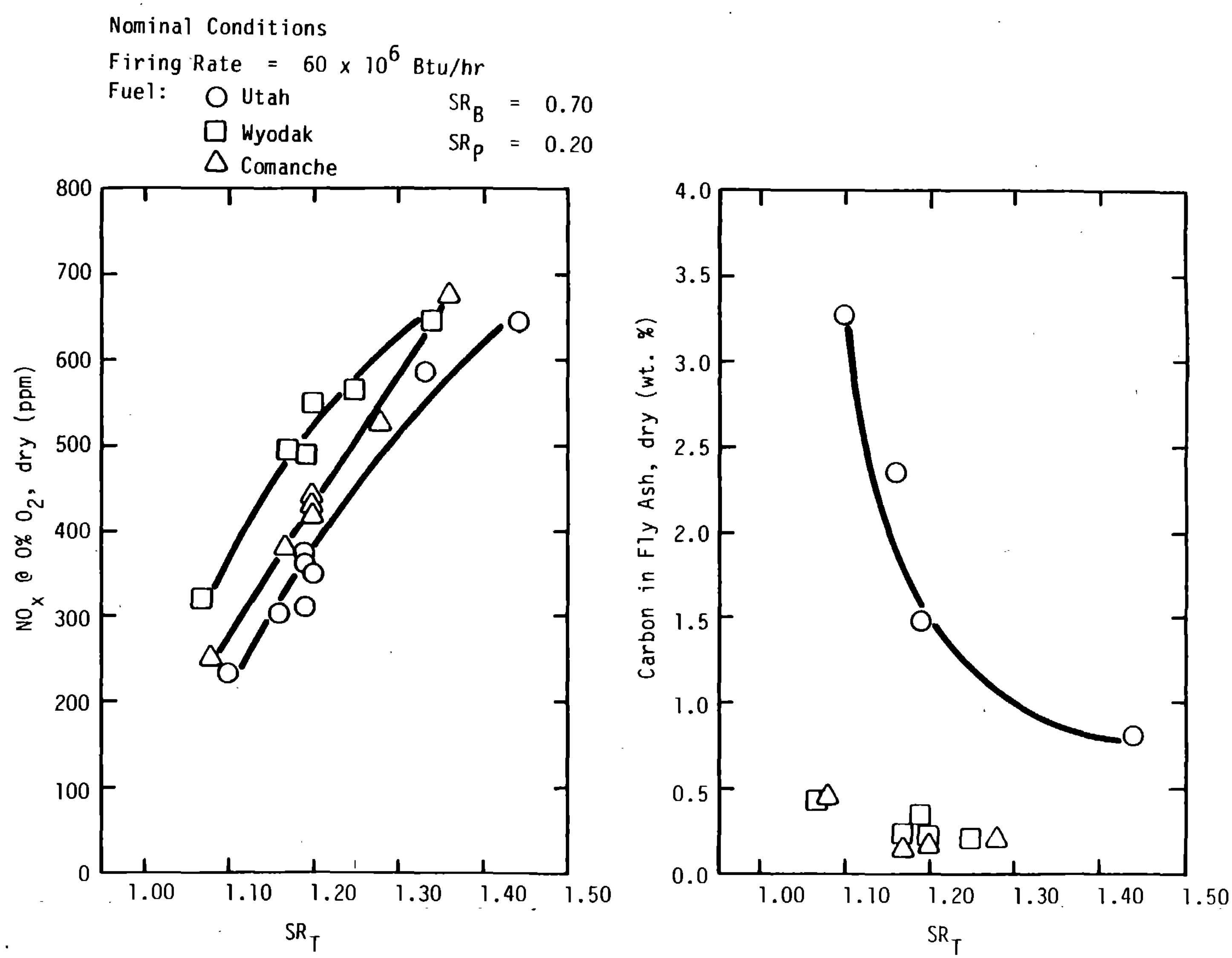


Figure 5-33. Effect of excess air on modified 60 x 10^6 Btu/hr DMB performance under staged conditions.

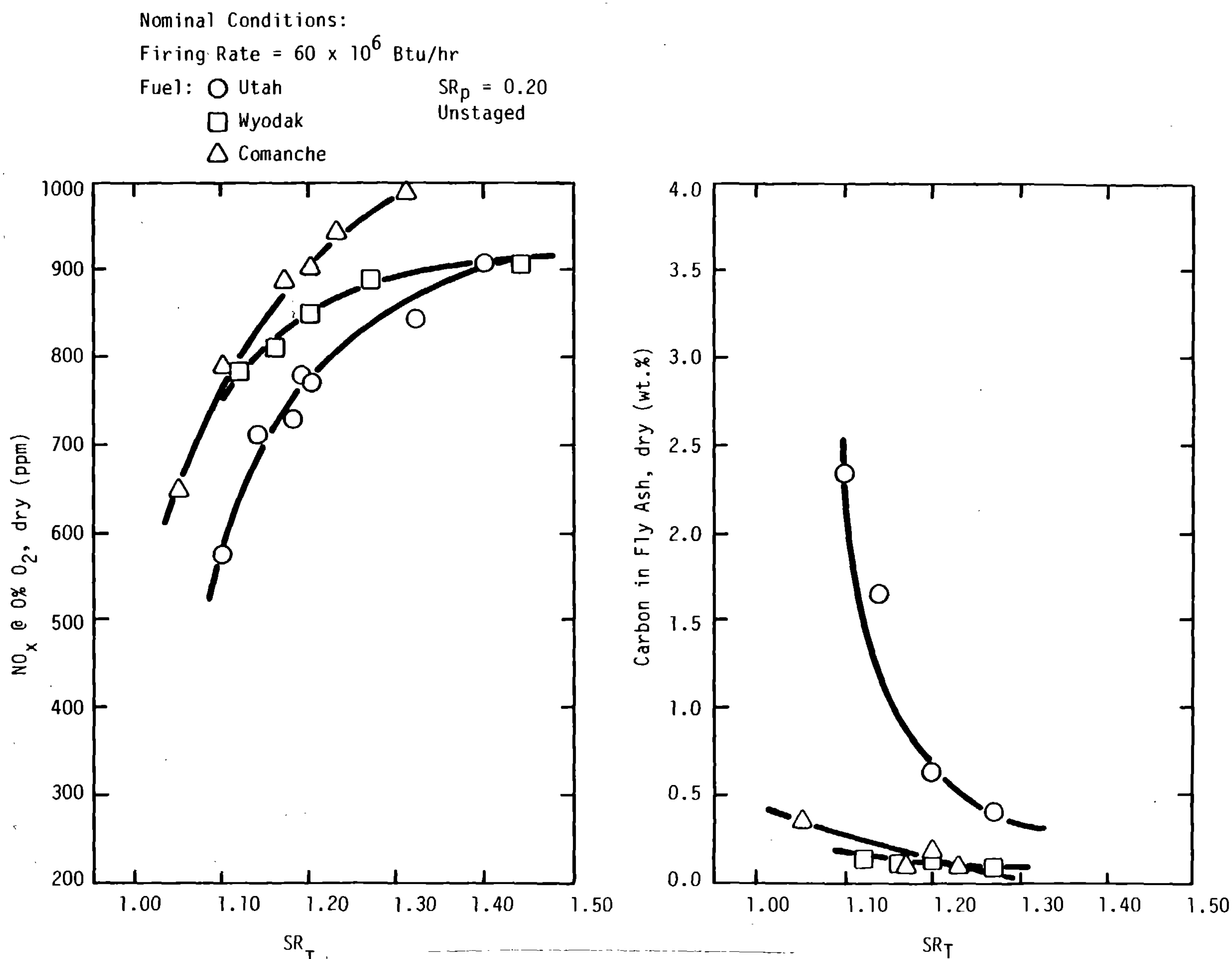


Figure 5-34. Effect of excess air on modified 60 x 10^6 Btu/hr DMB performance under unstaged conditions.

- Thermal environment
- Burner design/capacity scaling
- Single burner-to-multiple burner installations

The following sections will summarize the relative performance data and provide discussion on aspects related to scale-up and extrapolation to full-scale boiler systems.

5.6.1 Relative Burner Performance and Effects of Coal Type

The evaluation of a full-scale 120 x 10^6 Btu/hr Distributed Mixing Burner was a key element of this demonstration program. For burners of this size the LWS test furnace imposes some significant constraints on flame shape and length, since low-NO_x burners, like the DMB, rely on controlled, delayed mixing of the fuel with air. This delay generally produces a long flame which may cause operational problems in a boiler. Although equipped with adjustable inner and outer secondary air parameters as well as the tertiary air ports, the dominant factor in determining ultimate performance (NO_x, flame length) was the coal injector configuration. Iterative modifications were made to the coal injector to yield the optimum performance for the LWS. There was a direct tradeoff between NO_x emissions and flame length.

The final design selected resulted in unstaged flames about 16 ft long. At staged conditions (SR_B = 0.70), the flame length increased to approximately 22 ft. The optimum configuration for the 120 x 10^6 Btu/hr DMB was determined to be:

- Spreader design = 4-inch support pipe with four 8-inch blades at a 30^o angle from axial.
- Burner settings: Inner spin vanes = 35^o open CW
Outer register = 10^o open CW
Spreader portion = 3 in. retracted
Inner/outer secondary air distribution = 50/50

NO_x emissions for the DMB at these optimum settings at nominal full load conditions with a burner zone stoichiometry of 0.70 and 20 percent excess air were 300, 340, 298, and 273 ppm for Utah, Illinois, Comanche and Wyodak coals, respectively.

Performance data for the four main burner types are summarized in Table 5-3, for operation on Utah coal, which was the design coal for the DMB burners. In this table the half scale DMB data represents burner design parameters scaled from the 120 x 10^6 Btu/hr version, and test conditions for the two 60 x 10^6 Btu/hr burners are based on an insulated furnace where temperature levels are comparable to those at the higher load. The conditions listed represent stable operation where flame characteristics and carbon burnout were acceptable.

Further information comparing burner NO_x emission performance over a range of excess air levels and for different coals is presented in Figure 5-35. The data in this figure indicate that all burners tend to respond differently to these test parameters. Both of the 60 x 10^6 Btu/hr burners (the DRB and the DMB) show a strong sensitivity of NO_x emissions to increased excess air (100-150 ppm per % O_2), compared to the 120 x 10^6 Btu/hr burners for which this trend is less marked (50 ppm per % O_2). Although similar trends have been observed previously with comparable burner designs, other LWS data has suggested that fully optimized low-NO_x burners are relatively insensitive to many operational parameters. One reason for this behavior may be due to the comparatively high local temperatures of the insulated furnace configuration, and to the higher intrinsic mixing rates associated with the smaller burner dimensions.

Of particular interest in Figure 5-35 is the performance of the different burners with the different coal types. For the 60 x 10^6 Btu/hr DMB NO_x emissions with Wyodak coal are considerably higher than those achieved with the Utah coal. For the DRB burner the reverse is true, while comparatively small differences between coal types are observed for the 120 x 10^6 DMB. For the 60 x 10^6 Btu/hr DMB burners, particularly in the colder baseline furnace configuration, some difficulties were experienced in

TABLE 5-3. COMPARISON OF BURNER PERFORMANCE IN THE LWS FIRING UTAH COAL ($SR_T = 1.20$)

	DMB		DRB	Circular
	Full Scale	Half Scale	Half Scale	Full Scale
Firing Rate (10^6 Btu/hr)	120	60	60	120
SR_B	0.70	0.70	0.70	1.20
FEGT (^oF)	1792	1776	1776	1828
NO_x (ppm @ 0% O_2)	300	350	390	380
Flame Length (ft)	22	18	18	>22
Carbon in Ash (wt %)	5.5	1.5	0.9	5.2

FEGT = Furnace Exit Gas Temperature

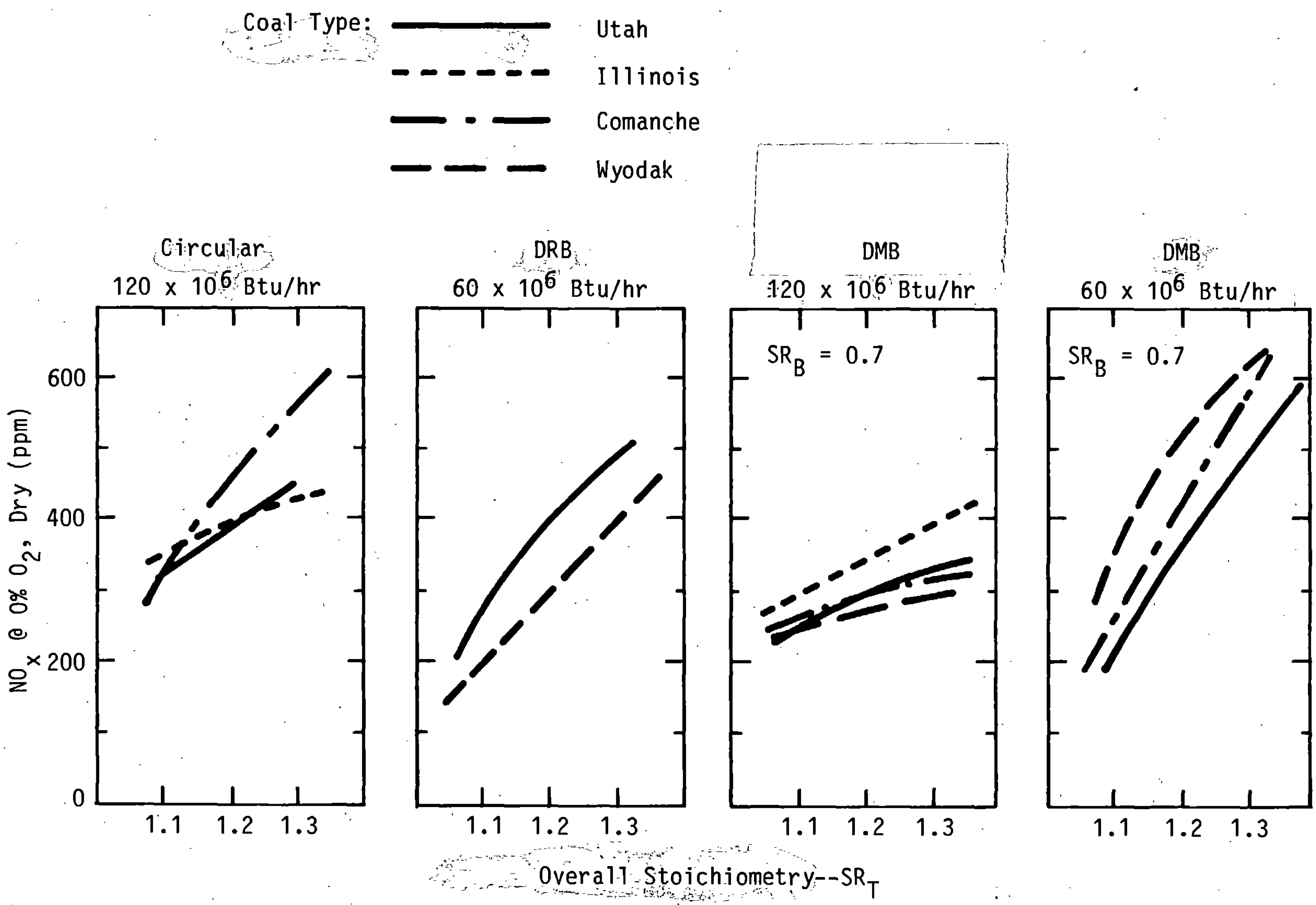


Figure 5-35. Effects of burner design and coal type on NO_x emissions.

achieving stable ignition for the Wyodak and Comanche coals under staged combustion conditions. This may have limited the achievement of lower NO_x emissions for these coals, and suggests that further design changes might be necessary to accommodate the lower heating value, higher moisture subbituminous coals.

In spite of difficulties in achieving acceptable flame stability under some conditions for Wyodak and Comanche coals, carbon burnout was generally good for these fuels, and commensurate with the expected high reactivity. For all burner designs, staging conditions, and under cold furnace conditions, the measured carbon in ash was never found to exceed one percent. This is a further indication that lower NO_x emissions should be possible with the subbituminous coals without compromising overall combustion performance.

For the two high volatile bituminous coals (Utah and Illinois) carbon burnout was found to be more sensitive to combustion staging and to firing rate. Carbon in ash values were generally found to increase as staging was applied, and were higher for the higher capacity burners. However, for most major operating conditions carbon in ash values were considered to be acceptable (5 percent or below), and only deteriorated significantly for operation at 60 x 10^6 Btu/hr in the baseline furnace configuration. Additionally both of the high capacity burners and both of the low capacity burners tended to yield similar burnout performance with the bituminous coals. These observations would tend to suggest that the measured carbon burnout values are more dependent upon coal type and furnace conditions than upon burner design.

5.6.2 Extrapolation of NO_x Emission Data

The correlation of NO_x emission data between different firing conditions in the test furnace, and the extrapolation of test data to full-scale systems is of particular interest the overall goals of this program. While fundamentally based computational tools are under development for the prediction and extrapolation of NO_x formation as influenced by burner and furnace parameters, most practical approaches are based on empirical relationships. In fact, all major boiler manufacturers have used a burner area heat release parameter at some stage in an attempt to correlate NO_X emissions from full-scale boilers, and in some cases to try and relate/ extrapolate the results of burner tests in small-scale furnaces. Burner area heat release rate is to some extent a measure or indicator of temperature levels in the flame region. It is also indirectly related to the volumetric heat release rate in the flame zone because most furnaces do not differ greatly in geometry in the burner region. High volumetric heat release rates reflect high air/fuel mixing and should thus correlate with NO_X emissions.

Each of the manufacturers--Babcock & Wilcox, Foster Wheeler, and Riley Stoker--has developed a correlation based on their own definition of burner area heat release rate. The correlations are similar but not strictly comparable because of differences in the methods of defining the cooled surface area in the burner region. For purposes of comparison, NO_X emission data available to EER for boilers and large-scale burner tests have been correlated using the B&W definition of cooled surface in the burner region (HA/SC). This considers the burner area cooled surface to be the four sides and bottom of a cuboid box with the same width and depth as the furnace and with a height extending half a burner spacing above and below the upper and lower burner rows, respectively.

The use of the HA/SC parameter as defined above is illustrated in Figure 5-36 for NO_X emission data from a wide variety of wall-fired boilers. A wide range of boiler and burner designs, unit size and firing patterns are incorporated into the data base. The data is, however, restricted to boilers firing high volatile bituminous coals. Although there is considerable scatter in these data points, an upper limit in NO_X emission can be identified, which increases with increasing burner zone heat loading. This upper limit is indicated by a trend line for which the slope (0.8 x HA/SC) is in good agreement with the correlation developed by B&W. Inspection of the data which lie close to the upper limit shows these points to be associated with boilers of pre-NSPS design in which high-turbulence burners are employed. On Figure 5-36 the NO_X emission data which lie below the upper

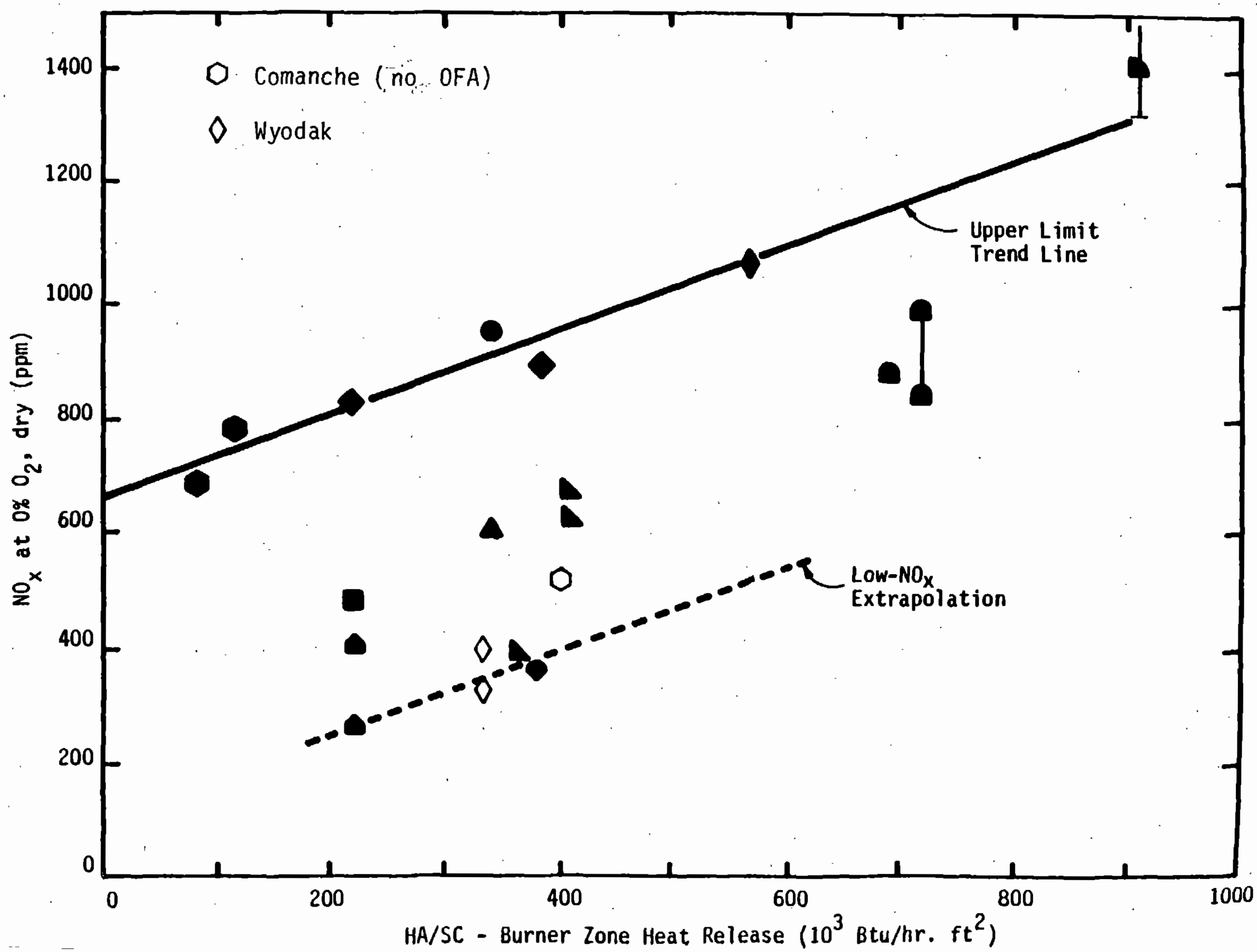


Figure 5-36. Correlation of boiler NO_x emissions.

limit line represent boilers with alternate burner designs, or situations where different NO_x control strategies have been applied. At the lower levels of NO_x emission the boilers have been retrofitted with low-NO_x burners and optimized for maximum NO_x control. As might be expected, the HA/SC parameter does not provide a universal correlation with NO_x emissions, since it fails to take into account the important effects of variables such as burner design and coal type. Indeed the burner zone heat release parameter was developed strictly to provide a means of extrapolating the performance of a given burner design into an alternate firing situation. Also shown on Figure 5-36 are baseline field data obtained from the two test boilers (Wyodak and Comanche), indicating their NO_x emission in relation to burner zone heat release.

In order to incorporate experimental data into this kind of analysis, the HA/SC correlation has been extended to include data obtained in the Large Watertube Simulator furnace (LWS). In developing the HA/SC correlation there is a problem in correctly representing the burner zone area for experimental facilities. This is because small-scale furnaces have a comparatively high surface-to-volume ratio, and consequently some degree of insulation on the walls is required to more correctly match the thermal environment of full-size boilers. Indeed, adding or removing refractory on the furnace walls has been used in this program as a means of changing the thermal environment to experimentally evaluate the effect of this parameter. In order to overcome this difficulty an "effective" burner zone cooled surface area has been defined depending upon firing rate and extent of refractory insulation. The effective HA/SC is determined by comparing maximum flame temperatures in the combustion zone with corresponding temperature levels in full-scale boilers, using heat transfer computer codes. Using these results, a correlation was obtained between the maximum predicted flame temperature and the burner area heat release rate calculated using the B&W definition. Using this correlation and similar predictions of gas temperatures in the experimental furnaces, effective burner belt cooling areas were obtained.

In Figure 5-37 selected experimental data are presented on the basis of HA/SC defined in the above manner for the appropriate firing configurations.

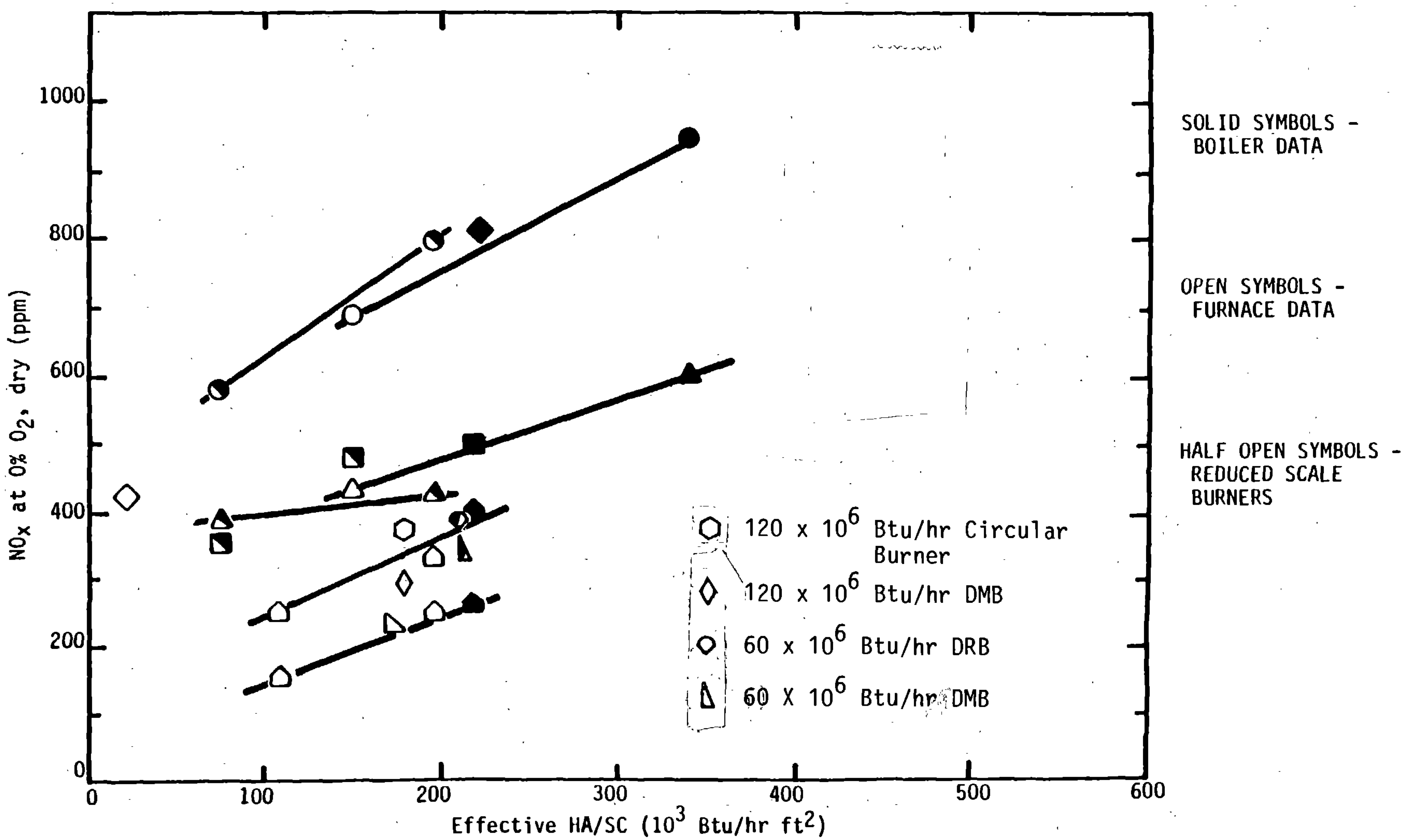


Figure 5-37. Correlation of experimental furnace data.

The experimental data (open symbols) are for selected single full-scale burners where corresponding boiler data (solid symbols) is available for the corresponding data sets, where again it can be seen that a reasonably consistent correlation exists. The use of a correlation of this type is, however, believed to be conditional upon a number of factors, namely:

a) The experimental data is derived from full-scale or near full-scale burners.

b) The same burner design and operating conditions are used both in the experimental furnace and in the field.

c) The same coal type is used at all scales.

d) Experimental data is restricted to acceptable firing conditions; i.e., where the flame fits within the confines of the furnace; unburned carbon levels are low; the burner operates satisfactorily over the required turn-down range.

Condition d) above is an obvious one, in that the extrapolation can be based only upon operating conditions which are acceptable in the final application. In this regard flame dimensions are an important consideration for low-NO_x burners, since the flame must be constrained within the space available in the boiler. This is related to condition a) which restricts the extrapolation essentially to full-scale burners. If reduced scale burners are used in the experimental evaluation, then another variable is introduced, that of the effect of burner size on NO_x emissions. The relationship between burner design, burner size, the burner scaling approach employed, and NO_x emissions, is not well understood and what little information is available is poorly documented.

Effective HA/SC values as defined above have been calculated for the main test conditions of this program. These are:

- Baseline furnace, 60 x 10^6 Btu/hr: HA/SC = 89 x 10^3 Btu/hr·ft^2.

- Baseline furnace, 120×10^6 Btu/hr: HA/SC = 178×10^3 Btu/hr·ft^2.
- Insulated furnace, 60×10^6 Btu/hr: HA/SC = 211×10^3 Btu/hr·ft^2.

Using these values the test data for the four burner designs firing on Utah coal are presented in Figure 5-37 to illustrate the relationship to previous experimental NO_x data.

The major issue addressed by the HA/SC parameter is the effect of thermal environment or firing density on the emission of NO_x from a burner of fixed design. In this program, this parameter was investigated as an independent variable by varying the insulation level in the LWS furnace. The initial 60×10^6 Btu/hr DMB configuration was tested in the LWS with two different insulation installations. The two levels of insulation yielded two distinct thermal environments that can be characterized by the furnace exit gas temperature. The LWS in its basic insulation scheme had an average exit temperature of 1562°F when fired at 60×10^6 Btu/hr. With additional insulation, the exit temperature was increased to 1776°F. The level of insulation was designed so that the exit temperature when fired at 60×10^6 Btu/hr would match the exit temperature achieved in the baseline LWS when fired at 120×10^6 Btu/hr. As shown previously this insulation objective was achieved successfully (within 35°F). The effect of thermal environment on burner performance, specifically NO_x emissions, is shown in Figure 5-38. The effect varies with coal type. There was only a small effect on emissions from either subbituminous coal, while for the high volatile bituminous coals, NO_x emissions were about 100 ppm higher in the insulated furnace.

The effect of thermal environment on NO_x emissions is further illustrated in Figure 5-39 where, for the short flame 60×10^6 Btu/hr DMB, HA/SC is used as parameter. Data for nominal burner operating conditions of $SR_B = 0.7$ and $SR_T = 1.2$ is used throughout. Here it can again be seen that for the Utah and Illinois coals there is a constant relationship between HA/SC and NO_x emission for the same burner fired under different thermal conditions. For these coals, the increase in NO_x emission is approximately 1.0 x HA/SC and is comparable to trends derived earlier and presented in Figures 5-36 and 5-37. However, for the two subbituminous coals, under cold

Load = 60 x 10^6 Btu/hr

SR_T = 1.20

NOTE: Shaded symbols in LWS w/insulation

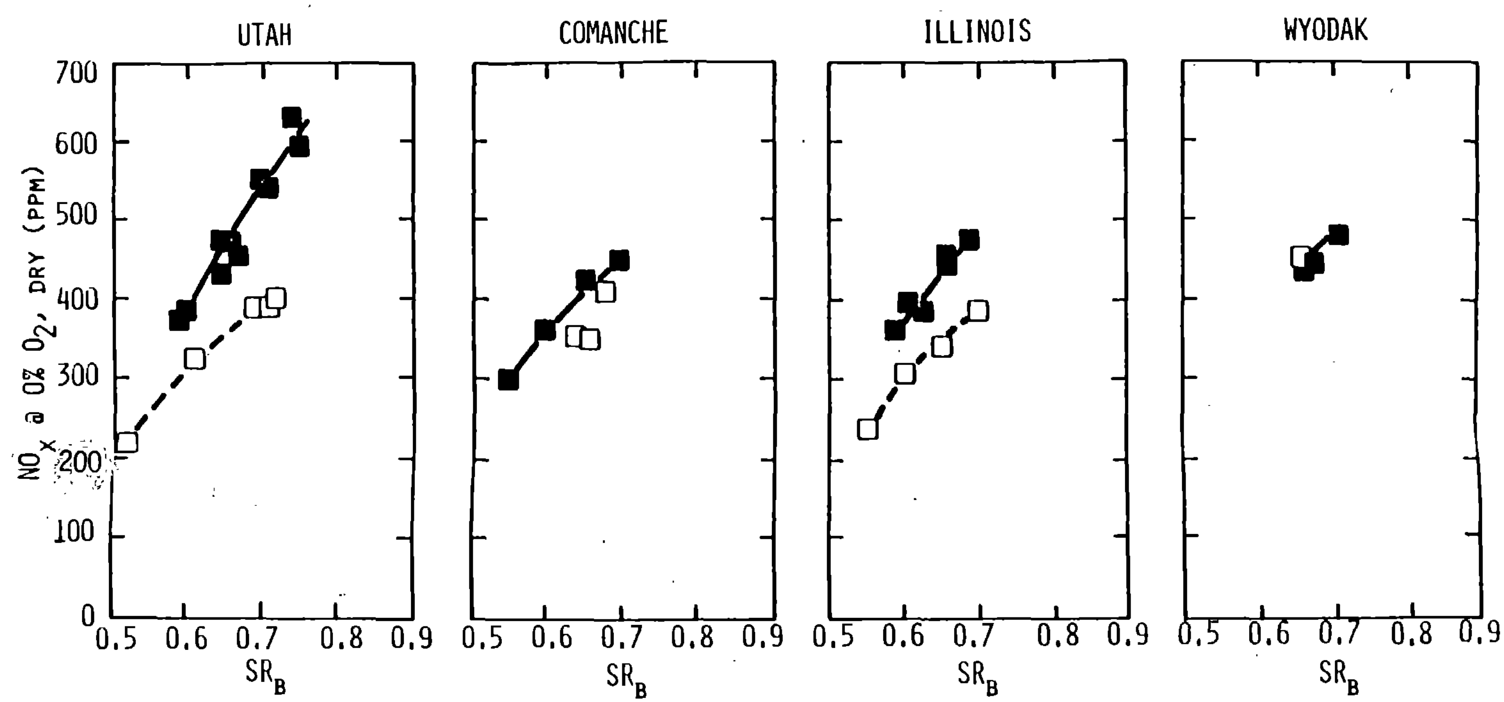


Figure 5-38. Effect of thermal environment on NO_x emissions from initial short flame 60 x 10^6 Btu/hr DMB.

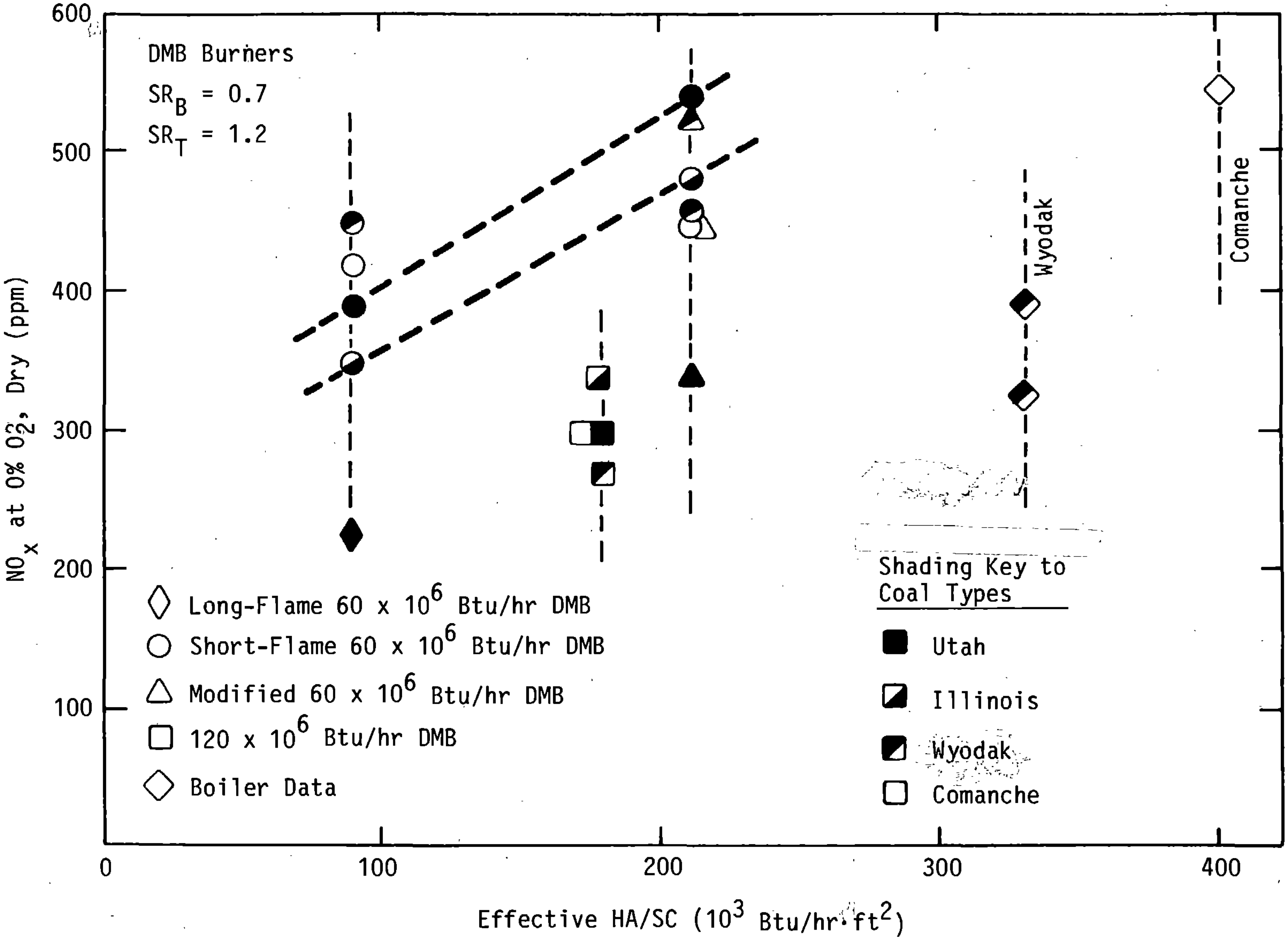


Figure 5-39. Correlation of DMB NO_x emissions.

furnace conditions NO_x emissions are higher than would be expected according to the correlation. This effect may have been caused by the flame stability problems experienced with the two subbituminous coals under staged combustion conditions, which were particularly apparent in the cold furnace.

5.6.3 Burner Scale Effects

The aspect of burner scaling was evaluated by testing a 60 x 10^6 Btu/hr and a 120 x 10^6 Btu/hr DMB in a comparable thermal environment. As described above, this was achieved by adding sufficient insulation to the LWS to achieve the same furnace exit temperature at 60 x 10^6 Btu/hr as achieved in the basic LWS configuration at 120 x 10^6 Btu/hr. The 60 x 10^6 Btu/hr DMB, denoted as the modified configuration, was scaled down from the full-scale 120 x 10^6 Btu/hr based on maintaining constant velocity. Figure 5-40 summarizes NO_x emissions from the full- and half-scale DMBs from three test coals for a similar thermal environment as determined by furnace exit temperature. From this figure it can be seen that the larger 120 x 10^6 Btu/hr burner tends to produce lower NO_x emissions than the comparable 60 x 10^6 Btu/hr burner. For operation on Utah coal the differences are not large (approximately 40 ppm under nominal staged conditions), while for the two subbituminous coals NO_x is substantially higher for the half scale burner.

In general, it might be expected that smaller burners would produce somewhat higher NO_x emissions than a corresponding larger burner. For constant burner velocities at both scales, mixing would be expected to occur more rapidly for the smaller burner dimensions, resulting in correspondingly shorter flames and higher combustion intensities. However, in practice much will depend on the details of the burner scaling approach employed and the corresponding performance of the various devices (e.g. swirlers, impellers) used to control mixing.

As was indicated previously, the burner zone heat release parameter, HA/SC varies slightly for the firing conditions of the 60 and 120 x 10^6 Btu/hr. The effect of this parameter can be estimated from Figure 5.39 by comparing the data for the 120 x 10^6 Btu/hr DMB with the modified 60 x 10^6 Btu/hr DMB

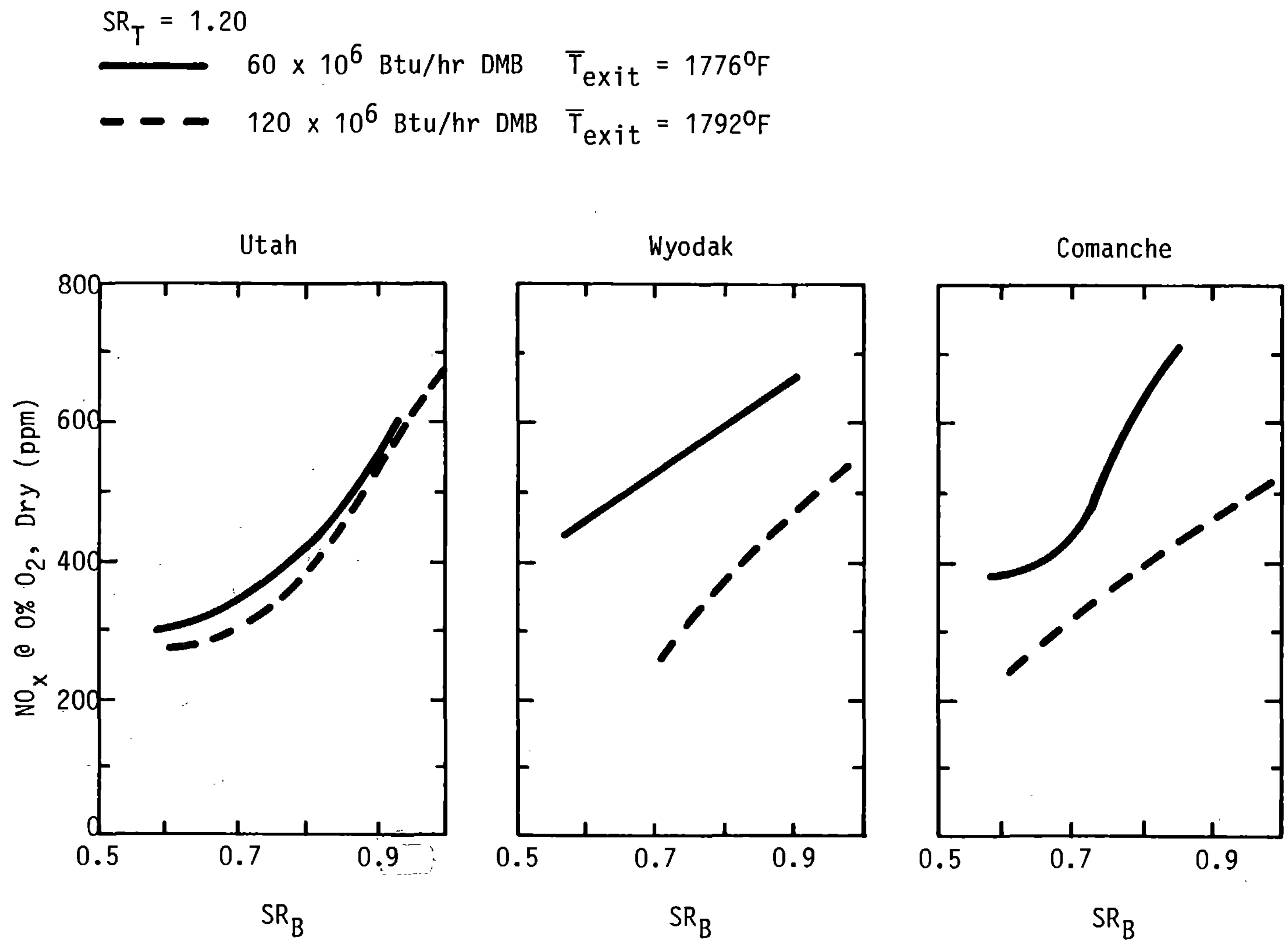


Figure 5-40. Effect of burner scale on NO_x emission.

fired on Utah coal. If the HA/SC vs. NO_x trend established with the short flame DMBs is assumed to hold, then this figure suggests that the NO_x emission from the 120 x 10^6 Btu/hr burner is only slightly lower than the half scale burner, when burner zone heat release is taken into account. This implies an almost 1:1 scale relationship for the full- and half-scale DMBs. However, this does not appear to be true for either the Wyodak or Comanche coals since both produce substantially higher NO_x emissions in the reduced scale burners, and also rank differently in relation to Utah coal. The reasons for this are not clear, but imply that burner conditions may not necessarily be optimum for the two subbituminous coals at both burner scales.

5.6.4 Extrapolation to Full Scale

Experimental data for the Circular and DRB burners, obtained both in the LWS and in field tests on operating boilers, provides an opportunity to evaluate the scalability of NO_x emission performance.

In Figure 5-41 the HA/SC parameter is again used as a means to present NO_x data for the Comanche boiler, and for a corresponding full-scale circular burner fired in the LWS. The boiler data presented in Figure 5-41 represents operation with all burners in service and shows the effect of boiler load, and the dramatic decrease in NO_x resulting from the application of overfire air. The boiler load data shows a trend with HA/SC which is comparable to that derived previously for experimental burners and other boilers.

Also shown in Figure 5-41 are data for the 120 x 10^6 Btu/hr Circular Burner operating at full and reduced loads with Comanche, Illinois, and Utah coals. The effect of load with all three coals is consistent, but shows a much steeper trend with HA/SC. This implies that differences in NO_x emission with load may be due to changes in burner performance in addition to overall burner zone heat release. If the HA/SC correlation is used to extrapolate the LWS data to the conditions of the Comanche boiler, then it can be seen from Figure 5-41 that NO_x emissions would be overpredicted by approximately 100 ppm. This suggests either that NO_x emissions cannot be correlated in

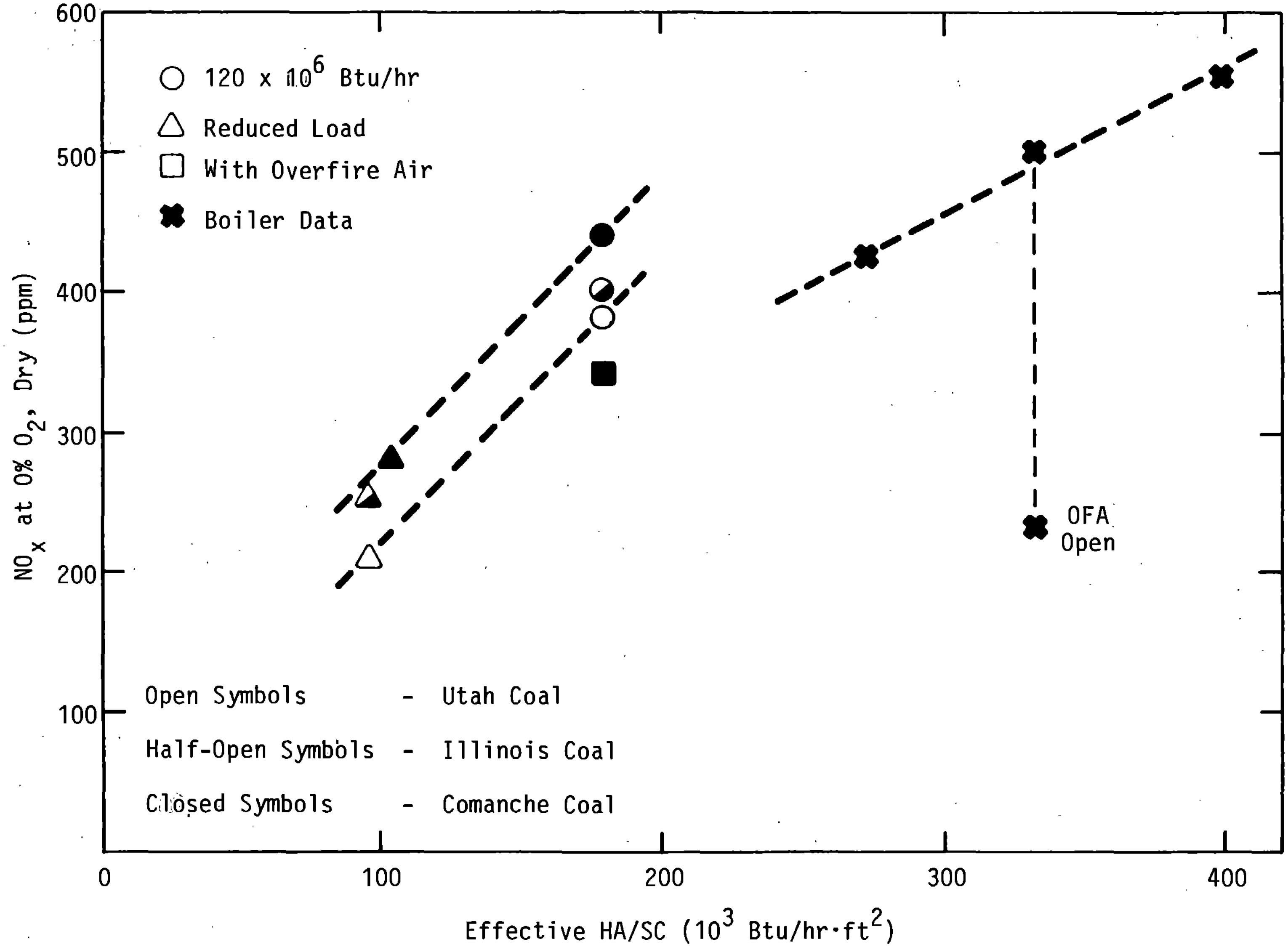


Figure 5-41. Correlation of NO_x emissions for the Circular Burner.

this way, or that there are differences in burner performance characteristics at the two scales.

The relationship between DRB NO_x emission performance in the LWS furnace and the Wyodak boiler are presented in Figure 5-42. Here the three lower data points for the Wyodak boiler represent the effect of boiler load with one mill out of service. For this data set there is again a consistent correlation with the HA/SC parameter. Also shown on Figure 5-42 are data from the 60 x 10^6 Btu/hr DRB with three coals, and corresponding data for Pittsburgh #8 coal on an 80 x 10^6 Btu/hr version of the same burner. There is good agreement between the performance of the two reduced scale burners, where NO_x emissions appear to follow the established HA/SC trend.

The direct extrapolation of the measured DRB performance on Wyodak coal to boiler conditions is not possible because of the difference in burner sizes (60 x 10^6 Btu/hr compared to 120 x 10^6 Btu/hr in the field). In order to facilitate this the NO_x emission of an equivalent 120 x 10^6 Btu/hr DRB has been estimated assuming that the ratio observed for the 60 and 120 x 10^6 Btu/hr DMB burners operating on Utah coal is applicable. (The DMB data on Wyodak coal is not considered sufficiently representative for this purpose). This yields an estimated NO_x level of approximately 250 ppm (compared to 290 ppm for the half-scale burner), and this point is also shown on Figure 5-42. Extrapolation of this estimated data point to Wyodak conditions yields reasonable agreement with the single data point obtained with all burners in service.

On the basis of the HA/SC correlations, the performance of the 120 x 10^6 Btu/hr DMB burner may be extrapolated to the conditions of both the Wyodak and Comanche boilers for their respective coal types. Figure 5-39 suggests that this would yield NO_x emissions comparable to those already obtained on these units. In this respect it should, however, be noted that flames observed in the LWS were confined within the available firing depth of 22 feet, while boiler observations indicated flame lengths considerably in excess of this. For the Wyodak unit in particular, flame lengths were estimated at 35-44 feet. This would suggest that burners of the DMB type can

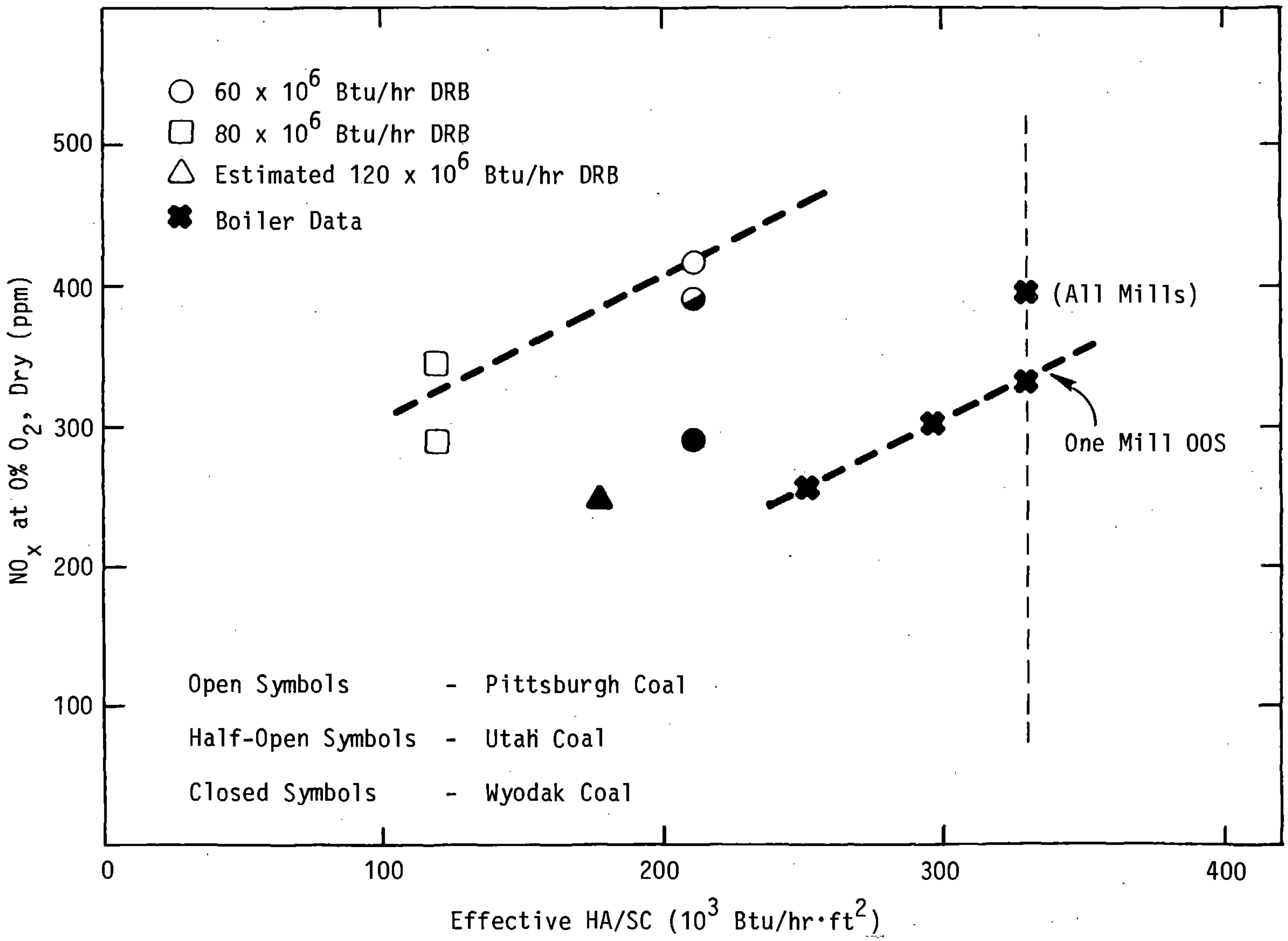


Figure 5-42. Correlation of NO_x emissions for the DRB.

be applied most successfully to achieve low NO_x emissions in confined situations, or that low NO_x performance may be further improved by adjusting the flames to utilize the available combustion space.

6.0 SO_2 REDUCTION POTENTIAL WITH SORBENT INJECTION

The LIMB (limestone Injection Multistage Burner) concept for SO_2 control was evaluated by injecting dry sorbent materials through or around burner passages. The following parameters were considered:

- Fuel composition
- Sorbent composition
- Injection location
- Sorbent feed rate

These tests were not intended to be a comprehensive process optimization; rather, they were only screening tests to evaluate possible differences resulting from burner design or thermal environment using established injection locations.

6.1 Injection Configurations

Sorbent injection tests for SO_2 control were completed for the following furnace configurations:

- limited 60 x 10^6 Btu/hr DMB with coal impeller in both baseline and insulated LWS
- 120 x 10^6 Btu/hr Circular burner
- 120 x 10^6 Btu/hr DMB

Each burner was operated at nominal full load with 20 percent excess air.

A total of six different injection locations were considered. The two near burner locations, with the coal and through nozzles located on the axis of each tertiary port for the DMBs, are illustrated in Figure 6-1. The four locations in the furnace above the burner are shown in Figure 6-2. Table 6-1 lists the locations used for each burner configuration.

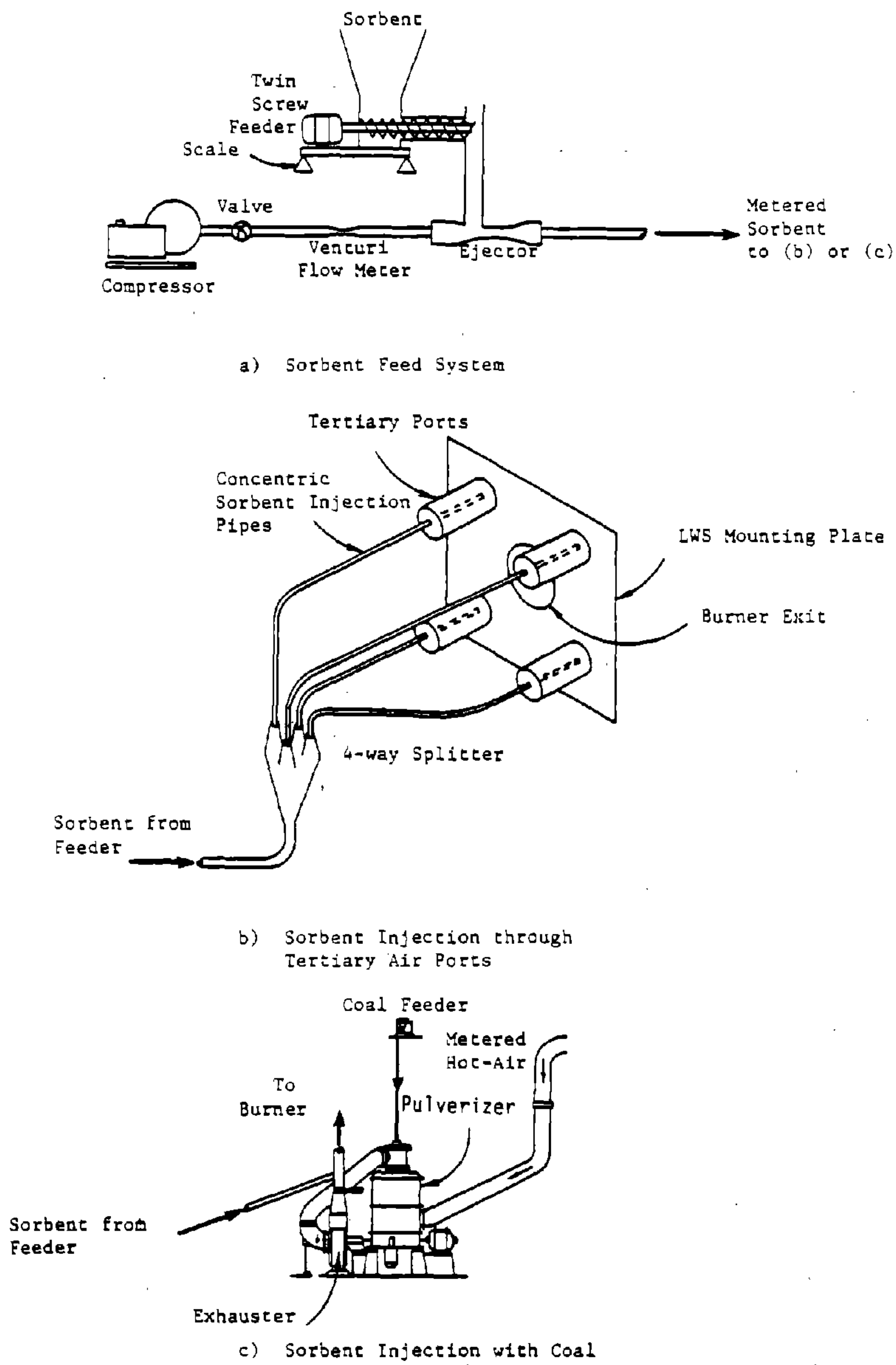
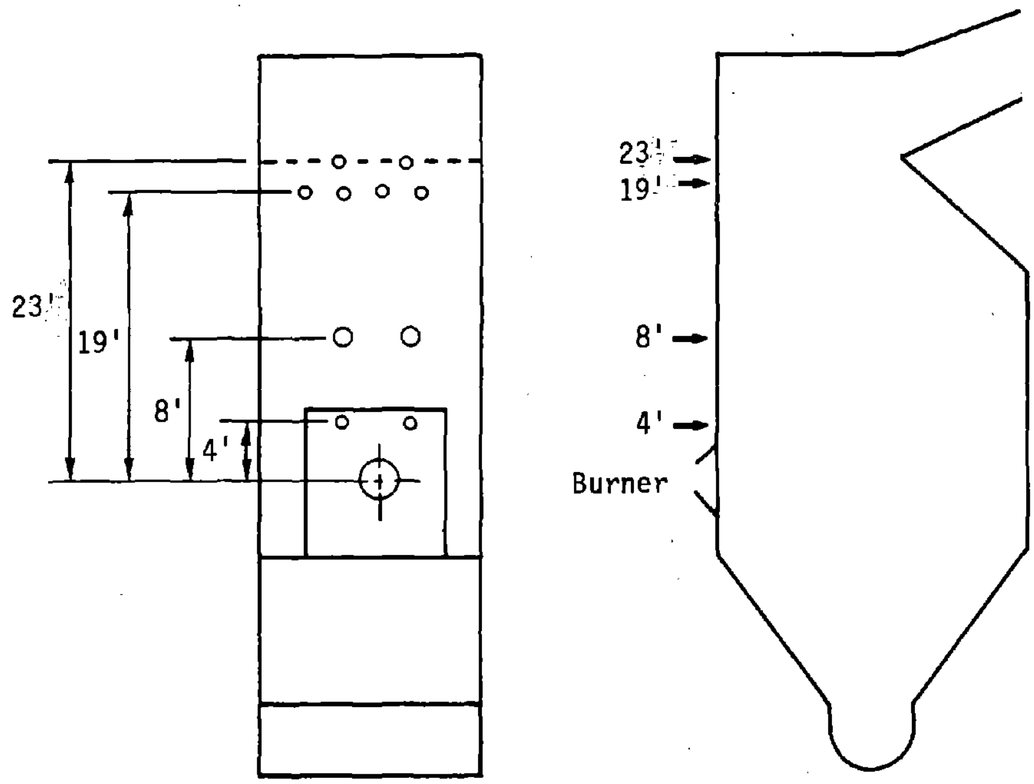


Figure 6-1. Schematic representation of sorbent injection system.



Furnace Locations

Figure 6-2. In-furnace sorbent injection locations.

TABLE 6-1. SORBENT INJECTION LOCATIONS EVALUATED FOR EACH BURNER CONFIGURATION

Sorbent Injection Location	60×10^6 Btu/hr DMB		120×10^6 Btu/hr Circular	120×10^6 Btu/hr DMB
	Baseline LWS	Insulated		
With Coal	X	X	X	X
Through Tertiary Air Ports	X	X		X
4' above burner	X	X		
8' above burner	X	X	X	X
19' above burner			X	X
23' above burner (LWS nose)			X	

6.2 Test Results

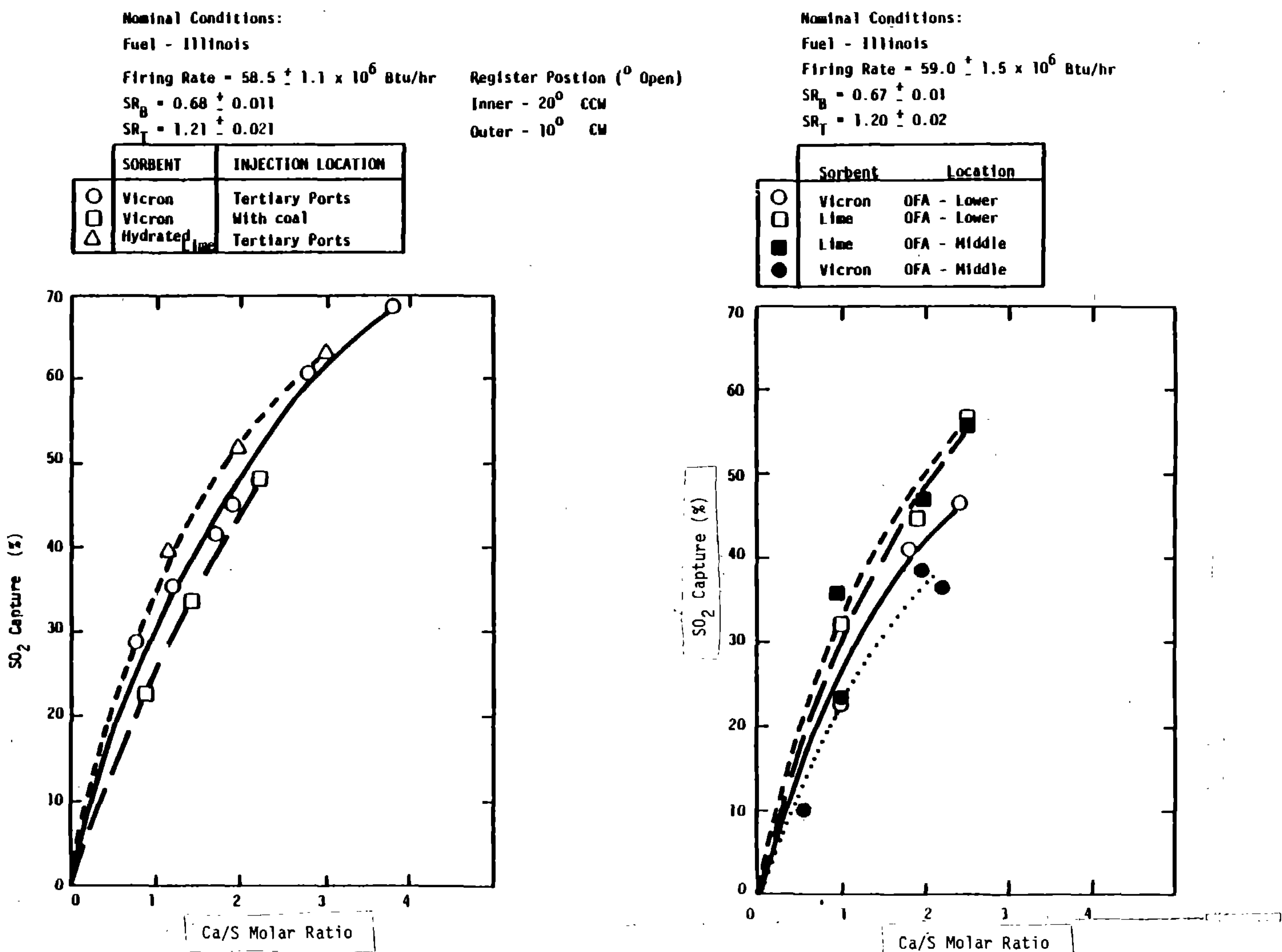
6.2.1 60 x 10^6 Btu/hr DMB

A series of tests were conducted to evaluate the potential of SO_2 reduction by injecting dry sorbents. Two processed calcium based sorbents, Vicron 45-3 limestone and Colton hydrated lime were used. Four different injection locations were evaluated with the 60 x 10^6 Btu/hr DMB.

1. With the coal at the outlet of mill exhauster
2. Through nozzles located on the axis of each tertiary air port
3. Lower level overfire air ports - 4 feet above burner centerline
4. Middle level overfire air ports - 8 feet above burner centerline

Extensive sorbent injection tests were conducted with Illinois Coal. Illinois coal, is a high sulfur coal (3.76 percent S dry) and has been used in previous LIMB development work at EER. Figure 6-3 summarizes the effects of sorbent injection on SO_2 capture with Illinois Coal. Figure 6-3(a) shows injection of Vicron and lime through the tertiary ports. Injection of hydrated lime yielded the highest capture of 53 percent compared to 48.5 percent with Vicron at a calcium-to-sulfur molar ratio of 2.0. Injection of Vicron with the coal yielded slightly lower capture, 44.5 percent at Ca/S = 2.0. Figure 6-3(b) summarizes the results of sorbent injection through two different overfire air (OFA) locations. The level of OFA ports had no significant effect on sulfur capture by the injection of hydrated lime. Injection of Vicron through the lower ports yielded higher capture than when injected through the upper ports.

An abbreviated series of tests were conducted for Utah, Wyodak, and Comanche coals with sorbent injection, summarized in Figure 6-4. The highest capture was achieved with injection of hydrated lime through the lower OFA ports for each coal. Injection with this configuration yielded SO_2 reduction of 50 and 48 percent at Ca/S = 2.0 for Utah and Comanche, respectively. Sulfur capture was significantly less for the Wyodak coal with only



a) Injection through burner passages

b) Injection through OFA ports.

Figure 6-3. Summary of sorbent injection with 60 x 10^6 Btu/hr DMB Illinois coal.

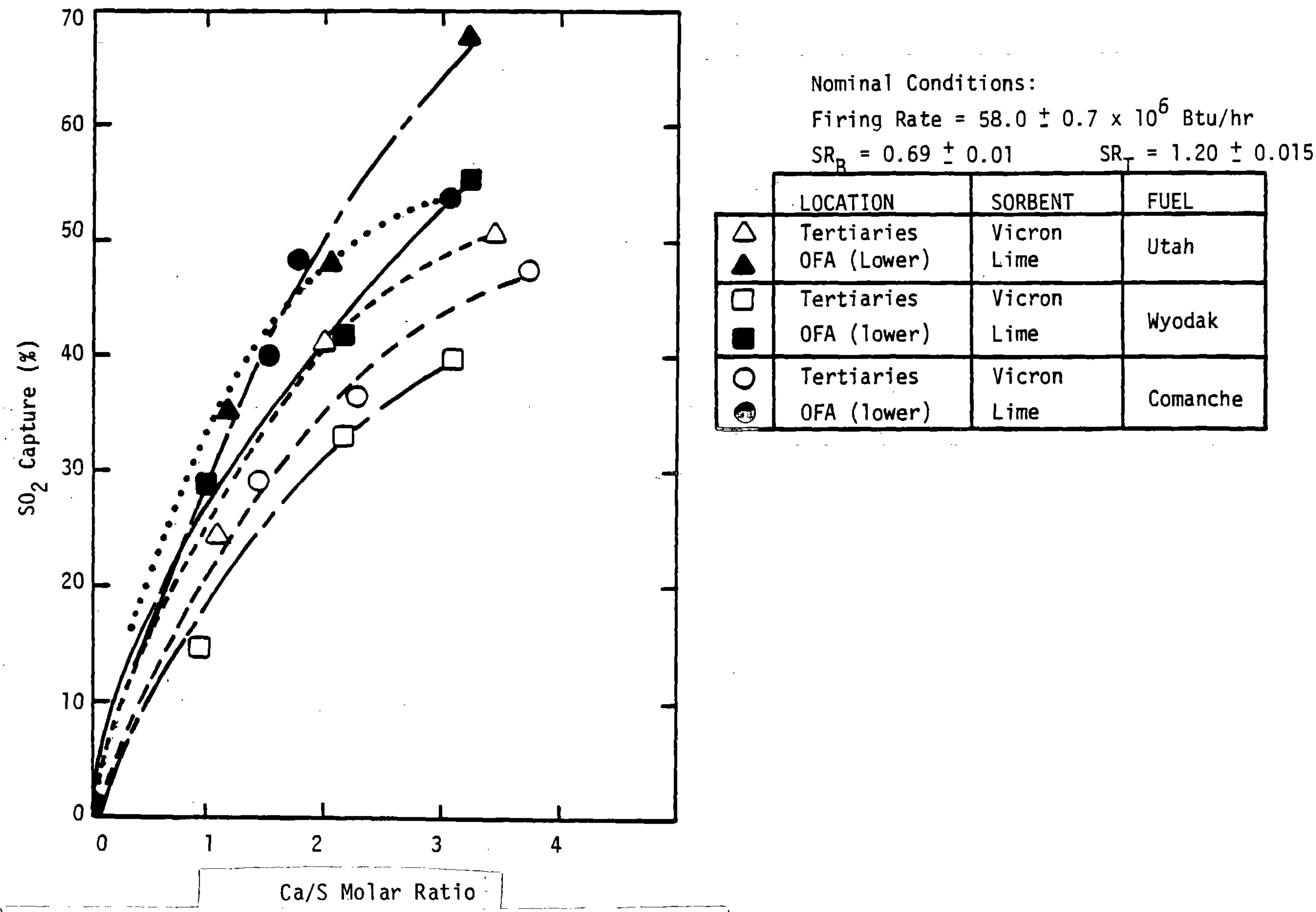


Figure 6-4. Summary of sorbent injection with 60 x 10^6 Btu/hr DMB burner.

41 percent at a comparable stoichiometry. Injection of Vicron limestone through the tertiary air ports reduced SO_2 by 42 percent with Utah Coal. Comanche and Wyodak had significantly lower SO_2 reductions with 35 and 32 percent respectively.

A series of tests were initiated to evaluate the effect of thermal environment on SO_2 reduction potential of the short flame 60 x 10^6 Btu/hr DMB with sorbent injection. The initial tests with Illinois coal are summarized in Figure 6-5 for sorbent injection through the tertiary and lower overfire air ports but with furnace temperatures increased through installation of additional insulation. For these injection locations the SO_2 capture was significantly less in the insulated LWS compared to results in the baseline furnace. Capture was higher for injection of hydrated lime through the lower overfire air ports (OFA), 37 percent at Ca/S = 2.0, than the other combinations. This is almost 7 percent less than achieved with the same conditions in the baseline furnace. Injection of the Vicron limestone through the tertiary air ports and the lower OFA ports produced similar SO_2 reduction, 26 percent at Ca/S = 2.0. This is much less than the 41.5 percent achieved in the baseline furnace for the same conditions. These results indicate the sensitivity of the SO_2 capture process by sorbent injection to thermal environment. Additional SO_2 capture data, for sorbent injection through the middle OFA ports (8 feet above the burner center), are presented in Figure 6-6. Here the SO_2 capture data for the insulated furnace are compared directly with the previous data for baseline conditions.

For the insulated furnace, the highest capture was obtained with injection of hydrated lime through the middle overfire air ports, yielding 53.3 percent capture at Ca/S = 1.93. Slightly lower SO_2 reduction, 50.3 percent, was obtained with Vicron. Vicron injected with the coal resulted in lower SO_2 capture, 45 percent at Ca/S = 2.0. The thermal environment had the greatest effect on the injection of Vicron through the middle OFA ports with capture increasing by about 12.5 percent at Ca/S = 2.0 in the insulated configuration. For hydrated lime injected through the middle OFA ports, the overall trend indicates generally no difference due to thermal environment.

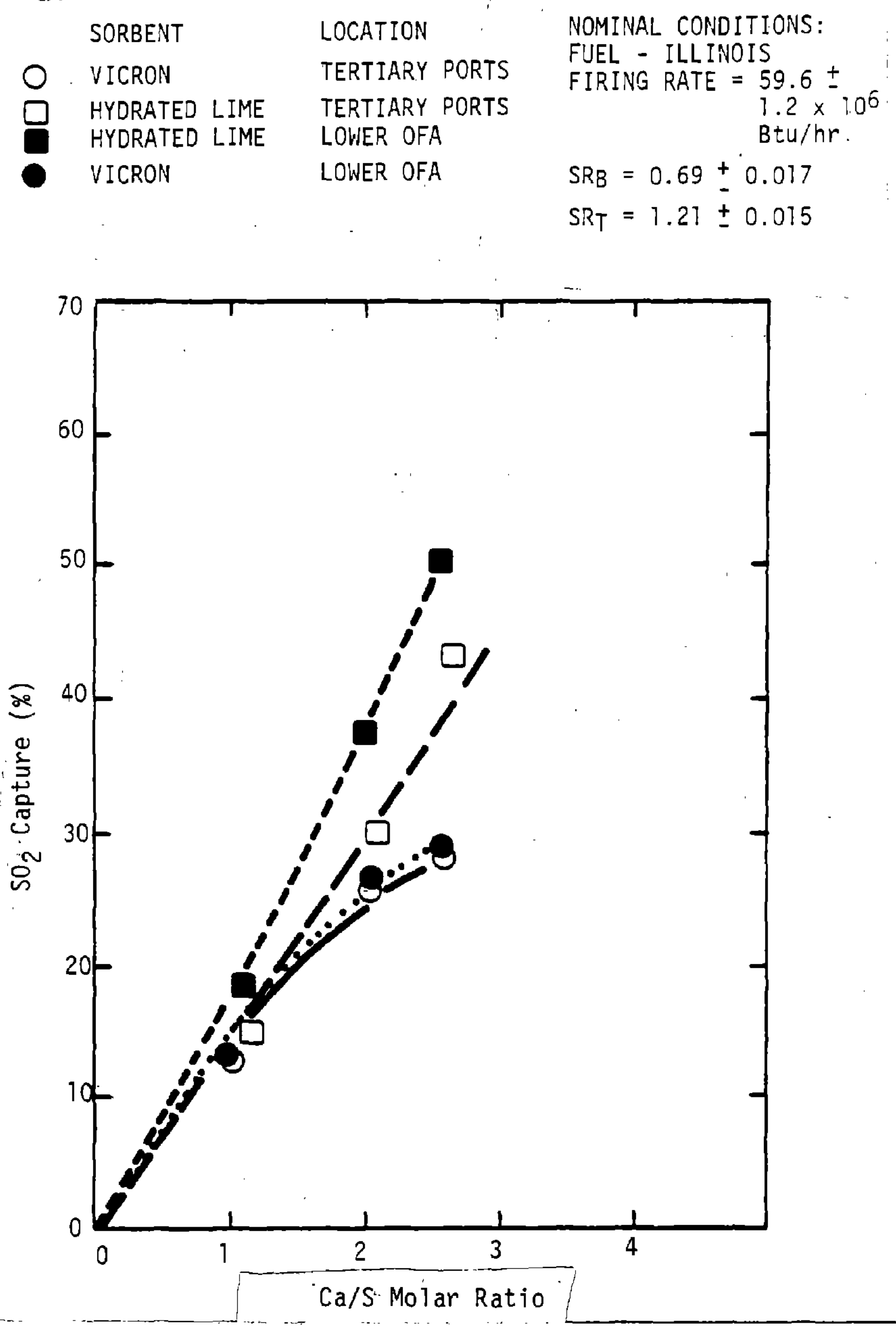


Figure 6-5. SO_2 reduction potential with sorbent injection of the 60 x 10^6 Btu/hr DMB in the insulated LWS.

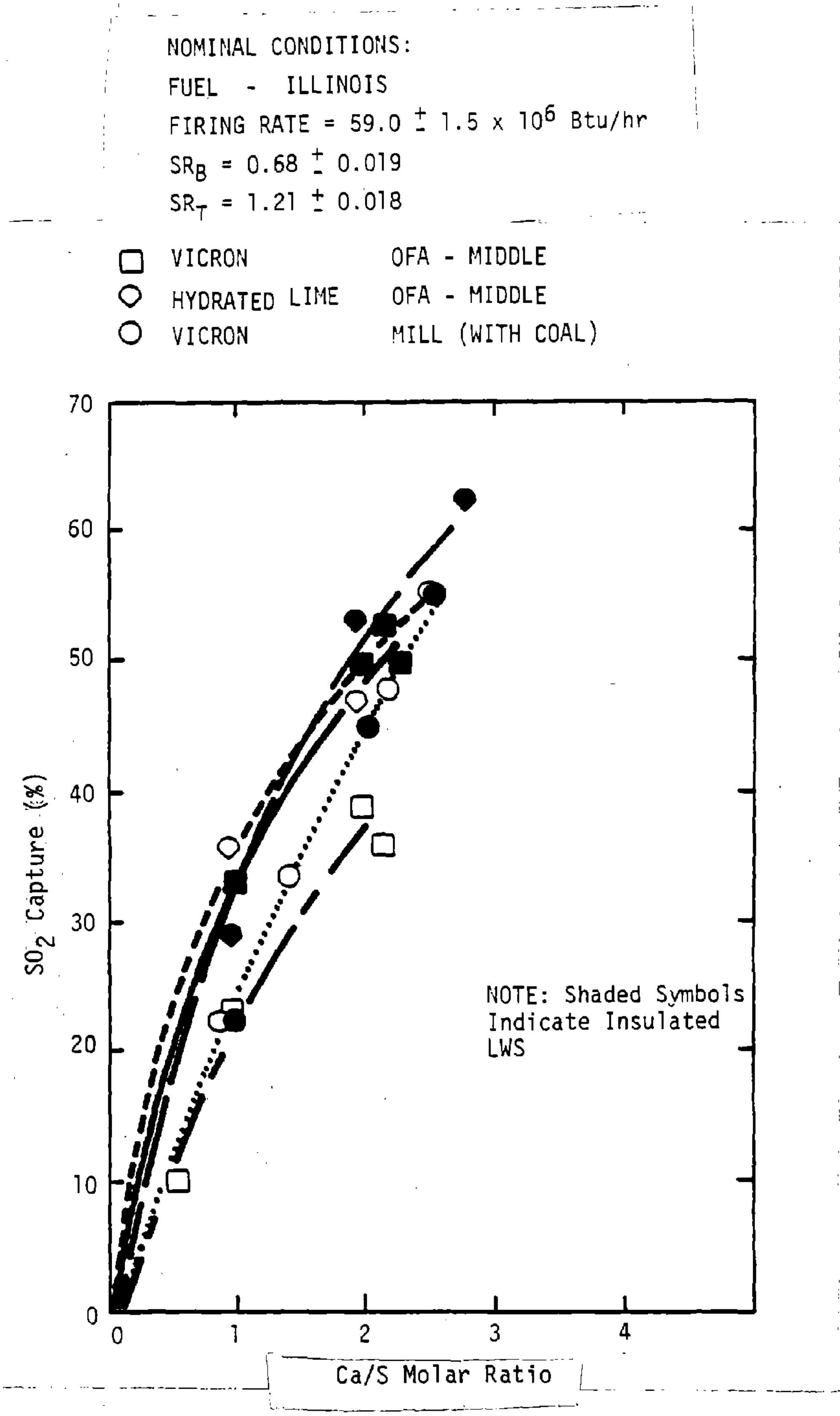


Figure 6-6. Summary of SO_2 reduction potential with 60×10^6 Btu/hr DMB burner with Illinois coal.

This same trend is found for the injection of Vicron with the coal with no change in capture over the tested range.

The effects of sorbent injection in the insulated furnace were also evaluated for two alternate fuels Utah and Wyodak. Figure 6-7 summarizes the effects of sorbent injection for Utah coal. The highest SO_2 capture 47.5 percent was obtained with the injection of lime through the OFA port at Ca/S = 2.0 for both temperature/injection location combinations. Substantially lower capture was obtained with injection of Vicron through the tertiary ports, with a 40 percent SO_2 reduction at Ca/S = 2.0 in the baseline furnace. Increasing the furnace temperature with additional insulation significantly decreased the SO_2 reduction to 29 percent at Ca/S = 2.0. Figure 6-8 summarizes the effects of sorbent injection on SO_2 reduction with Wyodak host coal through the OFA ports. Slightly higher capture was obtained in the insulated furnace, 48 percent compared to 41 percent at Ca/S = 2.0 with injection of hydrated lime through the OFA ports. The difference in capture was even less (less than 4 percent change) for other calcium-to-sulfur molar ratios.

6.2.2 120×10^6 Btu/hr Circular Burner

A comprehensive series of tests were conducted with the circular burner to evaluate the SO_2 reduction potential through injection of two dry sorbents, Vicron limestone and hydrated lime. Four different injection locations were utilized corresponding to OFA ports 8 feet, 19 feet, and 23 feet above the burner centerline, and with the coal. These locations correspond to a temperature range of about 2200-2300°F at the 8 foot level to approximately 1800-1850°F at the 23 foot level.

A brief series of tests were completed with Utah coal and is summarized in Figure 6-9. Injection of hydrated lime through the 8 foot ports resulted in SO_2 capture of about 35 percent at Ca/S = 2.0.

Injection of Vicron limestone with the coal resulted in significantly lower SO_2 reduction, about 10 percent at Ca/S = 2.0. This extremely low

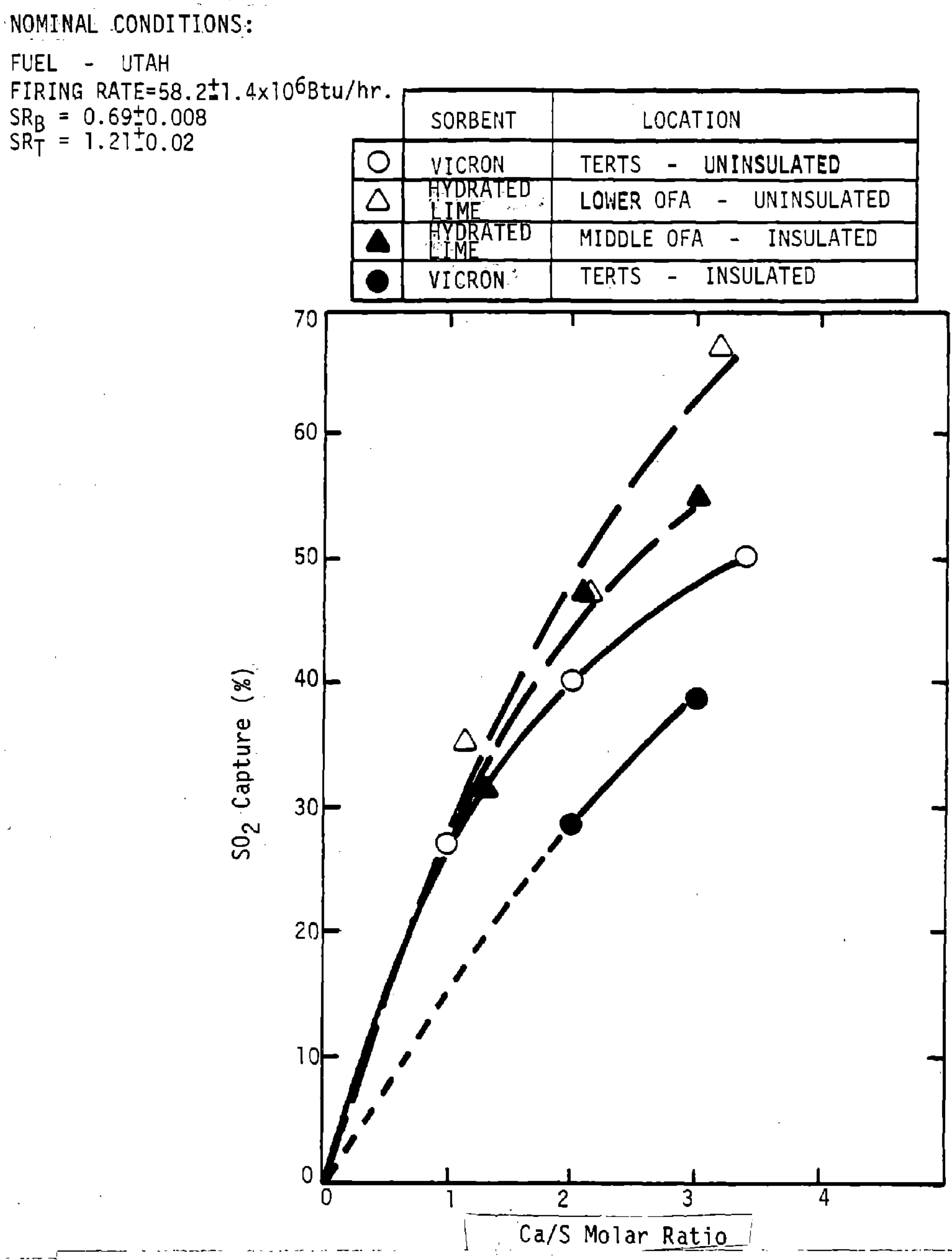


Figure 6-7. Summary of sorbent injection with 60 x 10^6 Btu/hr burner with Utah coal.

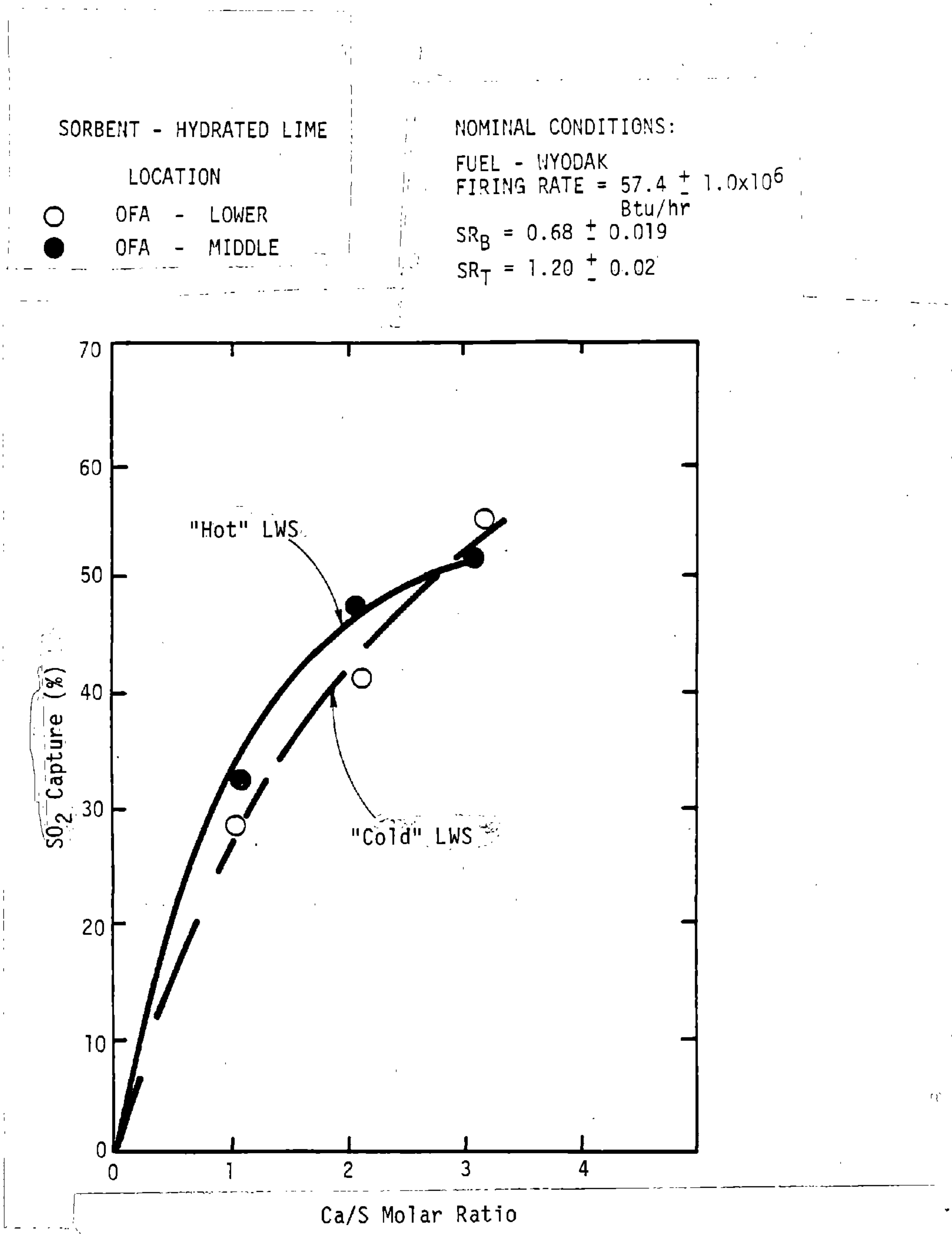


Figure 6-8. Effect of sorbent injection on SO_2 reduction potential with Wyodak coal.

Fuel - Utah
Firing Rate = 119.4 ± 2.5 x 10^6 Btu/hr
SR_T = 1.20 ± 0.1

	SORBENT	LOCATION
○	Vicron Limestone	Mill
□	Hydrated Lime	8'

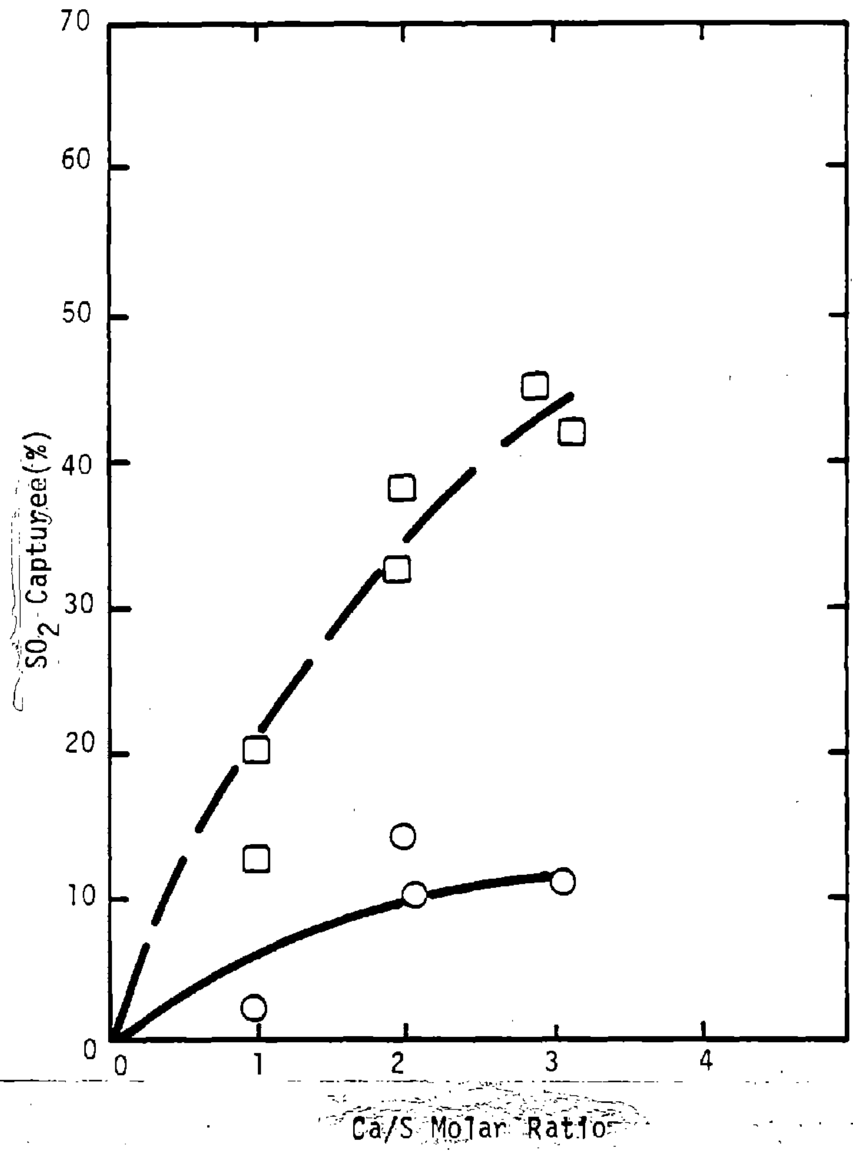


Figure 6-9. Summary of sorbent injection with 120×10^6 Btu/hr circular burner with Utah coal.

capture is probably due to the intense temperature (>2300^oF) to which the sorbent is exposed in the center of the flame zone.

A more extensive series of tests were conducted firing the high sulfur Illinois coal with the Circular burner. These results are summarized in Figure 6-10. Injection of Vicron limestone yielded similar SO_2 reduction, regardless of location. The best capture was achieved at the 19 foot and 23 foot level with capture rates of about 38 percent at Ca/S = 2.0. This is only slightly higher than the capture obtained when injected with the coal or at the 8 foot level which resulted in about 33.5 percent reduction. Injection of hydrated lime yielded increased capture rates of 42 percent at both the 8 foot and 19 foot level at Ca/S = 2.0. However, at the 23 foot level, capture was significantly lower with only 32 percent at Ca/S = 2.0. These results indicate a trade-off between residence time in the optimum sulfation window and the maximum temperatures to which the sorbent is exposed.

6.2.3 120 x 10^6 Btu/hr DMB

A series of tests were also conducted to evaluate the potential of SO_2 reduction with the 120 x 10^6 Btu/hr DMB. Three processed calcium-based sorbents were utilized, Vicron 45-3 limestone, Colton hydrated lime, and Genstar Type-S pressure hydrated dolomitic lime (PHDL). Four different injection locations were evaluated:

1. With the coal at the outlet of the mill exhauster.
2. Through nozzles located at the axis of each tertiary port.
3. Lower level overfire airports - 8 feet above burner centerline.
4. Upper level overfire airports - 19 feet above burner centerline.

An abbreviated series of tests were conducted with Utah coal and is summarized in Figure 6-11. Two injection locations, the tertiary air ports and the 8 foot level were evaluated. Figure 6-11(a) represents injection through the tertiary air ports. There is no significant difference between

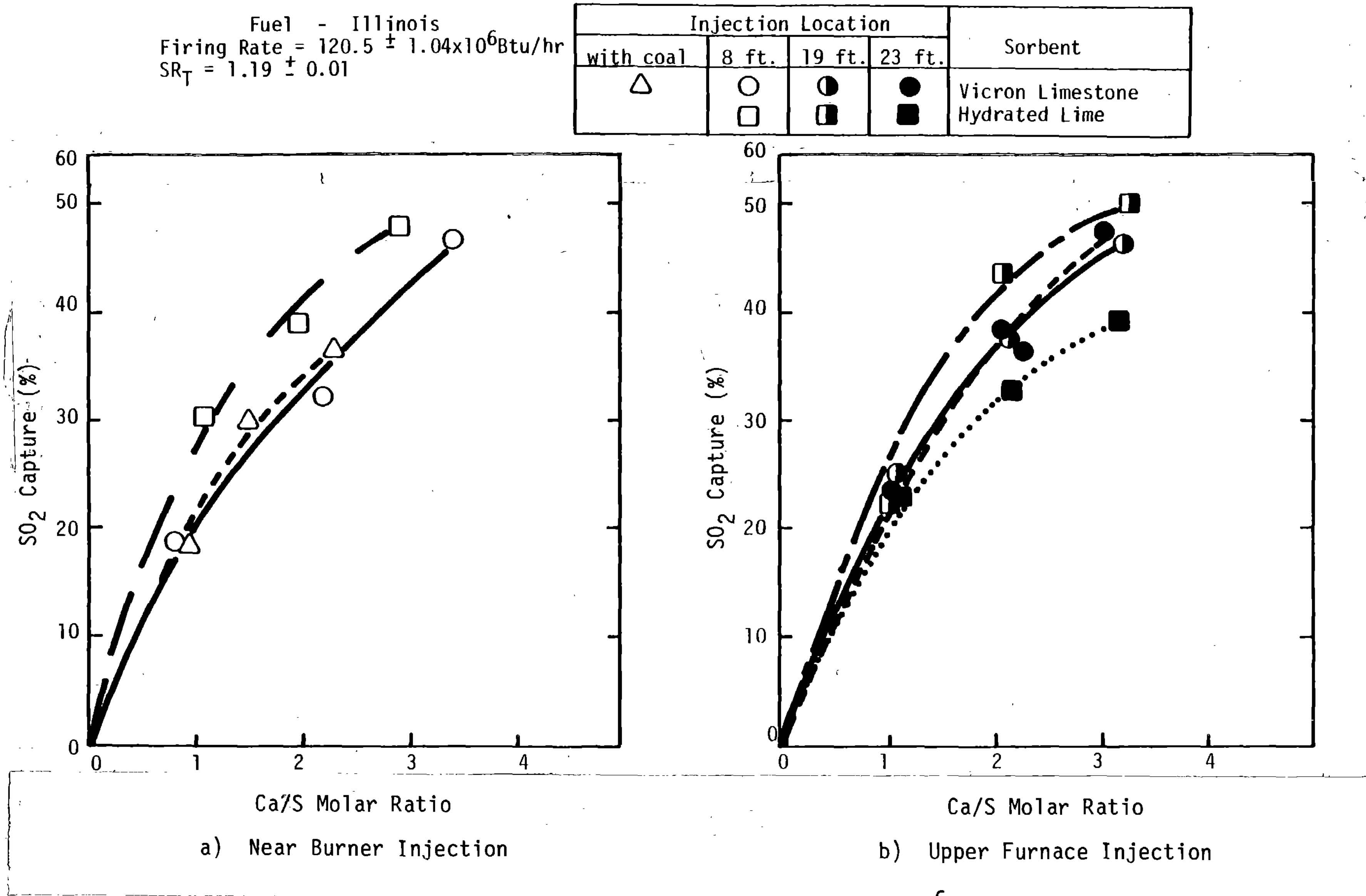


Figure 6-10. Summary of sorbent injection with 120 x 10^6 Btu/hr circular burner with Illinois coal.

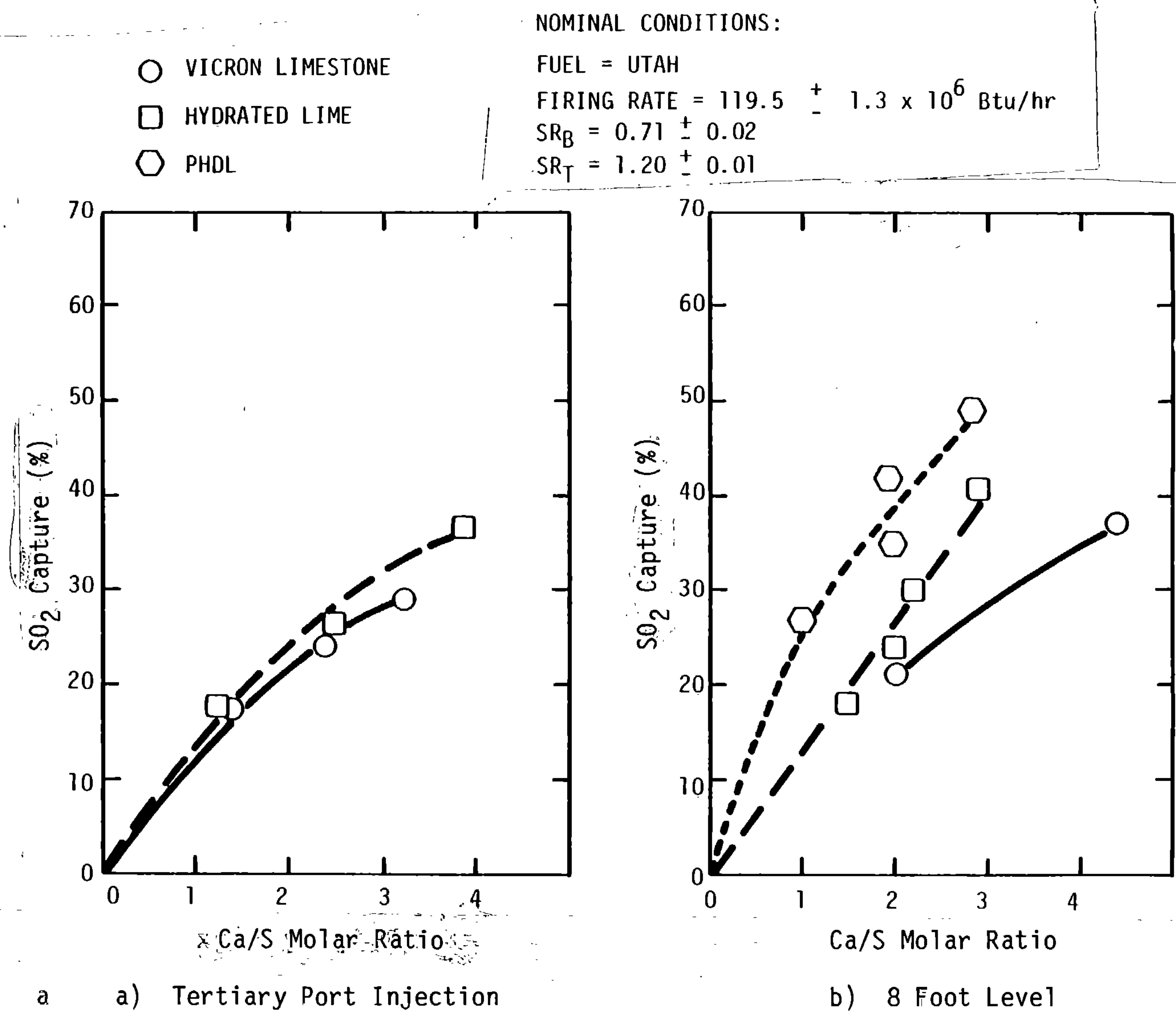


Figure 6-11. Summary of sorbent injection with the 120 x 10^6 Btu/hr DMB firing Utah coal.

the Vicron limestone or the hydrated lime with SO_2 capture at about 23 percent at Ca/S = 2.0. Figure 6-11(b) summarizes injection at the 8 foot level. There is no significant change in injection of Vicron limestone at this level compared to the near burner tertiary air locations. The 8 foot level yielded slightly higher capture with hydrated lime, up to about 27.5 percent at Ca/S = 2.0. The highest capture was obtained with injection of the PHDL at the 8 foot level with capture of about 40 percent at Ca/S = 2.0.

Extensive sorbent injection tests were conducted with the Illinois coal, and results are summarized in Figure 6-12. As with the Utah coal, there is no difference between injection of Vicron limestone or hydrated lime through the tertiary air ports although overall capture is slightly higher, 27 percent at Ca/S = 2.0. Injection of Vicron limestone with the coal is slightly lower with 25 percent SO_2 reduction at Ca/S = 2.0. Figure 6-12(b) shows the improved results obtained with injection into the upper furnace. The capture rates are higher in each case than with the Utah coal. Vicron limestone injected at the 8 foot level achieved slightly higher capture than either "near burner" location, 29 percent at Ca/S = 2.0. Injection with hydrated lime resulted in a more significant increase with SO_2 capture of about 33 percent at the 8 foot level and 40 percent at the 19 foot level at Ca/S = 2.0. Once again, the highest SO_2 reduction is achieved with the PHDL with capture of 40 percent at Ca/S = 1.0. Higher Ca/S molar ratios with the PHDL would result in increased capture, but due to the sorbent properties and higher feed rates required, it was not possible to inject at any higher Ca/S ratios at full load operation.

A brief series of tests were conducted to determine the effects of thermal environment on SO_2 reduction potential by injecting sorbent at a reduced firing rate of 65×10^6 Btu/hr with Illinois coal. These results are summarized in Figure 6-13. For each sorbent/injection location combination, SO_2 capture improved significantly. With injection of hydrated lime into the 8 foot level the capture increased from 40 at full load to 50 percent at the reduced load. Injection of Vicron limestone into the 8 foot level also increased capture rate from 29 to 40 percent. Hydrated lime injected through

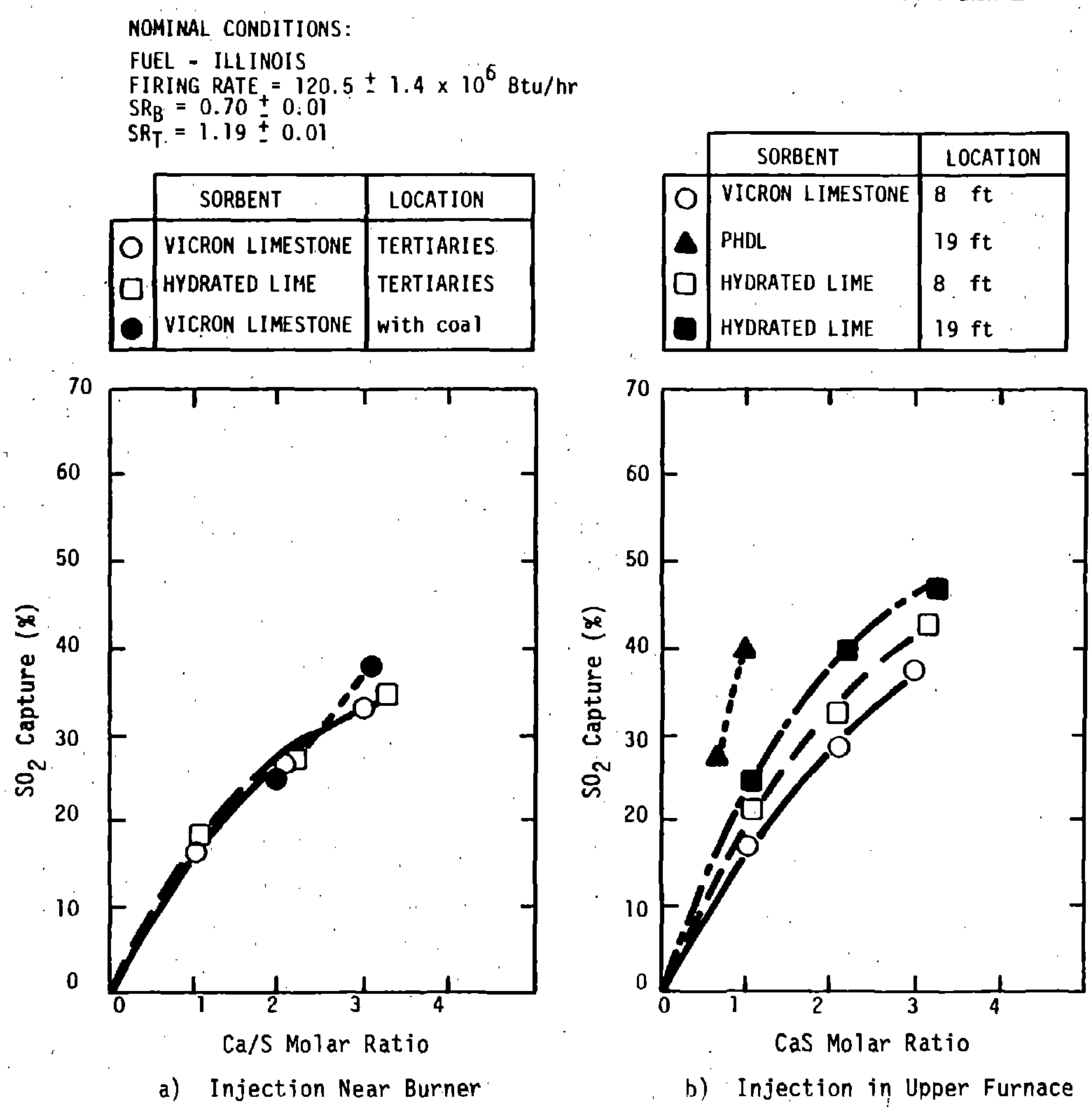


Figure 6-12. Summary of sorbent injection with staged 120 x 10^6 Btu/hr at design firing rate.

NOMINAL CONDITIONS:
FUEL - ILLINOIS
FIRING RATE = $65.7 \pm 1.3 \times 10^6$ Btu/hr
$SR_B = 0.70 \pm 0.01$
$SR_T = 1.19 \pm 0.01$

	SORBENT	LOCATION
○	VICRON LIMESTONE	8 ft.
□	HYDRATED LIME	8 ft.
△	PHDL	8 ft.
■	HYDRATED LIME	Tert. Ports
●	VICRON LIMESTONE	with coal

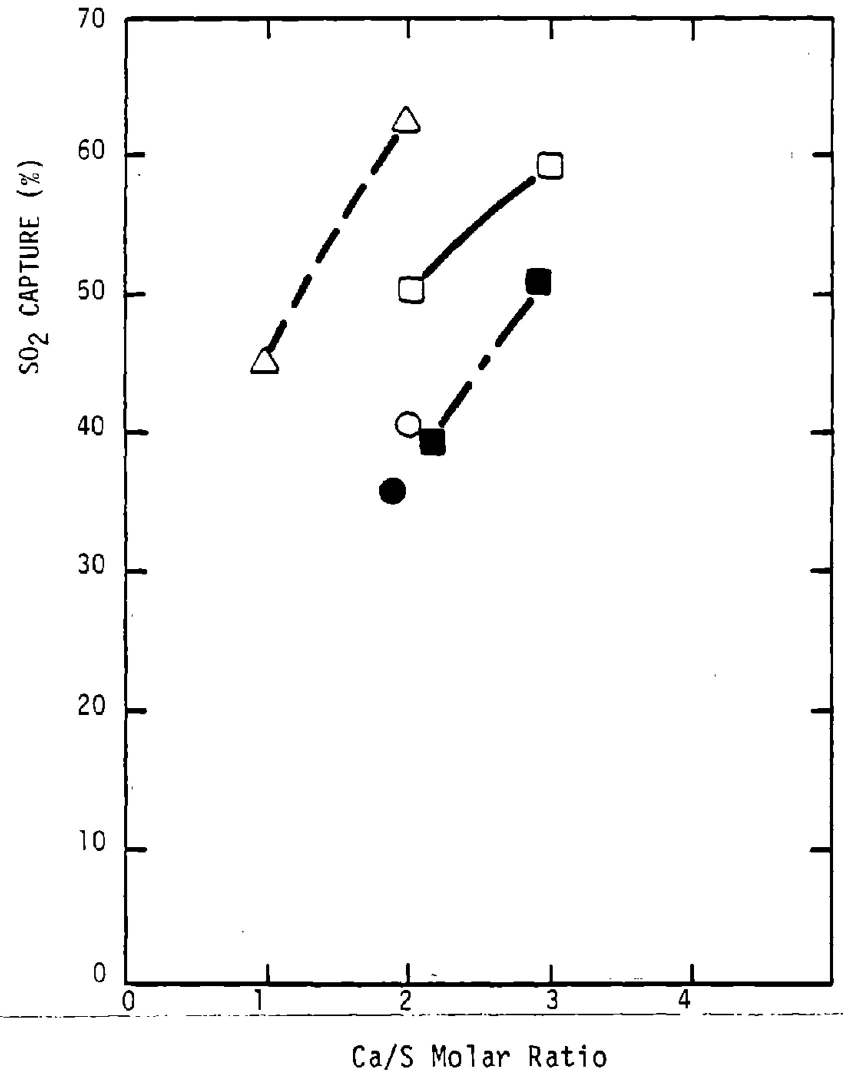


Figure 6-13. Summary of sorbent injection with staged 120×10^6 Btu/hr DMB at reduced firing rate.

the tertiary ports increased capture from 27 to 40 percent as a result of the decreased firing rate. SO_2 capture increased to 36 percent with injection of Vicron limestone with the coal. The highest SO_2 reduction was again obtained with the PHDL with 62.5 percent reduction at Ca/S = 2.0 for injection at the 8 foot level.

6.3 Discussion of SO_2 Removal Performance

Previous sections have presented detailed SO_2 removal results for the experimental burners investigated in this program. A wide range of SO_2 removal rates have been encountered in the study, depending upon the particular experimental conditions of individual tests. A summary of relevant SO_2 removal data is presented in Table 6-2 for limestone and hydrated lime injection at Ca/S = 2, and operation on Illinois coal, parameters for which the largest data base was obtained. This summary table also covers the effects of burner design, firing rate, furnace insulation, and sorbent injection location. In order to elucidate those parameters which have the greatest impact on the sorbent injection process some further discussion is necessary.

Over the past several years considerable work has been conducted at laboratory, bench, and pilot scales, in the study of both fundamental and practical aspects of sorbent injection. While the process is not completely understood, factors which are known to significantly affect SO_2 removal performance include:

- Sorbent type
- Temperature at the injection location
- Furnace temperature profile (quench rate)
- Coal type
- Mixing

The following sections will draw on the previous data presentation to illustrate the impacts of the above parameters.

TABLE 6-2. SUMMARY OF PERCENTAGE SO_2 REMOVAL DATA--ILLINOIS COAL, INJECTED Ca/S MOLAR RATIO = 2.

Sorbent Injection Location	60×10^6 Btu/hr DMB				120×10^6 Btu/hr Circular		120×10^6 Btu/hr DMB	
	Baseline LWS		Insulated					
	$CaCO_3$	$Ca(OH)_2$	$CaCO_3$	$Ca(OH)_2$	$CaCO_3$	$Ca(OH)_2$	$CaCO_3$	$Ca(OH)_2$
With Coal	44		44		35		27	
Through Tertiary Air Ports	48	53	25	30			27	27
4' Above Burner	42	51	25	38				
8' Above Burner	37	47	50	53	33	42	28	33
19' Above Burner					38	43		38
23' Above Burner (LWS nose)					38	32		

6.3.1 Sorbent Type

The data presented in Table 6-2 indicate that, for comparable firing and injection conditions, higher levels of SO_2 removal are generally achieved with hydrated lime than with limestone. Other limited data obtained with the pressure hydrated dolomitic sorbent (e.g. Figure 6-12) indicate that this material significantly outperforms both of the high calcium sorbents. This general ranking of sorbent materials is consistent with that found in other studies, and Figure 6-14 presents data for the test sorbents obtained in a bench scale furnace facility under carefully controlled experimental conditions. These data suggest that the Colton hydrate is only marginally more effective than Vicron limestone. It will be noted, however, that the majority of the SO_2 capture data obtained in the LWS furnace is considerably in excess of that reported in Figure 6-14 for more idealized conditions. The reasons for this are believed to relate to other parameters such as injection temperature, furnace thermal profile, and mixing.

6.3.2 Injection Temperature

In the execution of the experimental program the effect of sorbent injection temperature on SO_2 removal was evaluated by two means:

- The use of injection locations close to the burner and at different elevations above the burner.

- Increasing mean furnace temperatures through additional insulation.

For the 60 x 10^6 Btu/hr DMB the results of Table 6-2 and the preceding discussion indicates that:

- For equivalent injection locations increasing furnace temperature decreases SO_2 capture.

- Optimum SO_2 capture is achieved by injection at higher furnace elevations as furnace temperature is increased.

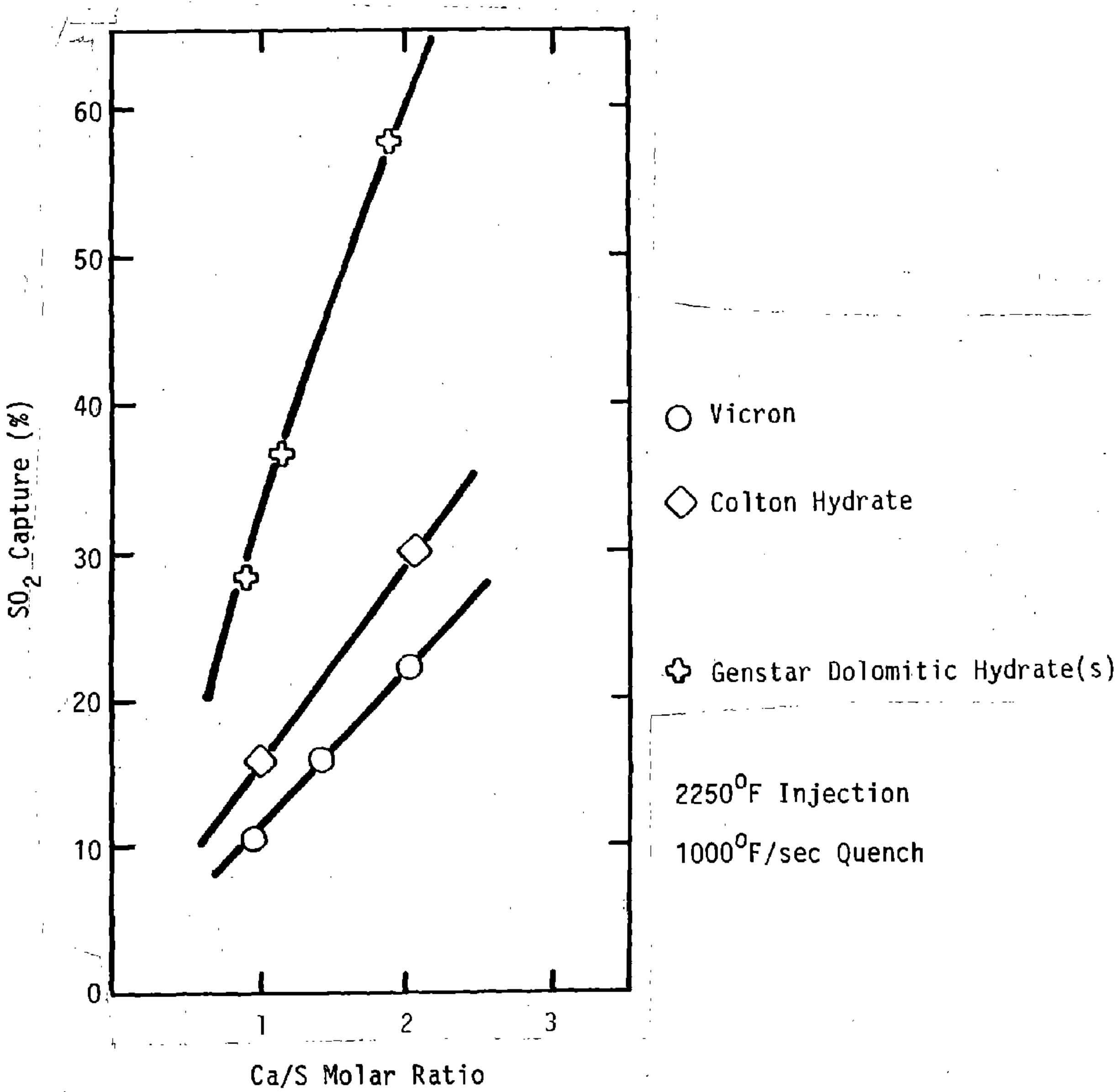


Figure 6-14. Bench scale data comparing SO_2 removal performance for different sorbents.

These results imply that there is an optimum injection location, which is determined by temperature for each furnace/burner configuration. The 60 x 10^6 Btu/hr DMB data from Table 6-2 are plotted in Figure 6-15 as a function of temperature at the sorbent injection plane. Temperature values assigned to the different injection locations and levels of furnace insulation are estimated from limited available measurement data, and from simple heat transfer models of furnace performance, and are intended to represent the maximum temperature experienced by the sorbent. Figure 6-15 shows a reasonable correlation between SO_2 capture and injection temperature, and indicates an optimum temperature of approximately 2200°F for both limestone and hydrated lime. For the baseline (cold) LWS this location corresponds approximately to the tertiary port location, while for the insulated furnace this temperature occurs at approximately 8 feet above the burner. This kind of dependency on injection temperature is again expected from smaller scale sorbent injection studies.

It will be noted, however, that the Table 6-2 data for the two 120 x 10^6 Btu/hr burners do not readily fit into the plot on Figure 6-15, either in terms of maximum SO_2 removal, or in terms of the relative location at which maximum capture occurs. This is in spite of the use of additional insulation in one 60 x 10^6 Btu/hr case in an attempt to match thermal conditions with the higher firing rate. The reason for this behavior is believed to be due both to the detailed temperature profile in the furnace and to sorbent/flue gas mixing.

6.3.3 Temperature Profile

A further parameter which has been shown to significantly impact SO_2 removal performance is that of the temperature profile in the furnace. This is often expressed as a mean quench rate or the rate of temperature decay over the internal 2200-1600°F. Results of studies in small scale furnaces are presented in Figure 6-16 to illustrate the effects of quench rate and injection temperature on SO_2 removal, for limestone and hydrated lime sorbents. The figure indicates that as conditions move from isothermal to

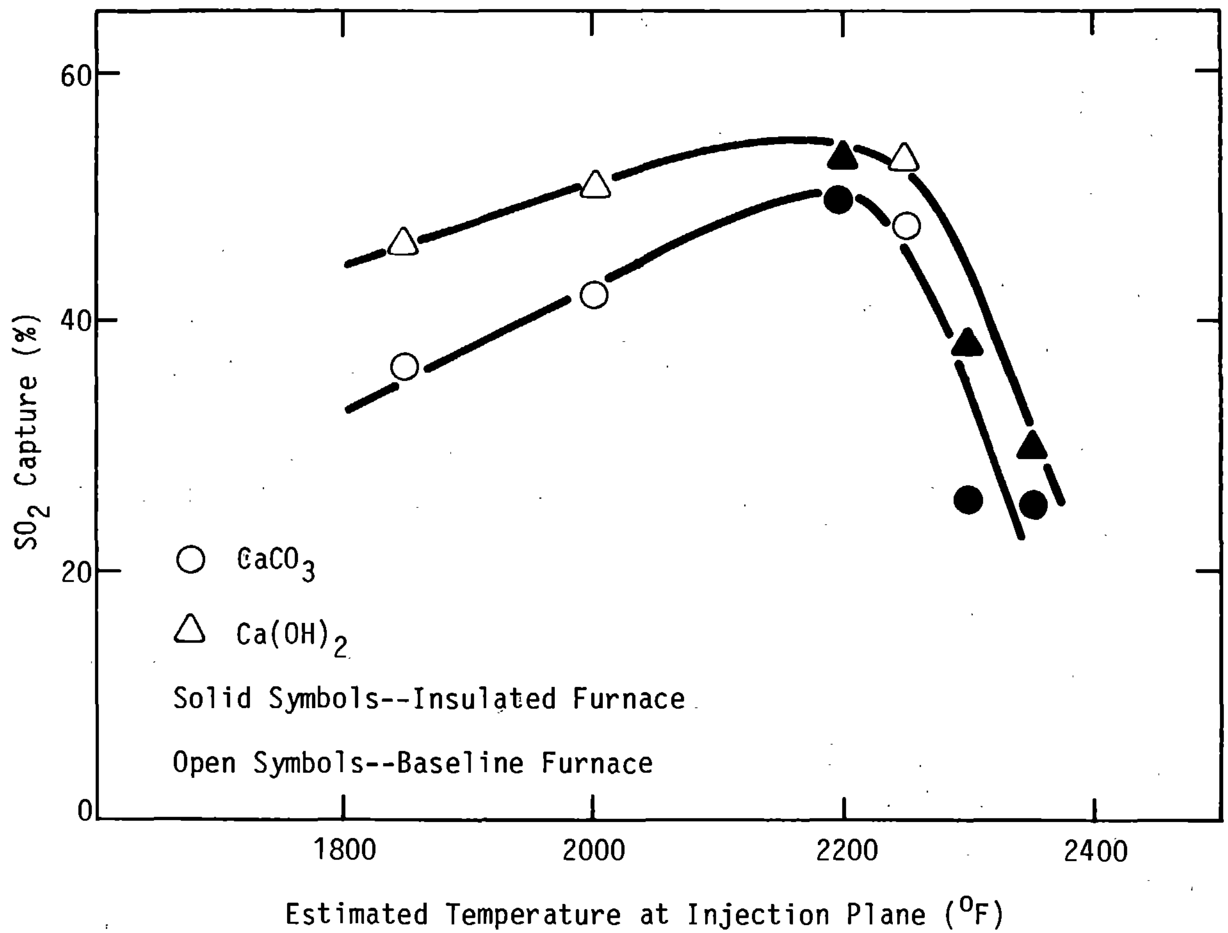


Figure 6-15. Estimated relationship between injection temperature and SO_2 Capture--60 x 10^6 Btu/hr DMB, Illinois coal.

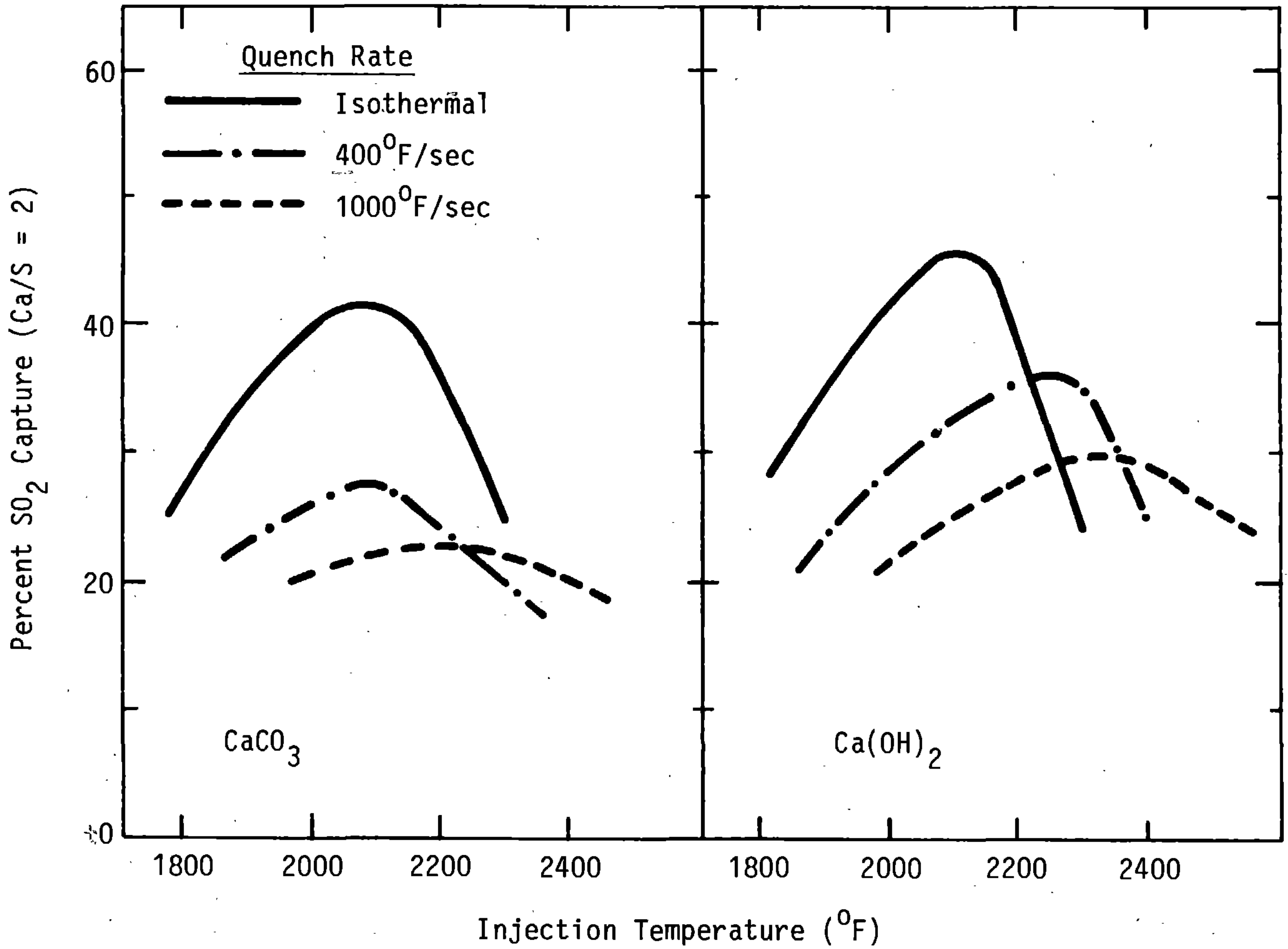


Figure 6-16. Small-scale data showing the effect of thermal conditions on SO_2 capture.

rapid quench the maximum SO_2 removal is significantly reduced, and optimum temperatures tend towards higher values.

In the context of the LWS furnace the applicable quench rate is estimated to be very low (below 200°F/sec), such that long mean residence times are available in the optimum temperature range. This is particularly true for the cold furnace condition and low firing rates. In comparing the 120 x 10^6 Btu/hr data with 60 x 10^6 Btu/hr data in the insulated furnace, it is clear that although mean temperature levels are approximately matched, the effective quench rate will approximately double at the higher firing rate. This is believed to be the primary reason for the decrease in optimum SO_2 removal at 120 x 10^6 compared to 60 x 10^6 Btu/hr. This point can be further illustrated by data obtained with the 120 x 10^6 Btu/hr burner at half load. In this mode of operation the furnace thermal conditions are comparable to those at 60 x 10^6 Btu/hr in the baseline LWS. Figure 6-13 shows that for the 120 x 10^6 Btu/hr DMB operated at half load, and $Ca(OH)_2$ injection at the 8 foot elevation, SO_2 capture at Ca/S = 2 is increased from 33 percent to 50 percent. This value is comparable to the 47 percent achieved with the 60 x 10^6 Btu/hr DMB in the baseline LWS with equivalent injection conditions.

6.3.4 Mixing

Mixing of the injected sorbent stream with the flue gases has been shown to be an important parameter in ensuring effective SO_2 removal. Although specific mixing studies were not conducted in connection with this program, mixing is believed to be important in influencing some of the results. The actual mixing of the sorbent jets with the bulk of the flue gases is not considered to be a problem, since injectors were designed for adequate penetration and coverage in the relatively low velocity flue gas stream. However, the general flow field in the LWS is characterized by large recirculation zones both above the burner and in the ash hopper as a result of the comparatively unconfined burner environment. For small burners (60 x 10^6 Btu/hr) and long flame configurations, the upper recirculation zone may be particularly strong and may re-entrain a large fraction of the flue gas flow. For the moderate thermal environment which characterizes many of the

LWS configurations, this can result in relatively long residence times, and even recycling of a significant fraction of the sorbent material, through relatively optimum thermal conditions. This effect is believed to be responsible for the high optimum SO_2 removal rates which are achieved, compared to small-scale data in more idealized (Figure 6-14) and isothermal (Figure 6-16) conditions.

6.3.5 Coal Type

The impact of coal type on SO_2 capture is believed to be due primarily to coal sulfur content and the resulting SO_2 concentration. However, small scale data indicate that for SO_2 concentrations above approximately 1000 ppm the impact on SO_2 removal is relatively small. Indeed, in the preceding presentation of LWS test data only comparatively small differences were apparent for the limited data on different coal types. In general, slightly higher SO_2 removal rates were observed for the higher sulfur Illinois coal, compared to the lower sulfur Utah, Comanche, and Wyodak fuels which tended to yield comparable results. Some of these results may also have been influenced by small changes in thermal conditions, e.g. as a result of firing bituminous vs. subbituminous coals. However, it should be noted that the majority of the coal comparison data was obtained at 60 x 10^6 Btu/hr, where SO_2 capture values were relatively high and where capture may have been dominated by combinations of the thermal and mixing criteria referenced above. This may have masked some of the differences between the different coal types which would be expected to be more apparent. The limited data available for 120 x 10^6 Btu/hr operation suggests that the relative differences between coal types (e.g. Illinois vs. Utah in Figures 6-10 and 6-11) might become more pronounced under different thermal and flow conditions where the overall level of SO_2 removal is reduced.

6.3.6 Extrapolation to Full Scale

The preceding discussion has indicated that the SO_2 removal process depends upon a complex interaction between a large number of physical, thermal, and chemical parameters. For this reason it considered not to be possible to directly extrapolate the data obtained in the LWS to full-scale boiler systems. At full scale the complex multiple burner interactions and different furnace geometry and confinement will result in flow fields and thermal profiles substantially different from those encountered in the LWS. Consequently, it is believed that each boiler application must be characterized on an individual basis, and sorbent injection locations and injection devices selected to provide thermal conditions and mixing characteristics which are optimum for that application.

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16. ABSTRACT The report gives results of a study in which NOx emissions and general combustion performance characteristics of four burners were evaluated under experimental furnace conditions. Of primary interest was the performance of a low-NOx Distributed Mixing burner (DMB), which was tested in a nominal full-scale (120 million Btu/hr or 35MW) version and in a corresponding half-scale version. Performance was compared against a half-scale commercial low-NOx Dual Register burner (DRB) and a 120 million Btu/hr commercial Circular burner. The report documents the performance of each burner type over a wide range of firing conditions and for different bituminous and subbituminous coals. Additional test program goals were to provide information relating to the effects of burner design, burner scale, and thermal environment on NOx emission performance. Full- and half-scale DMB performance was compared under equivalent thermal conditions; the DMB was tested under two levels of furnace insulation; results from the DRB and Circular burner were compared to field data from two utility boilers operating with corresponding burner designs and coal types. A burner zone heat liberation rate parameter was used to compare the relative performance of the different burners under the various firing conditions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Calcium Oxides	Pollution Control	13B	
Coal	Sorbents	Stationary Sources	21D	11G
Combustion	Dolomite	Low-NOx Burners	21B	08G
Nitrogen Oxides	Electric Utilities		07B	
Sulfur Dioxide				
Calcium Carbonates				

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