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Pilot Scale Evaluation of NO_x Combustion Control for Pulverized Coal:
Phase II Final Report

Interagency Energy/Environment R&D Program Report

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Pilot Scale Evaluation of NO_X Combustion Control for Pulverized Coal: Phase II Final Report

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SECTION 1

SUMMARY

Advanced NO_x control techniques for utility and industrial boilers were tested in a pilot-scale furnace firing pulverized coal. The impact of NO_x control techniques on other emissions, primarily CO and carbon loss, was also determined. Staged combustion, where combustion air is proportioned between first and second stages, was the primary control technique tested. Biased firing and flue gas recirculation as NO_x control techniques were also tested but to a lesser extent.

Air quality planning studies show that advanced NO_x control techniques will be needed in the 1980's and 1990's to meet projected NO_2 air quality standards. Because utility and industrial boilers together produce about two-thirds of the nationwide stationary NO_x emissions, control of NO_x emissions from these sources has been given high priority in federal, state and local NO_x abatement programs.

The EPA has several research programs underway to provide specific criteria for the optimum application of burner modifications and staged combustion techniques for NO_x control. A range of programs, from fundamental experiments through field test investigations, is being sponsored by EPA to develop NO_x control technology.

Pilot-scale tests bridge the gap between fundamental experiments,

which determine how local combustion environments affect pollutant emissions, and full or near full scale tests, which determine specific hardware and operating conditions needed to lower NO_x emissions for specific source types. Unlike fundamental experiments, pilot-scale tests can efficiently investigate fluid mechanics and mixing processes for full-scale units. Also a pilot-scale facility offers more flexiblity than full-scale units allowing a wide variety of fuels and combustion modification techniques to be tested efficiently. In summary, pilot-scale tests can help develop guidelines for NO_x combustion control techniques, such as staged combustion, which can be applied to full-scale combustion systems.

The pilot-scale test facility used for the NO_x combustion tests is briefly described below. The test results are summarized in the following subsections.

1.1 FACILITY DESCRIPTION

The EPA pilot-scale furnace can simulate front-wall, opposed, or tangentially-fired utility and industrial boilers. A horizontal furnace extension is also available which permits the facility to simulate a package boiler. A variety of heat exchange sections allows gas quenching time to be varied, and several stage-air ports, located over the length of the heat exchange section, provide variable first-stage residence times.

Furnace volume is typically 1.6 m^3 (57 ft^3), and the maximum heat release rate when firing coal is 440 kW (1.5 x 10^6 Btu/hr). Furnace volume may be varied by removing heat exchange surface or adding the horizontal extensions. Although hot refractory walls are typically employed during testing, water-cooled panels to cover the walls are available for testing the effect of cold walls on emissions.

Five burners typically are used in the front wall firing mode. These burners are patterned after variable swirl block burners developed at the International Flame Research Foundation (IFRF). Variable burner parameters include swirl, flow velocities, fuel injector type, fuel, and quarl design. Burner settings can be adjusted to closely simulate full scale system parameters.

For horizontal furnace extension firing, a single large burner of IFRF design or four of the IFRF burners used in the front-wall-fired tests can be employed. The large burner is also fully adjustable.

Corner-fired burners are employed during tangentially-fired testing. Patterned after Combustion Engineering's tangentially-fired burners, these burners have tilt and yaw capability and can be set at conditions characteristic of full-scale systems. The main difference between the pilot and full-scale burners is that the pilot-scale burners use a circular exit configuration while full-scale burners use a rectangular configuration. Normally, four burners are used for tangentially-fired testing. However, if needed, eight corner burners can be fired in two tiers.

Emissions and facility performance measurements are continuously monitored by a computerized data acquisition system and displayed every 30 seconds on a CRT in the control room. Pressures and temperatures of a variety of streams are monitored for facility control and safety. Continuous monitoring of emissions is provided by:

Instrument	Emission
Chemiluminescent	NO/NO_x
Nondispersive Infrared	CO/CO_2
Paramagnetic	O_2

Flame Ionization Detector	UHC
Pulsed Fluorescence	SO_2

Particulates are sampled with an isokinetic high volume stack sampler (EPA Method 5).

The versatile EPA pilot-scale furnace can be used to test and evaluate a wide range of staged and unstaged combustion conditions. The following section summarizes the parameters investigated during baseline and control technology evaluation testings.

1.2 TEST RESULTS

Results from the baseline and control technology evaluation testing are summarized in this section. Front-wall-fired (FWF), horizontal extension (HE), and tangential-fired tests on several coal types are discussed.

1.2.1 Baseline Testing

Baseline tests in both FWF and tangential coal-fired configurations have demonstrated that the EPA pilot-scale facility can duplicate full-scale boiler NO levels and trends with excess air. For the most part, burner parameters and firebox exit temperatures for these tests were equivalent to full-scale system parameters. In addition to these firebox tests, baseline tests in the HE with FWF type burners give NO results similar to firebox tests. The agreement between HE and firebox test results indicates that the firebox chamber geometry does not strongly influence NO results such as those from the FWF burner.

The variations of baseline NO levels and trends with system parameters are briefly discussed in the following subsections.

1.2.1.1 Excess Air

As observed in full-scale units, increases in excess air produce higher levels of NO. For a given excess air level, rapid-mix coal spreader injector FWF NO levels are higher than slow-mix tangential or axial coal injector FWF results. Similarly, at higher excess air levels, the increased oxygen availability appears to have more impact on NO levels for rapid-mix systems than for slow-mix systems.

1.2.1.2 Temperature

Hot refractory-lined walls in the pilot-scale facility produce sufficient heat transfer (loss) to model full-scale boiler exit gas temperatures. However, by using water-cooled walls and/or reduced air preheat, exit gas temperatures may be further reduced and the influence of temperature on NO could be assessed. By comparing the variation of NO with exit gas temperature for both gas and coal firing, it was demonstrated that exit gas temperature (and bulk furnace temperature) chiefly impact thermal NO. Since NO derived from fuel nitrogen during coal combustion is much greater than the thermal contribution, the majority of the work was performed at a single air preheat temperature and with the hot refractory walls.

1.2.1.3 Mixing

Exploratory tests were conducted to establish representative baseline burner settings for FWF and tangential firing configurations. Because these burner settings impact the mixing of the fuel and air, they influence NO levels.

Front Wall Fired Burners

The FWF burner swirl setting strongly impacts NO levels. At very low swirl, the flame produced is very lazy and can become lifted off the fuel injector. Under these conditions, fuel and air are well mixed prior to ignition and high NO levels are generated upon burning. For high swirl levels, intense well-mixed flames are produced near the burner exit, yielding high NO levels. Intermediate swirl levels produce the lowest NO levels; this condition was chosen for all baseline and control technology evaluation testing.

The percentage of air used to transport coal to the burners (percent primary air) strongly impacts NO levels. A high percentage of primary air gives high primary air velocity, leading to lifted flames in which fuel and air are thoroughly mixed prior to ignition. These flames have high NO emissions. Twelve percent primary air, characteristic of full-scale system values, produces non-lifted flames and was selected for baseline and control technology evaluation testing.

Injector design also strongly impacts NO levels. The coal spreader injector disperses the coal in a conical pattern from the fuel injector exit, rapidly mixing the coal and combustion air, producing a very intense flame. NO levels with this injector design are high compared to the slow-mix axial injector. Flames produced by the axial injector are lazy and probably have significant fuel/air ratio stratification over their flame length.

In conclusion, mixing of fuel and air plays a dominant role in coal fired, FWF burner NO production. Lifted flames and high-swirl well-mixed intense flames produce high NO levels. Slow-mix lazy, but attached, flames produce much less NO. It is conjectured that the slow-mix flames have considerable mixture ratio stratifications and that fuel-nitrogen (fuel-N) is converted to N_2 rather than NO within the rich combustion zones. In addition, NO formed elsewhere can be reduced to N_2 in these rich combustion zones. Since NO derived from fuel-N dominates in coal flames, fuel-N and NO reduction to N_2 in rich combustion zones can significantly lower NO levels.

Tangentially-Fired Burners

NO levels in tangential systems increase as the percentage of primary air increases. However, the high NO "lifted flame" condition present with the FWF burners at high primary air percentage was not observed with tangential firing. Hot adjacent flames impinging in the tangential system might maintain ignition near the fuel injector, thereby preventing lifted flames. Also, mixing of air from only two sides in tangential firing, in contrast to mixing from all sides in FWF firing, might give fuel-rich stratified combusting mixtures even if the flame was somewhat lifted from the burner face.

Changes in burner yaw, or angle between the burner centerline and the diagonal, did not significantly impact NO levels. Yaw angle was varied from 0^o to 9^o (6^o is full-scale practice). Since yaw angle affects the manner in which adjacent flames interact, NO processes in the tangentially-fired pilot scale facility must be dominated by near-burner processes rather than by intermediate-zone flame interaction processes. In support of this conjecture, it was found that axial-coal-injector FWF NO results are very similar to tangential results, but are much below spreader-coal-injector FWF results. This comparison indicates that the primary characteristic of the pilot-scale tangential systems is the slow-mix nature of the combusting jets. The interaction of adjacent flames in the pilot-scale firebox must play a secondary role to the slow-mixing nature of the jets.

1.2.1.4 Load

As load is increased, NO levels are increased for FWF, HE and tangential firing configurations. This is probably due in part to the increased combustion intensity and rise in combustion chamber temperature which in turn increases thermal NO. Additionally, fuel and air injection velocities and consequently enhanced fuel/air mixing at higher loads probably increases fuel-N derived NO production.

1.2.1.5 Coal Composition

Three coals, Pittsburgh #8, Western Kentucky and Montana were tested under baseline conditions. The Montana coal represented a departure from the other coals in that it had a significantly higher moisture and oxygen content and a lower carbon, nitrogen and sulfur content than the other coals. Under baseline excess air conditions, the Montana coal produced consistently higher NO levels than the Pittsburgh #8 and Western Kentucky coals. Laboratory experiments have shown that the presence of sulfur can inhibit NO formations under excess air conditions. Thus, this mechanism might be exhibited under these baseline operating conditions which gave higher NO levels with the lower sulfur Montana coal.

1.2.2 Evaluation of Control Technology

Staging in the FWF, HE, and tangential firing modes was the primary NO control technology investigated. During staging, only a fraction of the air needed for complete combustion is mixed with the fuel in the first stage. The rest of the combustion air is mixed with the products from the first stage in the second stage. Under staging, limiting the amount of available oxygen, which mixes with the fuel in the first stage, reduces NO production.

In addition to staging, flue gas recirculation and biased firing were also briefly investigated to determine their potential in reducing NO.

The variations of NO levels with first- and second-stage parameters and with flue gas recirculation and biased firing parameters are briefly discussed in the following subsections.

1.2.2.1 First-Stage Parameters

The first-stage parameters varied during the tests include stoichiometry, residence time, mixing, temperature and load.

Stoichiometry

For long first-stage residence times (greater than 3 seconds bulk residence time), minimum NO levels of from 80 to 160 ppm were achieved at first-stage stoichiometric ratios (SRs) of 0.75 to 0.85. The minimum NO level and associated SR was not strongly dependent on the type of firing mode tested. The similarity in minimum NO levels and SRs at which they were achieved, for all of the firing modes tested, indicates that chemical rather than physical processes are controlling minimum NO levels at long residence times under staged combustion conditions.

At SRs near 1.0, NO levels depend strongly on the firing mode, with FWF and HE rapid-mix firing producing more NO than tangential firing at the same SR. Physical processes, such as fuel/air mixing, are probably playing a more significant role at the higher SRs.

These results are consistent with fundamental studies which indicate that the maximum amount of fuel-N is converted to N_2 at a SR on the order of 0.8. Below this ratio, increased amounts of fuel-N are converted to nitrogen intermediates, such as HCN and NH_3, which unlike N_2, can be easily converted to NO in the oxygen-rich second stage. Above a SR of 0.8, sufficient overall oxygen is available to convert fuel N to NO, and the mixing rate, which determines local fuel-N-to-oxygen contacting, controls the amount of NO produced. If mixing is rapid, as in FWF firing, fuel-N conversion to NO can be high. Slow-mix tangential systems produce less NO at SRs near 1.0 for possibly two reasons:

- Less fuel-to-oxygen contacting
- Reduction of NO through flame-flame interaction.

Residence Time

NO levels were found to decrease with residence time at all fuel rich stoichiometry ratios for the FWF and HE firing modes. However the higher the SR, the higher the initial NO level appeared to be. As the SR decreases towards the minimum NO SR, the NO decay rate increases. Below the minimum NO SR, the NO decay rate decreases. Similar results are observed under tangential firing. However, at the same early bulk residence time, tangentially fired NO results are lower than FWF and HE NO results. A bulk residence time on the order of 3 seconds is required to decay NO levels to values characteristic of final stack NO levels.

The early residence time, high NO levels are probably due to the ready availability of primary air oxygen to the initial fuel-N volatiles. Even at low SRs, sufficient oxygen is initially present to convert early fuel N volatiles to NO.

The rate and extent of reduction of early NO depends on the local SR and the residence time at those conditions. Fuel-rich combustion zones will convert early NO to N_2. Overly fuel-rich combustion zones will produce fuel-N intermediates, such as HCN and NH_3, which will be converted to NO in the oxygen-rich second stage. Fuel-lean combustion zones will not reduce early NO and will generate additional NO.

At long residence times under overall fuel-rich conditions, decay processes reduce NO to minimum levels. At reduced first-stage residence times, NO decay becomes sensitive to fuel/air mixing or firing mode, with tangentially fired systems producing less NO than FWF systems at the same bulk residence time.

Mixing

FWF, HE and tangential system non-staged combustion NO results show that fuel/air mixing dominates NO levels with the slow-mixed tangential systems producing less NO than the rapid-mix FWF and HE systems. For long first-stage residence times, changes in mixing produced by burner swirl, primary air percentage, and fuel injector design do not significantly impact NO levels below or at the minimum NO SR. As the SR increases towards 1.0, mixing becomes of greater importance, until at excess air conditions, mixing dominates NO levels. It appears that at long residence times under fuel-rich conditions, the first-stage combustion volume acts somewhat like a homogenous reactor with NO levels independent of fuel/air injector design. However, for shorter residence times, mixing becomes important even at the fuel-rich stoichiometries.

Large single versus four small burner and axial versus spreader coal injector HE NO results show that, at reduced residence time, and very fuel-rich conditions, rapid fuel/air mixing systems give lower NO levels than slow fuel air mixing systems. As the SR is increased, the rapid- and slow-mix system NO levels cross over and slow-mix systems produce less NO. Apparently, mixing influences the extent of combustion in the first stage prior to stage air additions. For a highly mixed system, combustion is rapid and for very fuel rich SR available oxygen is depleted much before stage air addition. Decay reactions then have a longer time to reduce NO in the first stage than for slow-mix systems where available oxygen is depleted less rapidly. These results suggest that under staged conditions and low SR, rapid mixing should be used to minimize NO for a given residence time. At SRs approaching 1.0, slow mixing will minimize NO for a given residence time.

Temperature

For non-staged combustion or staged combustion with SR near 1.0, increases in first stage temperature increase NO levels. Comparison of coal- and gas-fired NO levels as a function of temperature indicates that the increase is primarily due to increases in thermal NO rather than fuel-N derived NO.

During staged combustion at a low SR, and a long residence time, an increase in first stage temperature decreases the NO level. This is probably the result of increased fuel-N volatilization in the fuel-rich first stage which, due to the greater fuel-N in the gas phase, has a lower NO conversion efficiency. In addition, the NO to N_2 decay reactions are probably more rapid under the higher temperature conditions leading to greater reductions of NO. At low SR the change in these processes with temperature are much more significant than the change of thermal NO with temperature. As SR increases these effects come into balance and finally, at SR near one, the thermal NO temperature effect is the dominant effect on NO.

At shorter residence times and all SRs, increasing the first stage temperature increases the NO levels. Apparently, at short residence time the decay processes under fuel rich conditions do not have sufficient time to reduce the NO produced in the early part of the flame.

Load

As firebox firing rate is increased, both firebox temperature and mixing are increased. Visually, the intensity of combustion is increased with load. As in the case of first-stage temperature changes, increases in load at long residence times increase NO levels at SRs near 1.0 and decrease NO levels at low SRs. For shorter residence times, NO levels increase as load increases for nearly all SRs. This behavior is consistent with the previously discussed effect of temperature on NO.

1.2.2.2 Second-Stage Parameters

The second-stage parameters varied during the tests include stoichiometry, residence time, mixing and temperature.

Stoichiometry

Second-stage stoichiometry or excess air levels do not strongly impact NO levels. As excess air is increased from 5 to 25 percent, NO levels increase slightly. This increase is probably due to the increased availability of oxygen in the second stage or possibly the increase of oxygen in the first stage, due to the backmixing of air into the first stage under high excess air conditions.

If the residence time in the second stage is less than 1 second, 20 to 25 percent excess air is needed to reduce CO levels below 100 ppm for SRs below 0.95. However, when the second-stage residence time is equal to or greater than 1 second, the CO is always under 100 ppm and carbon loss is less than 0.5 percent of fuel input on a Btu basis.

Residence Time

For the first-stage SRs of 0.85 and 1.02 tested, second-stage residence time changes from 0.6 to 2.4 seconds did not significantly impact

NO levels. This is expected since the gases in the second stage are more homogenous than the first-stage gases and homogenous NO reactions are sufficiently rapid compared to the residence time of the gases. As indicated in the previous section, at least 1 second is needed to reduce CO and carbon loss to acceptable levels in the second stage.

Mixing

If stage-air is added such that part of the air is backmixed into the first stage, NO levels will increase significantly. To achieve minimum NO under staged combustion conditions, particularly at low SR, stage-air must not be allowed to backmix into the first stage. Second stage mixing has very little influence on NO levels except as it influences the first-stage SR. However, slow second-stage air mixing produces higher CO and carbon loss (200 to 500 ppm CO and 1 to 2 percent carbon loss).

Temperature

Increases in second-stage temperature slightly increased NO levels at a SR of 1.02 and slightly increase or decrease NO at a SR of 0.85 depending on whether the mixing of stage-air is fast or slow respectively.

Since increases in stage-air temperature also increase velocity, the rise in NO with temperature may be due to backmixing. In addition, consistent with first-stage results, increases in temperature under lean first-stage conditions can increase thermal NO production. Also, at a SR of 0.85, slow mixing of stage-air may give stratified rich zones in the second stage which have the potential to more rapidly reduce NO as temperature is increased.

1.2.3 Coal Composition

Western Kentucky, Pittsburgh #8 and Montana coal were utilized in the control technology evaluation testing. As mentioned in Section 5. the Montana coal had a significantly higher water and oxygen content and a lower carbon and sulfur content than the other coals. For both FWF and tangential firing, Montana coal NO levels at SRs near 1.0 were higher than Western Kentucky and Pittsburgh #8 levels. However, below a SR of 0.8 Montana NO levels were lower than Western Kentucky and Pittsburgh #8 levels. The relative difference between the low sulfur Montana coal NO levels and the other coal data is consistent with laboratory experimental evidence which shows that the presence of sulfur in the fuel can reduce NO under fuel-lean conditions but can enhance NO under fuel-rich conditions. The effect of fuel sulfur on NO levels was further demonstrated by injecting SO_2 into the coal feed or air stream. These tests showed that SO_2 addition to the coal feed stream can significantly enhance NO formation under fuel-rich conditions.

1.2.4 Flue Gas Recirculation (FGR)

For tangential firing under baseline conditions, up to 30 percent of flue gas recirculated through the secondary air ports produces very little change in NO levels. The reduction in thermal NO expected with FGR is probably balanced by the increase in NO with mixing produced by the higher velocity secondary air/FGR jets. Under combined FGR additions and staging, NO levels increased from their staged-only levels. The loss of effectiveness in staging with FGR addition can be attributed to increased mixing, lower first-stage temperature under rich conditions, reduced residence time and the recycling of FGR-NO into the firebox.

Introduction of FGR into the secondary air ports while combusting coal has very little beneficial impact on fuel-N derived NO, which is the primary source of NO in coal fired systems.

1.2.5 Biased-Fired Results

Some FWF biased-firing configurations gave NO reductions on the order of 25 percent at baseline conditions. These reductions are in line with those achieved by full-scale biased-fired systems. For a rich burner stoichiometry of 0.85, the effectiveness of biased-firing in reducing NO is far below full staging techniques which yield 80 percent reductions in NO at a SR of 0.85. These results show that the separation of stage-air addition from the first-stage combustion zone is critical in achieving low NO levels with staging.

Tangential biased-fired results, where either two opposite or adjacent burners were fired rich (SR = 0.85) and the other burners fired lean, showed no change in NO levels with biasing. Stage-air separation under biased-firing was probably minimal during these tests. Also, introducing stage-air increases mixing and reduces residence time, both of which act to counter any NO reduction due to staging.

Tangential firing with overfire air, where the burners were run at SRs down to 0.75 and stage-air was added above the burners, showed only modest (15 percent at a SR of 0.75) reductions of NO. Staging, where stage-air is completely separated from the firebox, showed NO reductions of 71 percent at a SR of 0.85.

It is clear from these results that good separation of first and second stages is critical to achieving large reductions in NO through staging.

1.2.6 Staged-Combustion -- Natural Gas

Staged combustion with natural gas yields a NO versus first stage

SR curve which is similar in character to the coal-fired results discussed previously. Since molecular nitrogen can act like a fuel-N species under rich combustion conditions, the similarity in shape between coal and gas staged results indicates that chemical effects are dominating the shapes of the curves.

Staging position or residence time does not impact gas-fired staging results over the residence times (roughly seconds) investigated. Since coal-fired NO results changed with staging position, coal physical process time scales, such as those associated with volatilization, and diffusion to or from the particle surface, must be longer than those associated with homogenous pollutant formation processes.

SECTION 2

BACKGROUND

Utility and industrial boilers are the two largest stationary emitters of NO_x. Together they comprise about 60 percent of the 1974 nationwide stationary NO_x emissions (Reference 2-1). Because of this, control of NO_x from utility and industrial boilers has been given high priority in the Federal, State and local NO_x abatement programs created to attain and maintain the National Ambient Air Quality Standard for NO_2 (100 $\mu g/m^3$ annual average). Standards of Performance for New Stationary Sources were set in 1971 for gas, oil and bituminous coal fired steam generators with a heat input greater than 73 MW (250 MBTU/HR) (Reference 2-2). Revision of the standard for bituminous coal units from 301 ng/J (0.7 lb. NO_2 /10^6 Btu) (~580 ppm at zero percent O_2) to 260 ng/J (0.6 lb NO_2/10^6 Btu,) (~500 ppm,) to reflect advances in control technology (Reference 2-3) has been proposed. For solid fuels with greater than 50 weight percent subbituminous coal a standard of 220 ng/J (0.5 lb NO_2/ 10^6 Btu) has been considered. Standards for new industrial boilers are being prepared by EPA's Office of Air Quality Planning and Standards. In addition, emission standards for new or existing utility and large industrial boilers have been set as part of State Implementation Plans to maintain air quality in NO_2 critical regions (Reference 2-4).

Despite this regulatory activity, a number of air quality planning studies (References 2-5 to 2-8) have determined that additional stationary source control technology will be needed in the 1980s and 1990s to meet projected NO_2 air quality needs. These studies also concluded that, where possible, additional technology should focus on application to advanced design of new equipment. In response to the need for additional technology, EPA is developing and demonstrating advanced controls for utility and industrial boilers and other sources (References 2-9 and 2-10). Near term emphasis is on using major hardware modifications for new or existing sources. Far term emphasis is on major redesign of new sources. The ppm emission goals (at zero percent O_2) for the near and far term R&D programs for coal fired utility and industrial boilers are as follows (Reference 2-9 and 2-10):

	1980 Goal	1985 Goal
Utility	230 ppm	115 ppm
Industrial	175 ppm	115 ppm

As part of the EPA program to develop and demonstrate advanced controls for utility and industrial boilers and other sources, the tests described in this report function to define and demonstrate advanced NO_x control techniques for utility and industrial boilers firing conventional and alternate fuels (Reference 2-11). To date, pilot-scale testing has concentrated on firing coal in utility boiler configurations.

Table 2-1 summarizes some NO_x reduction research programs for coal fired equipment completed or ongoing at the initiation of the present effort. Several of these research programs have cast doubt on the effectiveness of flue gas recirculation in reducing NO_x in coal-fired systems.

In a pilot-scale study, Armento (References 2-13 and 2-14) found that a 15 percent flue gas recirculation resulted in only a 15 percent reduction in

TABLE 2-1. OVERVIEW OF EXPERIMENTAL EMISSIONS CONTROL WORK WITH COAL

Reference	Unit	Utility	City	State	Mfgr[1]	Firing[2]	Fuel[3] Rank	Fuel Origin (If given)	Fuel Analysis – Proximate					
									Moist.	Ash	Vol.	FC	S	HV(K)
	Dave Johnston 2	Pac. Power and Light	Glenrock	Wyoming	BW	FW	Lig A	Local	28	8	32	32	0.5	8
	Wildcat Creek 6	TVA		Alabama	BW	FW			7					
	E. D. Edwards 2	Central Ill. Light		Illinois	RS	FW	hvcb		16	9	32	41	3	11
	Crist 6	Gulf Power	Pensacola	Florida	FW	FW	hvcb		9	10	35	45		11
	Leland Olds 1	Basic Elec.	Stanton	N.Dakota	BW	HO	Lig A	Local	38	6	28	28	0.4	7
	Harlee Branch 3	Georgia Power		Georgia	BW	HO			7					
Crawford (Ref 2-12)	Four Corners 4	Ariz. Pub. Service	Farmington	New Mex.	BW	HO	sub c	Local	13	22	31	34		9
	Barry 3	Ala. Power	Mobile	Alabama	CE	T	hvcb	Ala.	7	11	32	49		12
	Haughton 3	Utah Power & Light	Kammerer	Wyoming	CE	T	sub b	Local	13	7	37	42		10
	Barry 4	Ala. Power	Mobile	Alabama	CE	T	hvcb	Ala. "midwest"	7 10	11 7	32 37	49 46		12 12
	Dave Johnston 4	Pac. Power & Light	Glenrock	Wyoming	RS	T	Lig A	Local	28	8	32	32	0.5	8
	Big Bend 2	Tampa Elec	Tampa	Florida	RS	Turbo	hvcb		11	14	34	42	3.6	11
Armento (Refs 2-13 and 2-14)	Pilot	--	Alliance	Ohio	--	SB	hvbb		6	12	36	46		12
Heap (Ref 2-15)	Pilot	--	IJmuiden	Holland	--	SB	Europ			6	32		0.75	
Pershing (Ref 2-16 and 2-17)	Pilot	--	Raleigh-Durham	N.Carol.	--	SB								
McCann (Ref 2-18)	Pilot	--	Pittsburgh	PA	--	FW	hvbb		2	10	37	52		13

Notes:
1. BW = Babcock & Wilcox, CE = Combustion Engineering, FW = Foster Wheeler, RS = Riley Stoker
2. FW = front-wall-fired, HO = horizontally opposed, T = tangentially fired, Turbo = turbo-fired, SB = single burner
3. hvbb = high volatile B bituminous (ASTM), sub c = sub-bituminous C (ASTM), etc.
4. Approximate effectiveness observed in tests, 1 → major controlling parameter, 2 → important effects, 3 → minor effects

TABLE 2-1. (concld.) OVERVIEW OF EXPERIMENTAL EMISSIONS CONTROL WORK WITH COAL

Reference	Unit	Fuel Analysis (Concluded)						Effectiveness of Reduction Technique[4]																		Important Combinations
		Ultimate Dry						Burner Modifications							Overall Parameters											
																			Recirculation							
								Primary/secondary ratio	Velocities	Swirl	Injection pattern type, splitters, etc.	Geometry; layout, tilt, etc.	Materials	Other	Load	Excess air	Staging, biasing	Preheat	Primary	Secondary	Stage	Other	Water injection	Quench	Other	
		C	H	S	N	O	A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
	Dave Johnston 2	64	5	0.7	0.8	19	10									1	2									9 + 10 = 1
	Wildcat Creek 6	68	5	3	1.4	5.6	17									1	2									
	E.D. Edwards 2	69	5	3.5	1.25	9.5	11								1	1	2									9 + 10 = 1
	Crist 6	70	5	3.5	1.4	8	11								3	1	3									
	Leland Olds 1	64	4	0.6	1.1	20	10								2	1	3									
	Harllee Branch 3	74	5	1.3	1.8	8	11								3	1	2									
Crawford (Ref.2-12)	Four Corners 4	58	4	0.8	1.3	11	24									1	2									
	Barry 3	72	5	2.7	1.6	6.6	13									1									3	
	Naughton 3	69	5	0.5	1.6	16	8									1	2								3	9 + 10 = 1
	Barry 4																									
	Ala.	72	5	2.7	1.6	6.6	13									1	2								3	
	"Midwest"	73	5	3.2	1.4	9.4	8																			
	Dave Johnston 4	64	5	0.7	0.8	19	10							3	2	1										
	Big Bend 2	66	5	4	1.4	8.5	15							3	2	1	3									
Armento (Refs. 2-13 & 2-14)	Pilot	69	5	2.8	1.1	10.3	12								2	1	2	2	3	2				3		10 + 13 = 2
Heap (Ref. 2-15)	Pilot	78	5	1.1	0.75		6	1	1	1	1	1														
Pershing (Refs. 2-16 & 2-17)	Pilot								1	1	1							2		2						
McCann (Ref. 2-18)	Pilot	73	5	2.1	1.4	8.4	10									1	2		2	2						

NO_x emissions. McCann (Reference 2-19) found FGR to be more effective; however, it is difficult to determine whether the large reductions are a direct result of the FGR or due to major changes in the primary zone mixing. Pershing (Reference 2-16) found only small reductions with FGR and subsequently demonstrated that these were almost certainly due to the suppression of the thermal NO_x. His work also suggests that a large portion of the total NO_x emissions from pulverized coal firing is the result of fuel nitrogen oxidation. Since fuel NO_x formation is relatively insensitive to temperature variations, it is not surprising that thermal dilution techniques such as FGR are not very effective with coal.

EPA research, both at IFRF and in-house, indicated that burner modifications leading to what might be termed "internal staging" (or staged combustion patterns in the near neighborhood of the burner) offer great potential for NO_x reductions in pulverized coal fired systems. Heap (Reference 2-15) demonstrated that the fuel injector design, swirl level and primary percentage all strongly impact NO_x emission levels. In some of his tests he found that burner conditions which promote rapid mixing of the coal and air before and during devolatization usually increase NO_x emissions. For example, by switching from a prototype commercial coal impeller or spreader to an axial fuel injector, he was able to reduce NO_x from 902 to 453 ppm at 12 percent primary air. Also, through staging (supplying part of the combustion air through tertiary injection ports), he was able to achieve NO_x levels well below 400 ppm without markedly changing the physical characteristics of the flame.

Staged combustion was found to be another effective and, fortunately, inexpensive means of controlling NO_x from pulverized coal systems. Armento

(Reference 2-13) found that with a burner stoichiometry of 0.80 a 38 percent decrease in NO_x was obtained. At similar stoichiometry, McCann (Reference 2-19) measured a 47 percent reduction. In full scale field testing Crawford (References 2-20 and 2-12) found roughly 40 percent reductions in NO_x with burner stoichiometry near 0.90. Crawford also found that in some cases particulate loadings increased with staging, but he found no evidence of increased tube wastage based on accelerated corrosion tests.

Thus, staged combustion is clearly effective in decreasing NO_x from pulverized coal systems. However, the best techniques for staging were not known and there were many unanswered questions about the existing staging information at the initiation of this effort. Crawford noted large variations in the effectiveness of staging depending on the type and size of boiler. Armento and McCann both noted major dependence on secondary air injection and location, but neither was able to quantify the effect. Armento noted a minimum in his NO_x versus primary zone stoichiometry data, which he attributed to an increase in second-stage thermal fixation at low burner stoichiometries. However, this effect possibly might have been the result of a major increase in the oxidizable nitrogen species coming from the first stage.

From the above brief comments, burner modifications and staging appear to offer significant potential for NO_x reduction. The EPA initiated several research programs to provide specific detailed criteria for the optimum application of burner modifications and staged combustion for NO_x control. The full spectrum from fundamental experiments to field test investigations was initiated by the EPA to solve the important NO_x reduction problems. The pilot scale tests, reported herein, help bridge the gap between fundamental experimental studies and full or near full-scale tests.

These results also allowed definition of specific hardware and operating conditions needed to lower NO_x emissions for specific boiler types. Unlike fundamental test facilities, fluid mechanics and mixing processes similar to full-scale units can be efficiently investigated in the pilot-scale facility. Also, the pilot-scale facility has a much greater flexibility than full-scale units permitting a wide variety of fuels and combustion modification techniques to be efficiently tested.

In summary, the pilot-scale tests sought to efficiently develop semiquantitative guidelines for NO_x combustion control techniques which could be generalized to full-scale combustion systems. These tests focused on the identification of low NO_x operating conditions for the staged combustion of pulverized coal. Burner design modifications were not addressed in this program because this activity is supported by another EPA program.

The pilot-scale tests results support both the near-term and far-term NO_x control efforts mentioned above. To support the near-term application of major hardware modifications on units of conventional design, the test facility was designed with a fairly realistic modeling of the geometry and aerodynamics of large multiburner boilers. This modeling aids in translating the present pilot-scale results to field demonstrations or design of major hardware changes. To support the far-term application of control through major redesign of new sources, the facility was designed with the flexibility to give a wide variation of combustion process modifications important in NO_x control. This flexibility offers the capacity to identify combined low NO_x process modifications which extend beyond the range of conventionally designed field units but which may relate to advanced designs.

Besides baseline testing, the combustion process modifications investigated in the current test program are as follows:

- First-stage stoichiometry
- First-stage residence time
- First-stage mixing
- First-stage temperature
- Second-stage stoichiometry
- Second-stage residence time
- Second-stage mixing
- Second-stage temperature

Baseline testing was done to verify that pilot-scale facility baseline NO_x emissions and trends with excess air level are representative of those achieved by full scale equipment. First-stage combustion parameters were investigated for both high ($SR \geq 0.95$) and low ($SR < 0.95$) first-stage stoichiometry. The high first-stage stoichiometry condition is representative of substoichiometric burning corrosive conditions which can be tolerated by present conventional boiler designs. The lower stoichiometry condition might be applicable to future major boiler redesigns when the corrosion problem can be alleviated. Second-stage combustion parameters were investigated to ensure that CO and carbon burnout were acceptable under low NO_x operating conditions.

Baseline, and first- and second-stage parameters were investigated for both the front wall fired and tangentially, corner fired configurations with three coal types. Emissions of CO and carbon particulate were monitored for all tests so that the impact of combined low NO_x modifications on unit efficiency could be determined. The background and rationale for the selection of the above test parameters is given in the following related sections.

REFERENCES

2-1. "Control Techniques for Nitrogen Oxide Emissions from Stationary Sources," Second Edition. EPA-450/1-78-001, January 1978.

2-2. Federal Register, 36 FR 24877, December 23, 1971.

2-3. Copeland, J. D., "An Investigation of the Best System of Emission Reduction for Nitrogen Oxides from Large Coal-Fired Steam Generators," Standards Support and Environmental Impact Statement, Office of Air Quality Planning and Standards, October 1976.

2-4. Environment Reporter, State Air Laws (2V.) Bureau of National Affairs, Inc., Washington, D.C.

2-5. Crenshaw, J. and A. Basala, "Analysis of Control Strategies to Attain the National Ambient Air Quality Standard for Nitrogen Dioxide." Presented at the Washington Operation Research Council's Third Cost Effectiveness Seminar, Gaithersburg, Md., March 18-19, 1974.

2-6. "Air Quality, Noise and Health - Report of a Panel of the Inter-agency Task Force on Motor Vehicle Goals Beyond 1980." Department of Transportation, March, 1976.

2-7. McCutchen, G.D., "NO_x Emission Trends and Federal Regulation," presented at AIChE 69th Annual Meeting, Chicago, November 28-December 2, 1976.

2-8. "Air Program Strategy for Attainment and Maintenance of Ambient Air Quality Standards and Control of Other Pollutants," Draft Report, U.S. EPA, Washington, D.C., October 8, 1976.

2-9. Norton, D.M. et al., "Status of Oil Fired NO_x Control Technology." Reported in the Proceedings of the NO_x Control Technology Seminar, EPRI Special Report SR-39, February 1976.

2-10. Martin, G.B. and J.S. Bowen, "Development of Combustion Modification Technology for Stationary Source NO_x Control," EPA-600/7-76-002, 1975, February, 1976.

2-11. Brown, R.A. et al., "Pilot Scale Investigation of Combustion Modification Techniques for NO_x Control in Industrial and Utility Boilers," In Proceedings of the Stationary Source Combustion Symposium, Volume II, EPA-600/2-76-152b, June, 1976.

2-12. Crawford, A.R., Manny, E.H. and Bartok, W., "Field Testing: Application of Combustion Modifications to Control NO_x Emissions from Utility Boilers," Exxon Research and Engineering Company, EPA-650/2-74-066, June 1974.

2-13. Armento, W.J., "Effects of Design and Operating Variables on NO_x from Coal Fired Furnaces -- Phase I," Babcock and Wilcox Company, EPA-650/2-74-002a, January 1974.

2-14. Armento, W.J., Proceedings, Coal Combustion Seminar, June 19-20, 1973, Research Triangle Park, North Carolina, 27711, EPA-650/2-73-021, September 1973.

2-15. Heap, M.P., Proceedings, Coal Combustion Seminar, June 19-20, 1973, Research Triangle Park, North Carolina, 27711, EPA-650/2-73-021, September 1973.

2-16. Pershing, D.W., Brown, J. W., Martin, G.B., Berkau, E. C., "Influence of Design Variables on the Production of Thermal and Fuel NO_x From Residual Oil and Coal Combustion," 66th Annual AIChE Meeting, Philadelphia, Pennsylvania, November 1973.

2-17. Pershing, D.W., Proceedings, Coal Combustion Seminar, June 19-20, 1973, Research Triangle Park, North Carolina, 27711, EPA-650/2-73-021, September 1973.

2-18. McCann, C., Demeter, J., Snedden, R., and Bienstock, D., "Combustion Control of Pollutants from Multi-Burner Coal Fired Systems," U.S. Bureau of Mines, EPA-650-2-74-038, May 1974.

2-19. McCann, C.R., Demeter, J.J., Bienstock, D., "Preliminary Evaluation of Combustion Modifications for Control of Pollutant Emissions from Multi-Burner Coal Fired Combustion Systems," Pulverized Coal Combustion Seminar, EPA, Research Triangle Park, North Carolina, June 1973.

2-20. Crawford, A.R., Manny, E.H., Bartok, W., "NO_x Emission Control for Coal Fired Utility Boilers," Pulverized Coal Combustion Seminar, EPA, Research Triangle Park, North Carolina, June 1973.

SECTION 3

FACILITY

This section discusses the EPA multiburner combustion facility at Acurex. It describes the basic furnace and burners together with the capabilities of all the support systems including instrumentation, data acquisition, and emission measurement equipment.

3.1 BASIC FURNACE DESIGN

The basic furnace and heat exchange section used in support of this program are shown in Figure 3.1. The basic firebox was designed to simulate the combustion aerodynamics of either a front-wall, opposed, or tangentially fired utility boiler. Horizontal extension sections can be added to simulate a package boiler. A variable geometry heat exchange section allows for a variable quench rate or increased combustion volume by removal of heat exchange surface.

The heat exchange surface consists of 24 U-tube drawer assemblies which can be inserted in "windows" in the heat exchange sections. The heat exchange sections are refractory lined so that they may become part of the combustion volume when the heat exchange surface is removed and the "windows" are plugged.

The facility was also designed for investigating staging as a NO_x control technique. Stage-air injection ports were provided at numerous locations over the length of the heat exchange section. Thus, the first-

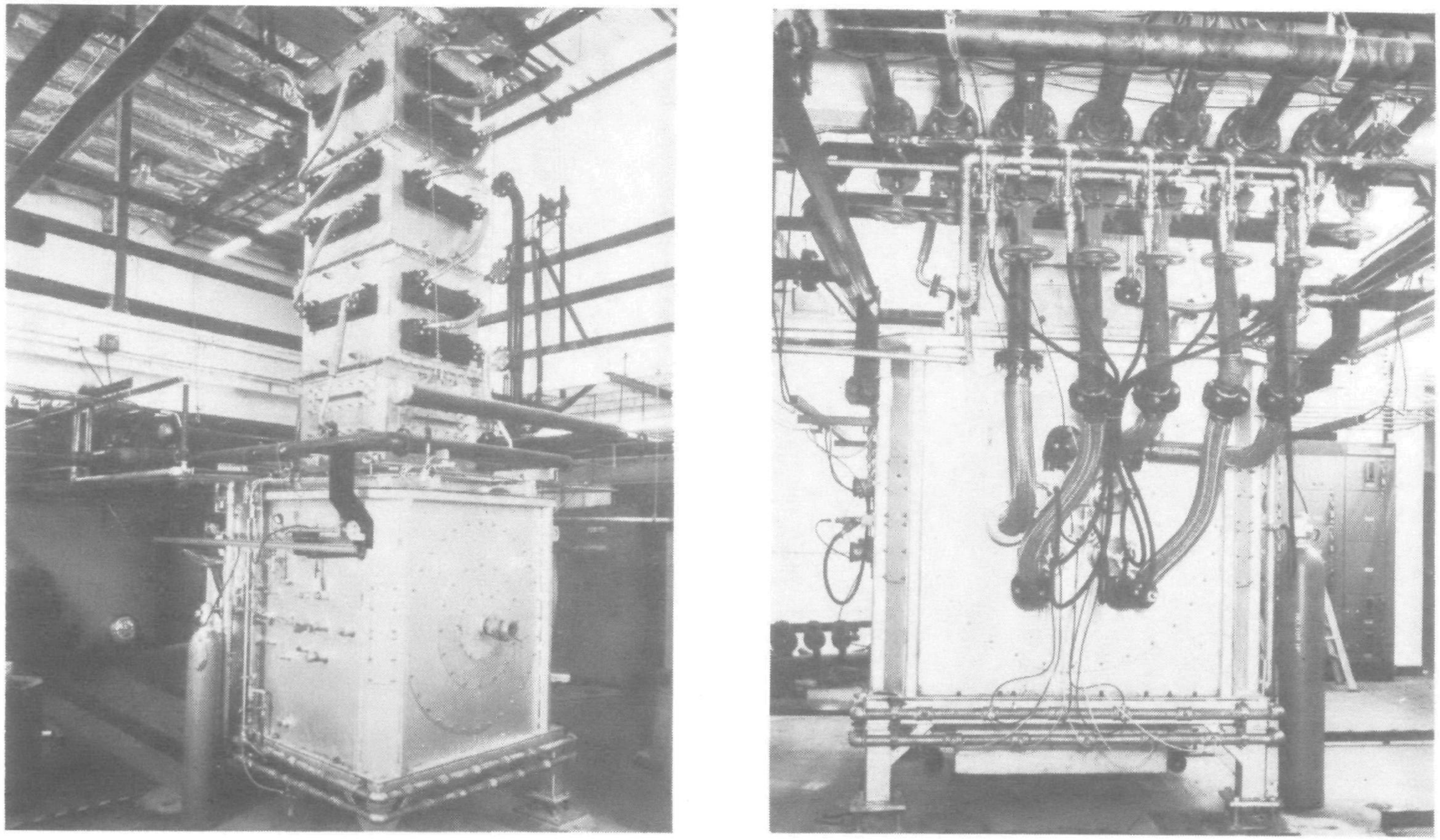


Figure 3-1. Coal/oil/gas combustor

stage residence time could be varied by positioning of the stage-air injection location. Similarly, the second-stage residence time (time from stage-air injection to quenching of the exhaust gases) can be varied by placement of the majority of the heat exchanger surface.

The main firebox is a refractory-lined chamber, 1.35 m^3 (47.7 $ft.^3$) in volume. Figure 3-2 shows a cross section of the firebox showing the ashpit and the first two heat exchange sections. Numerous sampling and viewports are located around the periphery of the main firebox.

Under this contract, a horizontal extension was fabricated as shown schematically in Figure 3-3. There are five sections, each two feet long with an end cap for mounting either single or multiple burners. Numerous ports are provided in each section for stage-air addition, temperature measurement, sampling access, or for cooling coil access. These units are 83.8 cm (33") inside diameter and lined with 25.4 cm (10") of 1650^{o}C (3000^{o}F) insulating castable backed up by 5.1 cm (2") of insulation block. Any number of sections may be connected together to vary the combustion chamber volume. Two of the sections have large rectangular windows for flame observations. A transition section connects the horizontal extension section to the main firebox. Two end caps were also fabricated so that the section could be set up in a horizontally opposed configuration.

Heat is extracted from the flue gases by a closed loop Dowtherm G® heat exchange system utilizing the drawer assemblies mentioned previously. The heat is then dissipated to the atmosphere through two Dowtherm® to air heat exchangers. A wide range of loads may be absorbed by bypassing flow around the Dowtherm®-to-air heat exchangers. A schematic of this system may be found in the Appendix. Temperature of the Downtherm® or tube wall may also be controlled from 65.6^{o}C (150^{o}F) to 232^{o}C (450^{o}F) by this valving system.

1. Combustion chamber (39" cube)
2. Ignition and flame safeguard
3. Observation ports
4. Ashpit
5. 1.5 x 10^6 Btu/hr IFRF burner
6. C.E.-type corner fired burners
7. 3200°F refractory
8. Heat exchange sections
9. Drawer assemblies
10. Staged injection ports

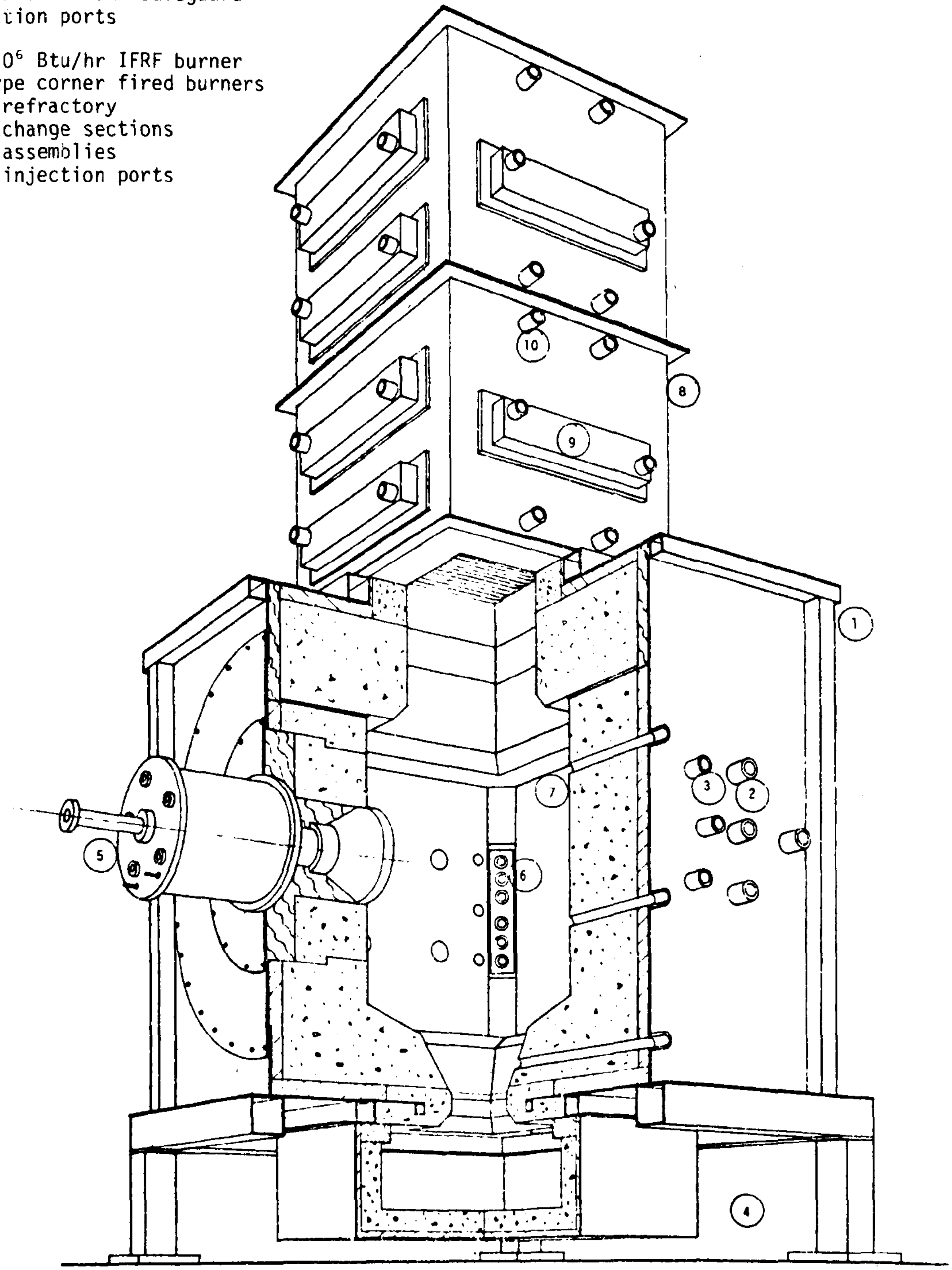


Figure 3-2. Furnace cross section.

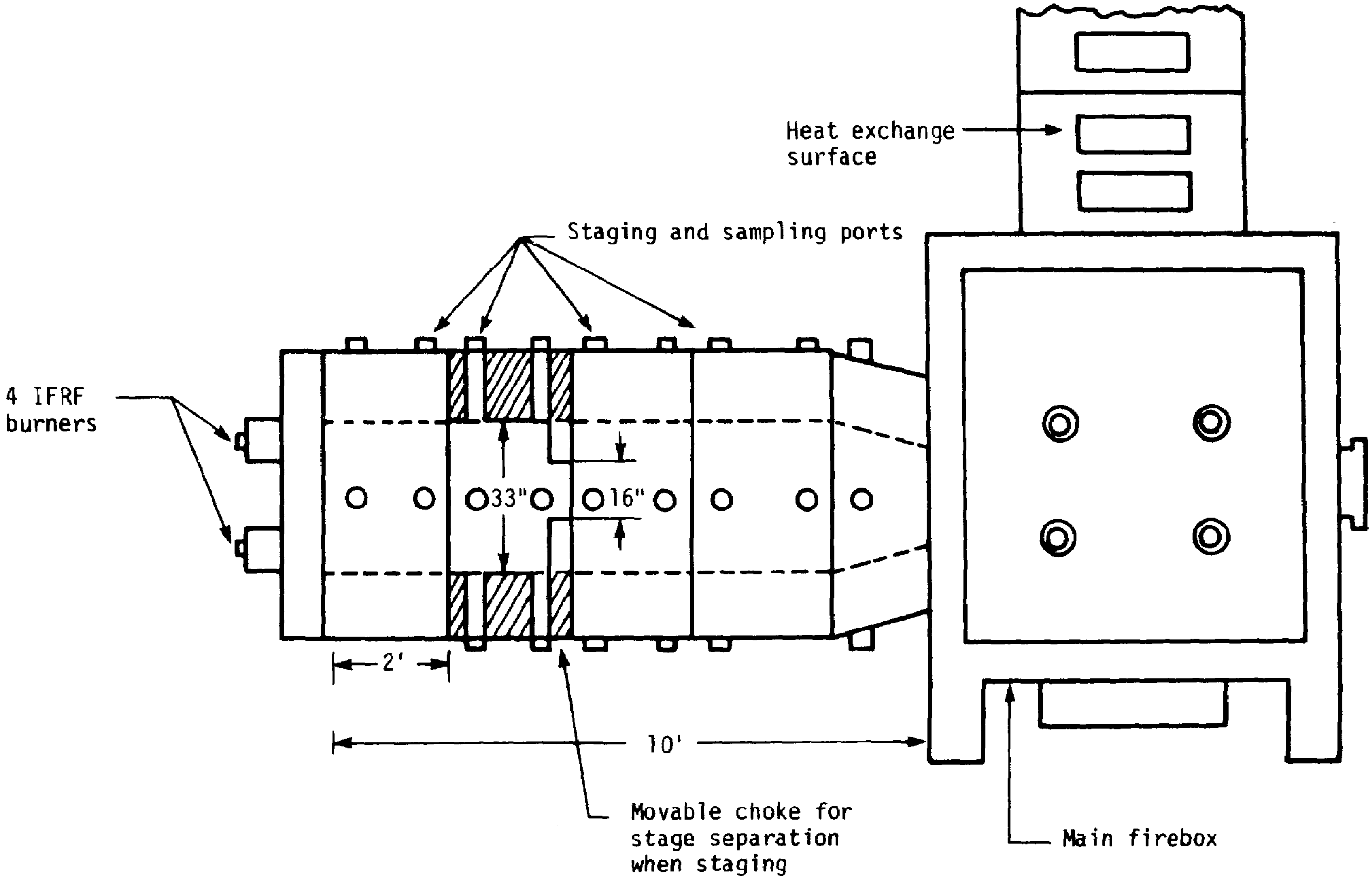


Figure 3-3. Horizontal extension configuration.

Combustion air is provided by a 0.38 m^3/s (800 SCFM), 55 KPa (8 psig) centrifugal blower for the primary (coal transport air), secondary, and staged air. The secondary air may be heated and controlled to a maximum temperature of 427°C (800°F) through a duct-type electrical heater. Heated staged air is supplied from the same heater, but the temperature can be varied by addition of cold air downstream of the heater.

Secondary air is supplied to two manifolds on either side of the furnace with 8 outlets on each side for a maximum of 16 outlets. The controlled air flow from each of these outlets is measured by a standard flange tap orifice. Attached to the secondary air manifold assembly are natural gas, compressed air, and oil manifolds, each with five outlets on each side of the furnace. The manifolds are positioned on overhead rails, allowing repositioning for use with the horizontal extensions.

A 10.16 cm (4") diameter U-shaped manifold supplies the stage-air to the heat exchange tower from a vertical manifold as shown in Figure 3-4. This vertical manifold allows the U-manifold to be positioned at four levels to access the staging air ports in the heat exchange tower.

Cooling water for the burners and firebox structural cooling is provided from a manifold at the base of the furnace. The water is supplied from a closed-loop cooling tower system. Coal is delivered to the furnace through four to eight (depending on the number of burners) copper tubes from a fluidized bed.

The coal system schematic is shown in Figure 3-5. Pre-pulverized coal is dumped into a large hopper using a commercial bagdump. The coal is fed intermittently from the hopper to a pressurized Acrison screw feeder. The screw feeder in turn transfers the coal at a uniform rate to the

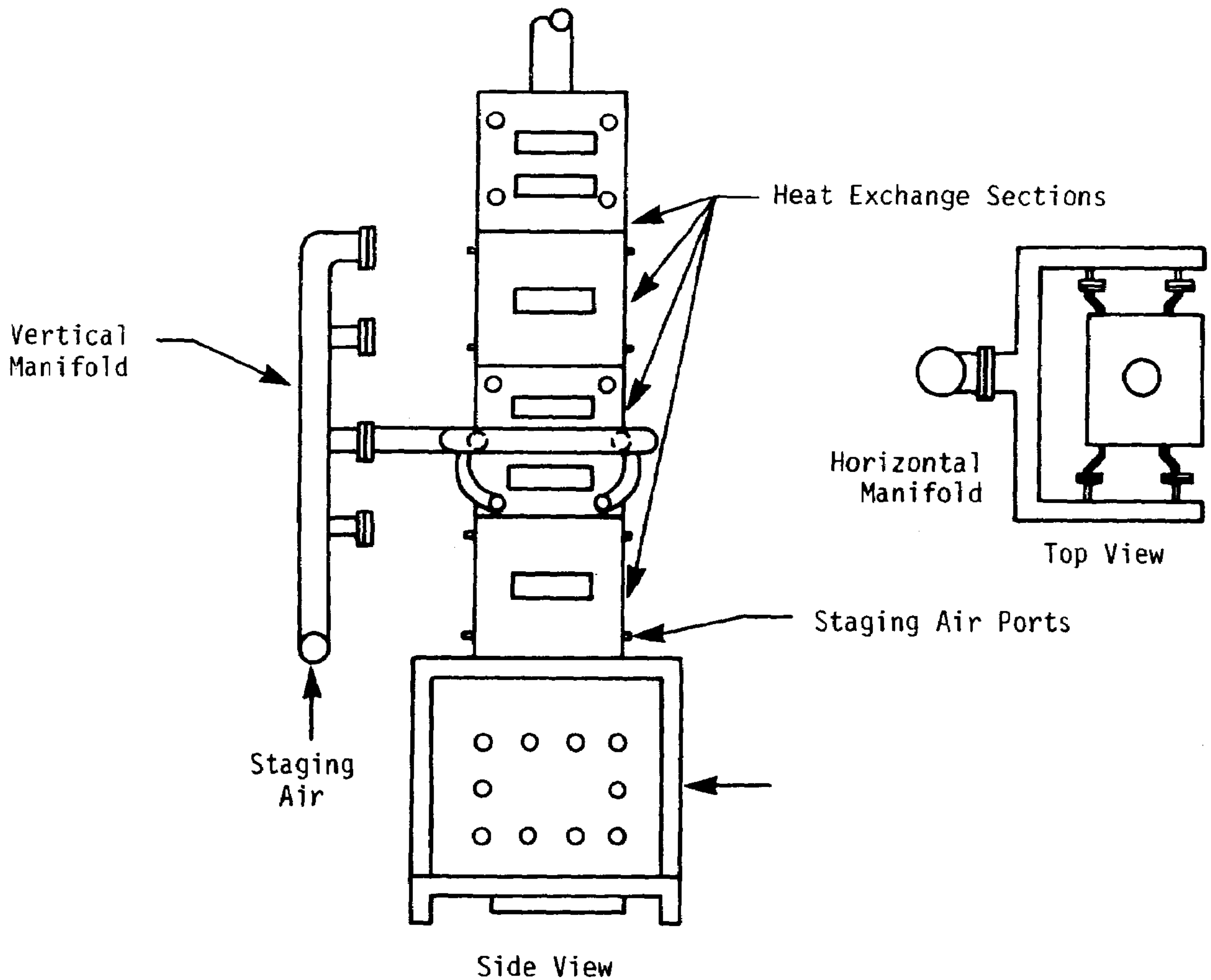


Figure 3-4. Staging-air system.

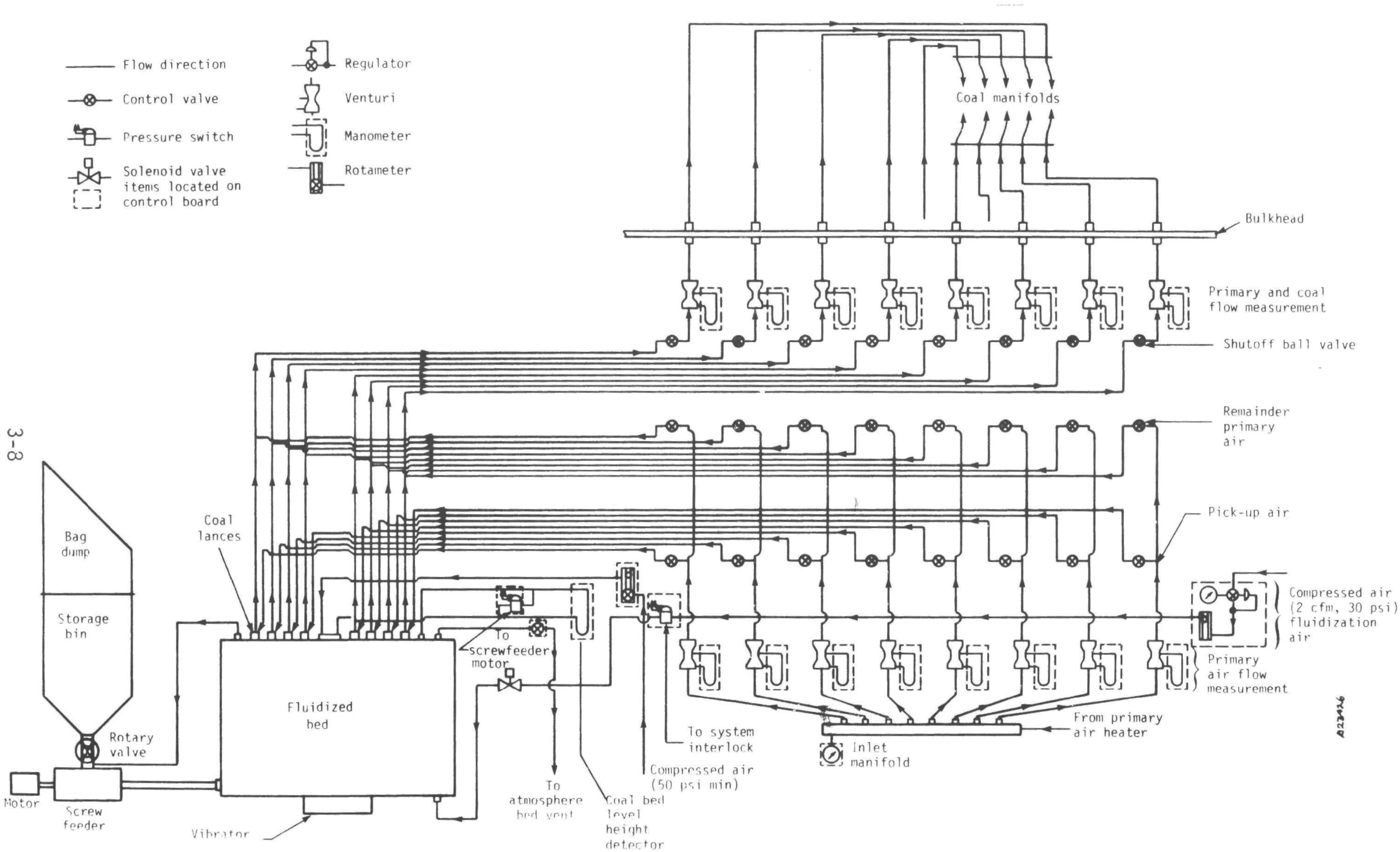


Figure 3-5. Coal system schematic.

fluidized bed. The coal feed rate to each line from the fluidized bed is metered by controlling the pressure drop across an orifice in a lance immersed in the fluidized bed (see Figure 3-6). The primary air flow to each line is individually controlled and measured while the burners' coal feed rate is balanced by flame observations.

After passing through the furnace heat exchange section, the flue gases enter the stack where the gaseous emission sample is taken. The flue is then ducted through the roof to the particulate sampling station, across the roof and down into a baghouse for particulate removal. An induced draft fan and damper downstream of the baghouse allow control of the furnace draft pressure from -5.1 cm (-2") H_2O to +5.1 cm (+2") H_2O.

The facility can also recirculate flue gas from the exit of the baghouse to the secondary air line downstream of the heater. Up to 50 percent flue gas recirculation is achieved using a 13.8 KPa (2 psi) Spencer centrifugal compressor.

3.2 BURNERS

As noted in the previous section, the facility was designed to simulate either a front-wall-fired or tangentially-fired utility boiler. In addition, the horizontal extensions provide for simulation of a package boiler configuration. The facility was also designed so that a variety of burner types may be utilized. For the research tasks of this contract, it was desirable to have both multiple front-wall-fired burners, a larger burner of the same capacity as all the multiple burners, and burners for the tangential configuration. It was also required that these burners be able to fire various fuels and easily change aerodynamic flow patterns such as air velocity and swirl. Therefore, five small and two large versatile research burners were designed for the front-wall-fired

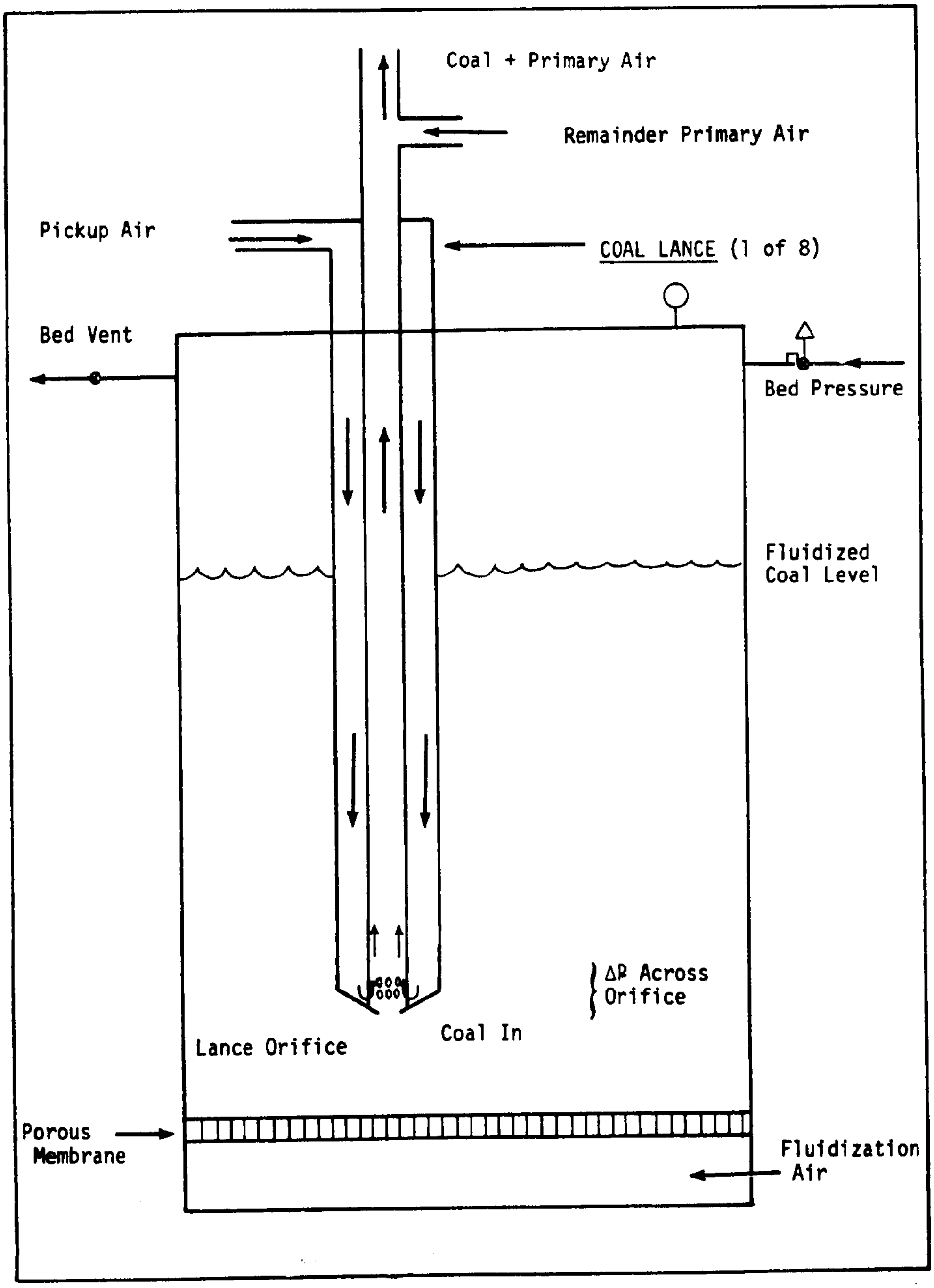


Figure 3-6. Coal lance detail.

configuration and eight corner-fired burners were designed and fabricated for the tangential configuration.

The small front-wall-fired burners, shown in Figure 3-7, have a nominal firing rate of 87.9 kW (3000,000 btu/hr.) each for a total of 440 kW (1.5 x 10^6 Btu/hr.). The burners are patterned after the IFRF variable swirl-block design and allow for great versatility. Some of the parameters that may be varied with these units include:

- Swirl (adjustable during operation)
- Axial fuel tube position
- Air velocity (through sleeving)
- Quarl design (water cooled, refractory, angle)
- Injector type
- Fuel type (coal, oil, gas and others)

The burners were designed for a secondary air exit velocity of 30.5 m/s (100 ft./sec.) at 316^{o}C (600^{o}F) and 25 percent excess air at 87.9 kW (300,000 Btu/hr.) heat release. The two larger 440 kW (1.5 x 10^6 Btu/hr.) IFRF burners were of identical design and were used in the horizontal extension work.

The corner-fired burners are patterned after the Combustion Engineering tangentially-fired burners. However, while the CE burners are a rectangular configuration, this version uses three concentric circular air fuel inlets, shown in Figure 3-8. The distribution of air and fuel in the vertical plane, as well as air velocities, were kept at the same levels as the CE units. A maximum of eight burners at 110 kw (375,000 Btu/hr.) each may be utilized in two tiers for a total of 880 kW (3 x 10^6 Btu/hr.). (Normally only four burners were used for a total of 440 kW 1.5 x 10^6 Btu/hr.). The burners also have the capability of $\pm$ 30^o

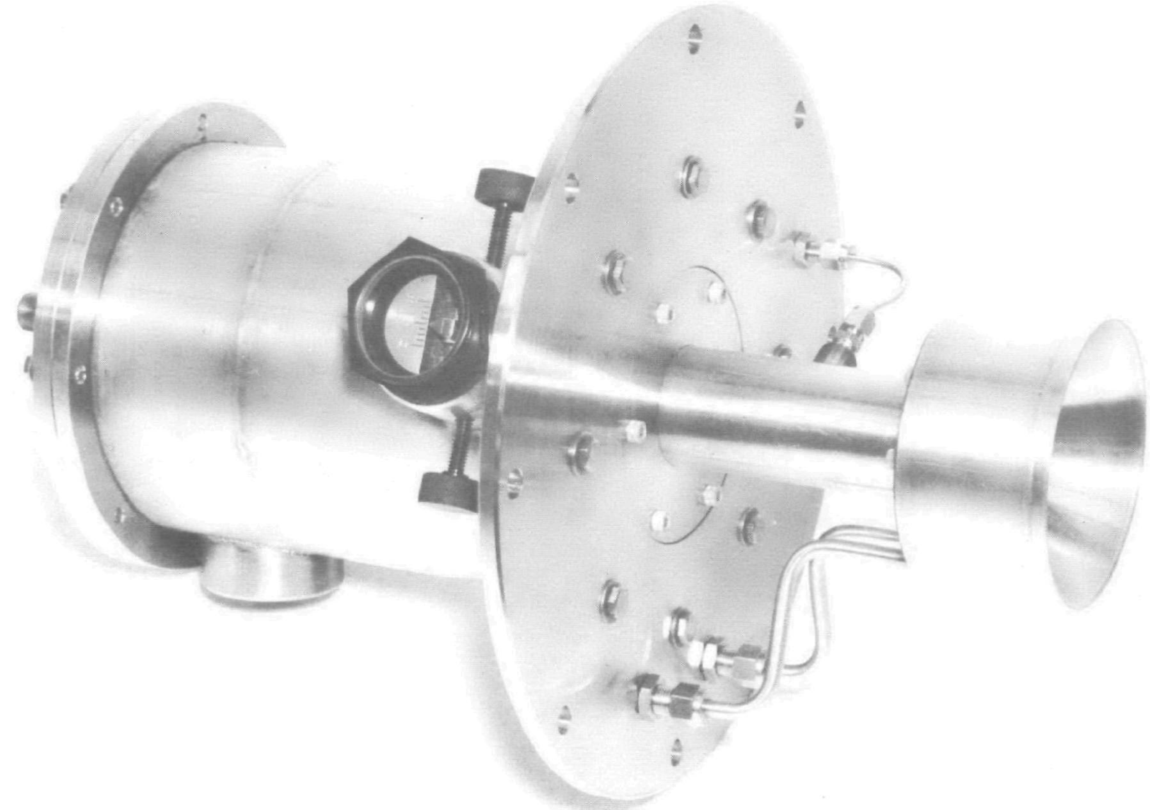


Figure 3-7. IFRF burner.

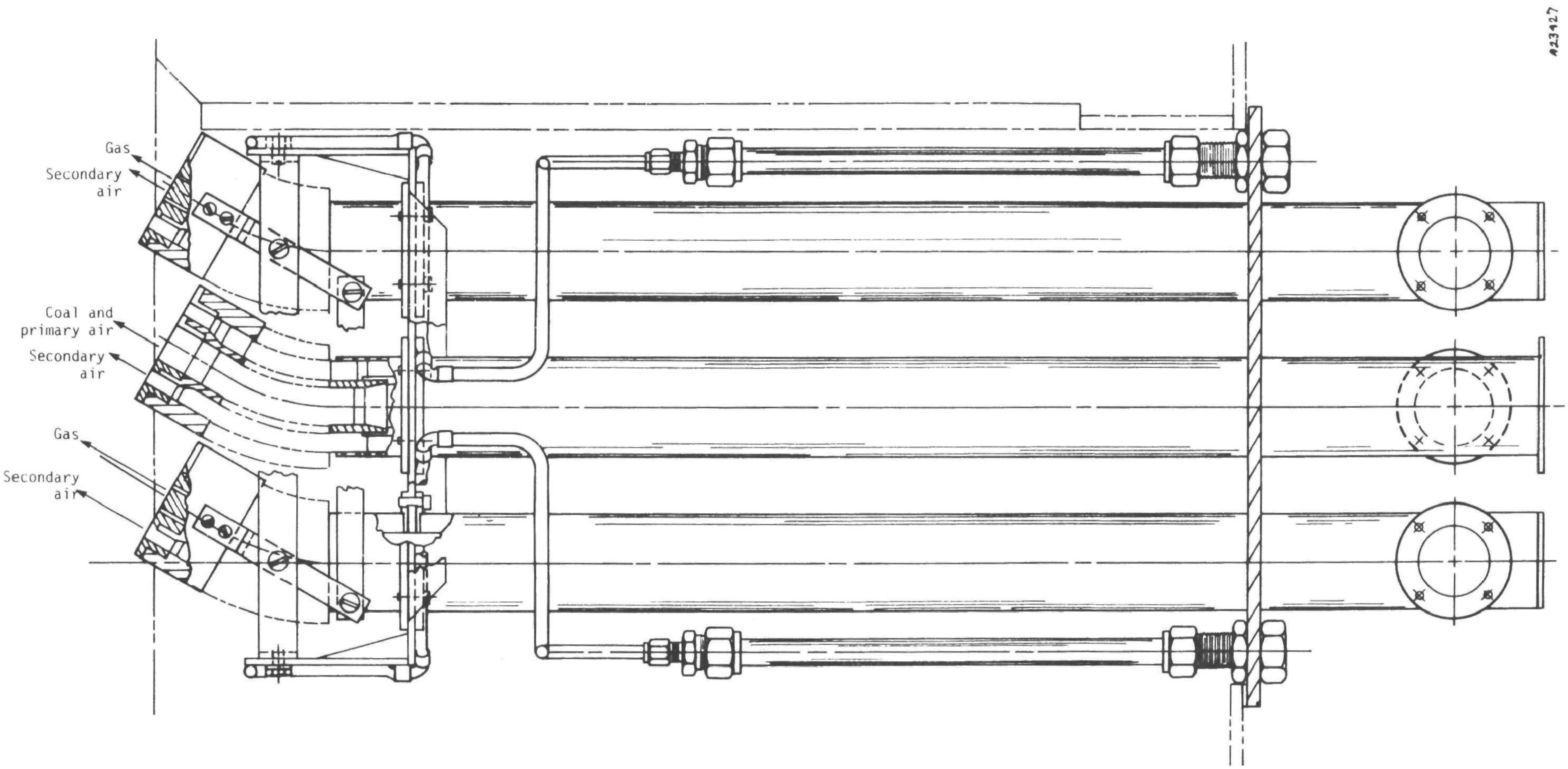


Figure 3-8. Corner-fired burner.

tilt, $\pm 10^0$ yaw, and have interchangeable air sleeves and fuel nozzles. The coal nozzles used in these burners were either the B & W-type spreader, shown in Figure 3-9a, or a straight axial nozzle, shown in Figure 3-9b. The axial nozzle consists of an open pipe with an exit velocity of from 18.3 to 30.5 m/s (60 to 100 ft./sec.) depending on firing rate. Only the axial nozzle was used in the tangential burners. The B & W-type spreader is patterned after typical full-scale hardware.

The normal gas nozzle used in the IFRF type burner is shown in Figure 3-10. Since this nozzle has six holes exiting radially and one axially, it is referred to as the radial/axial nozzle. The holes are sized so that fuel exits at sonic velocities. The gas nozzles on the tangential system are six-hole axial-only.

3.3 INSTRUMENTATION AND DATA ACQUISITION

The facility is fully instrumented for temperatures and pressure measurements. Each subsystem has temperature and pressure measurements for monitoring the status of the system as well as for input for flow measurements.

Flow measurements in the air system are accomplished using sharp edged orifice sets. The pressure drop across each orifice is read out on a manometer. The pressure at the orifice is monitored with a diaphram gauge. Orifice temperatures, as well as all other thermocouple measurements, are monitored by a mini-computer data acquisition system. The millivolt signals are sent to the computer where they are interpreted and displayed as temperatures every 30 seconds on a CRT screen in the control room of the furnace.

This same data acquisition system is used to monitor the emission data as well as to calculate and record the various flow rates.

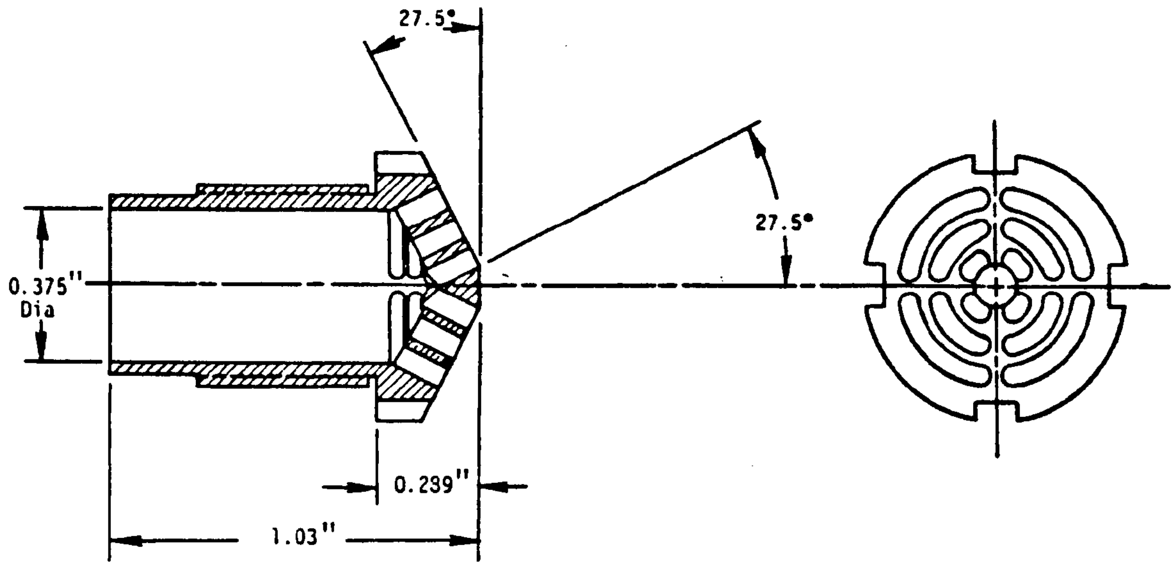


Figure 3-9a. B&W-type coal spreader.

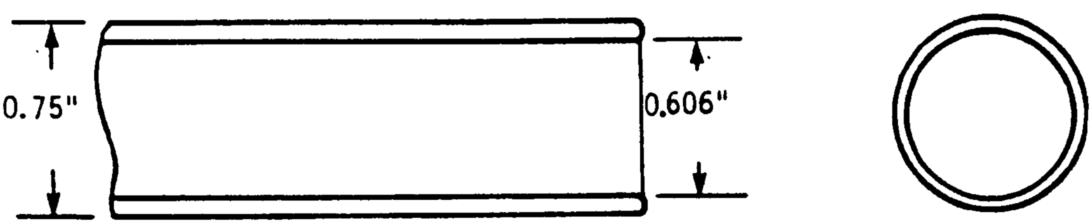
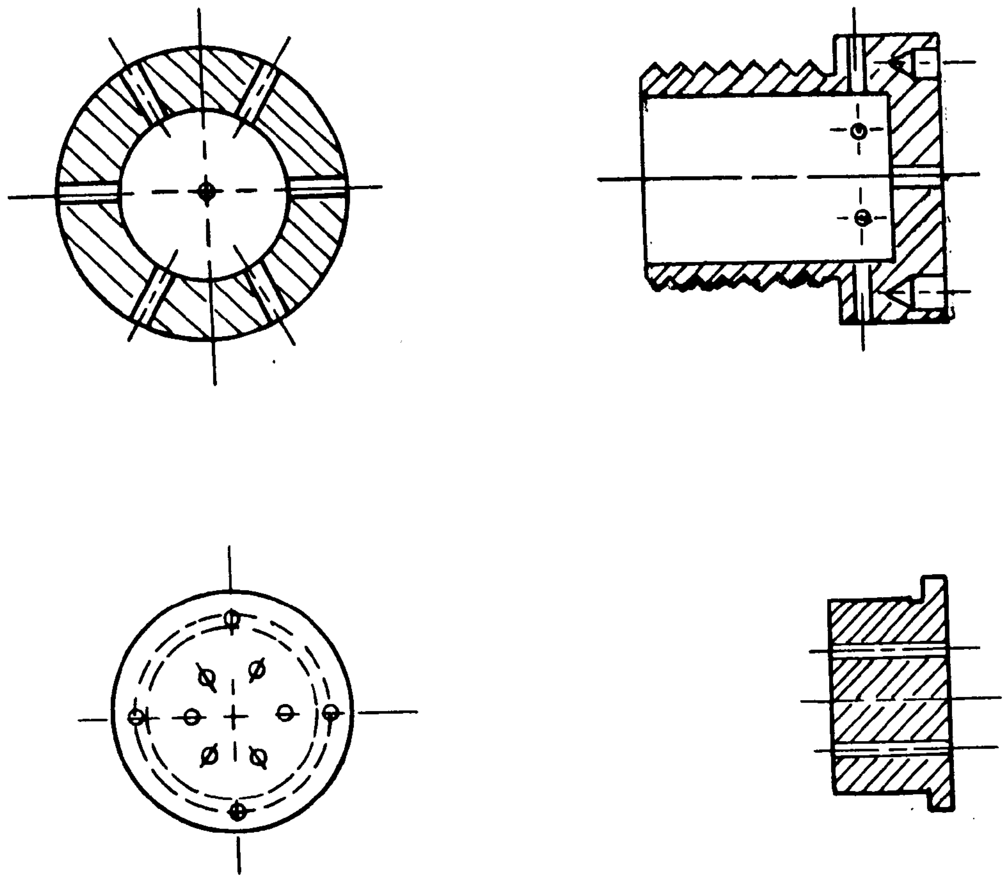


Figure 3-9b. Axial nozzle.



IFRF Gas Nozzle

Corner Burner Gas Nozzle

Figure 3-10. Gas nozzles.

The gas flow rate is determined using a rotameter and the Dowtherm® flow is monitored with a Barton flow indicator based on an orifice ΔP measurement. The coal flow rate is approximately set using the screw feeder setting but is normally back-calculated from the air flow and O_2 measurements.

Critical cooling water flows are monitored with flow switches which are tied to the flame safeguard system. If any of these flows are lost, the flow switches trip the fuel solenoid valves and the furnace is shut down. Other safeguard switches include overtemperature switches on the flue gas into the baghouse, the Dowtherm® exit temperature, and Dowtherm® minimum flow rate.

Firebox temperatures are measured roughly using a ceramic sheathed unshielded platinum-platinum/rhodium thermocouple. Although these measurements will incur considerable radiation error, they give an indication of the approximate temperature level. When more precise measurements are required a Land Suction Pyrometer is used.

The furnace draft is monitored by a magnehelic gauge both in the firebox and at the point in the stack where the emissions are sampled. During a test, the firebox and stack are maintained at positive pressure to ensure that air is not leaking into the system. Whenever a port is to be opened, the furnace is put under negative pressure using the damper control on the induced draft fan.

The pressure measurement between the firebox and the stack also gives an indication when the heat exchanger tubes are fouled and soot blowing is required. A similar pressure drop measurement is made across the baghouse to indicate when baghouse pulse cleaning is required.

3.4 EMISSION MONITORING

As mentioned in the previous section, emission samples are continuously drawn from the stack just downstream of the heat exchanger section but prior to the baghouse. The temperature of exhaust gases at this point is from 149°C (300°F) to 316°C (600°F).

A schematic of the gaseous emission monitoring system is shown in Figure 3-11. A sample is pulled through a heated filter where the bulk of the particulates are removed. From the heated filter, the sample flows through a heated Teflon line to an oven. Additional filtration is performed in the oven and the sample divided three ways. Calibration or zero gas may also be added at this point. From the heated oven, the three sample lines pass through a refrigerant dryer where the sample is condensed to a dew point of 2°C (35°F). From the dryer, each sample gas passes through a pump and another filter prior to entering the instruments. Table 3-1 lists the instruments and principle of operation for each of the gaseous emissions measured. These include O_2, CO, CO_2, NO, NO_x, H/C and SO_2. The SO_2 unit uses a separate heated filter, sample line, and condenser.

When particulate samples are required, an Aerotherm High Volume Stack Sampler is used (EPA Method 5). The sample port for this unit is located downstream of the gaseous emission sample port in a vertical section of the stack, but upstream of the baghouse. This port is easily accessible from the roof of the building. Grain loadings and percent combustibles are determined from the particulate stack samples.

Occasionally, sampling in the hot (>1094°C (2000°F)) combustion chamber for NO was performed during some of the horizontal extension tests. This sampling was accomplished using the water-cooled spray quench probe shown in Figure 3-12. Sufficient water is sprayed into the tip to quench

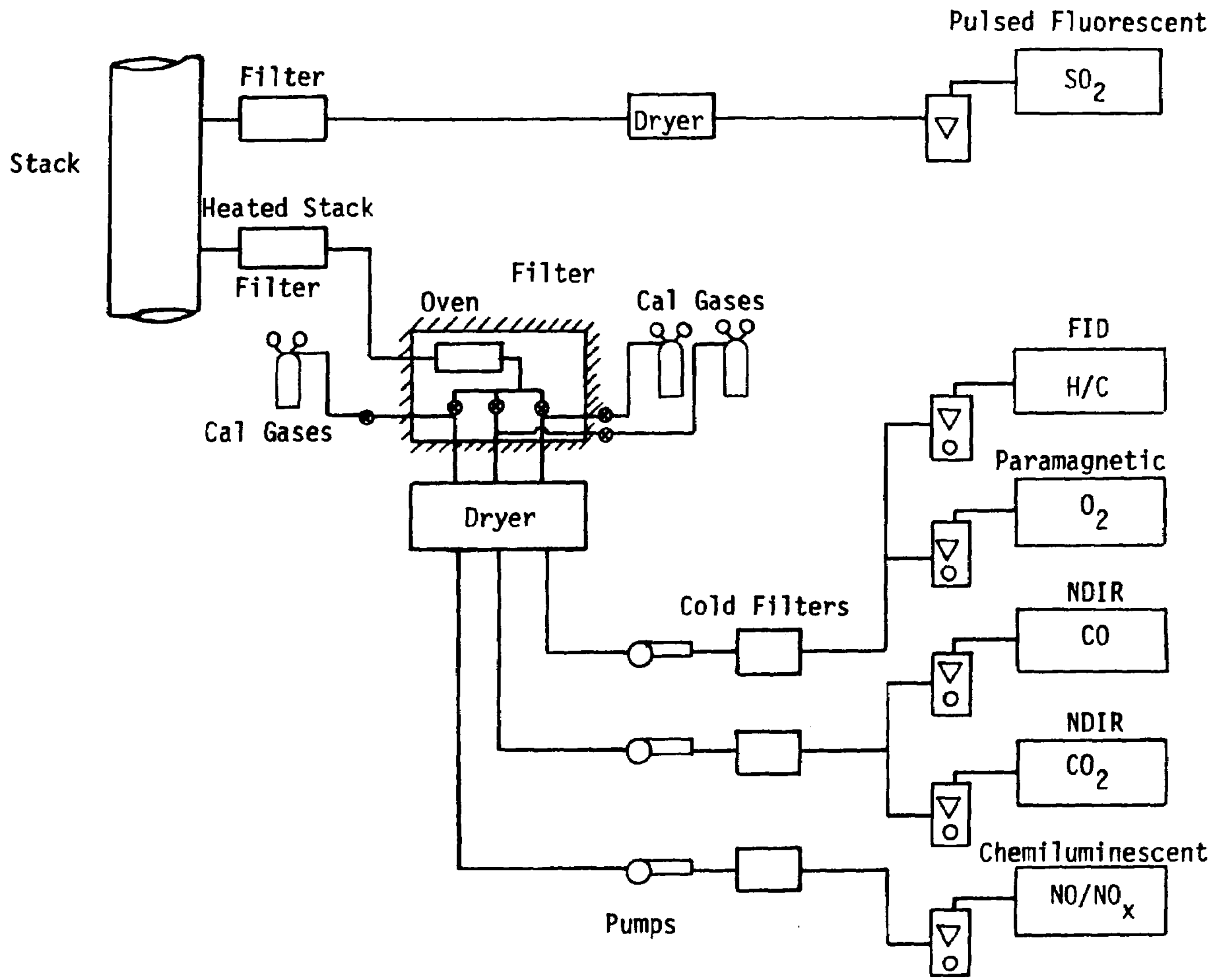


Figure 3-11. Emission monitoring system.

TABLE 3-1. ANALYTICAL POLLUTANT MEASUREMENT EQUIPMENT

NO/NO_x	Intertech Model 32C chemiluminescence analyzer
O_2	Intertech Model Magnos 5T paramagnetic O_2 analyzer
CO	Intertech Model URAS 2T NDIR CO analyzer
CO_2	Intertech Model URAS 2T NDIR CO_2 analyzer
U/HC	Intertech Model FID0008 FID H/C analyzer
SO_2	TECO Model 40 Pulsed Fluorescent analyzer

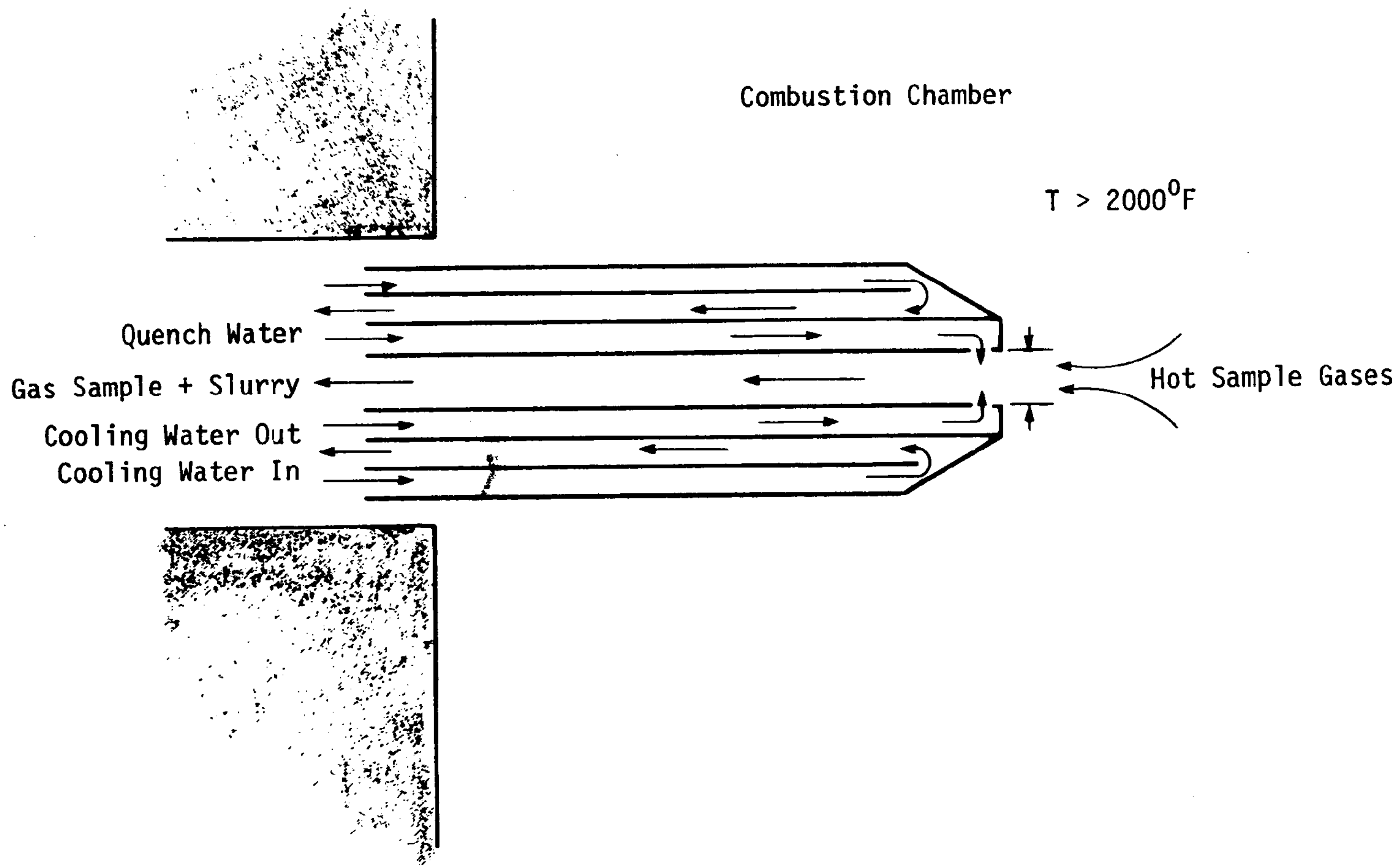


Figure 3-12. Hot sampling probe.

the reactions and unburned hot coal particles. This slurry of char, water and gaseous sample is drawn by a vacuum pump to a drop-out pot. Here the gases are routed to the emission system and the water and char slurry is separated. Although there may be absorption of NO_2 in the water, this system should give a good indication of the NO level at any point in the hot zone.

3.5 FACILITY SUMMARY

In summary, the EPA multiburner, multifuel facility is one of the most versatile facilities available for coal combustion research in the United States.

Table 3-2 gives a summary of the furnace and furnace subsystem capabilities. Detailed schematics appear in Appendix A.

Important to the formulation of the test plan in the next section is the relationship of heat release rate per unit volume and firing rate. This is illustrated by the performance map of the furnace and heat exchangers as illustrated in Figure 3-13. The upper boundary is determined with the full heat exchange surface installed (or using only the main firebox as the combustion volume). The lower boundary is determined by the required heat exchange surface to lower the gas temperature to 427°C (800°F) (the limit imposed by the exhaust ducting). Also shown on this curve are the typical ranges of heat release rates for various fuels. Clearly, coal firing is restricted to about 440 kW (1.5×10^6 Btu/hr.).

Table 3-3 further illustrates the current performance of this facility by giving the bulk residence times* and the heat release rates for various firing rates and combustion volumes. This shows that when

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*Bulk residence times at 25 percent excess air and an assumed average temperature between 1370°C - 1590°C (2500°F - 2900°F) for the various cases. These residence times could be longer for a tangentially fired arrangement.

TABLE 3-2. PRINCIPAL COMPONENTS AND CAPABILITIES

Component	Description
Main Furnace Combustion Chamber	Max. refractory temp: 1760°C (3200°F) Volume: 1.32 m^3 (46.6 ft^3) View ports: 4, 7.62 cm (3") dia. Ignition ports: 6, 2.54 cm (1") dia. Burner blocks 1, 5 hole, 71.1 cm (28") dia. and plugs: 1, single hold, 71.1 cm (28") dia. 8, corner, "x" Burner mounting: 1-5 horizontal opposed 1-5 wall fired 4,8 tangentially fired
Ash Pit	Volume: 226 m^3 (8 ft^3) Max. temp: 1427°C (2600°F)
Heat Exchangers	Sections: 4 refractory lined Max. temp: 1650°C (3000°F) Inside dimensions: 63.5x63.5x81.3 cm (25x25x32") high Drawers: 24 with 20 1.59 cm (5/8") U tubes /DWR - removable Length of Dwr.: 81.3 cm (32") Coolant: Dowtherm® Access ports: 4/section, 2.54 cm (1") dia. Mixing section: 15.2 cm (6") above and below drawers (access ports are located in those sections) Max. heat abs.: 645 kW (2.2 x 10^6 Btu/hr) Wt.: 680 kg (1500#)/section w/o drawers
Burners	2 - 440 kW (1.5 x 10^6 Btu/hr) Aerotherm/IFRF 5 - 87.9 kW (300,000 Btu/hr) Aerotherm/IFRF • Interchangeable fuel tips • Interchangeable quarls • Variable swirl • Air sleeves to change velocity 8 - 110 kW (375,000 Btu/hr) Aerotherm corner fired • Three identical circular air & fuel inlets/burner • ±30° tilt - all outlets ganged • ±10° yaw - all outlets ganged • Interchangeable air sleeves for each port • Interchangeable fuel nozzles
Air Supply Primary	• 0.378 m^3/s (800 SCFM) @ 55.1 kPag (8 psig) • Aftercooler: 70°F dew point • Cold control valve & orifice; separate heater
Secondary	• Hot control valves & orifices

TABLE 3-2. (Continued)

Component	Description
	• Individual control & measurement to 16 lines, 8 on each side of the furnace. Allows flow control of secondary air to each IFRF burner and control of annular and secondary air flows to the corner fired burners.
Staged Air	• Staged air manifold parallel to heat exchanger stack. Mixes hot secondary and cold secondary air to achieve any temperature up to the secondary air temperature. Presently only total staged air is controlled.
Heaters	• Secondary air 200 kW max. Temperature at the burner: 427°C (800°F) • Primary air heater 12 kW max. Temperature at the burner: 121°C (250°F) • Continuous control from 21°C (70°F) to the maximum temperature for 10:1 flow range
Flue Gas Recirculation	• Take off point downstream of baghouse • Max. temperature: 204°C (400°F) • Max. flow: 0.0566 m^3/s (120 SCFM) • Max. pressure: 13.8 kPag (2 psig) • Max. firing rate permissable at these conditions: 440 kW (1.5×10^6 Btu/hr) @ 10% excess air • Present introduction point is in the secondary air line downstream of the secondary air heater. (Simple modification could be made to introduce the flue gases in the stage air, primary air or individual burners. • No FGR heater at this time
Oil Delivery System	• Up to 26.3 ml/s (25 gal/hr) on #2 or #6 oil • Single pumping & supply system for both oils • Max. temperature #6: 104°C (220°F) at the nozzles • Two oil manifolds with 8 taps each on either side of the furnace • Quick disconnect fittings at the manifold and burners • Flow control valves to each burner • Max. pressure: 1.72 MPag (250 psig)

TABLE 3-2. (Concluded)

Component	Description
Gas System	• Up to 0.0236 m^3/s (300 ft^3/hr) @ 172 kPag (25 psig) • Manifold with quick disconnects, 8 outlets on each side of the furnace • Shutoff ball valves for each tap on the manifold and needle control valves for each burner inlet
Coal System	• Up to 31.5 g/s (250 lbs/hr) of pulverized coal • Ten delivery lines to two manifolds, one on each side of the furnace. Five flexible lines on each manifold deliver pulverized coal to one to five burners. The small lines must be recombined when firing the larger burners. • The coal and primary air flow rates are controlled and measured to each of the delivery lines. Uniform distribution is obtained from a fluidized bed distributor. • Bagged pulverized coal is fed into a bagdump from the second floor level and into a 1.4 m^3 (50 ft^3) hopper. This represents about a 1 day supply of coal. • The fuel flow may be stopped in the event of a flame-out or unstable condition through a solenoid operated air purge system. This purge system is controlled manually or by the flame safeguard system.
Dowtherm® System	• Two Dowtherm® to-air heat exchangers can remove up to 132 kW (2.5 x 10^6 Btu/hr) from the Dowtherm • A bypass arrangement around these coolers allows control of the heat removal rate.
Induced Draft Fan	• An induced draft fan with bypass allows control of the back pressure in the combustion chamber to ±5.1 cm (±2") H_2O over the full range of firing rates.

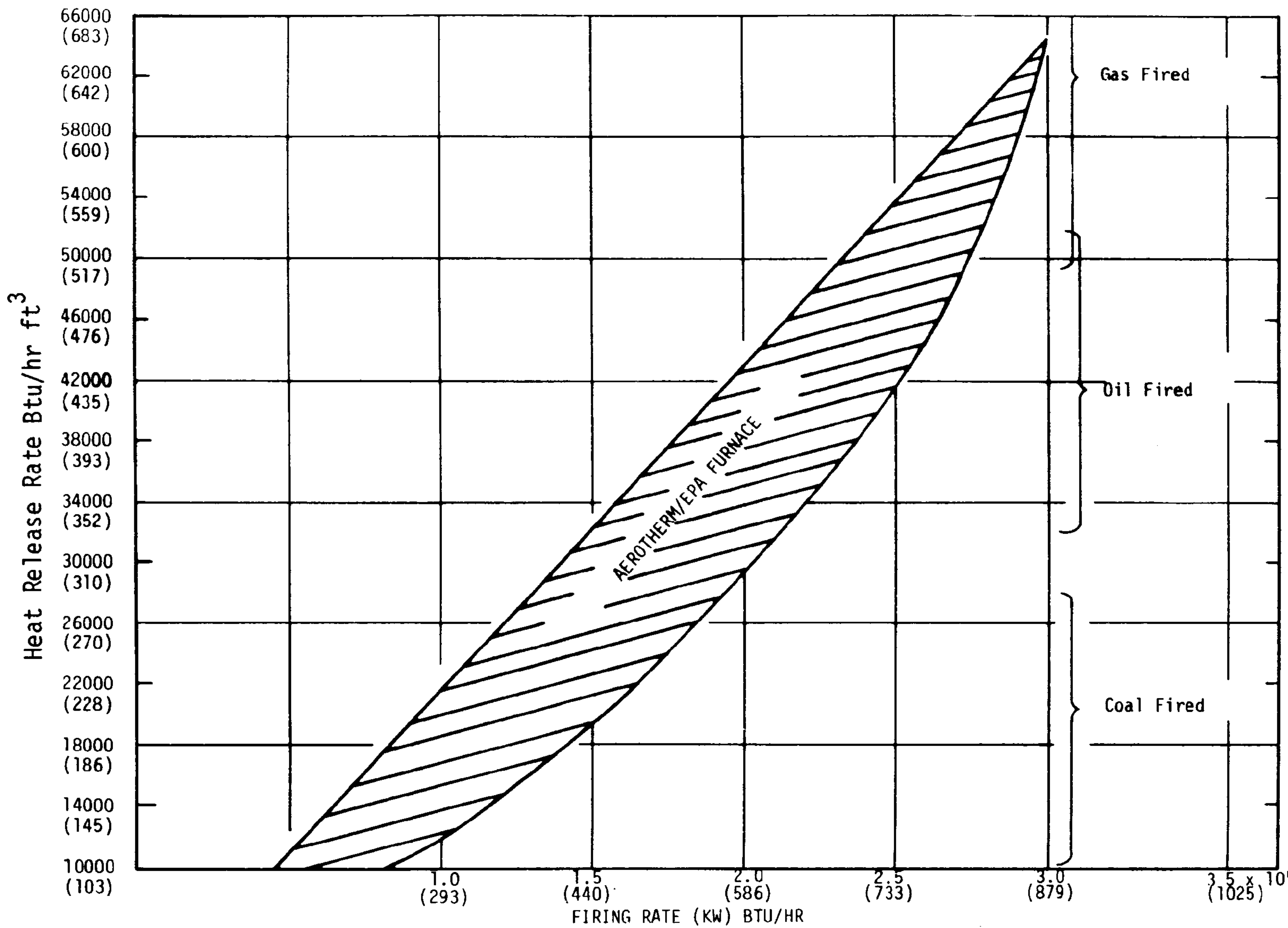

Figure 3-13. Furnace performance map.

TABLE 3-3. FURNACE PERFORMANCE PARAMETERS FOR VARIOUS CONFIGURATIONS

Configuration (Furnace plus n empty sections)	Vol m^3	Total Heat Release (kW)					
		880		440		293	
		R.T.	H.R.	R.T.	H.R.	R.T.	H.R.
Furnace	0.4022	0.67/0.83	2188	1.34/1.68	1094	2.01/2.51	728
Furnace + 1	0.4943	--	--	1.65/2.06	890	2.47/3.09	593
Furnace + 2	0.5863	--	--	1.96/2.45	750	2.93/3.66	500
Furnace + 3	0.6784	--	--	--	--	3.39/4.24	432

KEY:

R.T. = Residence time (sec) at 25 percent excess air/stoichiometric

H.R. = Volumetric heat release rate kW/m^3

-- = Insufficient heat exchange surface

TABLE 3-3. (Concld.) FURNACE PERFORMANCE PARAMETERS FOR VARIOUS CONFIGURATIONS

Configuration (Furnace plus n empty sections)	Vol ft^3	Total Heat Release (Btu/hr)					
		3×10^4		1.5×10^6		1.0×10^4	
		R.T.	H.R.	R.T.	H.R.	R.T.	H.R.
Furnace	46.60	0.67/0.83	67,378	1.34/1.68	32,189	2.01/2.51	21,459
Furnace + 1	57.27	--	--	1.65/2.06	26,191	2.47/3.09	17,461
Furnace + 2	67.93	--	--	1.96/2.45	22,068	2.93/3.66	14,721
Furnace + 3	73.60	--	--	--	--	3.39/4.24	12,723*

KEY:

R.T. = Residence time (sec) at 24 percent excess air/stoichiometric

H.R. = Volumetric heat release rate Btu/hr-ft^3

-- = Insufficient heat exchange surface

* = Marginal heat exchange surface

firing at 440 kW (1.5 x 10.6 Btu/hr.), a maximum residence time of 2.4 sec. may be obtained. This performance map was used extensively in setting up the test matrices described in the next section.

SECTION 4

TEST PLAN RATIONALE AND MATRICES

This section presents the test plan rationale and the test matrices developed to answer specific questions on advanced pollutant control techniques involving combustion modification. Section 4.1 presents the specific rationale for the Phase II test program, including baseline tests and the tests for evaluation of control techniques. Section 4.2 presents the detailed test program with explanations and test matrices.

4.1 TEST PLAN RATIONALE

The fossil-fuel studies (Phase II, Task 1) task is made up of two components. The objective of the first component, Furnace Characterization, is to conduct fuels-oriented research and development, to determine how the pollutant emissions measured from this facility relate to typical commercial combustion units under baseline conditions. The subscale results and the results from full-scale units will be compared to establish the merit of the control techniques derived from the second component of this task.

The objective of the second component, Evaluation of Control Technology, is to obtain general insight into control technology to lower the baseline emissions. The general guidelines developed will help burner and boiler manufacturers develop commercially feasible control technology. We have organized this second component of the task to make maximum use of the unique features of the combustion facility, emphasizing promising aspects of control technology not covered by other EPA programs or that are best suited for testing in this furnace. Tests to derive specific hardware burner designs for low emissions were not planned, but rather, tests were planned to derive semiquantitative guidelines to indicate how hardware and operating adjustments can change important combustion characteristics (such as particle heating rate, mixing, etc.) and how these characteristics affect pollutant emissions. Our rationale is described in more detail below.

4.1.1 Furnace Characterization

The objective in this subtask was to determine how this test facility compares to actual field hardware. To do this, we first answered preliminary questions about the conditions under which the furnace most directly corresponds to commercial units with respect to NO_x emissions. We then began baseline characterization with natural gas and three coals. Finally, we determined the baseline fuel NO_x emissions for the three coals.

Table 4-1 shows the structure of the test program in this furnace characterization activity, and summarizes the objectives. The following subsections amplifies these objectives.

Preliminary Studies

The test facility was designed with uncooled refractory walls in an effort to simulate the environment in most large multiburner furnances and boilers. However, because of the complexity of flame size and flame shielding effects, it is possible that water walls might give a better correspondence to field equipment. Since this directly impacted the credibility of the entire program, we decided to experimentally

TABLE 4-1. STRUCTURE OF FURNACE CHARACTERIZATION TESTS SERIES

Subtask	Element		Test Series	Principal Objectives	Other Objectives
Furnace Characterization (1.1)	Preliminary Studies	Wall Cooling	IIA	Determine importance of wall cooling in this facility in providing good duplication of full-scale data or trends	
		Baseline Burner Config.	IIC	Determine configuration of burners in wall-firing & tangential-firing which allows best duplication of full-scale data or trends	Define furnace operating characteristics
	Baseline Series	Front Fired	IID	Show that NO_x trends in this unit duplicate full-scale results over a range of values of 3 primary operating variables: excess air, preheat, & firing rate (load)	• Define furnace operating limits • Compare emission characteristics of 3 different fuels under same conditions • Establish data base for evaluation of control technology
		Tangentially Fired	IIE	Same as IID	
	Baseline Fuel NO_x Studies		IIF	Define NO_x distribution between thermal NO_x and fuel NO_x for coal	Investigate effect of FGR
			IIG	Define stage-air injections technique	Estimate back-mixing for various staging geometries

evaluate the problem. We used natural gas and coal to provide the different combustion and radiation characteristics. If water walls were found to be necessary to obtain a reasonable correspondence between our results and those of others (such as from full scale units), then they would be retained.

Baseline Testing

For the main baseline test series, emission characteristics were classified into two general categories:

- Front-fired conditions
- Tangentially-fired conditions

For each of these configurations the primary operating variables of excess air, air preheat, and firing rate were varied to obtain a detailed baseline characterization. This variation also showed that the dependence of NO_x on the three primary operating variables matches, or is at least related to, the dependence observed with full-scale units. Natural gas was used as the first fuel, since more full-scale data are available for this case. The hardware variables were initially set to correspond to utility practice and then adjusted, if necessary, until the correct (as defined by full scale data) dependence on excess air, air preheat, and firing rate was observed.

Baseline Fuel NO_x Emissions

In the final part of the furnace characterization tests, we established the importance of fuel NO_x at the various test conditions for coal firing. This was a difficult problem, since even the most accepted approach, argon/oxygen substitution, was impractical here because of economics (costs averaged $2,000 per data pt.). Turner (Reference 4-1) has proposed that fuel NO_x can be estimated using flue gas recirculation but Martin (Reference 4-2) has shown that there are potential problems associated with this method. We proposed to get around these problems by coordinating our tests with an independent test program at the University of Arizona. In this program, identical test fuels were burned under the "same" combustion conditions in a small-scale, multifuel combustor using both Ar/O_2 replacement and flue gas recirculation. The Arizona program developed a relationship that can be used to accurately estimate fuel NO_x using flue gas recirculation (FGR). However, the Arizona program also showed a relationship between the thermal portion and combustion of natural gas through the coal nozzle, that was simpler to use. Thus, we used the second method to establish the relationship between thermal NO_x and fuel NO_x.

Stage-Air Injection Cold Flow Tests

These tests were necessary to establish a stage-air injection technique with rapid mixing rates, but no appreciable back-mixing into the first stage.

4.1.2 Control Technology

Because only a fraction of all possible tests could be conducted in the time available, the specific scope of the research was narrowed to (a) make optimum use of the special design features of this facility, and (b) fill in research gaps not being investigated elsewhere. The specific research goals established for this program are explained below. As Figure 4-1 shows, for coal firing this program focuses on and uniquely contributes in two areas:

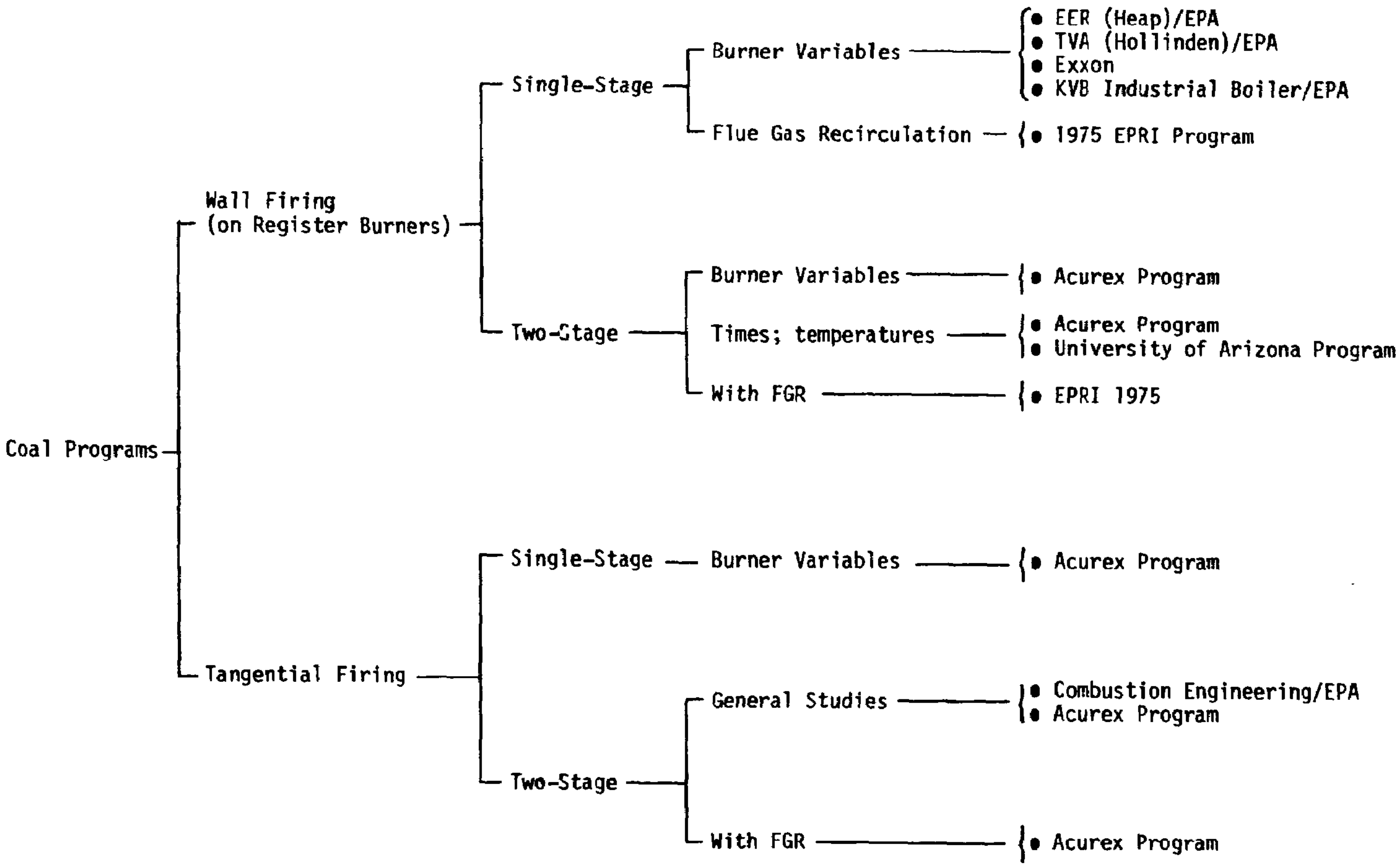

Figure 4-1. Relationship of current NO_x evaluation, full-scale and pilot-scale programs for coal.

- Front-fired configuration staging
- Tangentially-fired configuration burner variables

  and will provide support for a third area

- Tangentially-fired configuration staging

Research on wall-fired burner design modifications was deemphasized for the following reasons. First, an Energy and Environmental Research (EER) study is specifically oriented towards this problem (excluding FGR), using a nearly full-scale test facility. The time limitations precluded the luxury of duplicating results obtained on equipment more similar to actual combustion facilities. In addition, other important problems such as staging and flue gas recirculation are more attuned to the unique capabilities of this test furnance.

Because studies by Combustion Engineering promised very useful results on the effect of staging on tangentially-fired full scale units, our role was (and is) to support their program. Those tests that can be conducted only with difficulty in full-scale units, such as various adjustments in first-stage flame patterns, variations on second-stage air injection methods, and flue gas recirculation were conducted in this facility. In addition, the test facility provided additional flexibility in adjusting first-stage residence time and heat removal, compared to the full-scale program.

For staging on the front-fired configuration, the test facility can provide useful information not available or not being generated elsewhere, such as the effect of mixing in the fuel-rich primary stage. Studies elsewhere will help determine which is more desirable from a NO_x point of view -- volatile fuel nitrogen (XN) or char nitrogen. Our studies were to help determine how mixing affects this.

In addition, the test facility was ideally suited to allow variations in first-stage residence times, temperatures and stoichiometric ratios, as well as various methods of secondary air addition.

4.2 TEST MATRICES

The testing was categorized as baseline testing or verification of the simulation capability and the testing of NO_x control technology. The individual test matrices for each of these tests for the front-wall-fired, tangentially-fired, and the horizontal extension testing are presented in this section. Each matrix lists the test number (e.g., 100a, 118c*) for those test conditions. The purpose and rationale for each matrix is also included.

4.2.1 Baseline Testing

At the start of the test program, preliminary screening tests were made to define the various burner settings. On the front-wall-fired burners the parameters of interest were the swirl setting, axial fuel tube position and the primary air percentage. Table 4-2 shows the matrix for the front-wall-fired tests which explored these variables. From this test series came the nominal firing conditions of an axial fuel tube position of 11.8 cm (4.65 in.), swirl setting equals 4 and a primary air percentage of 12 percent. The results for these tests will be presented in the next section.

In establishing the facility as representative of full-scale units from a NO_x viewpoint it was important to determine the effect of temperature and the effect, if any, of the hot refractory walls compared to water walls.

*The test numbering sequence was organized with a new number for each test day and a letter designation for a particular test condition. Sometimes a prime was used for a slight modification to a test condition or where full emission measurements were not made.

TABLE 4-2. PRELIMINARY SCREENING MATRIX: BASELINE

Primary %	SW	EA	Axial Fuel Tube Position, cm (in.) 10.54 (4.15")	11.8 (4.65")	13.1 (5.15")	14 (5.5")	15.2 (6.0")
12	2	25		105b*			
	4	5	108j	9c 113a 114a			
		15	108h,i,k,l	9b, 113b, 114a 114c, 114d, 114f	108b	108d	108e
		25	107d*	105a*, d* 9a, 110a		108c	
	6	15		135b 135c**	107i		
		25		105c*			
	8	1		152a'			
25	4	15	108g		108f		

*Wall Cooling Employed; Load = 1.5 x 10^6 Btu/hr.
**427°C (800°F) Preheat.

The matrix to study the effect of temperature and additional wall cooling for coal is shown in Table 4-3a. A companion matrix to explore this effect on natural gas is shown in Table 4-3b. The purpose of these tests is to look at the effect of temperature for both a fuel containing fuel-bound nitrogen and a clean fuel. For the clean fuel we should see only the effect on the thermally generated NO_x. Another facet of this baseline work is to investigate which portion of the NO_x emissions from the coal is due to fuel nitrogen. It has been suggested that firing the coal nozzle on natural gas at the same firing rate would represent the thermal NO_x fraction and the remainder of the emissions would be associated with the fuel nitrogen. Table 4-4 presents the test matrix for this work.

The baseline matrix for the effect of excess air, fuel injector, firing rate and coal type on front-wall-fired burners is shown in Table 4-5. In addition, a baseline test with four instead of five front-wall-fired burners at the same firing rate was performed to determine the effect of reducing the number of burners while maintaining the same firing rate. Control technology tests were also conducted in this configuration, as shown in Table 4-5.

The baseline matrix for the tangentially-fired configuration is given in Table 4-6. These tests include the effects of excess air, firing rate, air preheat, primary stoichiometry and coal type.

The baseline tests for the horizontal extension configuration are given in Table 4-7. The objectives of these tests were as follows:

- Establish baseline data for four small IFRF burners with both the Babcock and Wilcox (B&W) spreader nozzle and axial injector in the horizontal extension mode
- Determine effect of preheat and firing rate

TABLE 4-3(a). BASELINE TESTS: EFFECT OF TEMPERATURE

Temp	Load											
	293 kW (1 x 10^6 Btu/hr)						440 kW (1.5 x 10^6 Btu/hr)					
	W. Cooling			No Cooling			W. Cooling			No Cooling		
	5	15	25	5	15	25	5	15	25	5	15	25
37.8°C (100°F)					140a							
149°C (300°F)				118d	118c	118a 118b 118e	107k	107j		115c	11 115b 115e	10 115a 115d
316°C (600°F)	107e	107f		116e	12 116c 116d 134a 140c 156n 182g 183a	116a 116b	107g 107c	105e 106a	105a 105d	9c 113a 114e	9b 113b 114a 114a 114d 114f	9a 110a
427°C (800°F)					135d 183g							

Western Kentucky Coal FWF

B & W Spreader Sw = 4

TABLE 4-3(b). BASELINE NATURAL GAS EFFECT OF TEMPERATURE AND WALL COOLING

		703 kW (2.4 x 10^6 Btu/hr)					440 kW (1.5 x 10^6 Btu/hr)		
	TEMP/EA	5	10	15	25	35	5	15	35
No Cooling	149°C (300°F)	100c	100b,d		100a,e				
	316°C (600°F)						100h	100f	100g
Cooling	82°C (180°F)	102b		102a		102a			
	149°C (300°F)	103c	103b		103a				
	316°C (600°F)	103f		103e		103d	103i	103h	103g

TABLE 4-4. BASELINE: NATURAL GAS THROUGH COAL NOZZLE

	LOAD							
	293 kW (1.0 x 10^6 Btu/hr)				440 kW (1.5 x 10^6 Btu/hr)			
Temp/EA	5	15	20	30	5	15	20	30
149°C (300°F)	121c	121d	121b 121e	121a	121g	121f		
316°C (600°F)	120e	120c,d	120b	120a, 120f				

TABLE 4-5. BASELINE: FRONT-WALL-FIRED, MAIN BOX

			B & W Type Spreader			Axial Injector		
			Excess Air			Excess Air		
Burners	Firing Rate	Coal Type	5	15	25	5	15	25
5 IFRF	293 kW (1 x 10^6 Btu/hr)	W. Kty.	116*e*	116*d*	116*b*	152*c*	152*a* 148*d* 181*a*,182*a*	152*b*
		Pitts #8	157*b*	157*a*	157*c*	157*v*	157*u*	
		Montana	159*j*	159*h*	159*i*	159*g*	159*k*	
	352 kW (1.2 x 10^6 Btu/hr)	W. Kty.	156*m*	156*ℓ*,*i*	156*k*,*j*	152*e*	152*d*	152*f*
	440 kW (1.5 x 10^6 Btu/hr)	W. Kty.	9*c*	9*b*	9*a*	161*f*	161*d*	161*e*
		Pitts #8	157*e*	157*d*	157*f*			
		Montana	158*j*	158*i*	159*a*			
4 IFRF	293 kW (1 x 10^6 Btu/hr)	W. Kty.	165*i*	165*g*	165*h*			

TABLE 4-6. BASELINE: TANGENTIAL

Preheat* Temp.	Load	Burner Yaw	Fuel** Type	Primary Stoich.	Excess Air		
					5%	15%	25%
316°C (600°)	293 kW (1 x 10^6 Btu/hr)	+6	C-1	12	168d	168b	168c
				15	169c 169T 174b 175e	169a 169r 174g 175a 175c 178d 179a	169b 169s 174h 175b 175d
				20	168g	168a 168e	168f
			C-2	15	171c	171a	171b
			C-3	15	171q	171ϕ	171p
	440 kW (1.5 x 10^6 Btu/hr)	+6	C-1	15	170c	170a	170b
			C-2	15	170p	170n	170ϕ
			C-3	15	171cc	171aa	171bb
427°C (500°F)	293 kW (1.0 x 10^6 Btu/hr)	+6	C-1	15		174k 175g 179g	
37.8°C (100°F)	293 kW .1.0 x 10^6 Btu/hr)	+6	C-1	15		176a 176n 177a	

*The range for the temperatures are as follows:

316°C:	288 - 316°C
(600°F:	550 - 600°F)
37.8°C:	27 - 47°C
(100°F:	81 - 117°

**C-1 = Western Kentucky Coal

C-2 = Pittsburgh #8 Coal

C-3 = Montana Coal

TABLE 4-7. BASELINE: HORIZONTAL EXTENSION

			Load	249 kW (0.85 x 10^6 Btu/hr)			381 kW (1.3 x 10^6 Btu/hr)		
			EA	5	15	25	5	15	25
Fuel	Inj./SW	Burner	Preheat Temp.						
Western Kentucky Coal	Sp.-4	4IFRF	32°C (90°F)		188a			188c	
			149°C (300°F)		188g			188e	
			316°C (600°F)	186d	186b 189a 189b	186c	186m	186k	186ℓ
			427°C (800°F)		187f			187d	
		Single Lg IFRF w/4" Sleeve	316°C (600°F)	203i 205d	203h 205e	203g 205f	203f 205c	203e 205b	203d 205a
		Lg IFRF No Sleeve	316°C (600°F)	204f	204e	204d	204c	204b	204a
	Ax-6	4 IFRF	316°C (600°F)		193g				
Montana Coal	Sp.-4	Single Lg IFRF w/4" Sleeve	316°C (600°F)	206bb	206dd 207a	206gg	206j	206h	206f
Montana Coal w/ SO_2 Inj. In Sec	Sp.-4	Single Lg IFRF w/4" Sleeve		206cc	206ee	206ff	206k	206i	206g
Montana Coal w/ SO_2 Inj. In Prim.	Sp.-4				2076b				

- Determine the baseline data on Montana coal with and without SO_2 injection in the secondary and primary air streams
- Compare the baseline data for a single large International Flame Research Foundation (IFRF) burner with the four small IFRF burners
- Determine the effect of changing the secondary air velocity on the large burner by sleeving the burner.

It should be noted that only four of the small IFRF burners were used in the horizontal extension configuration and that the firing rate was reduced from 293 kW and 440 kW (1.0 and 1.5 x 10^6 Btu/hr.) to 243 kW and 381 kW (0.83 and 1.3 x 10^6 Btu/hr.) respectively. This reduction was done so that the heat release per unit volume in the main combustion zone was approximately the same as in the main firebox. However, in order to achieve the same burner aerodynamics, the number of burners was reduced from five to four.

In addition to the baseline test matrices for the Phase II test program described above, at the start of every control technology test (described in the next section) a baseline point at 15 percent excess was usually taken for the particular firing rate and preheat to be tested. When the data for a particular test were then plotted, for example, as a function of stoichiometric ratio (SR), the baseline point for that particular test was included as the reference point rather than using the baseline data taken early in the test program. Thus some differences will be noted in the reference points. These differences can be attributed to changes in the combustion chamber temperature, to changes in the coal spreader pattern due to wear on the nozzles (a significant change as the nozzles become worn), and to ash clinkers on the fuel tube that changed the secondary air flow patterns.

4.2.2 Control Technology Testing

Most of the control technology testing was concerned with staging as a NO_x control technique in both a front-wall-fired and tangentially fired configuration. The objective was to explore the effects of the first stage and second-stage parameters on the stack NO_x emissions and to determine the optimum set of first- and second-stage conditions to achieve minimum NO_x emissions while maintaining low CO, unburned hydrocarbon levels, and low carbon loss in the ash.

As mentioned earlier, burner parameter changes were kept to a minimum with first-stage parameter changes focusing on variables which would affect the whole first stage. The general parameters of interest for both the first- and second-stage are as follows:

- Stoichiometry (excess air in second stage)
- Residence time in each stage
- Temperature & Firing rate
- Mixing
- Coal Composition

A series of matrices was developed to explore each of these variables in each stage for both the FWF and tangentially-fired configurations. These matrices appear in Tables 4-8 to 4-14. Most of the testing was done in the front-wall-fired configuration and thus these tests are divided into four principal matrices and several miscellaneous matrices. The four principal matrices are described below.

Front-Wall-Fired Tests

Table 4.8, First-Stage Parameters

This matrix includes most of the first-stage variables, such as temperature or additional heat removal, mixing (both swirl

TABLE 4-8. FIRST-STAGE PARAMETERS

Additional Heat Removal	Stagnation Point	SW	Firing Rate	Preheat	Nozzle									
					B&W					Axial				
					Stoichiometric Ratio									
			kW/ 10^6 Btu/hr	°C/°F	0.65	0.75	0.85	0.95	1.02	0.65	0.75	0.85	0.95	1.02
None	1st	0	293/1.0	316/600		182j'	182i"							
		2	293/1.0	316/600		150d								
				427/800		150h								
		4	293/1.0	149/300				124c 127c	124d 127f					
				316/600	182k	182j	182i 127b	182h 123a 125e 127a	122b					
				427/800		150g								
			1.2	316/600	156g	156d	156b	155e	155b					
			440/1.5	316/600	160j	160i	160f	160c	160a					
		6	293/1.0	149/300				124f 127d	124g 127e					
				316/600			128a 129a	123b 124c 126c	124b 126b	182d	182c	182b	182e	182f
			1.2	316/600							154e	154d	154a 154f	153c
		8	293/1.0	316/600		150e 182j"	182i 129b	128h	128i					
				427/800			129c 129d							

TABLE 4-8. (Concld.) FIRST-STAGE PARAMETERS

Additional Heat Removal	Stagnation Point	SW	Firing Rate kW/ 10^6 Btu/hr	Preheat °C/°F	Nozzle B&W Stoichiometric Ratio 0.65	B&W 0.75	B&W 0.85	B&W 0.95	B&W 1.02	Axial 0.65	Axial 0.75	Axial 0.85	Axial 0.95	Axial 1.02
None	2nd	0	293/1.0	316/600								181g"		
		4	293/1.0	316/600	164b	162d	162c 164a 164c 164u	162e 162i	164h					
				427/800			162f							
			440/1.5	316/600	164f	164e	164d	164g	164h					
				427/800		162h	162h							
		6	293/1.0	316/600						181f	181e	181d 181g	181c	181b
		8	293/1.0	316/600								181g'		
	3rd	4	293/1.0	149/300				132h	132e					
				316/600	183d	183c	131e 134b 138c 183b	131b 138b 183e	132d 138a 183f					
				427/800	183k	135g 137a 138e 183j	135f 183i	135e 183h						
			440/1.5	316/600		183n	183m							
		6	293/1.0	149/300				132g	132f					
				316/600			131d	131c	132c					
		8	293/1.0	316/600			134c							
29.3 kW (100,000 Btu/hr)	3rd	4	293/1.0	32/90			139c	139b	139a 139d 140b					
				316/600			140e		140d					

TABLE 4-9. SECOND-STAGE PARAMETERS

Overall Excess Air	First Stage Mixing	SR	Second-Stage Residence Time and Injection Method								
			Secondary Air Preheat 90°C - 200 C (200°F - 400 F)				Secondary Air Preheat 200°C - 316°C (400°F - 600°F				
			Fast		Slow		Fast		Slow		Down
			Short	Long	Short	Long	Short	Long	Short	Long	Short
5%	Sw = 4 Slow	1.02	146B	143c	145c	144b	146j				
		0.85	146d 144d' 144d"	143d	145f	144d	146h				
	Sw = 8 Intense	1.02									
		0.85									
15%	Sw = 4 Slow	1.02	122b	143a	145a	144a	146i		145h		146e
		0.85	127b	143e 149c 150a 165a	145d	144c	146g		145g		146f 146f'
	Sw = 8 Intense	1.02	128i	143b							
		0.85	129b	143f							
25%	Sw = 4 Slow	1.02	146a		145b						
		0.85	146c		145e						
	Sw = 8 Intense	1.02									
		0.85									

Common Conditions: Western Kentucky Coal
293 kW (1.0 x 10^6 Btu/hr)
316°C (600°F) secondary air preheat
12% primary stoichiometry
First staging position

TABLE 4-10. EFFECT OF COAL TYPE

Swirl/ Injector	Coal	Firing Rate kW (10^6 Btu/ hr)	Overall Excess Air																	
			5%						15%							25%				
			SR						SR							SR				
			0.65	0.75	0.85	0.95	1.02	1.05≠	0.55	0.65	0.75	0.85	0.95	1.02	1.15≠	0.75	0.85	0.95	1.02	1.25≠
Swirl = 2 Spreader	#1 Western Kentucky	293 (1.0)			143d 146d 146h		143c 143b 146j				149b 150b 150c 165b	149a 150a 143e 165a 146g	123a 125e 127a	143a 146i 122b			146c		146d	
		352 (1.2)				154b					154e	154d	154a 154f	153c				154c		
		440 (1.5)			160g	160d	160b		160k	160j	160i	160f	160c	160a		161b	160h	160e	161a	
	#2 Pittsburgh	293 (1.0)			157p	157m	157k					157o	157ℓ	157j	157a			157n		157c
		440 (1.5)			157h	157i		157e	158h	158f	158g	158e	157g		157d					157f
	#3 Montana	293 (1.0)			159p	159n	159ℓ	159j		159g	159f	159o	159m	159k	159h					159i
		440 (1.5)				159q		158j	159e	159d	159c		195b		158i					159a
Swirl = 6 Axial	#1 Western Kentucky	293 (1.0)				153a		152c			154g	148b	148a	148c	152a 148d 181a 182a			153b		152b
		352 (1.2)	156h	156e	155f	155d	155a			156g	156d	155e	155b		156f	156c	156a	155c		
		440 (1.5)				161i		161f	161n	161m	161ℓ	161r	161y	161g	161d			161j		161e
	#2 Pittsburgh	293 (1.0)			157r	158c	158a	157v			158d	157d	157t	158b	158b	157u				
	#3 Montana	293 (1.0)						159s	159x	159w	159v	159u	159t		159r					

≠ Not staged

Common Conditions: 316°C (600°F) secondary air preheat
149°C (300°F) second stage preheat
Fast second stage mixing

12% pri stoichiometry
@ 293 kW (1.0 x 10^6Btu/hr)
@ 440 kW (1.5 x 10^6Btu/hr)
First staging position
Long second stage residence time

TABLE 4-11. EFFECT OF RESIDENCE TIME

Firing Rate kW - Thermal (10^6 Btu/hr)	Staging Position	2nd Stage Residence Time	15% Overall Excess Air — Stoichiometric Ratio 0.55	0.65	0.75	0.85	0.95	1.02	1.15
293 (1.0)	3rd	Short		183d	183c	131e 134b 183b	131b 138b 183e	132d 138a 183f	135a
	2nd	Short		164b	162d	162c 164a 164c 164j	162e 164i	164h	162b
	1st	Long		182k	165b 149b 150c 182j	165a 149a 150a 143e 182i	123a 125e 127a 182h	143a	
		Short				127b	123a 123e 127a	122b	
440 (1.5)	3rd	Short			183n	183m			
	2nd	Long		164f	164e	164d	164g	164k	162a
	1st	Long	160k	160j	160i	160f	160c	160a	

Common Conditions
- Western Kentucky coal
- 316°C (600°F) secondary air preheat
- 149°C (300°F) second stage air preheat
- 12% pri stoich
- 15% excess air
- fast second stage mixing

TABLE 4-12. BIASED-FIRED TESTS

LOAD	SR_1^*	Configuration** 1	Configuration** 2	Configuration** 3
293 kW (1 x 10^6 Btu/hr)	0.85	165c	165d	165e
352 kW (1.2 x 10^6 Btu/hr)	0.85	156p	156q	
	0.85	156o		

*SR_1 = Stoichiometric ratio of fuel-rich burner

**Configuration description (also Figure 5-71)

1. Overfire air
2. Burners out of service, air only
3. Burner out of service, air only

TABLE 4-13. FOUR BURNERS ONLY

LOAD	SR 0.75	SR 0.85	SR 0.95	1.02
293 kW (1 x 10^6 Btu/hr)	165m	1651	165k	165j

TABLE 4-14. NATURAL GAS STAGING MATRIX

Stg. Pos	Excess Air/ Sampling	SR 0.65	SR 0.75	SR 0.85	SR 0.95	SR 1.15
1st	15	165r	165q 165t	164n 165rs	164m 165ϕ	164ℓ 165n
	Stg Air Off, Flue Sample	165r'	165t'	165s'		
2nd	25	166ℓ				
	15	166i	166f, m	166c,n	166b	166a
	10	166j	166g	166d		
	5	166k	166n	166e		
	Sample at End of 1st Stg.	166i' 166j' 166k',ℓ'	166f',m' 166g' 166n'	166c',n' 166d 166e'	166b'	166a'
	Stg. Air Off Flue Sample	166k"	166m"	166e"		
	Stg. Air Off Sample End of 1st Stg.		166m"			

Common Conditions

Preheat $316^{o}C$ ($600^{o}F$)
Firing Rate: 293 kW (1.0×10^{6} Btu/hr)
Burner: 5 IFRF
Noz/Sw: Radial/axial - Sw = 2

and injector type), first-stage residence time, and firing rate, as a function of the first-stage stoichiometry. These tests are with common second-stage parameters, such as excess air and residence time.

Table 4.9, Second-Stage Parameters

This matrix includes the second-stage air, preheat, mixing (such as slow, fast, and down mixing as defined in Section 5), residence time and the second-stage stoichiometry (excess air).

Table 4.10, Effect of Coal Type

This matrix shows the staging tests conducted on the various coal types as a function of several first- and second-stage parameters including injector type, first-stage stoichiometry, excess air, and firing rate.

Table 4.11, Effect of Residence Times

This matrix has been separated for interest to show the effects of both first- and second-stage residence times as a function of first-stage stoichiometry.

A number of additional special tests were made in the front-wall fired configuration and are shown in Tables 4-12 through 4-14. Each of these are described below.

Table 4.12, Biased-Fired Test

This matrix shows the effect at two loads of three biased-fired arrangements, including an off-stoichiometric arrangement and two burners-out-of-service arrangements.

Table 4.13, 4 Burners Only

A short series was conducted to determine the effect of staging on four burners compared to the five burners previously used.

Table 4.14, Natural Gas Staging

A set of tests was run on natural gas to determine the response of a clean fuel to staging. Tests were run at two staging positions over a range of first-stage stoichiometric and excess air levels to estimate the first-stage NO levels. Hot sampling of NO was made at the end of the first-stage and a flue sample was taken with the stage-air off. The hot samples were taken with a water cooled stainless steel probe.

A number of test points fell into the miscellaneous category, and are shown in Table 4-15. In many cases these points are at various primary percentages, and excess air levels combinations not covered in the previous matrices. Some of these were special points chosen to explore a particular effect and others are points that do not fit into any of the other matrices.

<u>Tangentially-Fired Matrices</u>

The main matrix for the tangentially-fired staging tests is shown in Table 4-16. This matrix is primarily concerned with first-stage parameters, since the tests in the front-wall-fired configuration showed very little effect of second-stage parameters. However, there were some tests made to examine the effect of excess air on CO and carbon loss in the stack. The principal parameters of interest were the first-stage residence time, the firing rate, the secondary air preheat, and the coal type. A few tests were also run at various primary air percentages.

Table 4-17 shows the matrix for a variety of alternate control techniques for the tangential configuration. These include biased-fired tests and flue gas recirculation tests. The effect of burner yaw was

TABLE 4-15. MISCELLANEOUS TEST CONDITIONS

Coal	Firing Rate kW(10^6 Btu/hr)	Stg. Pos.	NO_2	Preheat °C(°F)	SW	Prim.	EA	SR 0.75	SR 0.85	SR 0.95	SR 1.02	SR 1.05	
W. Ky	293 (1.0)	1st	B & W Spr.	316 (600)	6	12	25			125b,c	125a	131c	Higher Swirl; High Excess Air
↓	↓		↓	↓	↓	↓	20			125d			
					4	33	15				128b		Effect of Primary Stoichiometry & Increased Swirl
					8	↓					128c		
					4	25				128f	128e		
					8	↓	↓			128g	128d		
		3rd		149 (300)	4	12	25			132i			Effect of Temperature at High Excess Air and Max. Stg. Position
				316 (600)	4	12	25		134d	138b'			
				427 (800)	4	12	25		134f,g				
		1st		316 (600)	2	10	↓	150f					
	440 (1.5)	1st		↓	4	12	5	161c					
Pitts	293 (1.0)	1st	Ax	316 (600)	6	15	5			157g			Higher Primary
W. Ky	293 (1.0)	↓	B & W	427 (800)	4	12	25				135f'		Higher to Lower Excess Air, Etc.
↓	↓	↓	↓	316 (600)	8	12	5	143f'					
				↓	8	25	15		182ℓ"				
					4	↓	↓		182'				
					0				182				

TABLE 4-16. STAGED-AIR: TANGENTIAL MATRIX

Staging Position	Preheat* Temp	Firing Rate	Burner Yaw	Fuel** Type	Primary Stoich	Excess Air	SR 0.55	SR 0.65	SR 0.75	SR 0.85	SR 0.95	SR 1.02
1st	317°C (600°F)	293 kW (1.0 x 10^6 Btu/hr)	+6	C-1	15	15		173c	173b	173a	173j	173k
	317°C (600°F)	440 kW (1.5 x 10^6 Btu/hr)	+6	C-1	15	15	173g	173f	173c	173c	173h	173i
2nd	317°C (600°F)	293 kW (1.0 x 10^6 Btu/hr)	+6	C-1	15	5		169k	169f	169m		169q
						15		169i	169g	169e	169n	169o
						25		169j 179f	169h 174e 179e	169ℓ 179d	179c	169d 169p 179b
					20	15			168h			
				C-2	10	15				71m		
					15	5		171ℓ				171e
						15		171j	171i	171h	171g	171d
						20		171k				171f
					25	15				171h		
				C-3	15	5		171v				171z
						15		171t	171s	171r	171w	171x 171dd
						25		171u				171y

*The range for the temperatures are as follows: 316°C: 288 - 316°C (600°F: 550 - 600°F)
37.8°C: 27 - 47°C (100°F: 81 - 117°F)

**C-1 = Western Kentucky Coal
C-2 = Pittsburgh #8 Coal
C-3 = Montana Coal

TABLE 4-16. (Concld.) STAGED-AIR: TANGENTIAL MATRIX

Staging Position	Preheat* Temp	Firing Rate	Burner Yaw	Fuel** Type	Primary Stoich	Excess Air	SR					
							0.55	0.65	0.75	0.85	0.95	1.02
2nd	317°C (600°F)	440 kW (1.5 x 10^6 Btu/hr)	+6	C-1	15	5		170j				170e
						15	170m	170k	170i	170h	170f	170d
						25		170ℓ				170g
				C-2	15	5		170u				170z
						15	170x	170v	170t	170s	170r	170y
						25		170w				170g
				C-3	15	5		171kk				171ee
						15	170ℓℓ	171iii	171hh	171gg 171nn	171ff	
						25		171jj	171hh'	171nn'		171mm
	427°C (800°F)	293 kW (1.0 x 10^6 Btu/hr)	+6	C-1	15	15		179k	179j	179i	179h	179ℓ
	37.8°C (100°F)	293 kW (1.0 x 10^6 Btu/hr)	+6	C-1	15	15			177e	177d	177c	177b
3rd	317°C (600°F)	293 kW (1.0 x 10^6 Btu/hr)	+6	C-1	15	15		174f	174d	174b	174a	174c
						25			174e	174b'		
		440 kW (1.5 x 10^6 Btu/hr)	+6	C-1	15	15				174j		
	427°C (800°F)	293 kW (1.0 x 10^6 Btu/hr)	+6	C-1	15	15		174n	174m	174ℓ 175n	174o	
	37.8°C (100°F)	293 kW (1.0 x 10^6 Btu/hr)	+6	C-1	15	15			171e	176d	176c 171f	171h 176c

TABLE 4-17. ALTERNATE CONTROL TECHNIQUES: TANGENTIAL MATRIX

Configuration	Preheat* Temp °C	Firing Rate kW	Burner Yaw	Fuel** Type	Primary Stoich	Excess Air	Staging Position	SR					
								0.65	0.75	0.85	0.95	1.02	1.15
Bias-Fired													
Diag. corner, same side	317[†]	293[††]	+6	C-1	15	15	---			178e 178f			
Tiered	317	293	+6	C-1	15	15	---		178c	178b	178a		
Flue Gas Recirculation													
0%	317	293	+6	C-1	15	15	2nd			180e	180e		180a
10%	317	293	+6	C-1	15	15	2nd						180b
30%	317	293	+6	C-1	15	15	2nd			180d	180d		180c
Burner													
Yaw	317	293	0 +9	C-1 C-1	15 15	15 15	2nd 2nd			180h 180k	180h 180k		180i 180j
No annular air	317	293	+6	C-1	15	15	---						178g
Cold Walls***													
Natural gas	317	293	+6	NG	15	15	1st	172c	172c	172c	172b		172a
Coal	317	293	+6	C-1	15	15	1st	172i	172h	172g	172f	172e	

*The range for the temperatures are as follows: 317°C: 288-317°C
600°F: 550-700°F)

**C-1 = Western Kentucky Coal
NG = Natural Gas

***Very cold from H_2O leak in previous test

†317°C = 600°F

††293 kW = 1,000,000 Btu/hr

tested as well as the effect of shutting off the annular air. Additionally, the effect of very cold walls was observed in a staging mode for both natural gas and coal.

Finally, a number of points were fired substoichiometrically with no staging air. These points at two firing rates are listed in Table 4-18.

Horizontal Extension: Staging

Matrices were developed for the horizontal extension to investigate the effects on staging of the following:

- Residence time, at much shorter residence times than were possible in the main firebox
- Temperature and well mixed first stage, using baffles, air preheat and cooling
- Cooling just prior to the second stage addition
- Axisymetric flow field vs. the aerodynamics of the main firebox
- A single large burner vs. four small burners
- An axial injector vs. the Babcock and Wilcox-type spreader in this configuration
- Coal type
- SO_2 injection in the primary and secondary air under staged conditions.

Table 4-19 provides the matrix for all of these variables except the tests on Montana coal and SO_2 injection. These later tests are given in Table 4-20. The tests of SO_2 injection with the Montana coal were made to determine if the lower NO emissions at lower SRs experienced in previous testing with the Montana coal were due, at least in part, to the lower sulfur content of the fuel.

TABLE 4-18. TANGENTIAL: SUBSTOICHIOMETRIC FIRING MATRIX

	SR				
Firing Rate	0.55	0.65	0.75	0.85	0.95
293 kW (1.0×10^6 Btu/hr)		169k'		169ℓ'	169n'
440 kW (1.5×10^6 Btu/hr)	170m'	170ℓ'	170i'		

TABLE 4-19. STAGING: HORIZONTAL EXTENSION MATRIX

SR					0.55		0.65		0.75		0.85		0.95		1.02	
FIRING RATE					249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)
Fuel	Inj/Sw#	Burner	Config	Preheat Temp												
Western Kentucky Coal	SP 4	4 IFRF	10	32°C (90°F) 149°C (300°F) 317°C (600°F) 427°C (800°F)			186 g	187 c	188 b 188 h 186 f 186 h 187 g	188 d 188 f 187 b 187 e	186 e	187 a	186 i	186 o	186 j	186 n
			7	317°C (600°F)			189 f 194 i	189 o	189 e 194 h	189 p	189 d 190 l 194 g	190 a 189 q	189 c 194 f	190 b		
		4 IFRF w/cooling	7	317°C (600°F)			189	189 n	189 h	189 m	189 i	189 l	189 j	189 k		
		4 IFRF	4	317°C (600°F) 427°C (800°F)	193 f	190 g	190 k 193 e	190 f	190 j 193 d	190 c	190 i 193 c	190 d	190 h	190 e		
		4 IFRF w/cooling	4	317°C (600°F)					193 b		193 a					
		4 IFRF	6	317°C (600°F)		191 i	191 d	191 h	191 c	191 g	191 b	191 f	191 a	191 e		
			8	317°C (600°F)		192 j	192 d	192 i	192 c	192 h	192 b	192 g	192 a	192 f	192 e	
			5 w/o B	317°C (600°F)	194 e		194 d		194 c		194 b		194 a			
			5	317°C (600°F)		195 i	195 a	195 h	195 b	195 g	195 c	195 f	195 d	195 e		
Western Kentucky Coal	AX 6	4 IFRF	4	317°C (600°F)			193 k		193 j		193 i		193 h			
	SP 4	Single Lg IFRF w/4" Sleeve	4	317°C (600°F)	207 n	207 w	207 o	207 v	207 p	207 u	207 q	207 t	207 r	207 s		
			3	317°C (600°F)	208 e	208 j	208 d	208 i	208 c	208 h	208 b	208 g	208 a	208 f		
	SP2/SP6		1	317°C (600°F)			203 k	203 e	203 j	206 d	203 l	206 c	203 m	206 a 206 b		
	SP 4	Lg IFRF No Sleeve	1	317°C (600°F)					204 g				[illegible]			

TABLE 4-20. STAGING: HORIZONTAL EXTENSION MATRIX

				SR	0.55		0.65		0.75		0.85		0.95		1.02	
				FIRING RATE	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)	249 kW (0.85 x 10^6 Btu/hr)	381 kW (1.3 x 10^6 Btu/hr)
Fuel	Spreader	Burner	Config	Preheat Temp												
Montana Coal	Sp-4	Single lg IFRF w/4" sleeve	4	317°C (600°F)	207m		207i		207e		207e		207c			
			1	317°C (600°F)					206t	206y	206y	206p	206x	206n	206z	206l
Montana Coal w/SO_2 in Sec.	Sp-4	Single lg IFRF w/4" sleeve	1	317°C (600°F)					206u	206s	206w	206q	206y	206ϕ	206aa	206m
Montana Coal w/SO_2 in Prim.	Sp-4	Single lg IFRF w/4" sleeve	4	317°C (600°F)			207j 207l*		207h		207f		207d			
Montana Coal w SO_2 in Sec.	Sp-4	Single lg IFRF w/4" sleeve	4	317°C (600°F)			207k									

*High SO_2 Inj Rate

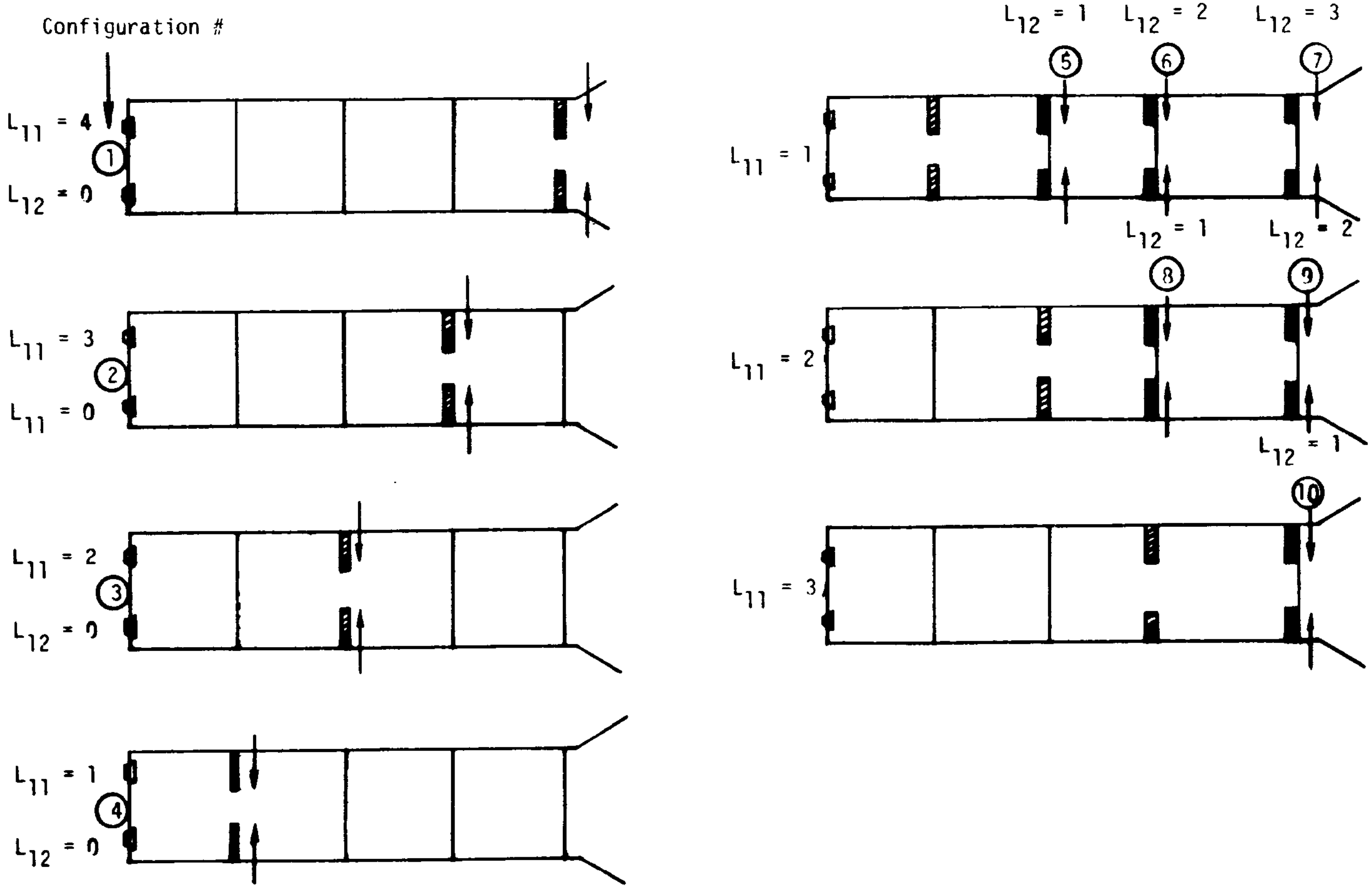

Figure 4-2. Horizontal extension test configurations.

TABLE 4-21. HOT SAMPLING TESTS

Staging Conf.	Burner Conf.	Test #	Firing Rate	Preheat (°C)	SR	Sample Locations*
H-4	B&W SPR	193b	249 kW (.85 Btu/hr.)	37.8°C (100°F)	0.75	2-0, 2-17.8(7)
H-4	B&W SPR	193a	249 kW x 10^6 (.85 Btu/hr.)	37.8°C (100°F)	0.85	2-0, 2-17.8(7)
H-4	B&W SPR	193i	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.85	2-0, 2-17.8(7)
H-4	B&W SPR	193c	249 kW x 10^6 (.85 Btu/hr.)	427°C (800°F)	0.85	2-0, 2-17.8(7)
H-4	B&W SPR	193d	249 kW x 10^6 (.85 Btu/hr.)	427°C (800°F)	0.75	2-0, 2-8.9(3.5), 2-17.8(7), 2-25.4(10)
H-4	B&W SPR	193e	249 kW x 10^6 (.85 Btu/hr.)	427°C (800°F)	0.65	2-0
H-4	B&W SPR	193f	249 kW x 10^6 (.85 Btu/hr.)	427°C (800°F)	0.55	2-0, 2-8.9(3.5), 2-17.8(7), 2-25.4(10)
H-4	Ax. Inj	193h	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.95	2-0, 2-8.9(3.5), 2-17.8(7), 2-25.4(10)
H-7	B&W SPR	194f	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.95	2-0, 2-8.9(3.5), 2-17.8(7), 4-0, 4-17.8(7), 4-25.4(10), 6-0, 6-8.9(3.5), 6-17.8(7), 6-25.4(10), 6-17.8(7)
H-7	B&W SPR	194g	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.85	2-0, 2-17.8(7), 4-0, 4-17.8(7), 6-0, 6-17.8(7), 8-17.8(7)
H-7	B&W SPR	190t	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.85	3-0
H-7	B&W SPR	194h	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.75	2-0, 2-8.9(3.5), 2-17.8(7), 2-25.4(10), 4-0, 4-17.8(7), 8-17.8(7)
H-7	B&W SPR	189e	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.75	3-0, 4-0, 6-0
H-7	B&W SPR	194i	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.65	2-0, 2-17.8(7), 8-17.8(7)
H-7	B&W SPR	189f	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.65	3-0, 6-0
H-10	B&W SPR	186j	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	1.02	4-0
H-10	B&W SPR	186i	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.95	4-0
H-10	B&W SPR	186e	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.85	4-0, 6-0
H-10	B&W SPR	186h	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.75	4-0, 6-0
H-10	B&W SPR	186g	249 kW x 10^6 (.85 Btu/hr.)	317°C (600°F)	0.65	4-0, 6-0
H-10	B&W SPR	187a	381 kW x 10^6 (1.3 Btu/hr.)	317°C (600°F)	0.85	4-0, 6-0
H-10	B&W SPR	187b	381 kW x 10^6 (1.3 Btu/hr.)	317°C (600°F)	0.75	4-0, 6-0
H-10	B&W SPR	187c	381 kW x 10^6 (1.3 Btu/hr.)	317°C (600°F)	0.65	4-0, 6-0

*The first number indicates the sample port # as illustrated in Figure 4-3; The second number indicates in centimeters (inches) the distance from the centerline of the furnace towards the wall. Therefore, 3-25.4(10) would indicate sample 3,254. cm (10") from the centerline of the furnace.

The description of the various configuration numbers listed on these matrices is illustrated in Figure 4-2.

For the horizontal extension tests, a hot sampling quench probe for NO was designed and fabricated. This probe was used to obtain information on the NO levels in the first stage. Table 4-21 summarizes the conditions at which these samples were taken, using the same configuration number as referred to earlier. The code for the sample locations is described on the table and the sample position may be found in Figure 4.3.

This section has summarized the test matrices. If additional correlations other than those given in Section 5 are required, refer to the matrices to find the specific condition and test number. The emission levels for each of these tests are then given in the appendix under the Data Summary Tables. In all approximately 766 test points were completed in the Phase II program.

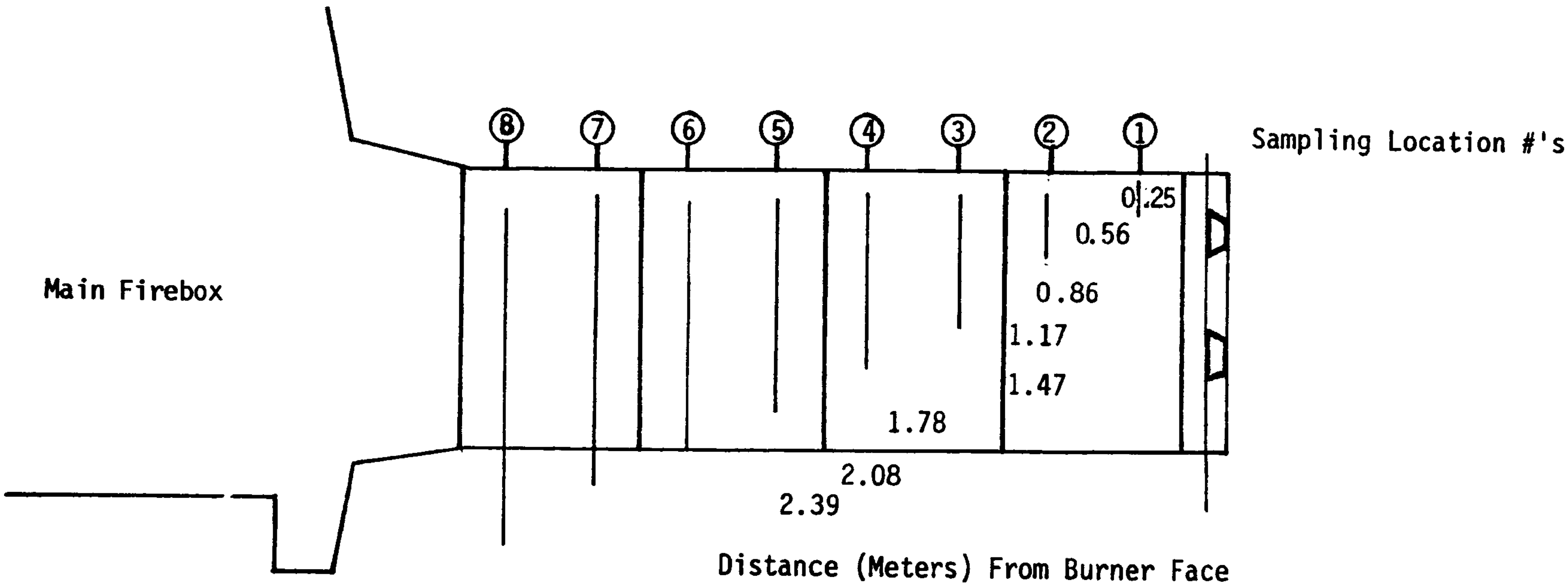

Figure 4-3. Horizontal extension sampling locations.

REFERENCES

4-1 Turner, D. W., Andrews, R. L., and Siegmund, C. W., "Influence of Combustion Modification and Fuel Nitrogen Content on Nitrogen Oxides Emissions from Fuel Oil Combustion," in Air Pollution and Its Control, R. W. Coughlin, et al, ed., American Institute of Chemical Engineers, Vol. 68, 1972.

4-2 Martin, G., Berkau, E. E., "Evaluation of Various Combustion Modification Techniques for Control of Thermal and Fuel-Related Nitrogen Oxide Emissions," presented at 14th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, 1973.

SECTION 5

TEST RESULTS

The results and conclusions from the baseline and control technology tests are presented in this section. Following a brief description of the terminology to be used (Section 5.1), the results of the experimental program are presented according to baseline tests (Section 5.2) and the control technology tests (Section 5.3). The baseline results are subdivided into effects of stoichiometry or excess air, temperature, mixing, load and coal composition on NO. The control technology tests are given for first and second-stage parameters and coal composition. Miscellaneous results on flue gas recirculation, biased firing, and staged combustion with natural gas are also presented.

Within each of the first- and second-stage parameter sections, stoichiometry, residence time, mixing, and temperature are addressed. Baseline and control technology results are presented for the front-wall fired, tangentially-fired, and horizontal extension configurations.

5.1 DEFINITION OF TERMS

The most important terms which need to be defined are:

- Primary Air - Air used to convey the coal to the burner, expressed as percent of total at 15 percent excess air, $\dot{m}_{pr}$
- Secondary Air - Air introduced through the burners into the first stage exclusive of the primary air, $\dot{m}_{sec}$

- First-Stage Air - Secondary + primary air, $\dot{m}_{1st}$
- Stage-Air - Air introduced into the second stage, $\dot{m}_{st}$
- Total Air - Primary + secondary + stage, $\dot{m}_t$
- Stoichiometric Ratio (SR) - $\dfrac{\text{First Stage Air}}{\text{Stoichiometric Air}} = SR = \dfrac{\dot{m}_{1st}}{\dot{m}_s}$
- Residence Time (RT) - Mean volumetric residence time of the mass flow using a measured temperature to calculate an average density

% Flue Gas Recirculation (% FGR) - Flue gas is drawn off downstream of baghouse and reintroduced with the secondary air. The definition is

$$\% \text{ FGR} = \frac{\dot{m}_{fgr}}{\dot{m}_{sec} + \dot{m}_{pri} + \dot{m}_{st} + \dot{m}_{fgr}}$$

5.2 BASELINE TESTING

The first series of combustion tests were designed to determine the baseline or uncontrolled NO emissions for the front-wall-fired (FWF) and tangentially-fired configurations. This section presents the test data from which the baseline operating parameters were developed. These data are presented in parametric format rather than the chronological order in which the data were taken. The primary result of this test series was the development of a baseline curve of NO versus excess air for each configuration. These results simulate quite well full-scale NO_x emission trends and levels.

Following the presentation of the baseline curves, the effect of temperature, mixing, coal composition and load on NO_x emissions will be discussed.

5.2.1. Excess Air

The baseline NO data as a function of excess air for the FWF and tangentially-fired configurations are shown in Figure 5-1*. Also plotted on this curve are a number of field and pilot-scale results (References 5-1 through 5-5). As can be seen in Figure 5-1, both the emission levels and trends measured in this study are representative of full-scale data. The nominal NO level at 15% excess air is 875 ppm for the FWF configuration and 430 ppm for the tangential configuration. The tangential plot also shows the baseline curve for the axial injectors in the FWF mode. It should be noted that the axial injector for slow-mix data is closer to the tangential results than the FWF results using the spreader. The correspondence of these results is probably due to the near burner slow-mix nature of these two configurations.

The base conditions for each of these configurations are listed on the figure. These conditions were established by a number of preliminary combustion tests. In general the burner parameters simulated were kept close to conventional utility practice. These parameters include the secondary air preheat, secondary air axial velocity, primary air percentage, the coal nozzle design, the secondary air swirl, heat release per unit volume and residence time to the convective section. The primary air percentage for the FWF configuration was a little lower than conventional (12% of total air at 15% excess air) because of a more effective spreader in the small scale. A summary of these parameters is given in Table 5-1 for the FWF and tangentially fired configurations.

One of the most important tests was to determine if wall cooling would be required to simulate full-scale test results. As will be demonstrated

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*All emission data are corrected to 0% O_2, and NO rather than NO_x is given in all cases. Periodically the total NO_x levels were checked but were never found to be significantly different from the NO levels.

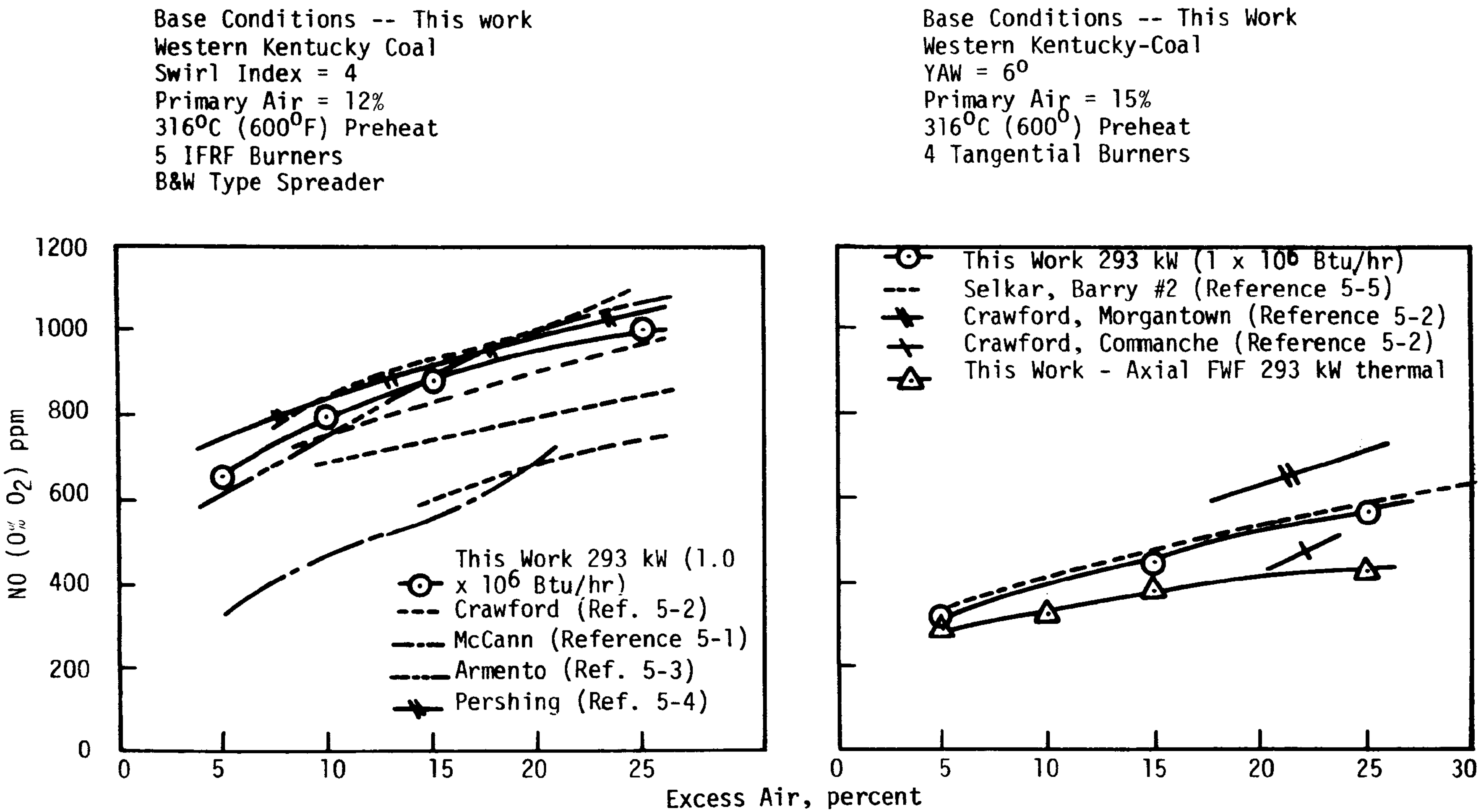


Figure 5-1. Front-wall and tangentially-fired baseline NO emissions

TABLE 5-1. BASELINE BURNER TEST CONDITIONS

Firing Rate: 293 kW (1.0 x 10^6 Btu/hr) -- 15 Percent Excess Air

Front Wall Fired		Tangentially Fired	
Secondary Air Preheat:	316°C	Secondary Air Preheat:	316°C
Secondary Air Velocity:	10.8 m/sec	Secondary Air Velocity:	20.3 m/sec
Primary Air:[1]	12%	Primary Air:	15%
Coal Nozzle Design:	B & W Type Spreader	Annular Air Velocity:	20.3 m/sec
Secondary Air Swirl:	Swirl Block Setting[2] = 4	Yaw Angle:	6° From Diagonal
Heat Release Per Unit Volume:	180.5 kW/m^3		
Residence Time to Convective Section	2.84 sec		

1. Primary Percentage is percent of total combustion air at 15% excess air.
2. The swirl block setting is not a "Swirl Number." It is merely an indication on the burner. A swirl block setting of zero achieves pure axial flow of the secondary air with no tangential component. A setting of 8 yields a tangential component from the swirl blocks.

in the next section, wall cooling was not required to model full-scale results for this pilot-scale facility. Therefore, the data in Figure 5-1 and all other data not specifically denoted as cool wall were taken with hot refractory walls.

Baseline tests were also run in a later series in the horizontal extension (HE) configuration. These results are compared to the firebox data in Figure 5-2. For the Western Kentucky Coal and a range of excess air levels the HE baseline results follow the same trend and are at approximately the same level as the FWF results. These results were obtained with four small IFRF burners as opposed to five used in the main firebox tests. These four burners were fired at a load of 249 kW (0.85 x 10^6 Btu hr) compared to 293 kW (1.0 x 10^6 Btu hr) in the firebox tests. This heat release rate maintained the same heat release per unit volume in the HE as in the main firebox. The four burners and lower firing rate also maintained nearly constant burner aerodynamics between the HE and FWF configurations.

It can be seen that the HE results are slightly higher than the FWF results. This is possibly due to two factors. First, the burner velocities were slightly higher for the HE configuration resulting in increased mixing. Secondly the proximity of the refractory walls may have resulted in both an increased local temperature near the burner and a change in the internal flue gas recirculation. However, the changes in NO levels are relatively minor and indicate that, at excess air conditions, FWF NO levels are not sensitive to the combustion chamber configuration.

5.2.2 Effect of Temperature

Concern was expressed early in the program that the pilot-scale facility might not simulate conventional water-wall boilers since hot

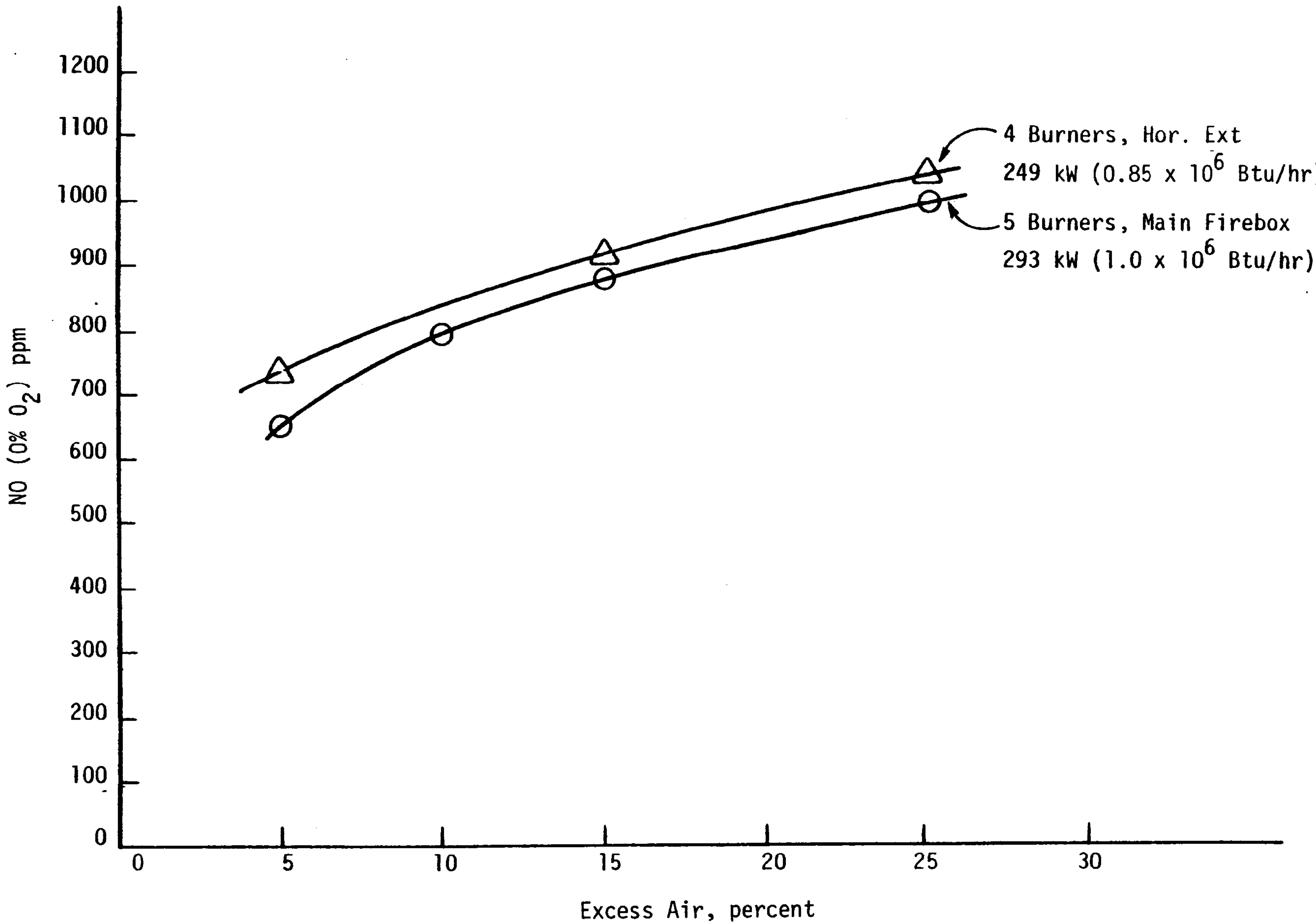


Figure 5-2. Horizontal extension and firebox front-wall-fired results.

refractory walls were used in this pilot-scale facility. It was believed that the difference in wall cooling would affect the early temperature history and thereby the NO production (both through aerodynamics and the absolute temperature history). Although other investigators (Reference 5-4) have shown that temperature does not significantly influence NO levels when firing coal, a series of tests were run to determine the effect of wall temperature on the pilot-scale facility baseline NO levels.

The measured temperatures at the inlet to the convective section with the refractory walls and a firing rate of 293 kW (1.0×10^6 Btu/hr) were on the order of 1149°C to 1204°C (2100°F to 2200°F). This temperature corresponds roughly to utility practice and indicates that a heat loss characteristic of water tube boilers is being realized in the refractory walled firebox. This correspondence is possible because the heat loss per unit volume of the furnace is inversely proportional to the furnace volume characteristic dimension, L. Therefore the amount of active cooling required to achieve the same heat loss per unit of heat input for a small-scale furnace is much less than that for a large unit. Even though overall heat loss and exit temperature were well modeled with the refractory-lined walls, pilot scale facility tests were run to investigate the effect of water-walls and local wall temperature on NO levels. Tests were run on both natural gas and Western Kentucky coal to demonstrate the effect of wall cooling on NO, for fuels that produce only thermal NO and predominantly fuel NO respectively. Tests were run with and without a wall cooling surface which consisted of approximately 1.09m^2 (11.8ft^2) of water cooled tubing laid along the inside surface of the main firebox as shown in Figure 5-3. When the heat transfer surface is clean, this amounted to an additional heat loss from the furnace of

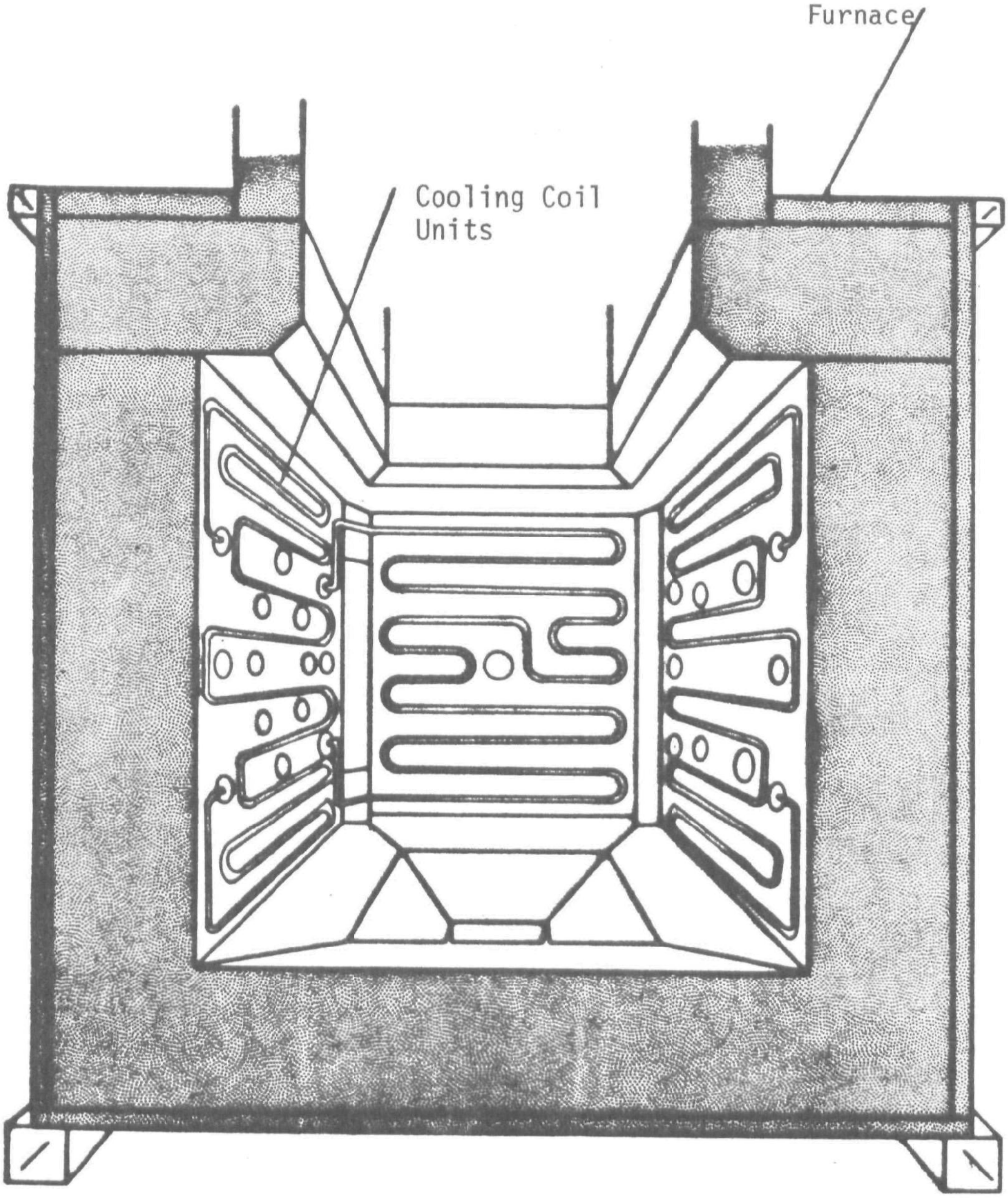


Figure 5-3. Wall cooling units.

approximately 87.9 kW (300,000 Btu/hr) in addition to the normal loss from the refractory walls of 44 kW (150,000 Btu/hr.)

Figure 5-4 shows the effect of these water-walls for the natural gas and pulverized coal flames. As expected, the percent effect on natural gas was much more dramatic than the effect on coal. For the pulverized coal flame the greatest decrease achieved by wall cooling was approximately 80 ppm out of 1100 ppm or a 7% decrease. The natural gas NO levels decreased by approximately 110 ppm when wall cooling was applied. This is about a 50% decrease at the 220 ppm level. These results confirm that the bulk of the baseline NO in a front-wall-fired pulverized coal flame is not strongly temperature sensitive.

Since water-wall cooling only impacted pulverized coal results to a minor extent and because it was desirable to avoid a variable heat absorption rate due to fouling and the necessity of water tube soot blowing, it was decided to conduct the bulk of the main firebox control technology tests without water walls. A few tests with additional heat extraction by cooled walls were run during the control technology test series to determine the effect of cooling under staged or fuel-rich conditions.

In addition to the wall cooling tests, a number of baseline tests were run at a variety of air preheats. Preheat not only affects the bulk flame temperature but also the early mixing due to changes in secondary air exit velocities as preheat temperature is varied. The effect of preheat for a variety of test conditions is show in Figure 5-5.

It is interesting to note that the slope of the data is nearly the same for the tangential, FWF, HE and both gas and coal fuels. Also the coal fired data from the University of Arizona (Reference 5-4) has a similar slope. Because fuels with no fuel-N and a great deal of fuel-N give similar

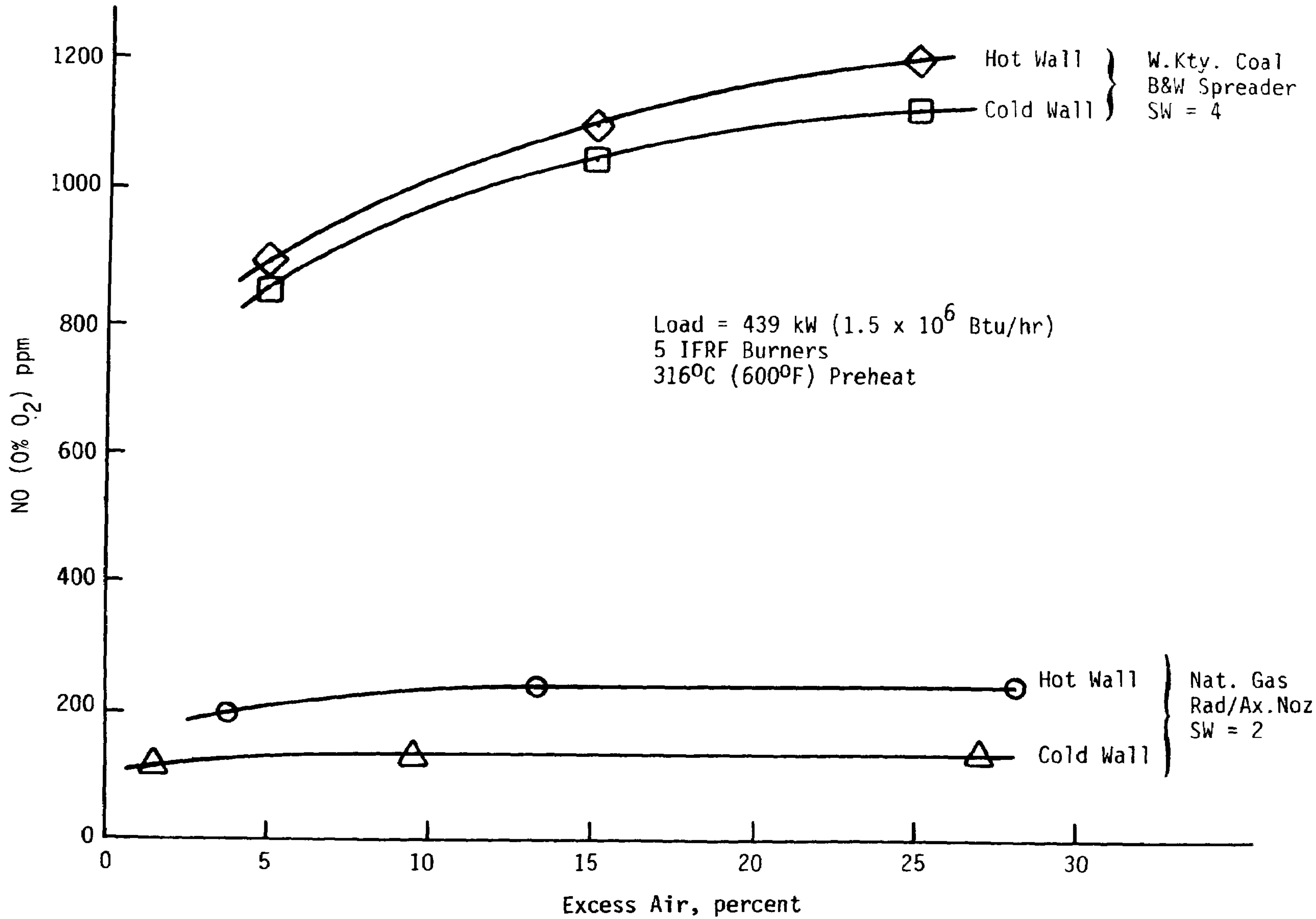


Figure 5-4. Effect of water-wall cooling (baseline).

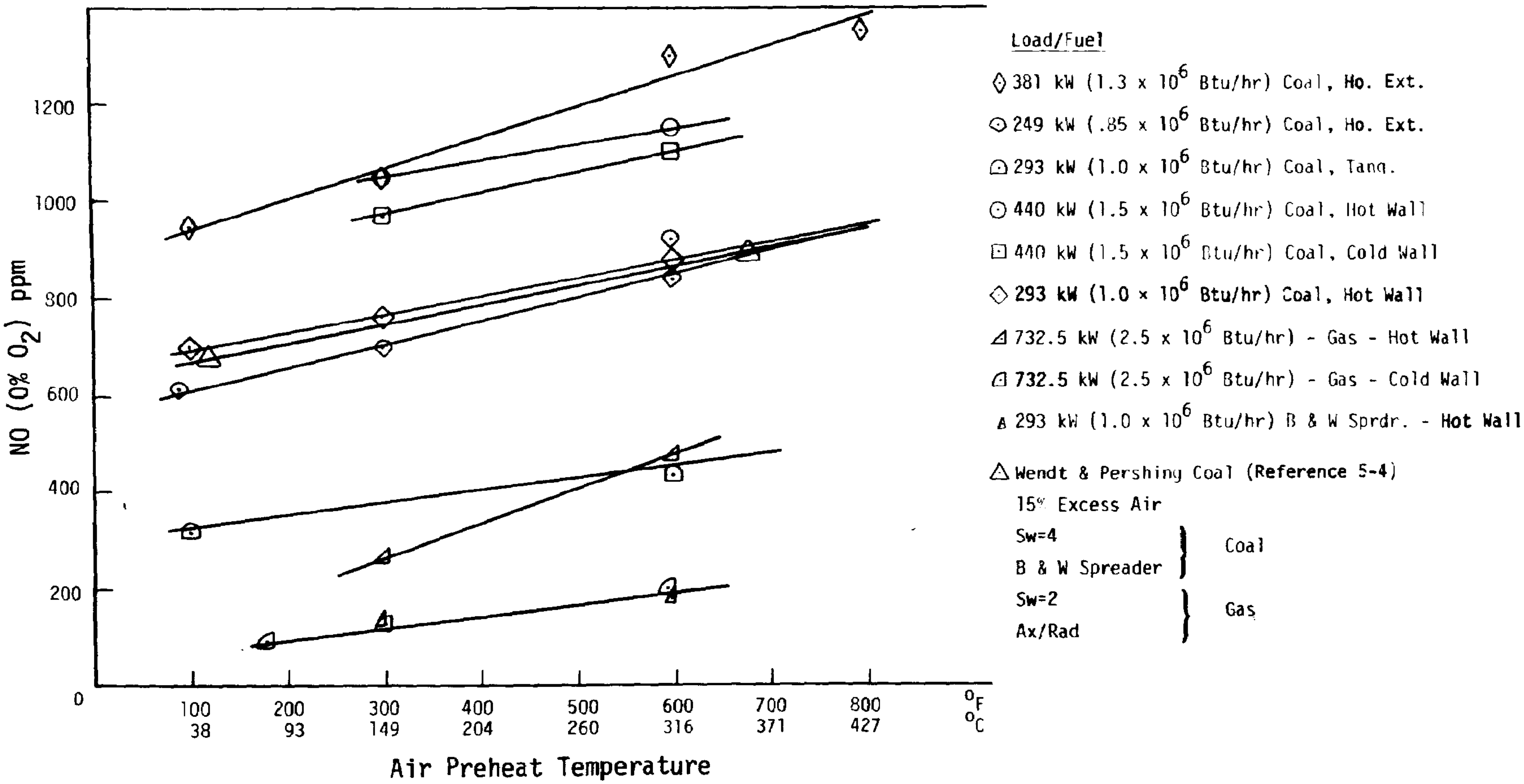


Figure 5-5. Effect of preheat (baseline).

increases with temperature, the increase in the NO levels is probably due to increases in the thermal NO fraction rather than the fuel-nitrogen-derived NO. It has been suggested by Pershing (Reference 5-4) that gas firing may roughly represent the thermal portion of the total NO emissions when fired at the same firing rate and in the same firebox configuration. This gas data will be used in a later section on coal composition to discuss fuel-nitrogen conversion rates.

Another demonstration of the effect of temperature on NO levels is given in Figure 5-6. This plot gives tangentially-fired NO emissions as a function of firebox exit plane temperature. Although the absolute exit temperature measurement is not precise (a bare Platinum/Platinum-Rhodium thermocouple was used) the plot clearly demonstrates the relationship with temperature. Note that the slope of the gas curve is parallel to the coal curve. This relationship again supports the concept that the temperature primarily affects the thermal NO fraction when firing coal.

5.2.3 Early Mixing Studies

Although the primary purpose of this work was to investigate staging as a NO_x control technique rather than burner parameters, a number of exploratory tests were conducted to establish representative burner settings for the baseline tests. Some of these exploratory tests involved investigation of burner early mixing parameters. Included in these FWF exploratory tests were the effects of primary air percentage, swirl, axial fuel tube position and injector design on stack NO levels. For the tangentially-fired test series, primary percentage, yaw and distribution of air among the various air registers were varied.

5.2.3.1 Front-Wall-Fired Burners

For the majority of FWF tests, five IFRF burners (described in

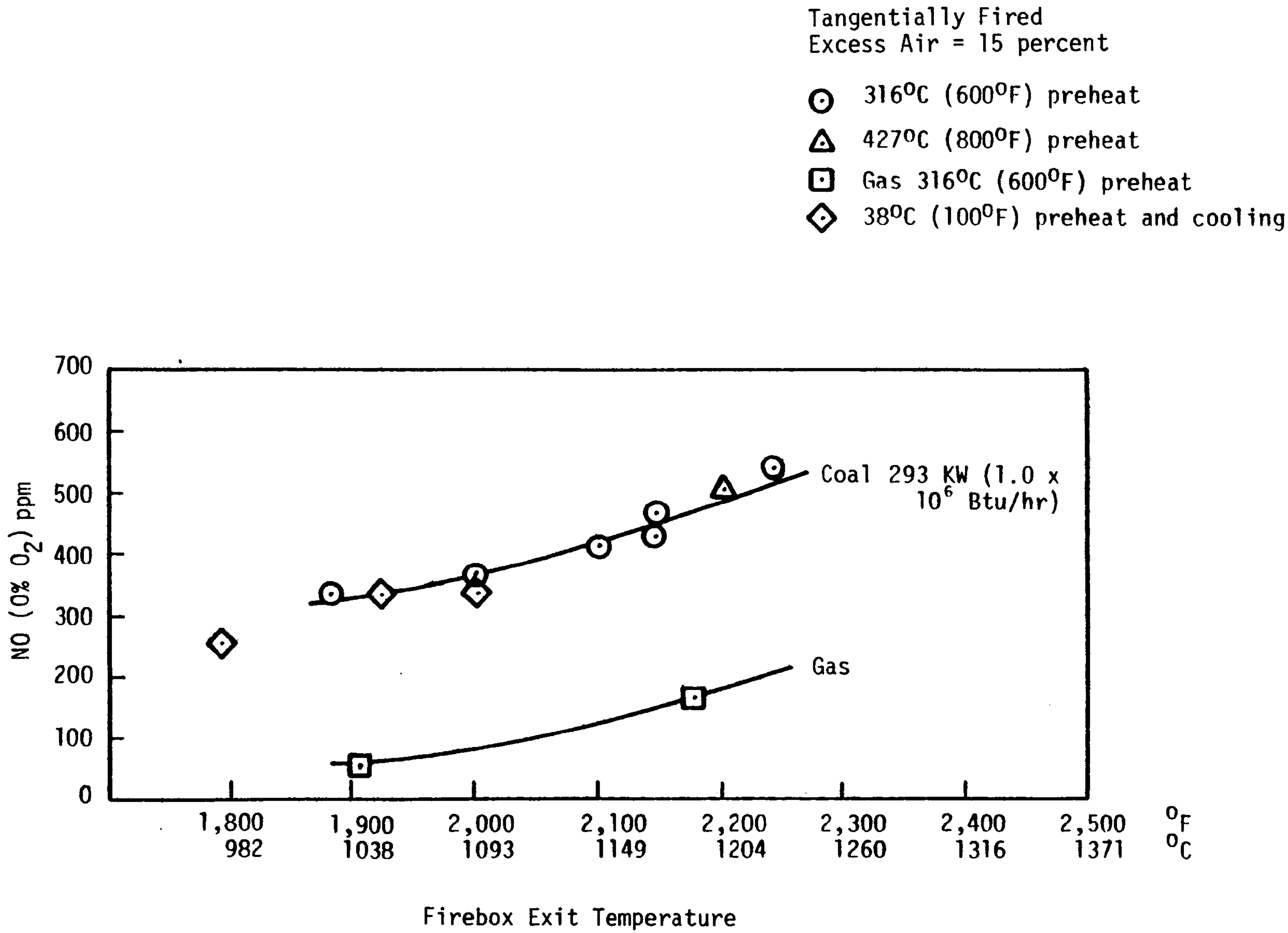


Figure 5-6. Effect of temperature (baseline).

Section 2.2) were used to simulate utility boiler results. These burners allow variation in the nozzle design, swirl of the secondary air, and the axial fuel tube position. In addition, the coal feed system allows for variation of the primary air flow rate. Test results for each of the above parameter variations are discussed below.

Swirl Setting

Tests were conducted over swirl settings from S = 2 to S = 8 (Note: these are the index numbers on the burner and do not correspond to a "Swirl Number." At S = 0 the air flow is totally axial whereas at a S = 8 the flow has the maximum tangential component). Figure 5-7 shows the effect of swirl on NO emissions at 15% excess air and a load of 440 kW (1.5 x 10^6 Btu/hr) for the Western Kentucky coal. A minimum in NO occurred at swirl setting of 4. Flame observations showed that as the swirl is increased above S = 4 the flame becomes more compact and intense. This is probably due to the increased fuel/air mixing rate giving a more intense flame which, for conventional burners, can yield high percent conversion of the fuel-nitrogen fraction to NO (Reference 5-4). As the swirl is decreased below a value of 4 the flame becomes lazier and less stable. It has been shown by others (Reference 5-6) that under these conditions the flame can be blown off the nozzle to the point where the coal and air are more thoroughly mixed prior to ignition. Very high NO levels can be achieved under these conditions. A swirl setting of S = 4 was chosen as the base condition because it gives a stable flame with NO levels representative of full-scale furnace results.

Axial Fuel Tube Position

The position of the fuel tube within the burner throat can change the fuel/air mixing patterns and thereby the NO emissions. An optimum position was sought such that the nozzle tip did not become too hot

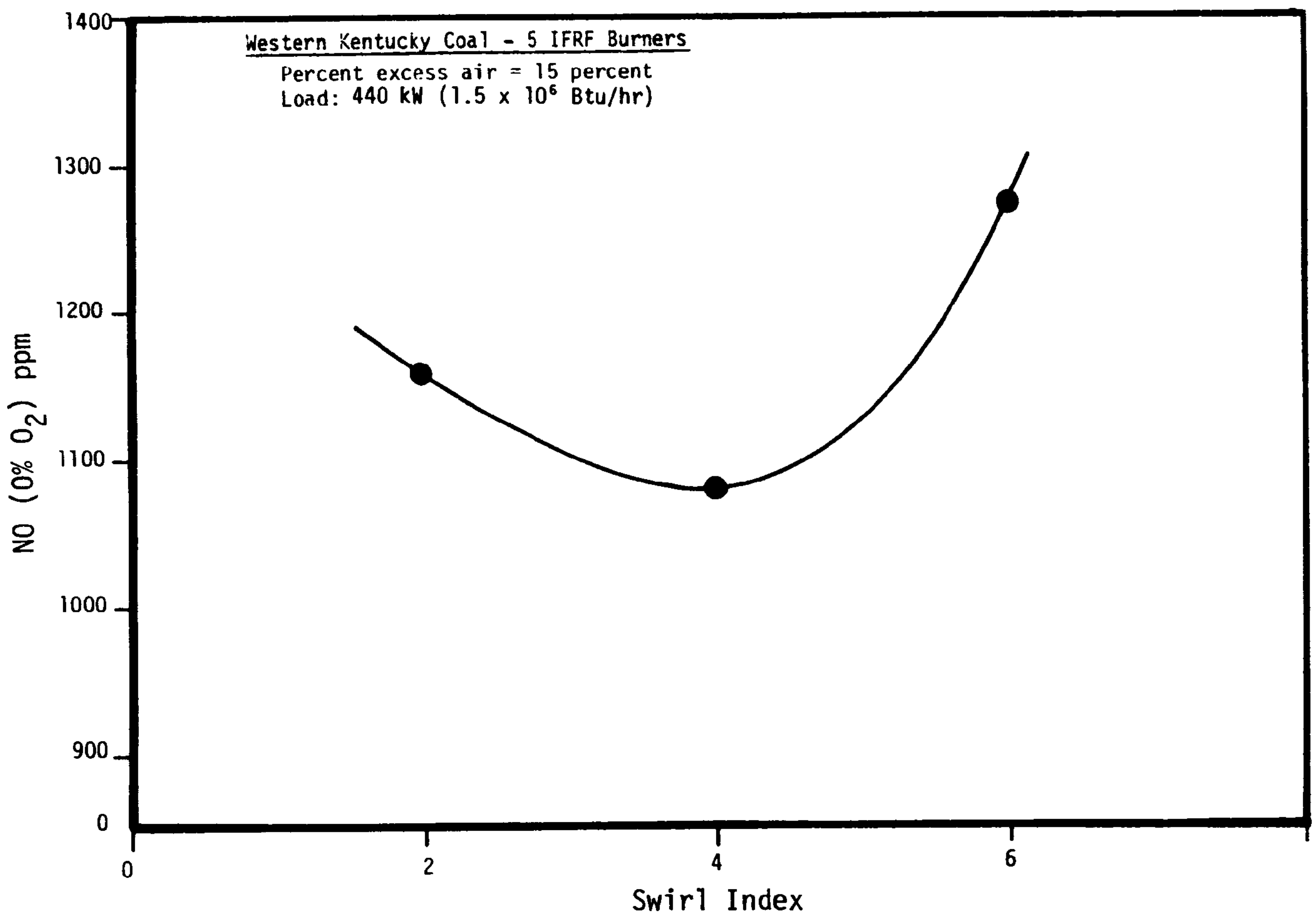


Figure 5-7. Effect of burner swirl.

and the coal would not impinge on the quarl. Figure 5-8 shows the relationship of stack NO to the position of the fuel tube in the burner throat. Again, the position which gave the minimum NO level was chosen as the base condition. Figure 5-9 shows the positioning of the fuel tube in the burner quarl at this optimum condition.

Primary Stoichimetry

Another parameter which has a strong effect on NO emissions is the primary stoichiometry. This is shown in Figure 5-10 where at the high stoichiometry condition the flame became unstable and lifted from the nozzle. This result is similar to that experienced by others (References 5-4 & 5-6). To avoid unstable flames and for minimum baseline NO levels, a primary stoichiometry of around 12% was chosen for most of the FWF test cases.

Injector Design

As was pointed out in Section 5.2.1 an axial injector was tested as well as the Babcock & Wilcox type coal spreader. The baseline data for these nozzles are given in Figure 5-1. The axial injector produced a long lazy flame which essentially delayed the mixing of the coal and air. A swirl setting of six was required to stabilize the flame with the axial injector. The delayed-mix axial flame produces considerably lower NO levels than the coal spreader flame. As indicated by others (Reference 5-7) the lower levels for the axial injector probably are due to the substantially greater extent of fuel-rich regions which occurs with this type of mixing. It is also interesting to note that the level and trend of the axial data are very similar to that of the tangentially-fired configuration. Low tangentially-fired system NO levels are believed to be a result of their slow-mix

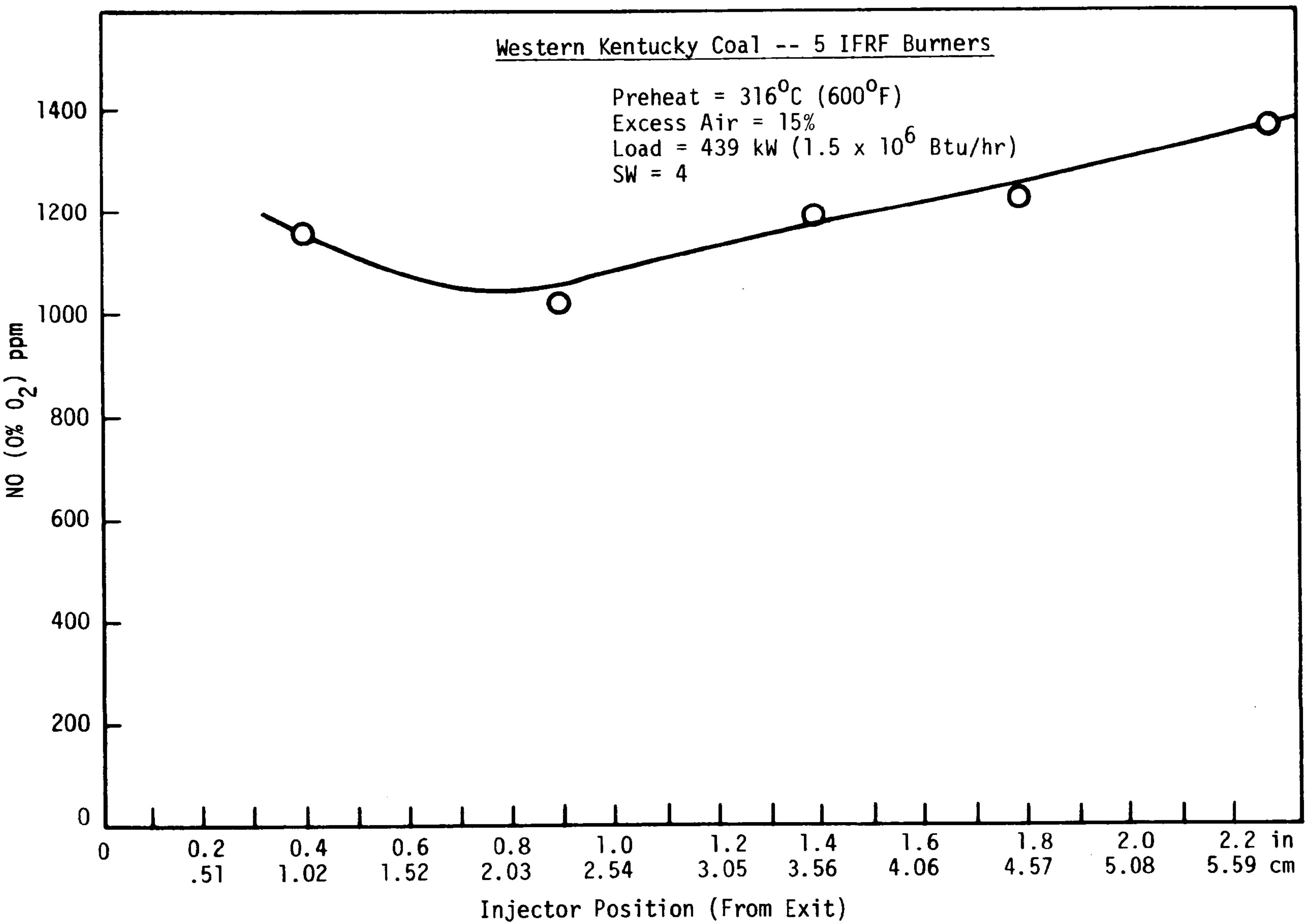


Figure 5-8. Effect of injector position.

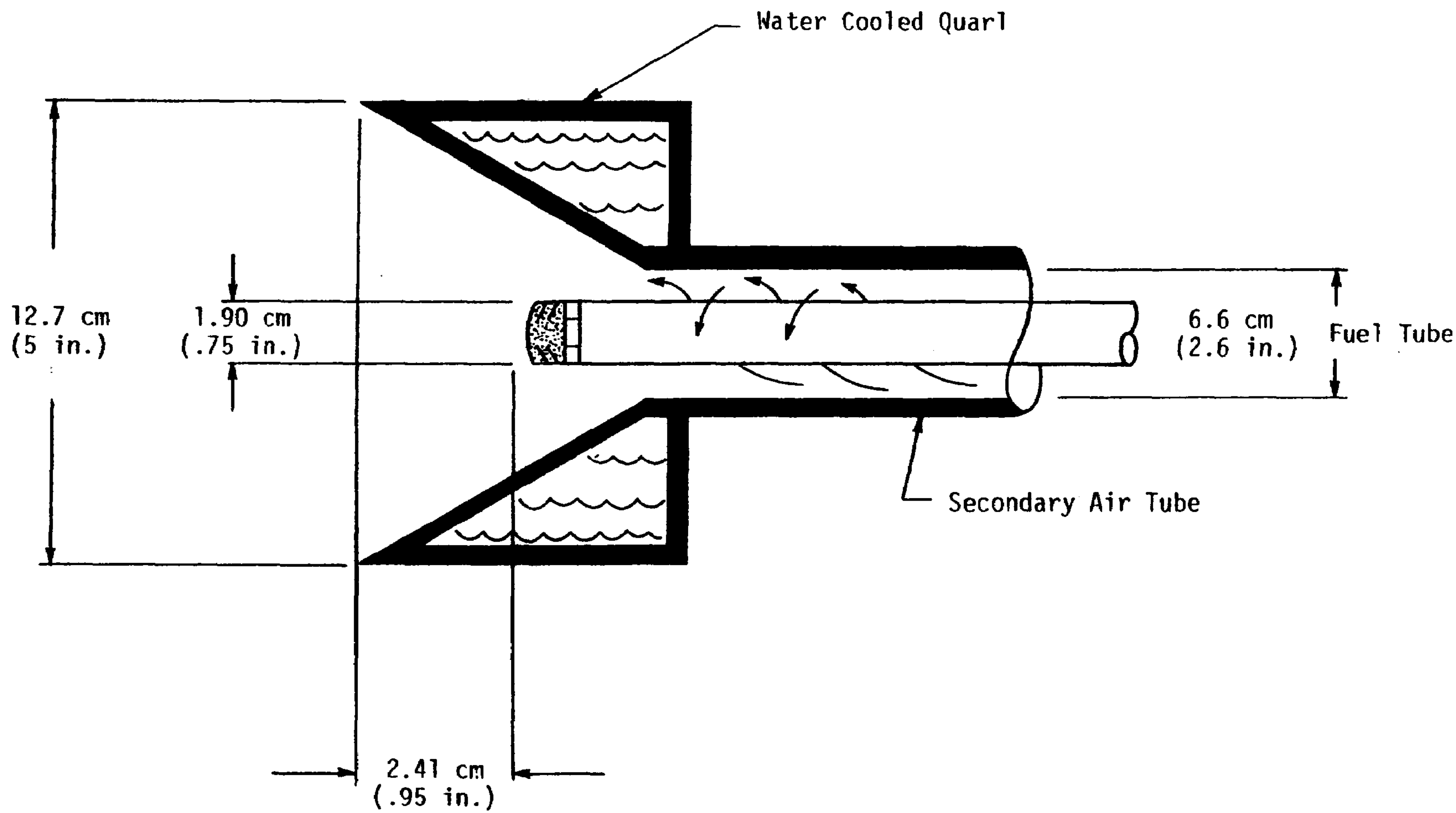


Figure 5-9. Location of fuel tube.

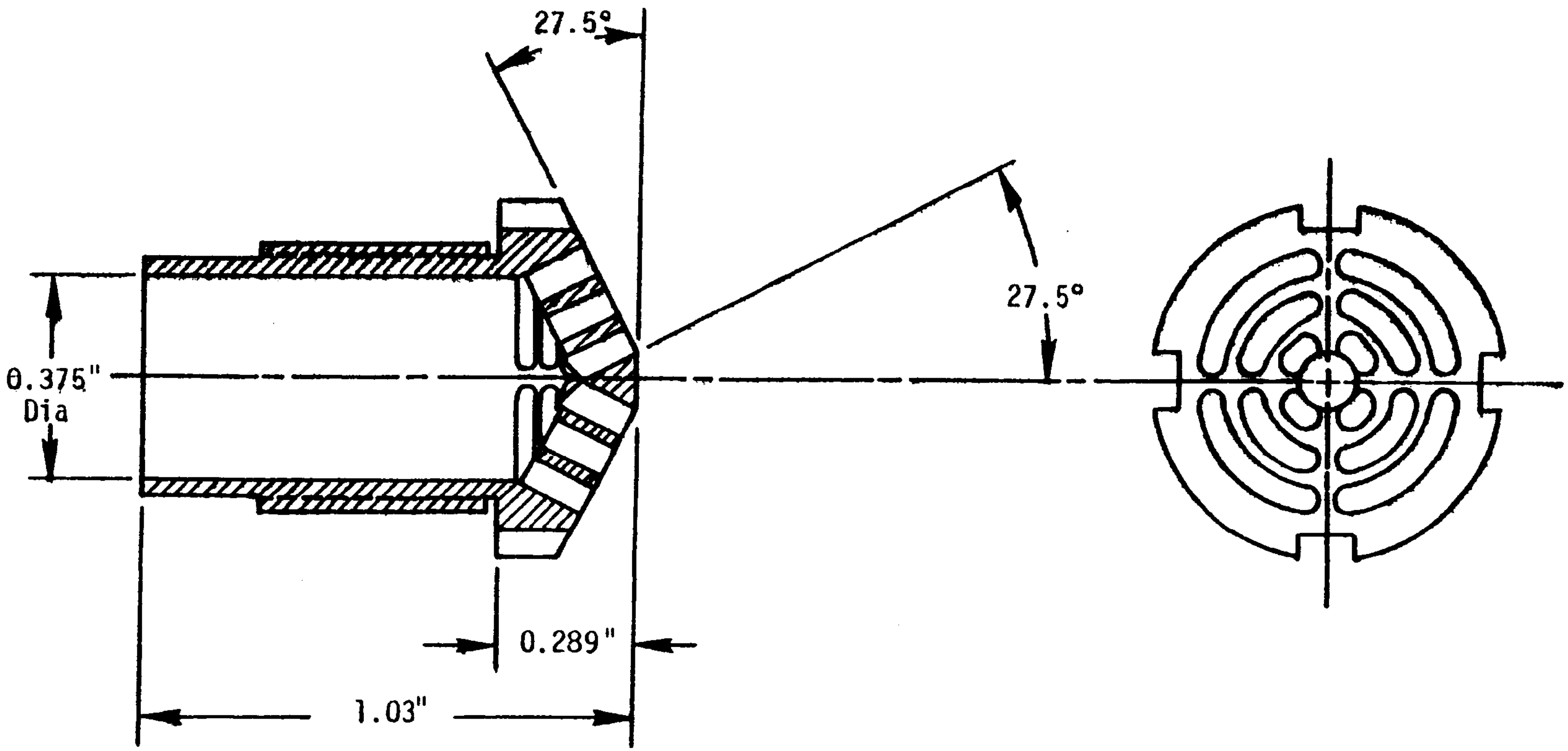


Figure 9a. B&W-type coal spreader.

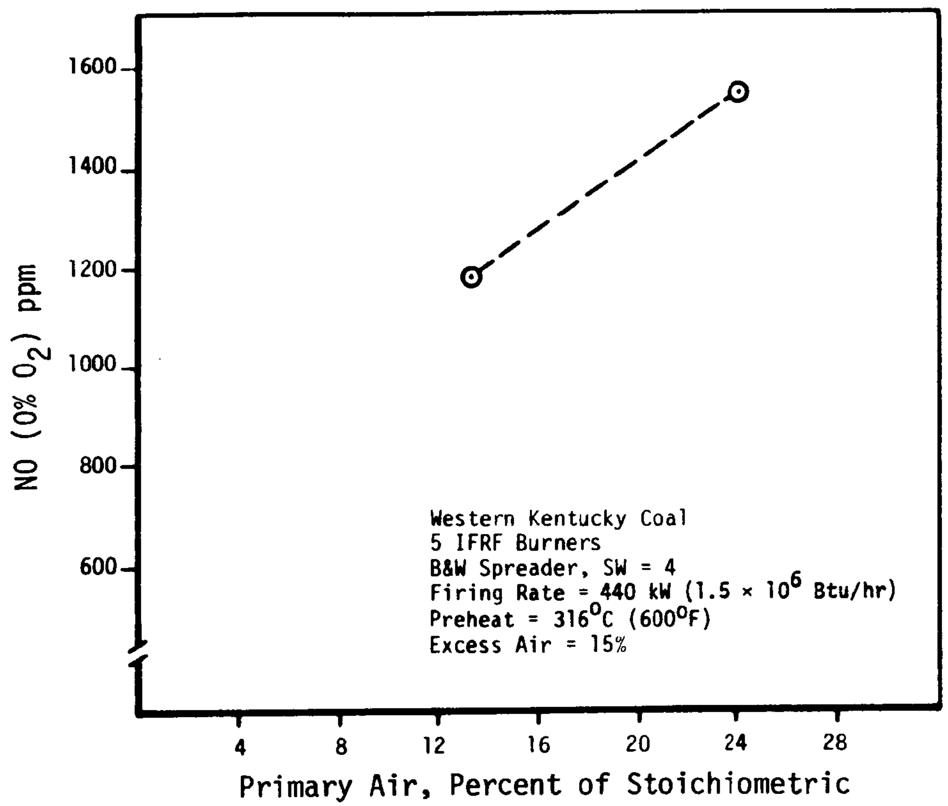


Figure 5-10. Effect of primary stoichiometry.

(Reference 5-8). The correspondence between axial injector and tangentially-fired data seems to confirm this conjecture.

5.2.3.2 Tangentially-Fired Burners

In the tangentially-fired mode the mixing parameters that were varied in the firebox included the primary air percentage, the yaw (or tangent circle diameter) and the distribution of the air between the various ports. These latter variations in air distribution will be described in the control technology section. The nominal distributions between the various air ports are listed in Table 5-2. The burners were designed such that the exit velocities of each of the streams was approximately 30.5m/sec (100 ft/sec) with 316^{o}C (600^{o}F) air preheat at a load of 440 kW (1.5 x 10^6 Btu/hr) and 15% excess air. These burner design variables fall within the typical ranges of full-scale equipment. The percent air distribution between ports was held constant during most of the tangential test program with the exception that the primary air flow rate was held constant so as to maintain the coal entrained in the primary air. The primary air effects and the yaw effects are discussed below.

Primary Air Percentage

Figure 5-11 shows the effect of the primary air percentage on the baseline NO_x emissions. As expected, the results were similar to the FWF data in that with increased primary percentage the NO levels increased. However, the NO did not increase as fast as the FWF burner results. The increase is most likely due to the greater availability of oxygen within the fuel-rich jet and possibly due to an increased mixing rate as a result of higher velocities. The rate of NO increase is not as great as FWF results probably because the difference in the annular and primary jet velocities

TABLE 5-2. TANGENTIAL AIR DISTRIBUTION

	%[1]
Secondary Air, Top	32
Primary Air	15
Annular	21
Secondary Air, Bottom	32
	100%

1. Percent at an overall Excess Air Level of 15%.

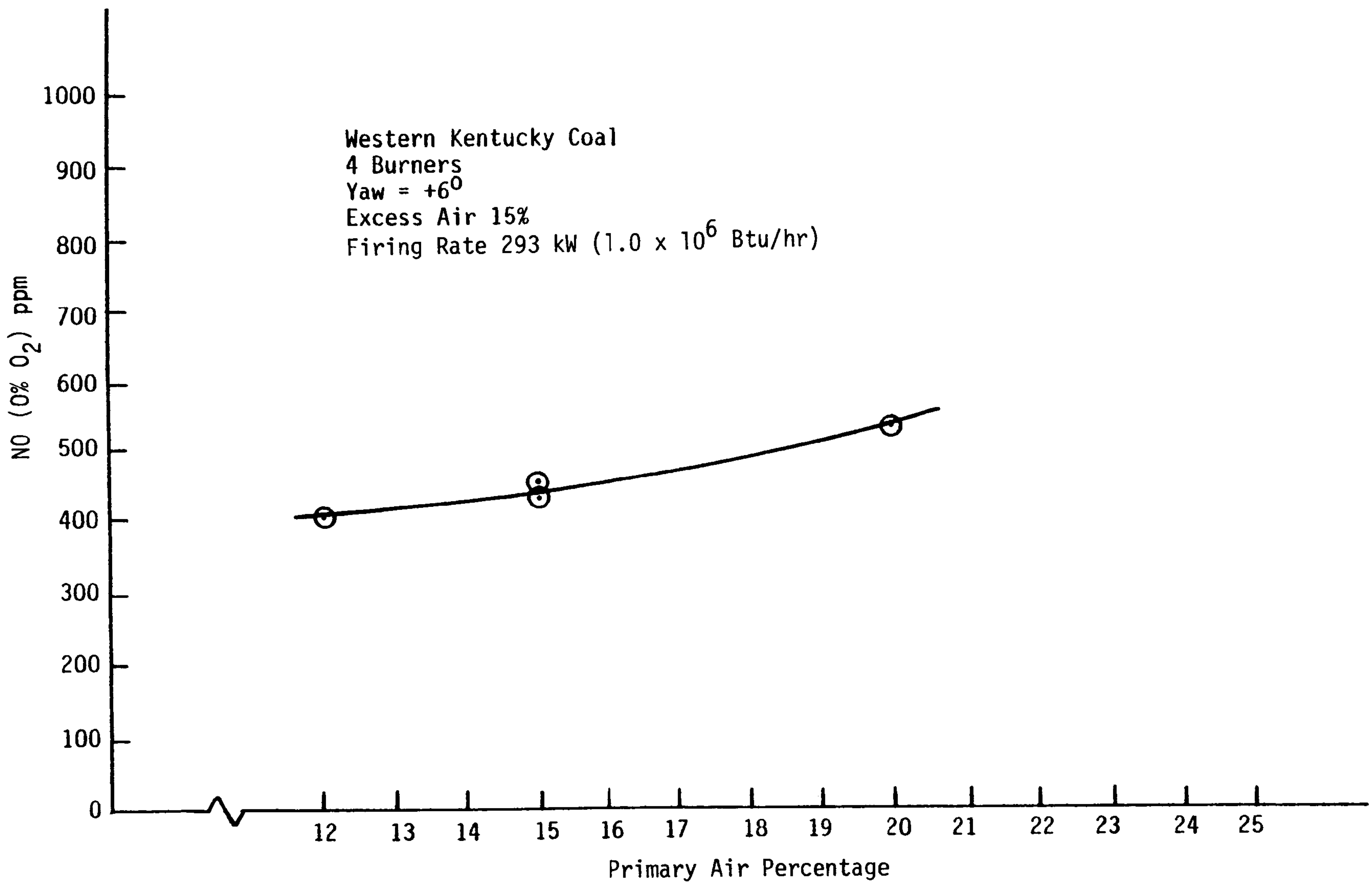


Figure 5-11. Effect of primary air percentage (tangentially fired).

is not as great as the swirling FWF burner velocities. Also "lifted flame" conditions which occurred with the FWF configuration did not occur to the same extent with the tangentially-fired tests.

At 293 kW load, 316^{o}C preheat and 15 percent primary and excess air, turning off the annular air flow and increasing secondary air flow a corresponding 33 percent resulted in a 19 percent reduction in NO_x. This drop, which is comparable to a primary air reduction of 6 percent, is probably the result of reduced oxygen availability in the fuel-rich jet.

Yaw

During the majority of the tests, the nominal yaw angle was set at 6^{o} off the firebox diagonal. This yaw setting is the same as in many full scale units. This angle was varied from 0^{o} to 9^{o} to determine if yaw angle had any effect on NO. At 0^{o} the flames are directly opposed and little vortex motion exists in the firebox. At 9^{o} the vortex motion within the firebox is substantial. The effect was negligible as seen in Table 5-3.

5.2.3.3 Horizontal Extension

Another example of the influence of mixing under baseline conditions is a comparison of the emissions of the four small burners to those from the single large IFRF burner fired in the horizontal extension configuration. Figure 5-12 compares the baseline NO data for the four small burners with the large burner data with and without the burner throat being sleeved. The sleeve reduced the diameter of the burner throat from the normal 15cm (5-7/8") down to 10cm (4"), and thereby increased the secondary air velocity.

As can be seen, the data from the four small burners falls between the large burner data with and without the sleeve. The burner velocities should be the same between the small and large burners without the sleeve. The lower NO data for the larger burner indicate the influence of the

TABLE 5-3. EFFECT OF YAW ANGLE

Yaw	NO (0% O_2) PPM
0	512
6	550
9	551

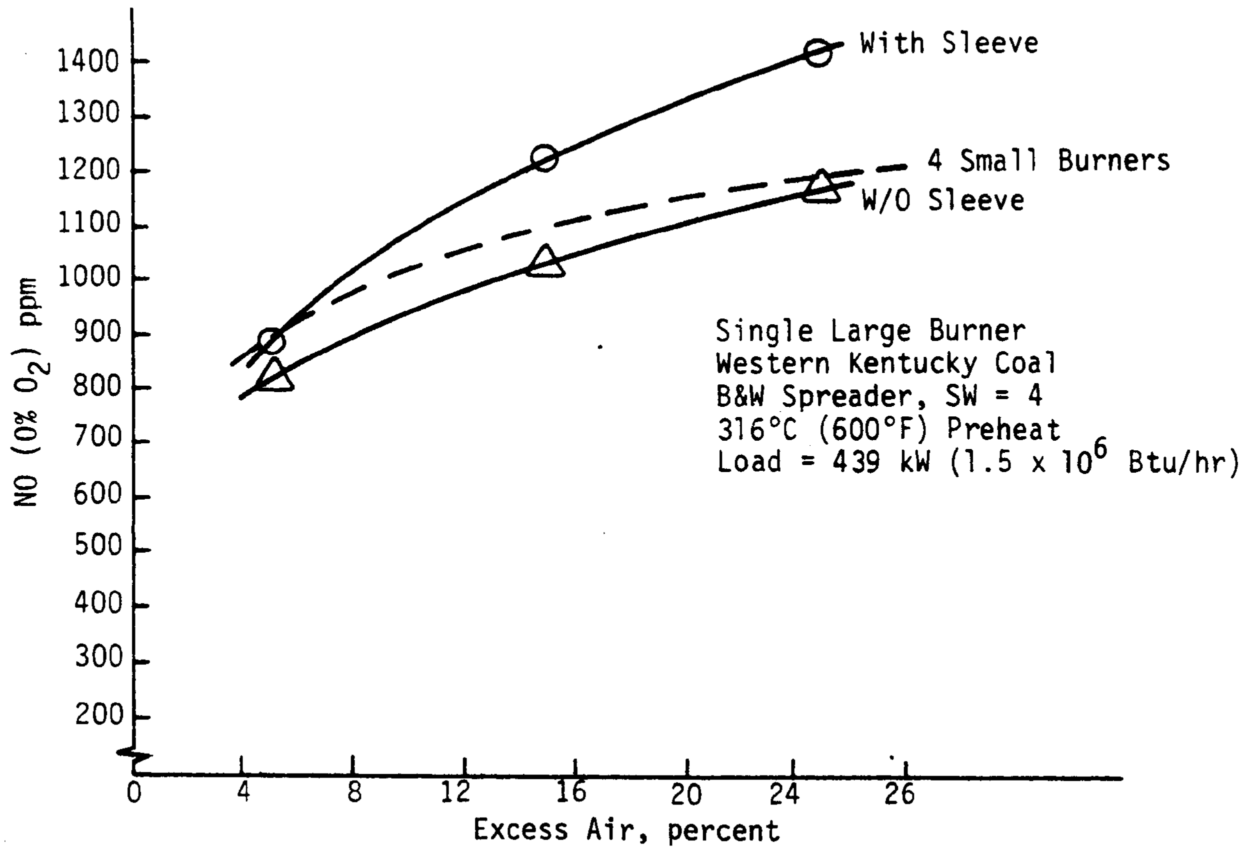
Coal: Western Kentucky

Firing Rate: 293 kW (1.0 x 10^6 Btu/hr)

Excess Air: 15%

Air Preheat: 316°C (600°F)

Exit Plane Temp: 1260°C (2300°F)



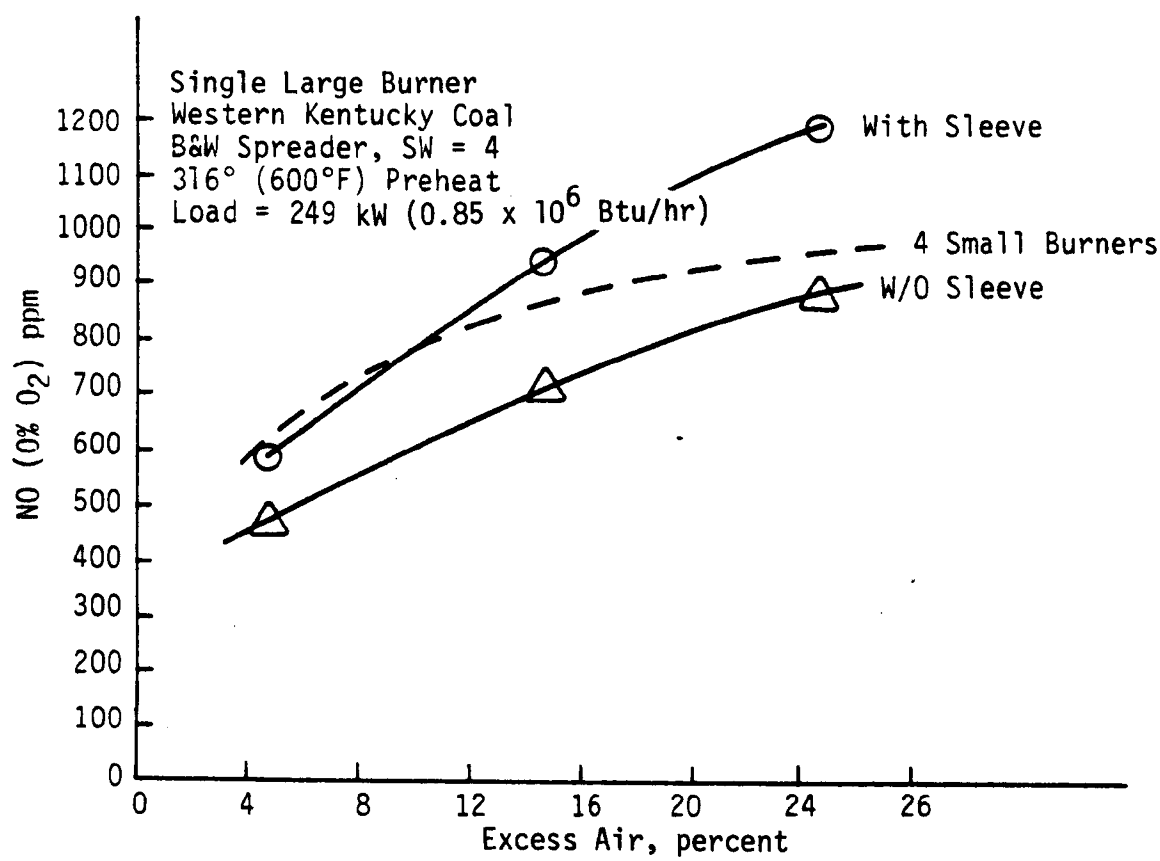


Figure 5-12. Effect of burner size.

larger coal jet diameter. The larger coal jet diameter effectively allows a longer fuel-rich residence time before the air diffuses into the fuel-rich region. By increasing the velocities with the use of the sleeve more rapid mixing is achieved, especially at the lower firing rate, and more rapid mixing increases the NO levels.

The slopes of the NO curves are greater for the large burner indicating that there may be some differences in the secondary air mixing processes between the large and small burners. For scale up-purposes it appears the higher NO associated with the mixing difference caused by the sleeve is offset by the fuel jet diameter effect.

For control technology tests of the large burner in the horizontal extension the burner was used with the sleeve in place. This choice was made because results close to full-scale practice were achieved with the sleeved burner. Also, it was of interest to determine the effect of higher burner velocities on NO during staged combustion.

5.2.4 Load

The facility in all its configurations was operated over a variety of loads under baseline and staged conditions. In the FWF and tangential configurations, the two primary loads were 293 kW and 440 kW (1.0 and 1.5 x 10^6 Btu/hr). In the HE configuration the primary loads were 249 kW and 380 kW (0.85 and 1.3 x 10^6 Btu/hr). The HE was fired at a lower heat release rate to maintain the heat release per unit volume within the HE at approximately the same level as in the firebox. Also, to keep burner aerodynamics approximately the same at the lower firing rate, the number of burners was reduced from five to four.

The effect of load on NO for both the FWF and tangentially-fired configurations is shown in Figure 5-13. Also, Figure 5-14 shows a similar

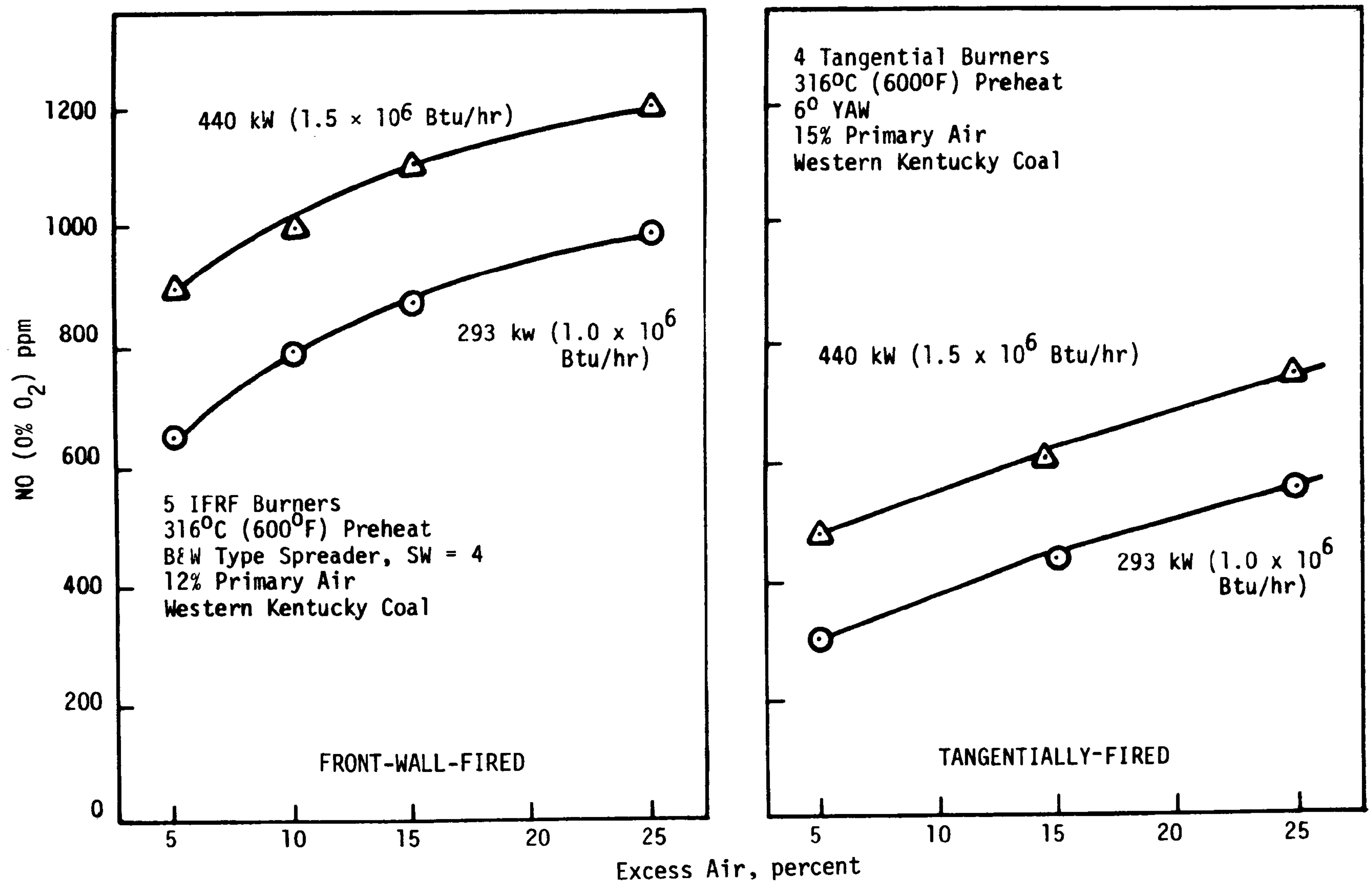


Figure 5-13. Effect of load (baseline).

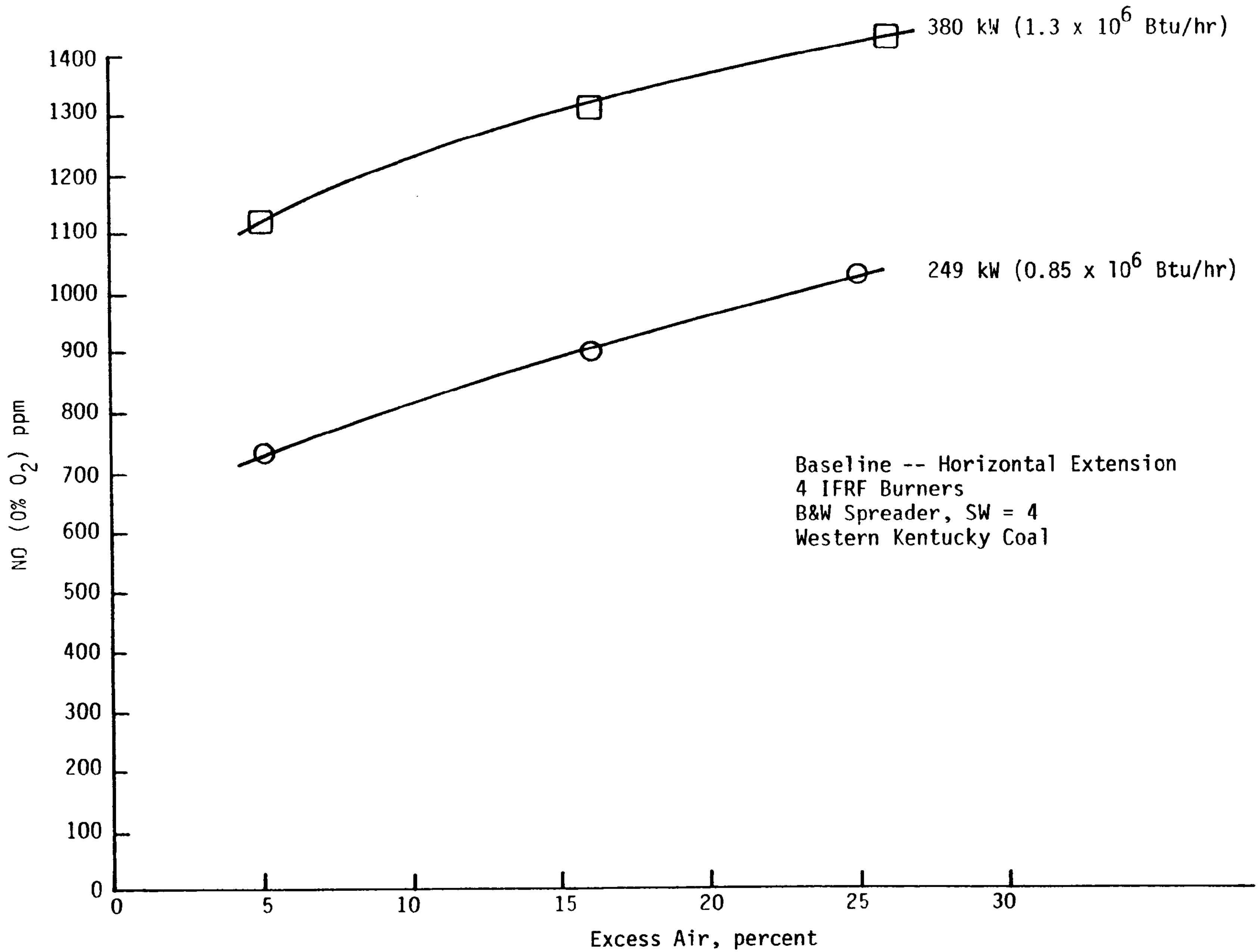


Figure 5-14. Effect of load (horizontal extensions).

result for the HE configuration. The data shows that NO increases with load for all configurations. This is probably due in part to the increase in combustion chamber temperature with load which causes the thermal NO to increase. In addition, fuel NO could be increasing due to enhancement of fuel/air mixing at increased load. Figure 5-15 is a plot of NO versus load at two preheats for the Western Kentucky coal and gas (both the radial/axial nozzle and Babcock & Wilcox spreader were used in the gas test). This plot shows that the NO levels from coal are increasing at a more rapid rate with load than the gas NO levels. If the gas NO levels at the same load truly represent the coal thermal NO, then these results imply that the conversion ratio of coal fuel-nitrogen to NO is increasing as the load increases. Observations of flame patterns under these conditions suggest that aerodynamics may be playing a major role. At 440 kW (1.5 x 10^6 Btu/hr), the flames were more compact and intense than at 293 kW (1.0 x 10^6 Btu/hr). The higher intensity indicates that more rapid fuel/air mixing is occurring at increased load as a result of the higher injection velocity. As discussed in Section 5.2.3, increased mixing causes NO to increase.

Figure 5-16 gives the percent conversion of fuel-N to NO for two loads as a function of percent nitrogen in the fuel for the three fuels tested (See Section 5.2.5 for a description of the coals used in this study). The percent conversion of fuel-N was found by subtracting the thermal NO (assumed equal to the gas NO levels) from the total coal NO. As can be seen in Figure 5-16, fuel-N conversion ratio increases from 24-27 percent to 31-33 percent as load increases. The shape of the curves do not change very much but the level is significantly increased. At a load of 293 kW (1 x 10^6 Btu/hr) the percent conversion derived in this study is somewhat consistent with the results of Pershing (Reference 5-4).

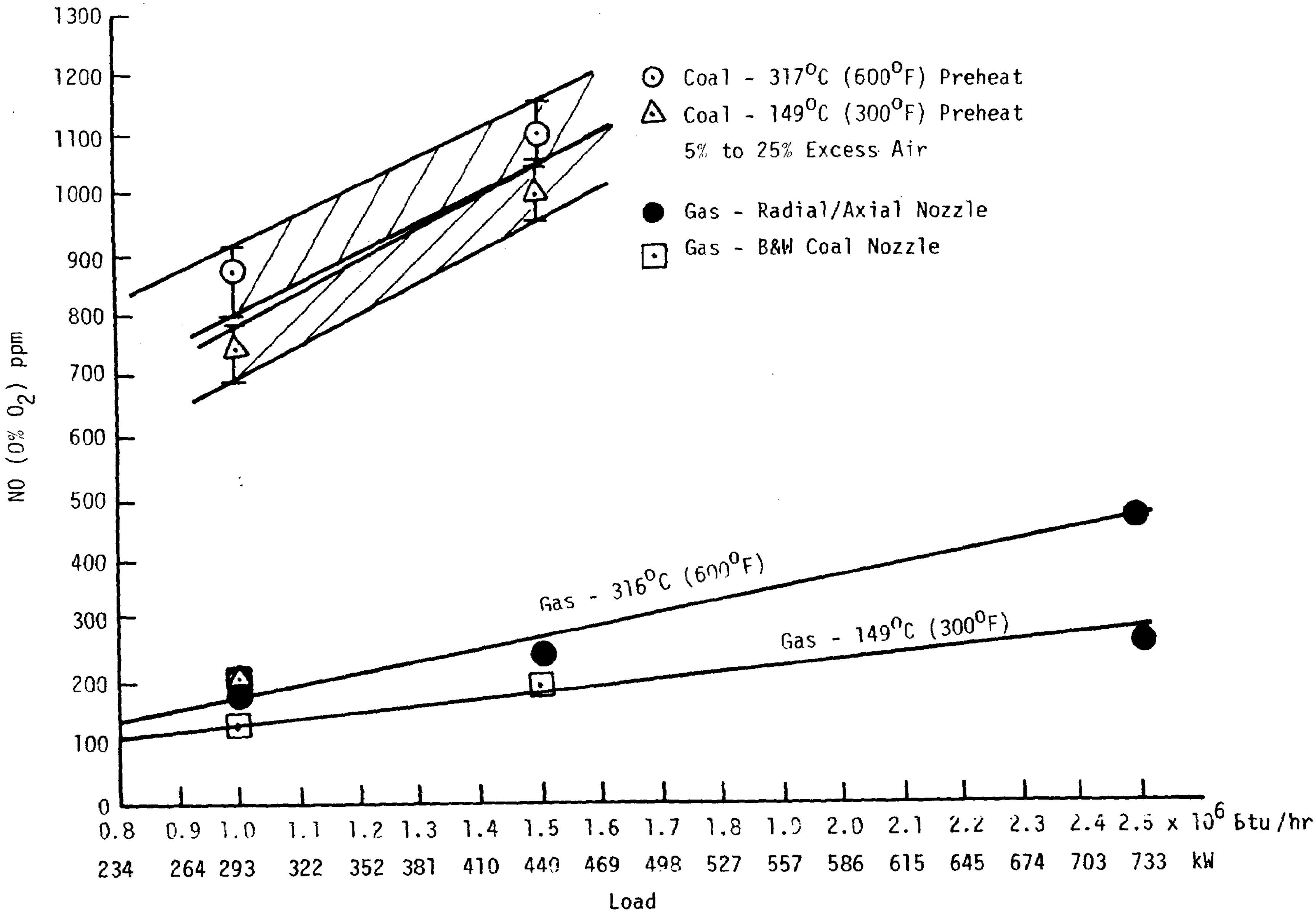


Figure 5-15. Effect of load.

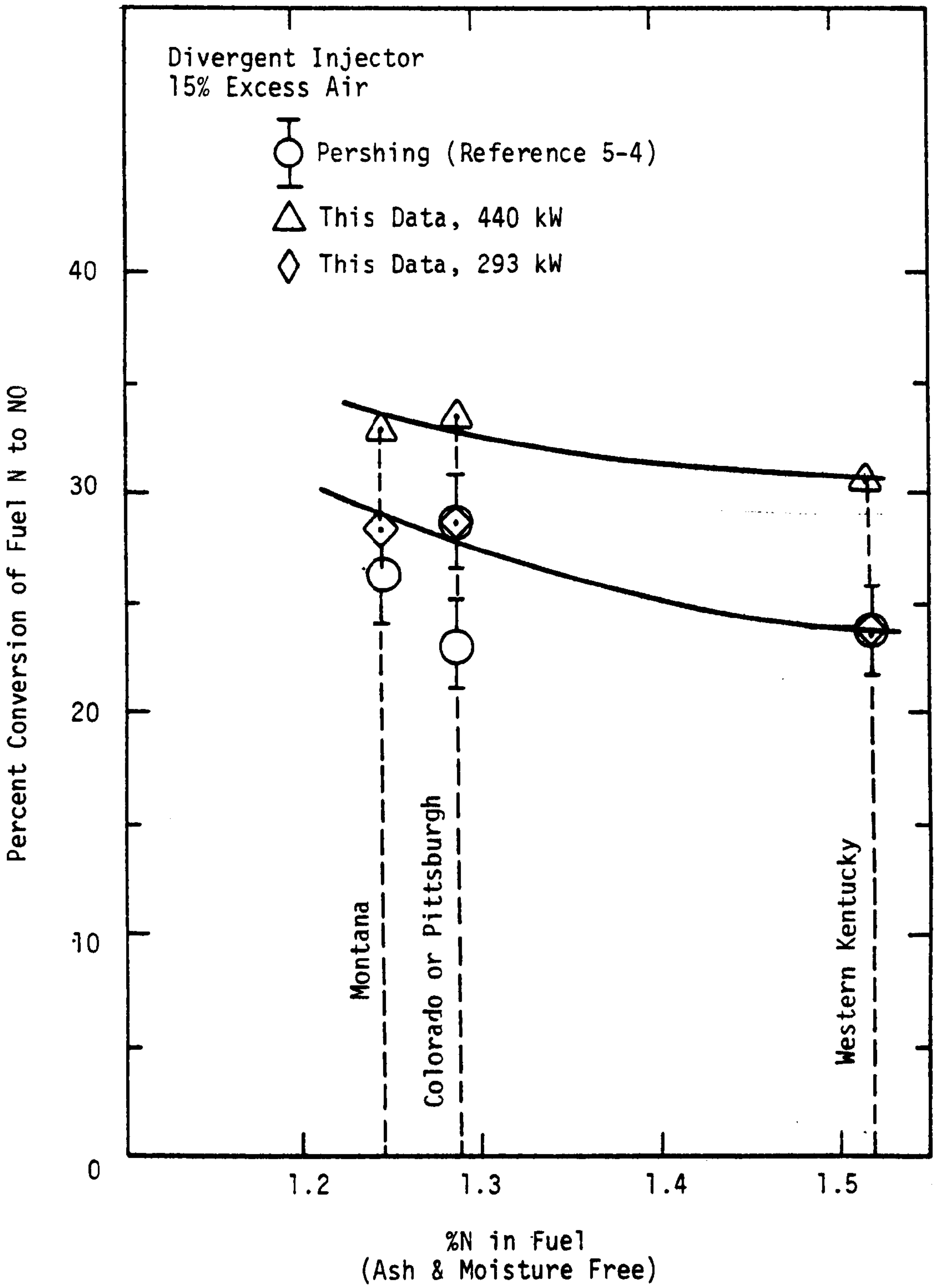


Figure 5-16. Effect of coal composition on fuel nitrogen conversion (divergent injector, 15% excess air).

5.2.5 Coal Composition

Three coals were tested to determine the applicability of the control technology to a range of coal types. Table 5-4 shows the ultimate and proximate analysis of these three coals. The Pittsburgh #8 coal is a fairly high sulfur, high grade bituminous steam raising coal. The Western Kentucky coal is a good grade bituminous coal, typical of what is being fired in the Midwest and Southern states. It is also very similar to the coals used in previous EPA field tests. Finally, the Montana coal represents a typical low sulfur Western coal which has a potentially large market in the future. It should be noted that the Montana coal has a higher water, oxygen and ash content and a lower carbon and sulfur content than the other two coals.

Although the dry ultimate analyses for the three coals are somewhat similar (except for sulfur content) the combustion characteristics of the three coals are known to be quite different. The Pittsburgh #8 coal is a sticky coal that has a tendency to become soft just prior to burning. Fouling the fuel tips when firing the Pittsburgh coal necessitated moving the fuel tip further into the throat of the burner to minimize fouling.

Prior to the control technology tests with the three coals, baseline results of NO versus excess air were obtained. FWF and tangentially-fired NO results are given in Figure 5-17. The Western Kentucky and Pittsburgh #8 coal results were very close over the entire range of excess air levels. The Montana coal was consistently higher at all excess air levels. These trends were also found at a load of 440 kW (1.5×10^6 Btu/hr) as seen in Figure 5-18.

The nitrogen content of the Montana coal on a dry and ash-free basis is the lowest of all the coals tested. Since the Montana coal NO levels are

TABLE 5-4. PULVERIZED COAL CHARACTERISTICS

Coal	Pittsburgh #8	Western Kentucky	Montana-Powder River Region
Ultimate Analysis (%, Dry)			
C	77.2	73.0	67.2
H	5.2	5.0	4.4
N	1.19	1.40	1.10
S	2.6	3.1	0.9
O	5.9	9.3	14.0
Ash	7.9	8.2	11.7
Heating Value (Btu/lb, Wet)	13,700	12,450	8,900
Proximate Analysis (%, Wet)			
Volatile	37.0	36.1	30.5
Fixed Carbon	54.0	51.2	39.0
Moisture	1.2	4.8	21.2
Ash	7.8	7.8	9.2
Rationale for Selection	• Most important general class of U.S. steam raising coals • Highest quality U.S. steam coals • Standard against which others are usually compared • Wide distribution • Expanded production likely	• Extensively used for steam generation in Ohio and Mississippi Valley areas • Good quality steam coal • Wide distribution • Some published Esso full-scale data for comparison	• Current local importance; future national significance • "Typical" Western subbmituminous in abundant supply

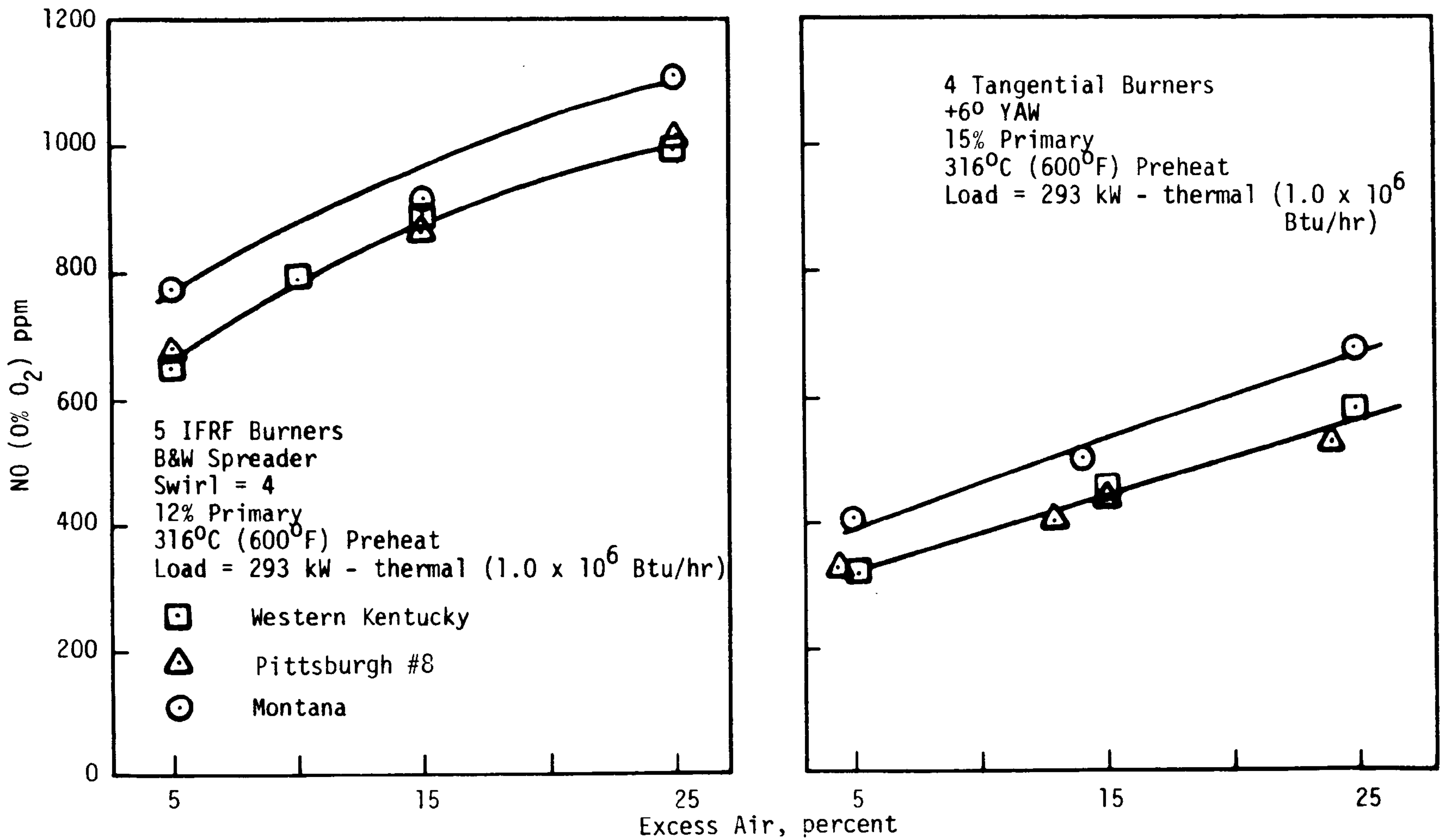


Figure 5-17. Effect of coal composition (baseline).

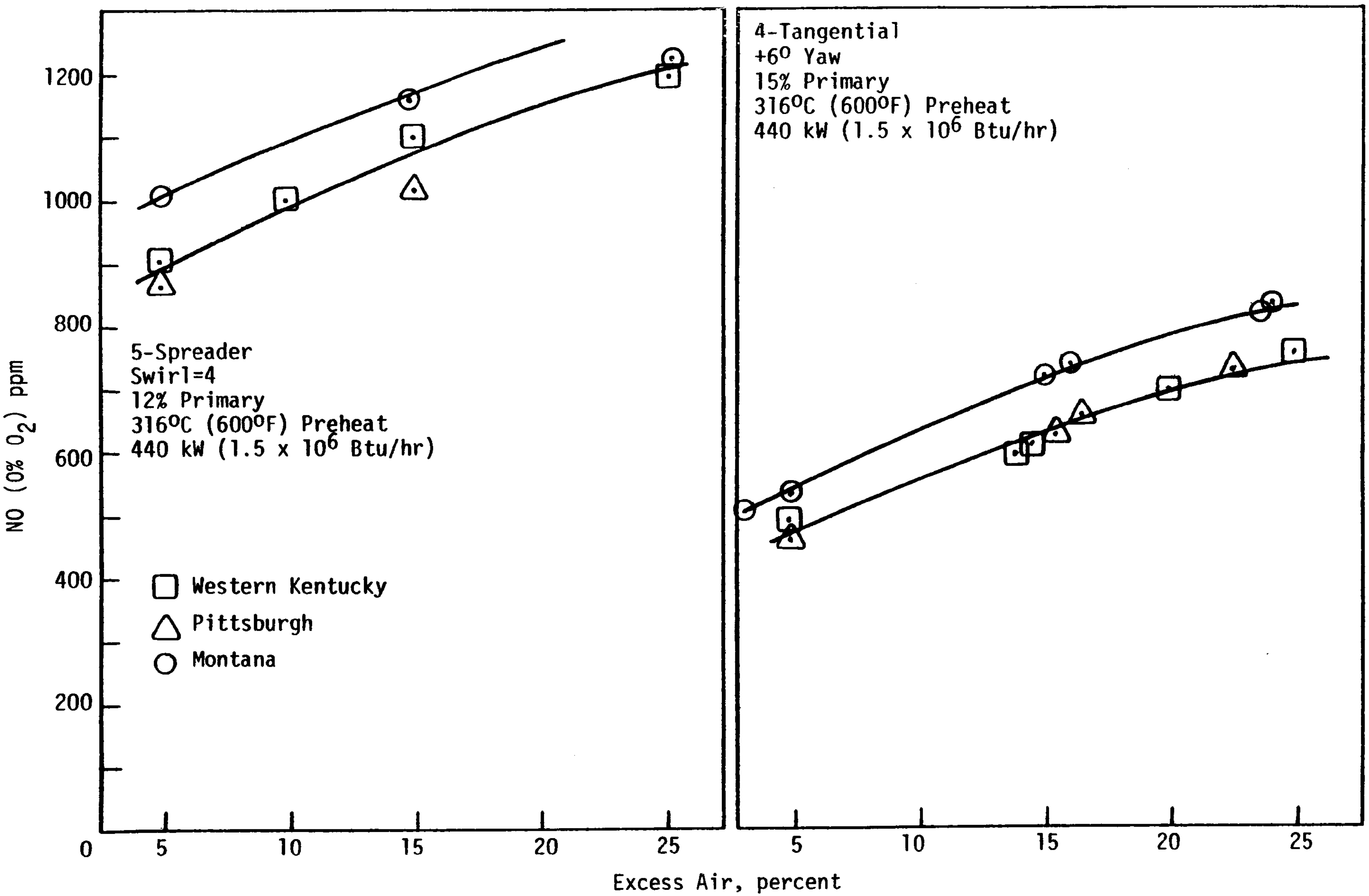


Figure 5-18. Effect of coal composition at the higher load (baseline).

higher, the fuel nitrogen conversion ratio must be greater for the Montana coal than the other coals. The higher conversion may be a result of the moisture, oxygen or sulfur content differences between the coals. Recently Wendt (Reference 5-9) has indicated that sulfur in the fuel can either enhance or depress NO levels depending on the stoichiometry and temperature of the combustion zone as well as whether the fuel contains significant bound nitrogen. To check if the reduced sulfur content of the Montana coal was the cause of higher NO, a series of baseline tests where SO_2 was injected into the secondary air flow, were carried out. The normal level of stack SO_2 without injection was 1300 ppm. Sufficient SO_2 was injected into the secondary air while burning Montana coal to bring the SO_2 to levels (2300 ppm) comparable to those achieved with the other coals. As can be seen in Figure 5-19, SO_2 injection in the secondary air has not caused any substantial change in NO Level. As Wendt indicated (Reference 5-9) fuel sulfur can decrease thermal NO emissions from well-mixed flames but increase fuel-N conversion to NO in fuel-rich combustion zones within the flame. It is possible that the flame configuration results presented in Figure 5-19 were obtained as a result of a balance between these two sulfur effects. It will be demonstrated in the section on control technology that fuel sulfur can either enhance or reduce NO under the proper combustion conditions. The results shown in Figures 5-17 and 5-18 might be due to the smaller amount of sulfur in the Montana coal and the proper combustion conditions.

5.3 EVALUATION OF CONTROL TECHNOLOGY

During this phase of the study, combustion condition changes were sought which would yield minimum NO levels when burning pulverized coal.

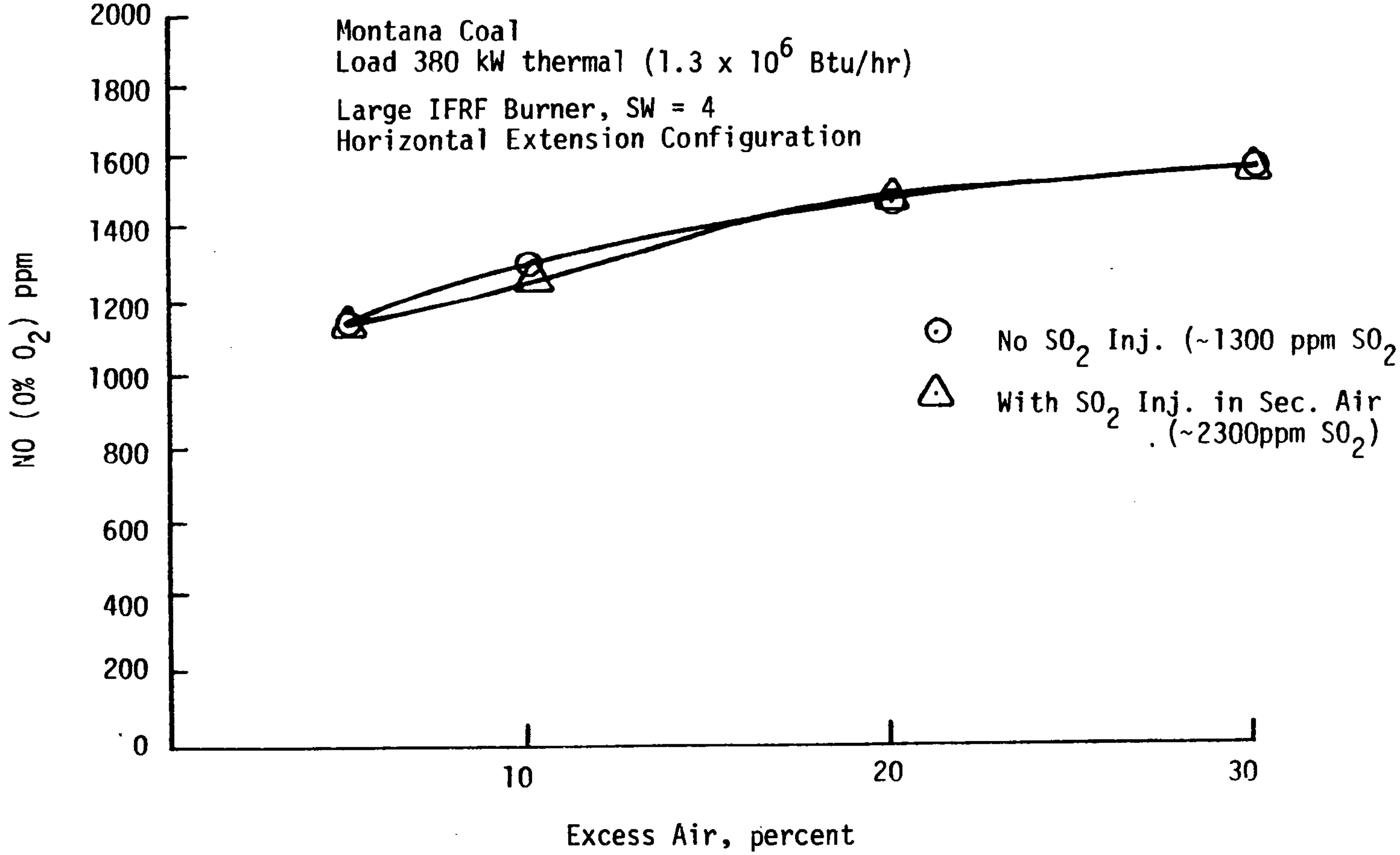


Figure 5-19. Effect of SO_2 doping (baseline).

Large parameter variations, such as overall stage stoichiometric ratio (SR), were emphasized in this study rather than detailed burner effects. Staging was the primary NO_x control method investigated. To a lesser extent flue gas recirculation and biased firing were investigated for their potentials to control NO_x.

Front-wall-fired (FWF), tangential and horizontal extension (HE) firing modes were employed in this control technology study. A straightforward experimental approach was applied during parameter variation tests. This caused several parameters to vary at once. For example, when first stage SR is changed, for a fixed load, the ratio of primary to secondary stream velocities changes, giving an altered mixing history as well as first stage SR. Therefore, results are complex and care must be used when interpreting the NO levels. However, the results yielded the gross effects of the main parameter variations and were characteristic of what could be achieved in a real system by system parameter variations without major hardware design changes.

This section first discusses the results of some preliminary cold flow experiments to determine flow patterns for a variety of staging injection techniques. These tests were helpful in determining the appropriate stage air injection technique and in interpreting the hot flow combustion data. This is followed by a discussion of the results of the parametric testing of the first- and second-stage parameters as well as coal composition. A discussion of data taken on a variety of other control technology tests including flue gas recirculation and biased firing follows these results. Finally, staged combustion results for natural gas firing are presented.

5.3.1 Flow Field Visualization

The first series of tests were conducted to establish a qualitative idea of the stage-air mixing patterns and degree of backmixing into the first stage for a variety of injection techniques. This was accomplished by fabricating two simulated clear plastic heat exchange sections and using smoke injection to establish the flow patterns. This apparatus is illustrated in Figure 5-20. The plastic unit was set atop the main furnace volume prior to installation of the actual heat exchange sections. A duct connected the plastic sections to an induced draft fan on the roof. Smoke was generated using the apparatus illustrated in Figure 5-21. Air was passed through a bubbler for humidification and then passed over pure $TiCl_4$ in a large vessel. The resultant mixture of TiO_2 smoke, HCl and air was then passed to one of several injection points, including the stage-air ports, the fuel nozzles of the burners or a multiport rake. This rake could be positioned anywhere in the main firebox or heat exchange section.

A variety of stage-air inlet designs were tested as listed below and as illustrated in Figure 5-22.

- Normal stage-air ports
- Normal stage-air ports with flare nozzles
- Multitube injector located in the heat exchanger drawer window locations
- Multihole rake

During the testing of each of these techniques, flow patterns were observed in the heat exchange sections and backmixing was noted through a large plastic viewport. The main firebox was illuminated with a floodlamp placed in the ashpit. In addition, black and white motion pictures and still photos were taken of the mixing patterns.

Flow rates of the secondary and stage air were adjusted so that the relative momentums of the air streams were consistent with those values

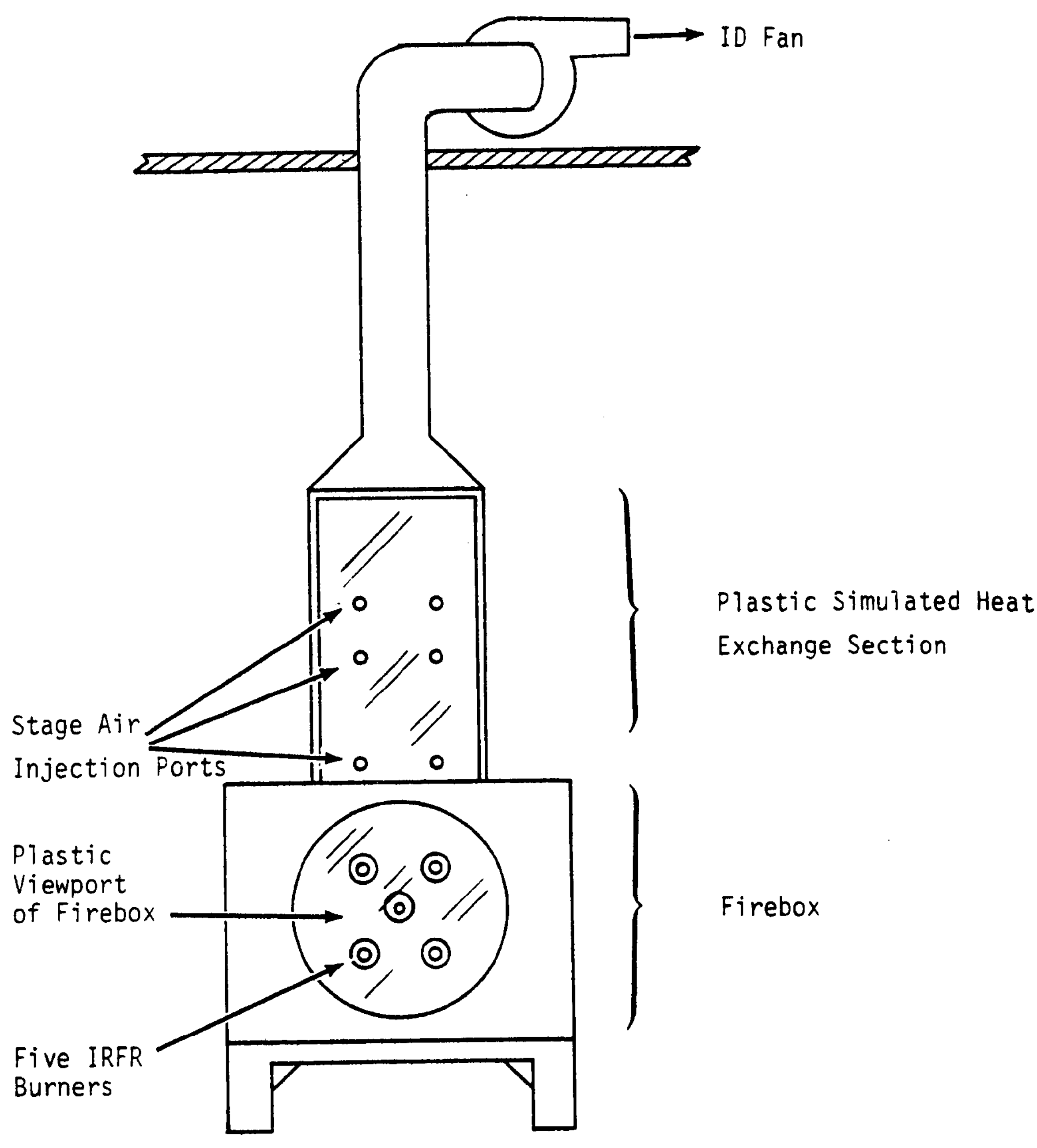


Figure 5-20. Cold flow apparatus.

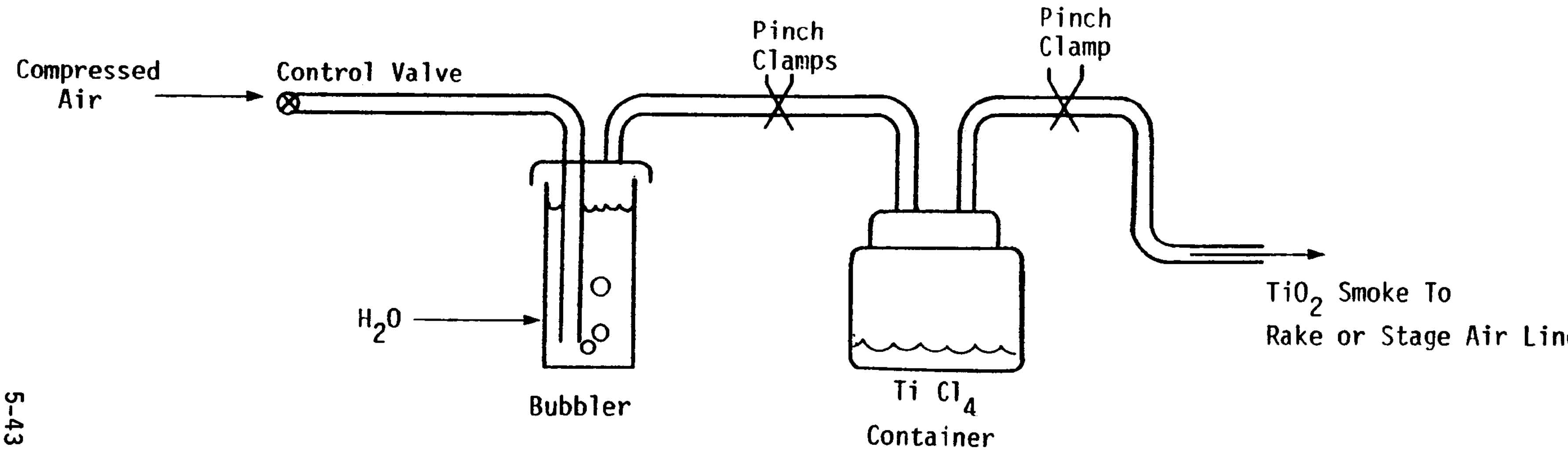
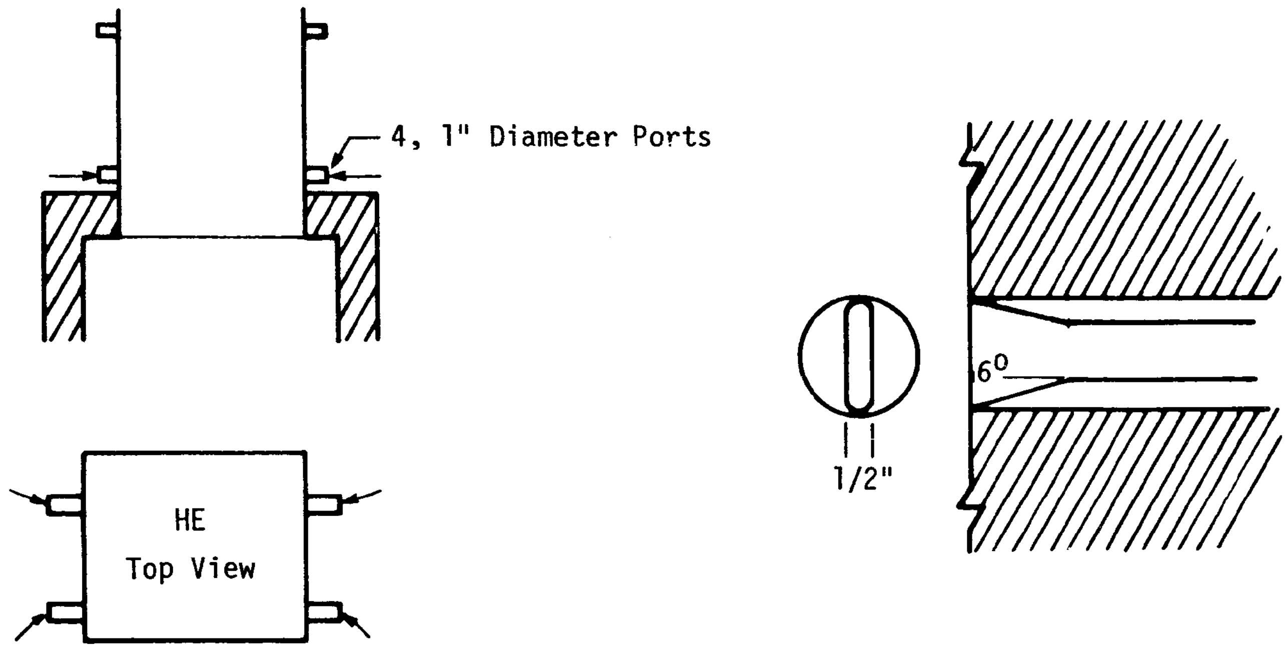


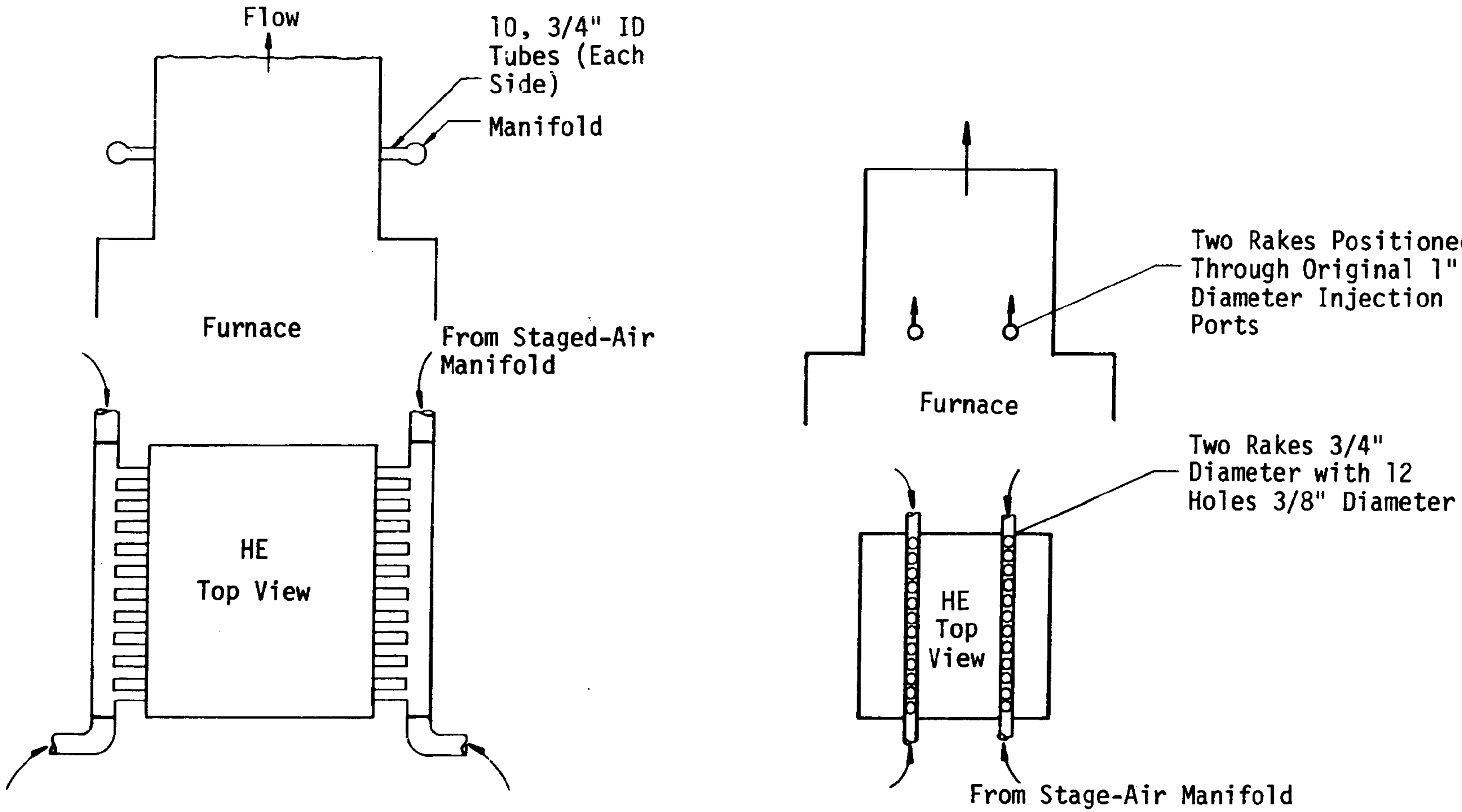
Figure 5-21. Smoke generator.



a) Normal Staged-Air Ports

b) Flared Nozzle Inserted in Normal Staged-Air Ports

Figure 5-22. Stage-air injection techniques.



c) Multiple opposed jet injection technique.

d) Multihole rakes.

Figure 5-22. Stage-air injection technique (continued).

achieved under hot conditions for a typical firing rate of 293 kW (1.0×10^6 Btu/hr).

Table 5-5 summarizes the conditions and observations of the tests performed and refers to the figures of the observed flow patterns. These cold flow tests led to the following conclusions:

- The four opposed jet nozzles produce rapid and efficient mixing with no backmixing into the main combustion chamber
- Some backmixing occurs with the opposed jets but it is limited to a few inches below the injection point
- Intentional backmixing into the first stage may be achieved by injecting the stage-air only from one side
- When backmixing occurs, the amount is proportional to the swirl of the main burners and the amount of stage-air flow
- Instabilities can be developed in the flow patterns if the stage-air jets do not directly impinge
- Reducing the penetration velocity results in poor mixing
- The rake pointed upward gave poor mixing
- The optimum position for good mixing and minimum backflow for the rake technique was with the jets opposed and pointed upward at a 45^0 angle.
- A solid-body clockwise rotation of the flow in the firebox was observed. The degree of this rotation is proportional to the swirl.
- At high swirl (smoke injected through the fuel tube) a high degree of recirculation back into the burner quarl and throat was noted.

TABLE 5-5. SUMMARY OF COLD FLOW TESTS

Test #	Inj. Type & Position	Smoke Inj. Type & Position	Stg. Air Flow	Burner Swirl	Degree of Firebox Backmixing	Comments	Figure No.
1	None	ROB	None	8	-	Whole chamber swirling for clockwise rotation 1 rev/5 sec; effect all the way across chamber	
2	None	ROB	None	4	-	About 1/2 chamber swirling in manner of Test 1	
3	None	ROB	None	0	-	Flow impinges window, heads down then up the side wall	
5	S-1	CHE	Low	0	None	Smoke recirculates below injection point about 2"; rapid turbulent mixing of impinging jets	
6	S-1	CHE	Low	4	None	Smoke recirculates below injection point about 4"; rapid turbulent mixing of impinging jets	
7	S-1	CHE	Low	8	None	Smoke recirculates below injection point about 10"; rapid turbulent mixing of impinging jets	
8	S-1	CHE	High	8	None		
9	S-1	CHE	High	4	None		
10	S-1	CHE	High	0	None		
11	S-2	ST	Low	8	None		
12	S-2	ST	Low	4	None		5-23
13	S-2	ST	Low	0	None		
14	S-2	ST	High	0	None	Smokes recirculates below injection point about 16"; rapid turbulent mixing of impinging jets	
15	S-2	ST	High	4	None	Smokes recirculates below injection point about 12"; rapid turbulent mixing of impinging jets	
16	S-2	ST	High	8	None	Smokes recirculates below injection point about 12"; rapid turbulent mixing of impinging jets	5-24
17	S-2/M	ST	Low	4	None	Smokes recirculates below injection point about 24"; rapid turbulent mixing of impinging jets	
18	S-2/M	ST	High	4	None	Smokes recircuIates below injection point about 32"; rapid turbulent mixing of impinging jets	

KEY

Injector Type and Position:

S = Normal 4 horizontal opposed 1" diameter jets; -1 = 1st staging position, -2 heat exchange section up.

F = Flare nozzle inserted in normal staged air port.

M = Multitube injector located in heat exhange lower window (See Figure

RU = Two rakes pointed upward.

RHO = Two rakes horizontal opposed - /45 pointed upward 45°/RHD/45 = Two rakes horizontal divergent (pointed towards wall) at 45° angle upward

Smoke Injector Type and Position:

ROB = Through a rake opposite the burners

RC = Through a rake in the bottom middle of the first heat exchange section

ST = Together with the stage air

CHE = Center of heat exchanger through rake

TABLE 5-5 (Continued)

Test #	Inj. Type & Position	Smoke Inj. Type & Position	Stg. Air Flow	Burner Swirl	Degree of Firebox Backmixing	Comments	Figure No.
19	S-1/W	ST	High	8	High	Flow impinges on opposite wall and partially flow downward	5-25
20	S-1/W	ST	Low	8	Med.	Flow penetrater 1/2 the heat exchanger - some pulled down	
21	S-1/W	ST	Low	4	None	Flow penetrater 1/2 the heat exchanger - some pulled down	
22	S-1/W	ST	High	4	Med.	Flow impinges on opposite wall and partially flows downward	
23	S-1/W	ST	High	0	Low	Flow impinges on opposite wall and partially flows downward	
24	S-1/W	ST	Low	0	None	Flow penetrates 1/2 the heat exchanger - some heads down	
25	S-1	ST	High	0	None	Smoke recirculates below injection point to some degree	
26	S-1	ST	High	4	None	Smoke recirculates below injection point to some degree	
27	S-1	ST	High	8	None	Smoke recirculates below injection point to some degree	
28	S-1/E	ST	High	8	High	Flow impinges opposite wall and partially flows downward	
29	F-1	ST	High	8	None	Flow the same as straight jets	
30	F-1/W	ST	Med.	8	High	Same as straight jet when flowing from one side	
31	F-1/W	ST	Low	8	Med.	Same as straight jet when flowing from one side (Test #20)	
32	F-1/W	ST	Low	4	Med.	Same as straight jet when flowing from one side Comes toward firebox viewport in puffs	
33	F-1/W	ST	Med.	4	High	Same as straight jet when flowing from one side Comes toward firebox viewport in puffs	
34	F-1/W	ST	Med	0	Med.	Same	
35	M-1	ST	High	0	None	Instability in the flow pattern	5-26

KEY

Injector Type and Position:

S = Normal 4 horizontal opposed 1" diameter jets; -1 = 1st staging position, -2 heat exchange section up.

F = Flare nozzle inserted in normal staged air port.

M = Multitube injector located in heat exhange lower window (See Figure

RU = Two rakes pointed upward.

RHO = Two rakes horizontal opposed ·/45 pointed upward 45°/RHD/45 = Two rakes horizontal divergent (pointed towards wall) at 45° angle upward

Smoke Injector Type and Position:

ROB = Through a rake opposite the burners

RC = Through a rake in the bottom middle of the first heat exchange section

ST = Together with the stage air

CHE = Center of heat exchanger through rake

TABLE 5-5 (Concluded)

Test #	Inj. Type & Position	Smoke Inj. Type & Position	Stg. Air Flow	Burner Swirl	Degree of Firebox Backmixing	Comments	Figure No.
36	M-1	ST	High	4	None	Same	
37	M-1	ST	High	8	None	Same	
38	M-1	ST	Low	8	None	Stage air flow does not penetrate bulk of upward flow	
39	M-1	ST	Low	0	None	Unstable pulsing returns	
40	M-1	ST	Low	4	None	Same as Test #38	
41	M-1/W	RC	High	8	Med.	Flow impinges opposite wall and partially flow down	
42	M-1/W	RC	Low	8	None	Flow does not penetrate heat exchange section; turns upward almost immediately	
43	M-1/W	RC	None	0	None	Rake in upper section shows very slow mixing patterns w/o staged air on	
44	M-1/W	RC	Low	0	None	Flow does not penetrate goes straight up	
45	RU-1	St	How	8	None	Local recirculation patterns around rake but generally very poor mixing into main stream	5-27
46	RU-1	St	Low	0	None	Same	
47	RU-1	St	High	0	None	Highly turbulent but little backmixing	
48	RHO-1	St	Low	8	High	Highly turbulent fast mixing - lots of backmixing	
49	RHO-1	St	Low	0	Med.	Highly turbulent fast mixing - lots of backmixing	
50	RHO-1	St	High	0	High	Highly turbulent fast mixing - lots of backmixing	5-28
51	RHO/45-1	St	Low	0	None	Highly turbulent; less backmixing	
52	RHO/45-1	St	High	0	Low	Highly turbulent; good mixing	
53	RHO/45-1	St	High	8	Low	Highly turbulent; good mixing	
54	RHO/45-1	St	Low	8	None	Highly turbulent; good mixing	5-29
55	RHD/45-1	St	Low	8	Low	Not as good mixing - recirculates down outer wall	
56	RHD/45-1	St	High	8	Low	Not much different than low staged air run	

KEY

Injector Type and Position:

- S = Normal 4 horizontal opposed 1" diameter jets; -1 = 1st staging position, -2 heat exchange section up.
- F = Flare nozzle inserted in normal staged air port.
- M = Multitube injector located in heat exhange lower window (See Figure
- RU = Two rakes pointed upward.
- RHO = Two rakes horizontal opposed - /45 pointed upward 45°/RHD/45 = Two rakes horizontal divergent (pointed towards wall) at 45° angle upward

Smoke Injector Type and Position:

- ROB = Through a rake opposite the burners
- RC = Through a rake in the bottom middle of the first heat exchange section
- ST = Together with the stage air
- CHE = Center of heat exchanger through rake

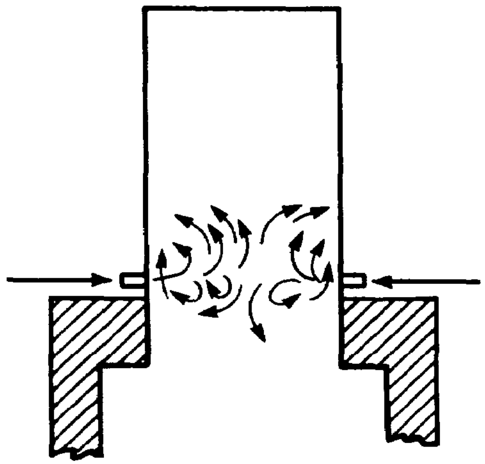


Figure 5-23. Opposed jets.
Test #6
low flow.

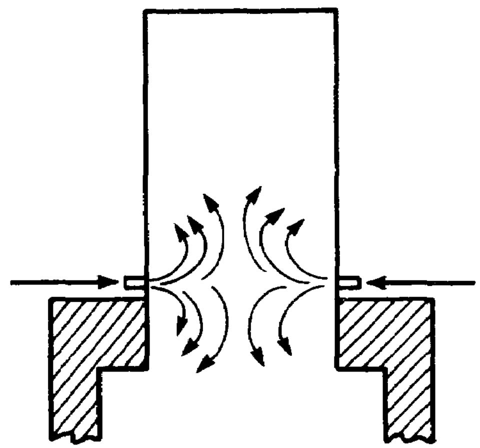


Figure 5-24. Opposed jets.
Test #9
high flow.

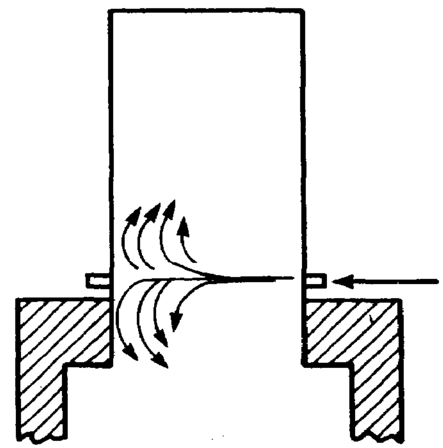
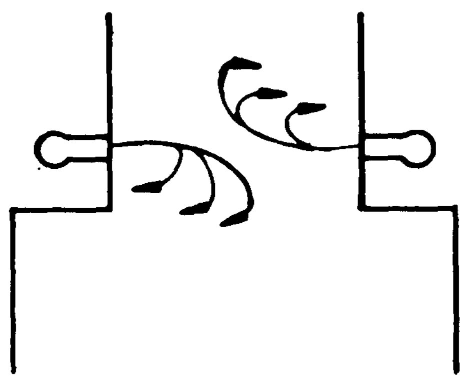
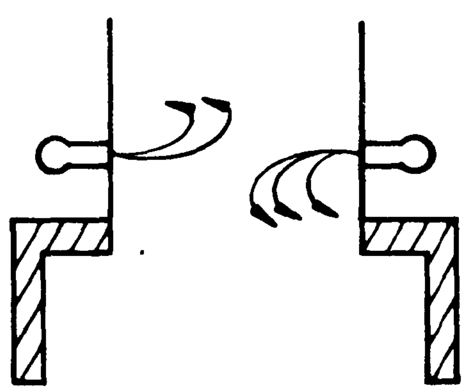


Figure 5-25. Jets from one side only.
Test #19
high flow.



Stable Position a



Stable Postion b

Test #36

Figure 5-26. Multiple opposed jet flow configuration.

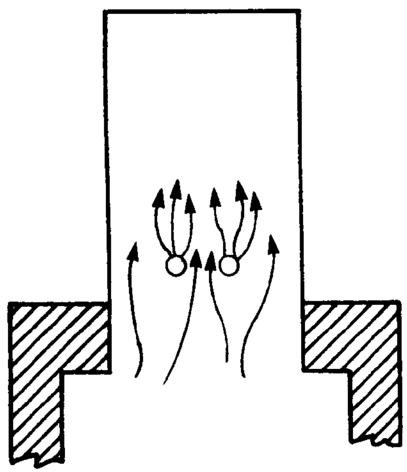


Figure 5-27. Multihole rakes pointed up. Test #36

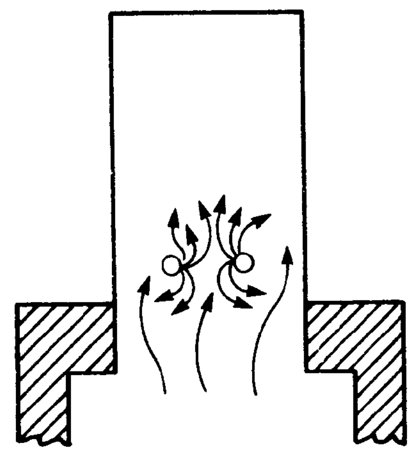


Figure 5-28. Multihole rakes horizontally opposed. Test #50

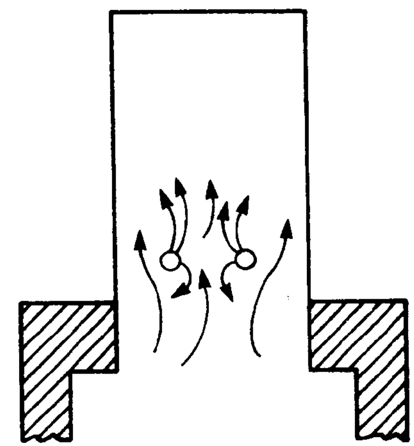


Figure 5-29. Multihold rakes pointed 45° toward each other. Test #51

These results showed that for the majority of the tests where fast mixing was required in the second stage, the normal four opposed jet stage-air injection ports should be used.

5.3.2 First-Stage Parameters

A number of first-stage parameters for FWF, tangential and HE firing configurations were varied to determine their impact on NO, CO and carbon loss emissions. The parameters varied during the tests include:

- First-stage stoichiometry
- First-stage residence time
- First-stage mixing
- Secondary air preheat temperature
- Load

The results of changing these parameters will be discussed in the following subsections.

5.3.2.1 First-Stage Stoichiometric Ratio

NO_x control by staged-air combustion has been widely tested since its initial development in the late 1950's (Reference 5-10). Operation with a near or substoichiometric first stage effectively suppresses both thermal and fuel NO_x formation. However, the degree of NO_x control achieved by increasing fuel-rich stoichiometry may be limited by both practical and theoretical considerations. First, from a practical standpoint, there is concern that the operation of conventional design boilers under reducing conditions of first-stage stoichiometric ratios (SR) below about 0.95 may yield unacceptable rates of water-wall corrosion. One objective of the present program was to identify low NO_x conditions for SR $\geq$ 0.95 for potential application to conventional design boilers. However, low SRs may be acceptable for new unit designs, so a second objective was to identify the minimum achievable NO_x emission at low SR. Here, fundamental considerations suggest a limit to NO_x reductions.

During first-stage combustion, a portion of the fuel-N trapped in the coal is volatilized and mixed with the surrounding gases. If these gases are fuel-rich, due to substantial evolution of coal fuel volatiles, combustion processes will convert a fraction of the fuel-N to N_2, as well as to NO and bound nitrogen intermediates, such as NH_3 and HCN (Reference 5-11). Well stirred reactor experiments (Reference 5-12) using propane fuel doped with model fuel-N compounds show that as the SR decreases, the amount of N_2 produced from fuel-N reaches a peak and then decreases. Also, these experiments show that the concentration of bound nitrogen intermediates continue to increase as SR decreases. Equilibrium (Reference 5-13) and plug-flow and well-stirred reactor kinetic calculations (Reference 5-14) also exhibit similar trends. Adding second-stage air to the first-stage combustion products oxidizes the bound nitrogen intermediates such as NH_3 and HCN, (References 5-11, 5-15, 5-16) to NO. However, the fuel-N that has been converted to N_2 in the first stage remains relatively unavailable for conversion to NO.

These results suggest that an optimum first-stage SR exists which will maximize N_2 production and thereby minimize the second-stage NO level. The fuel which passes into the second stage trapped in the uncombusted coal or in the form of NO or bound N intermediates will probably be converted to NO within the second stage. This fuel-N represents the lower limit for NO_x production in the staged system.

Staging tests utilizing FWF or tangentially-fired configurations were performed over a range of SRs with the stage-air introduced into a number of positions in the heat exchange tower (see Figure 5-30 for a schematic of the staging ports). It should be noted that for this evolving, volatilizing fuel system, the local SR can be quite different from the overall SR. This has important implications to NO formation and this point will be discussed further in the sections on first-stage residence time and mixing.

Stack NO levels versus overall first-stage SRs are shown in Figure 5-31 for the FWF and tangential configurations for the second staging position (see Figure 5-30). Conditions for these tests are given on the figure. The first-stage SR was varied by altering the secondary air and staged air such that the overall excess air level remained constant at 15 percent. The primary air level remained constant during these tests. The effects of the staging position, i.e. first-stage residence time on stack NO will be discussed in the section on residence time. As seen in Figure 5-31, stack NO is a strong function of first-stage SR for all firing configurations. For the front-wall-fired configuration, a 52 percent reduction in NO was achieved at a stoichiometric first stage and an overall excess air of 15 percent. A minimum NO level of 160 ppm was achieved (82 percent reduction) at a SR of 0.80 to 0.85.

For the tangential case, a 31 percent reduction was achieved at a stoichiometric first stage and a minimum of 125 ppm (71 percent reduction) at a SR of 0.85. Further reductions in SR showed a corresponding rise in NO for both configurations at this staging position.

Stack NO levels for various SRs in the HE firing configuration are given in Figure 5-32. (For staging configuration 10, see Figure 5-33).

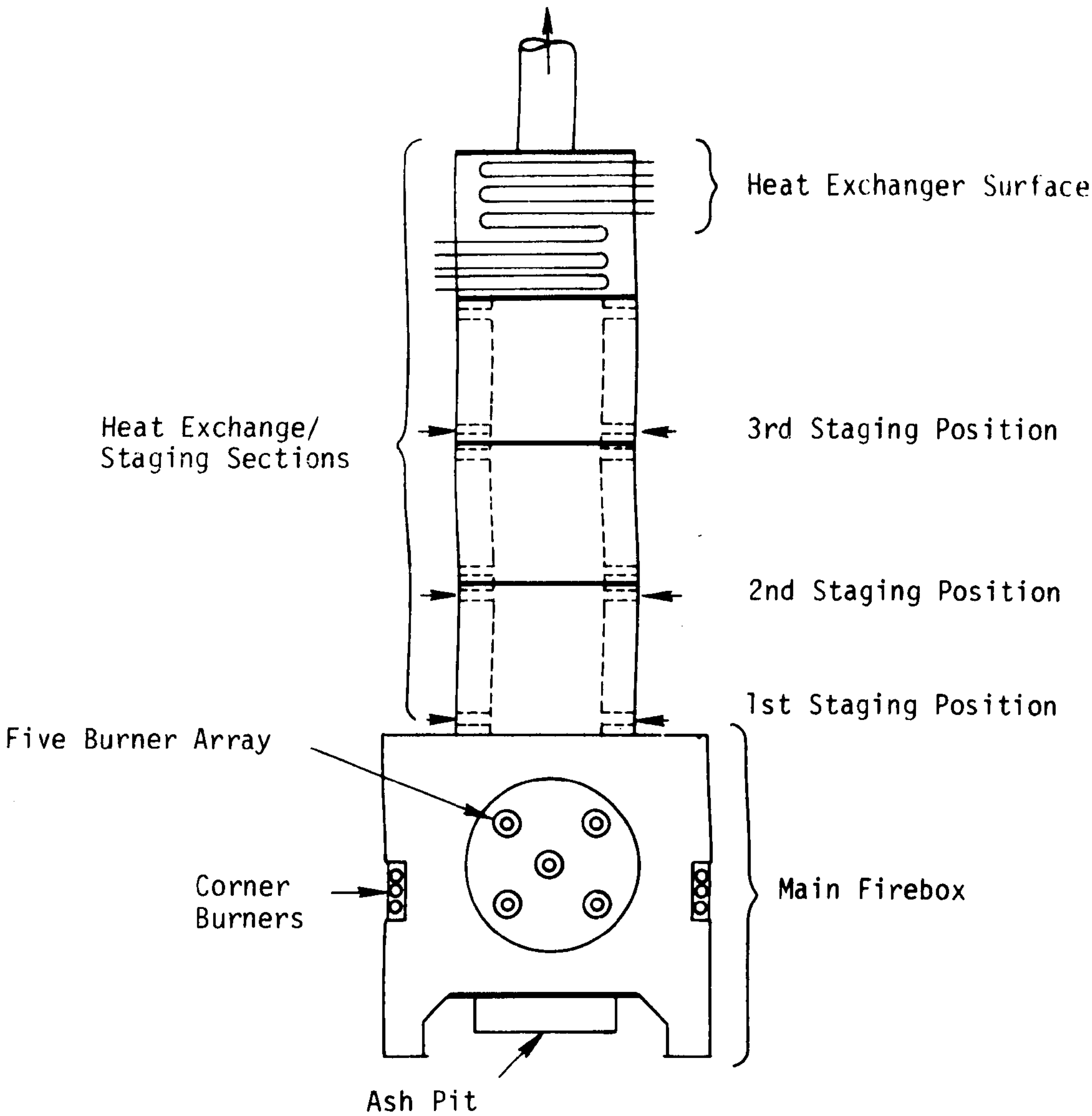


Figure 5-30. Staging-air locations.

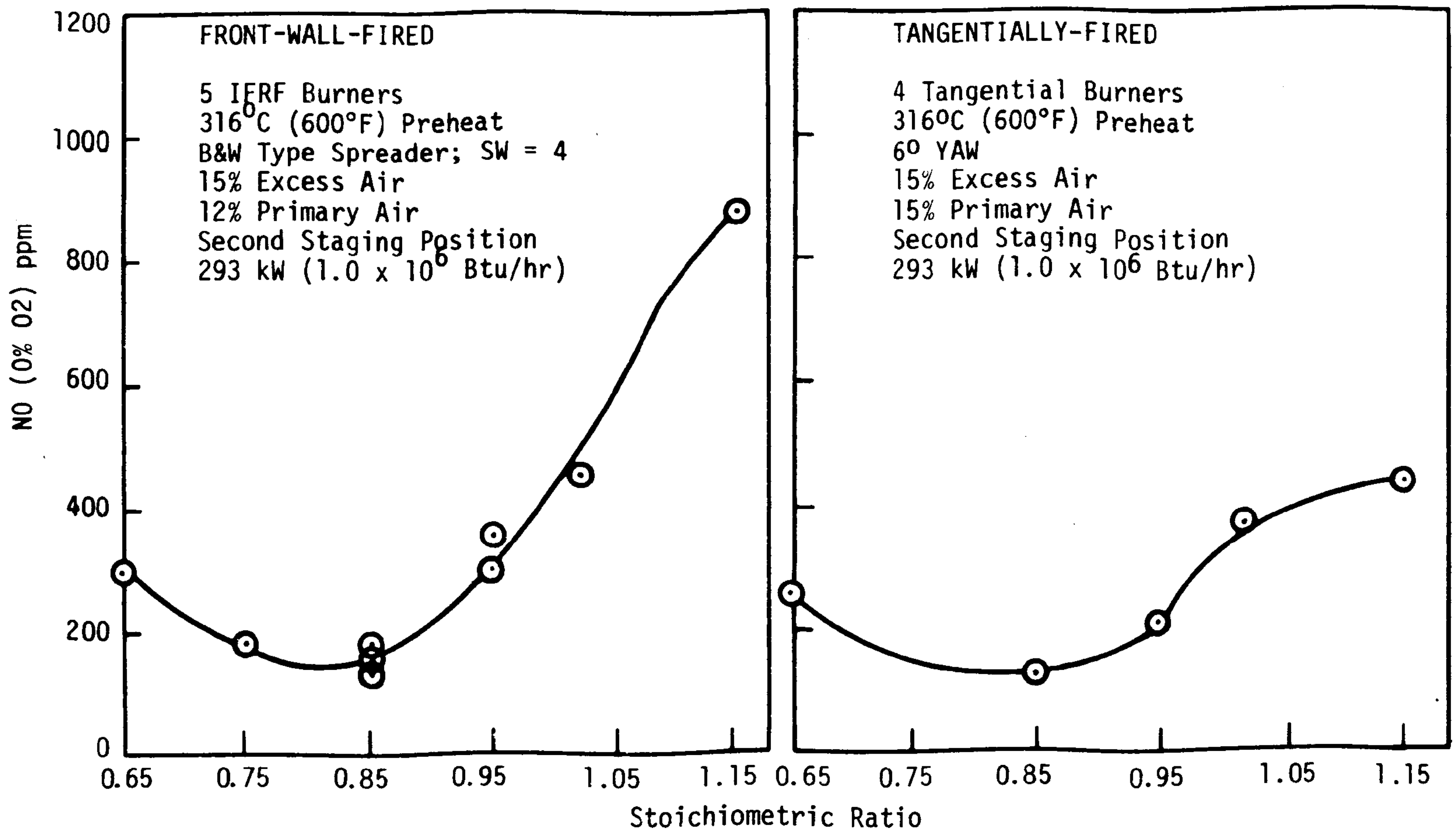


Figure 5-31. Effect of first-stage stoichiometry.

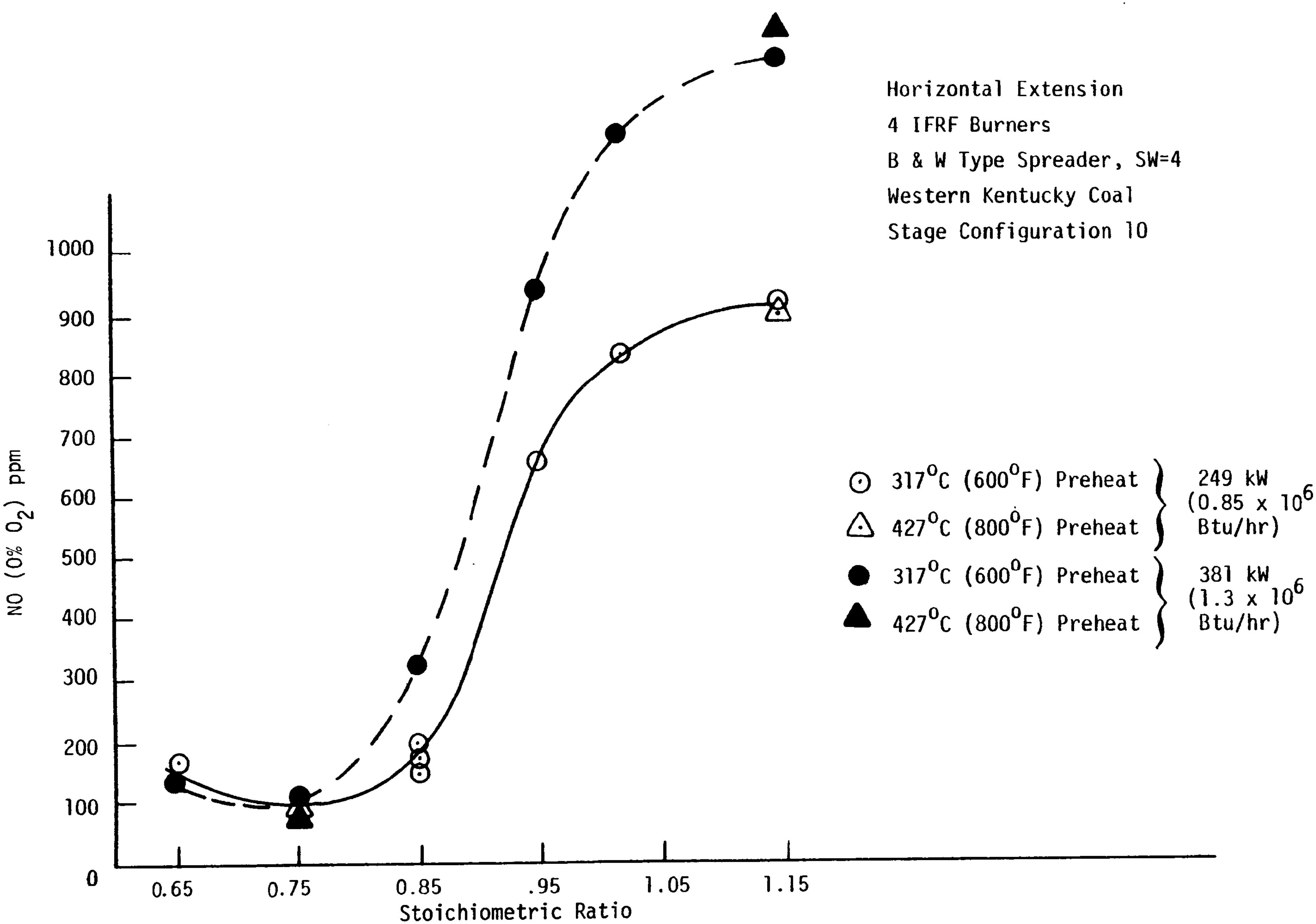


Figure 5-32. Effect of first-stage stoichiometry and load.

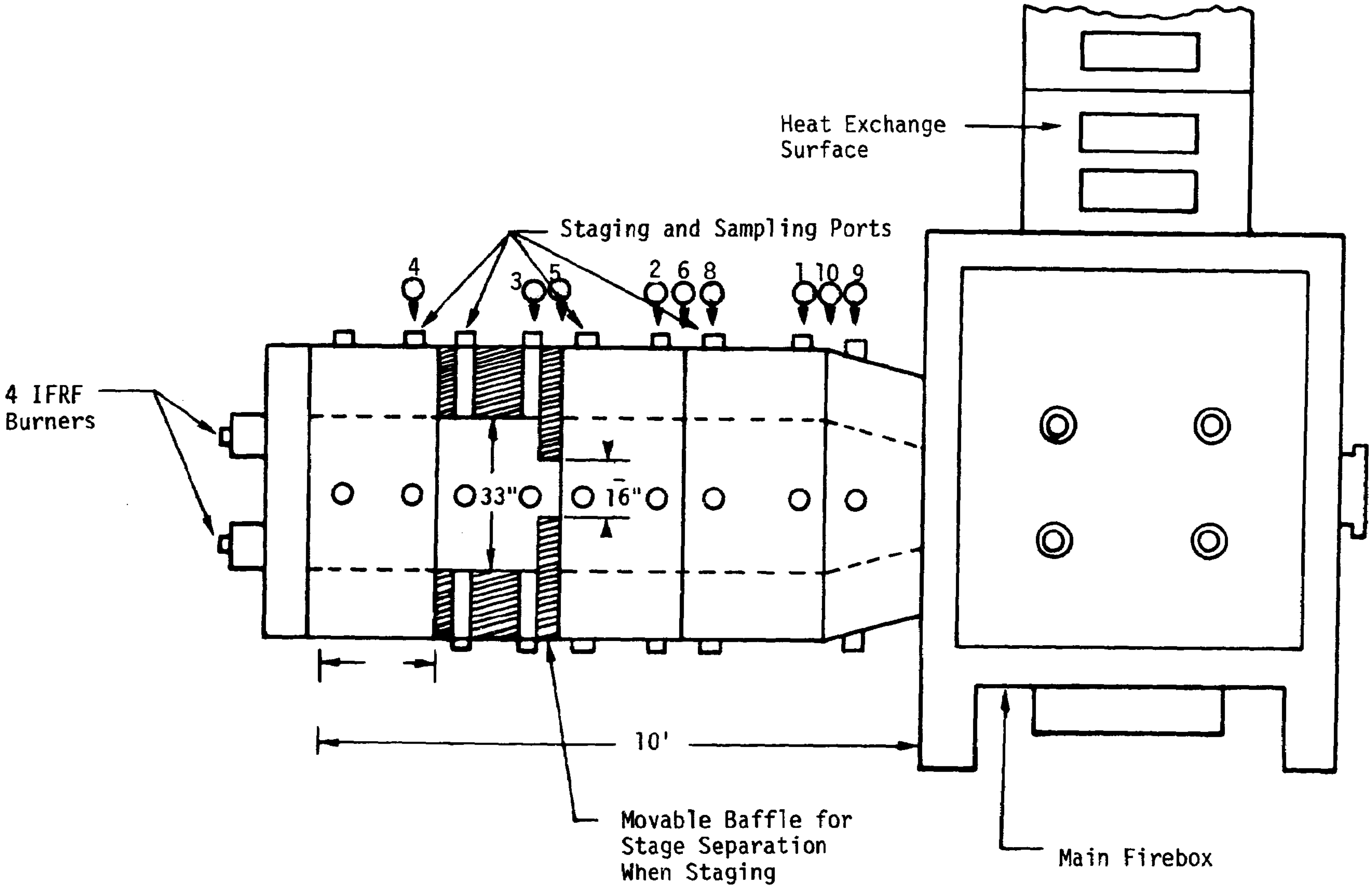


Figure 5-33. Horizontal extension configuration.

Both the 249 and 381 kW (0.85 and 1.3 MBtu/hr) load results are shown in this figure. The 249 kW (0.85 MBtu/hr) results using 4 IFRF burners roughly match to volmetric heat release obtained by 5 IFRF burners operating at 293 kW (1 MBtu/hr) in the FWF configuration. For the HE firing at 249 kW (0.85 MBtu/hr), an 11 percent reduction in stack NO level was achieved at a stoichiometric first stage and an overall excess air of 15 percent. A minimum NO level of 80 ppm was achieved at a SR of 0.75. As in the other firing configurations, reductions in the SR ratio below 0.75 resulted in increased NO levels.

Even though absolute NO levels are different for the various firing configurations, the general shape of the curves is similar with roughly the minimum NO levels occurring at a first-stage SR of between 0.75 and 0.85. These curves are qualitatively similar to well-stirred reactor experiments and calculations where the shape of the curves is due primarily to chemical effects, being only secondarily influenced by mixing and temperature. This suggests a possible chemical control leading to the general shapes of the curves exhibited in Figures 5-31 and 5-32.

The speculation is that with a SR of 0.75 to 0.85, the maximum amount of fuel-N is converted to N_2. This is consistent with the gas fired well-stirred reactor experiments (Reference 5-12) and calculations (References 5-13 and 5-14). This fuel-N derived N_2 is then essentially unavailable for conversion to NO in the oxygen rich second stage. At a SR near 0.8 and below, the amount of NO produced in the first-stage decreases with decreasing SR. Armento (Reference 5-3) suggests that first stage NO decreases to zero at a first-stage SR of 0.65. The bound-N intermediates, such as HCN and NH_3 formed in the first stage in lieu of NO or N_2, must then be oxidized to NO in the second stage to give the observed stack NO levels. Therefore, the key to low NO levels is to trap as much fuel-N in N_2 as is possible. This amount of fuel-N will then remain essentially unavailable for conversion to NO in the oxygen-rich second stage.

The experimental results are at least in qualitative agreement with equilibrium constraints. For example, Sarofim (Reference 5-13) has shown that the equilibrium concentration of NO and the bound nitrogen intermediaries, which can be oxidized to NO in the second stage, reach a minimum at a SR dependent on temperature and fuel type and increase as the SR is further reduced. The oxidation of the intermediaries in the second stage can constitute a lower limit to NO_x reduction achievable by staging. Another limiting condition could arise from the fraction of the fuel nitrogen which remains in the coal char after pyrolysis (References 5-4 and 5-11). Pershing (Reference 5-4) has estimated that 100 to 200 ppm of total NO_x emissions are due to char NO_x under fuel-lean conditions. Furthermore, the oxidation of the char nitrogen to char NO_x proceeds slowly and is relatively insensitive to first-stage conditions. The formation of char NO_x in the second stage could thus be another fundamental limit to the effectiveness of staged combustion for NO_x control.

It should be noted that all of the results presented in this section were for a single fuel of a given bound nitrogen and sulfur content. Fuel sulfur has been shown (Reference 5-9) to affect flame NO levels. This will impact the relative NO levels but not the general shape of the curves with SR. This point will be confirmed in Section 5.3.4.

Figure 5-34 compares the FWF results achieved in this study with those from other pilot-scale tests (References 5-1 and 5-3) on a

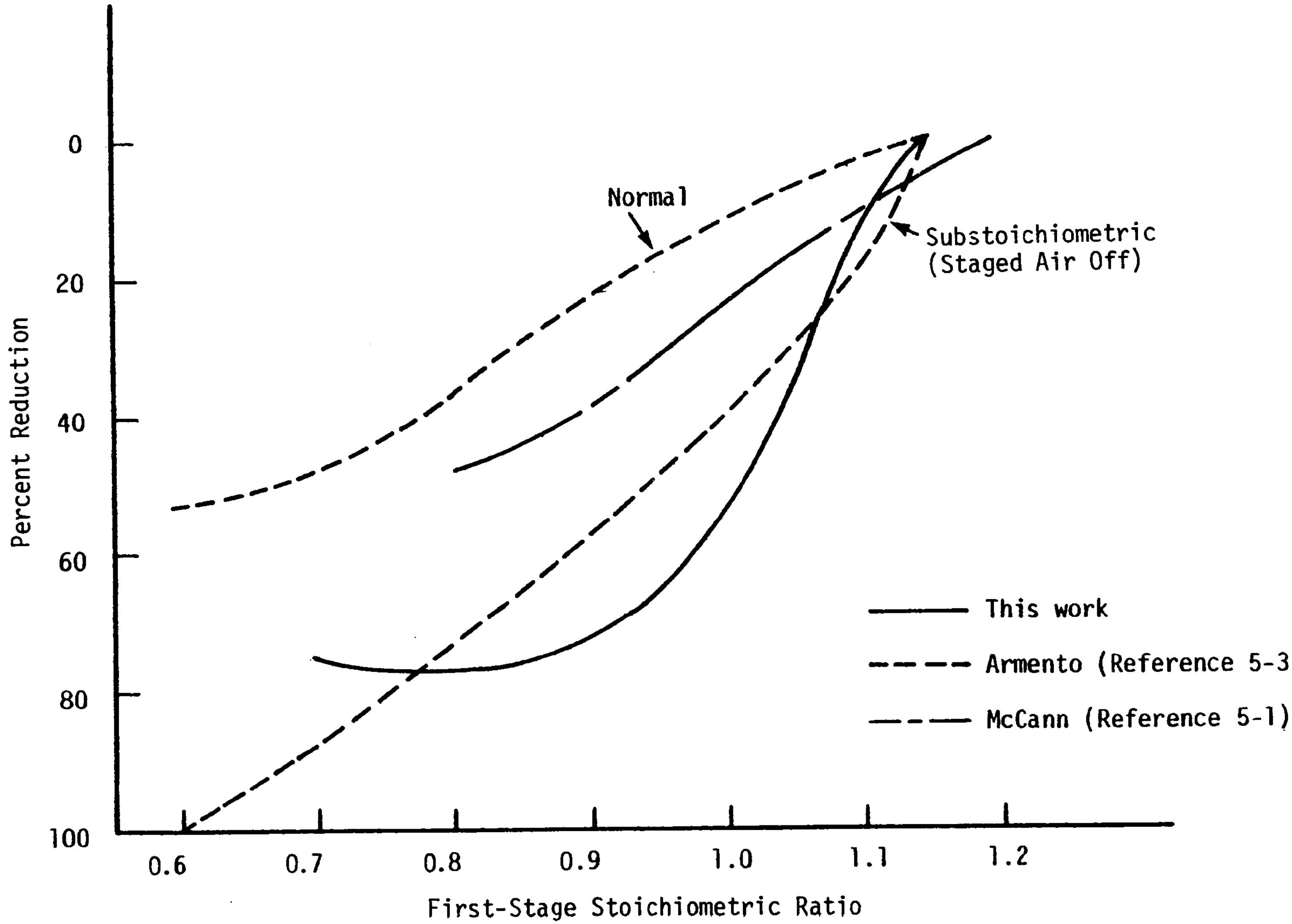


Figure 5-34. Comparison of NO reduction vs. first-stage stoichiometric ratio for front-wall-fired units.

percent reduction basis. Data from this study falls below that obtained elsewhere, except for the substoichiometric data of Armento (Reference 5-3). It is believed that the lower levels of NO achieved in this study are a result of a lack of the backmixing of second-stage air into the first stage. This conjecture is also somewhat borne out by the greater degree of comparison between the present results and the substoichiometric curve of Armento.

In conclusion, NO results for staged combustion have been achieved for a variety of first-stage SRs which are similar to results achieved elsewhere. For delayed staging or long residence times the shape of these curves appears to be consistent with a chemical limitation of fuel-N conversion to NO_x. The quantitative differences between the FWF, tangential and HE firing results are due to mixing, local SR, temperature and residence time effects. These effects will be addressed in subsequent sections.

5.3.2.2 First-Stage Residence Time

Conventional applications of staged combustion inject the staged air directly over the primary flow with a resulting first-stage bulk residence time of less than 1 second. This is done both for convenience and to ensure adequate second-stage residence time for CO and carbon burnout. Several studies have suggested, however, that increased first-stage residence time enhances NO_x reduction (References 5-1, 5-5, 5-16, 5-17 and 5-19). This is consistent with fundamentals since increased residence time at fuel-rich conditions should promote the driving off of the char-bound nitrogen prior to oxidation in the second stage, and promote the reactions which convert fuel-N to N_2.

Tests were conducted in the FWF, tangential and HE configurations to explore the effects of bulk residence time on NO_x formation.

It should be recognized that the bulk residence time is indicative of an average residence time assuming that all of the fluid within the furnace volume is in motion. If there are substantial pockets of stagnant nonreacting fluid within the combustion volume, then the actual residence time for the reacting gas is much less than the bulk value. The motion of the gases within the furnace is a complex function of burner parameters such as injection velocity, swirl and overall system parameters such as SR, load, combustion volume and combustion chamber configuration. The substantial difference in these parameters between tangential, FWF and HE configurations gives different actual residence times for essentially equivalent bulk residence times.

Taking the horizontal extension firing case as an example, if burner swirl were zero, it might take tens of burner diameters or several feet to significantly decay burner axial velocity. At this location, the actual residence time of particles and gases on the axis might be a factor of 10 less than the bulk residence time value. This difference in time is substantial and can lead to conditions quite different than expected for those of the order of the bulk residence time. Even though bulk residence time is not a precise measure of residence time, it is utilized as a correlating parameter in this study because it is easy to determine, can be correlated with the actual residence time for fixed geometry and flow conditions, and is a parameter which has been applied in similar studies. However, the limitations of this parameter, especially when comparing results from various firing configurations, should be kept in mind.

To examine residence time effects for tangential and FWF firing in the main firebox, three stage-air injection positions (see Figure 5-30 for location) and two loads, 293 and 440 kW (1.0 and 1.5 x 10^6 Btu/hr), were investigated. With the HE configuration (Figure 5-33) much shorter residence times were explored at loads of 249 and 381 kW (0.85 and 1.3 x 10^6 Btu/hr). The reduced loads were used in order to maintain approximately the same heat release per unit volume as with the firebox configuration. Also four burners were used instead of five in order to maintain constant burner aerodynamics. Baseline tests in this HE mode revealed nearly identical NO versus excess air curves as compared to the FWF firebox data.

The variation of NO with residence time is shown in Figures 5-35 and 5-36 at various first-stage stoichiometric ratios for the FWF and tangentially fired configurations, respectively. The variation in NO with residence time for the HE over a much broader range of residence times is shown in Figure 5-37. The residence times here are volumetric bulk residence times determined by the mass flowrate and flue gas density calculated at an average temperature of 1204°C (2,200°F) assuming well-stirred conditions over the furnace volume.

The FWF, tangential and HE stack NO data given in Figures 5-35, 5-36 and 5-37, respectively, show that, for all fuel-rich SRs, stack NO increases as bulk residence time decreases. These results also show that the rate of decrease of stack NO with residence time increases as SR decreases. This is clearly shown for FWF, tangential and HE firing in Figures 5-38, 5-39 and 5-40, respectively. In these figures, stack NO for two staging positions are presented as a function of SR. The two staging positions define the residence time to stage-air position, given the volumetric flow rate in the furnace and the temperature. For SRs near 0.8 the stack NO levels show a substantial sensitivity to staging position or residence time. For SRs near 1.0 or 0.6, stack NO is practically independent of residence time. Also,

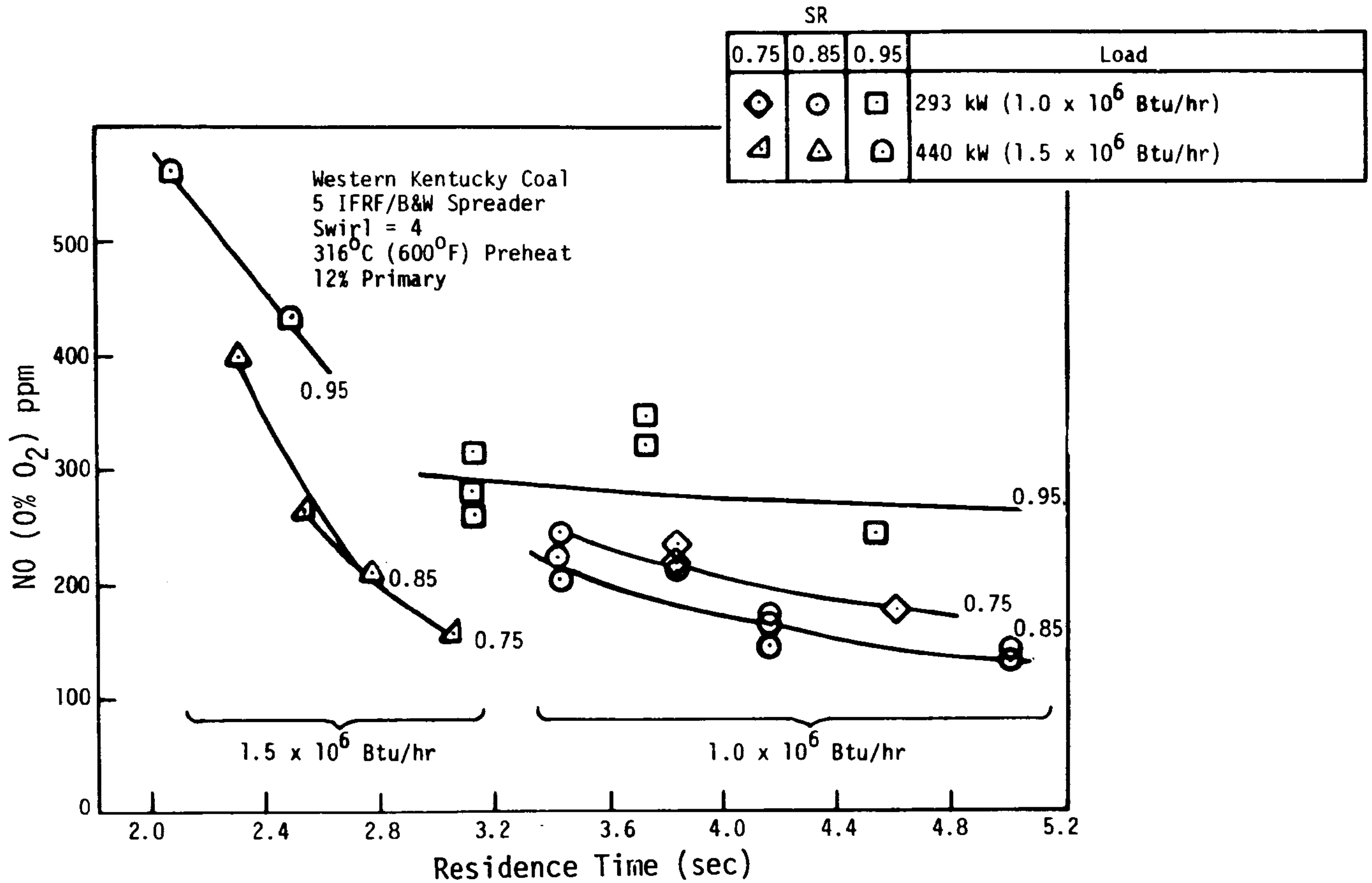


Figure 5-35. Effect of bulk residence time on stack NO (front-wall-fired).

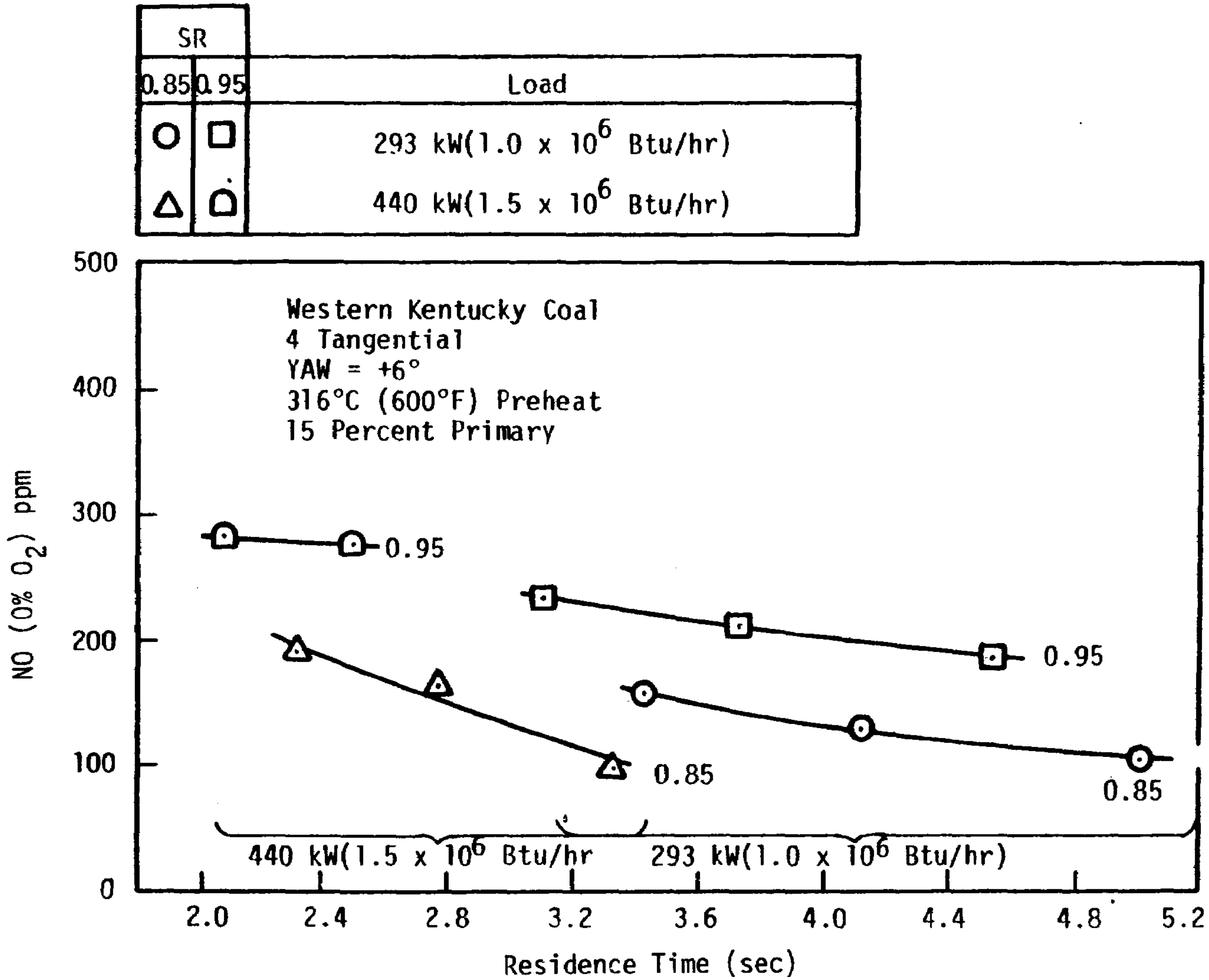


Figure 5-36. Effect of bulk residence time on stack NO (tangentially fired).

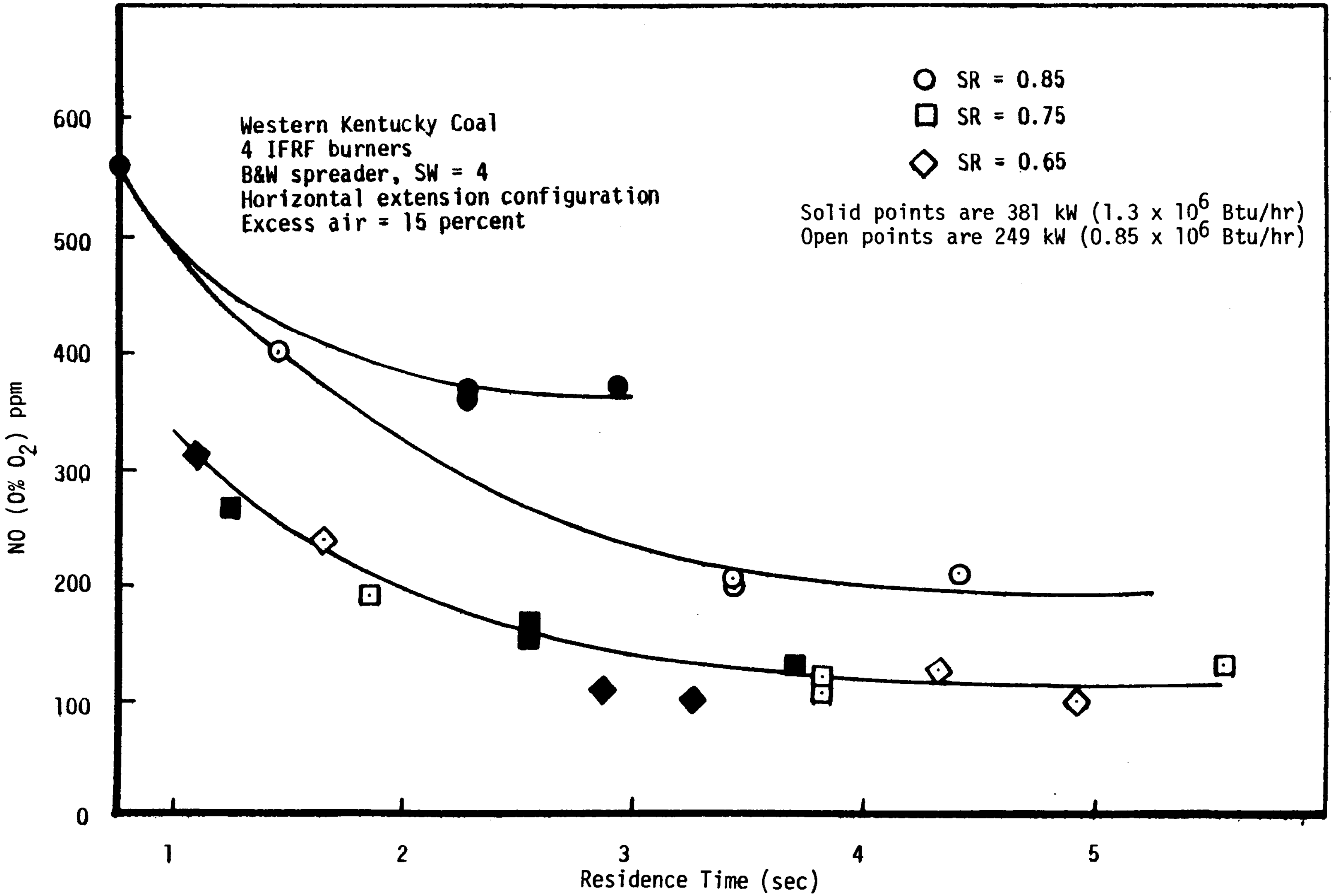


Figure 5-37. Effect of bulk residence time on stack NO (horizontal extension).

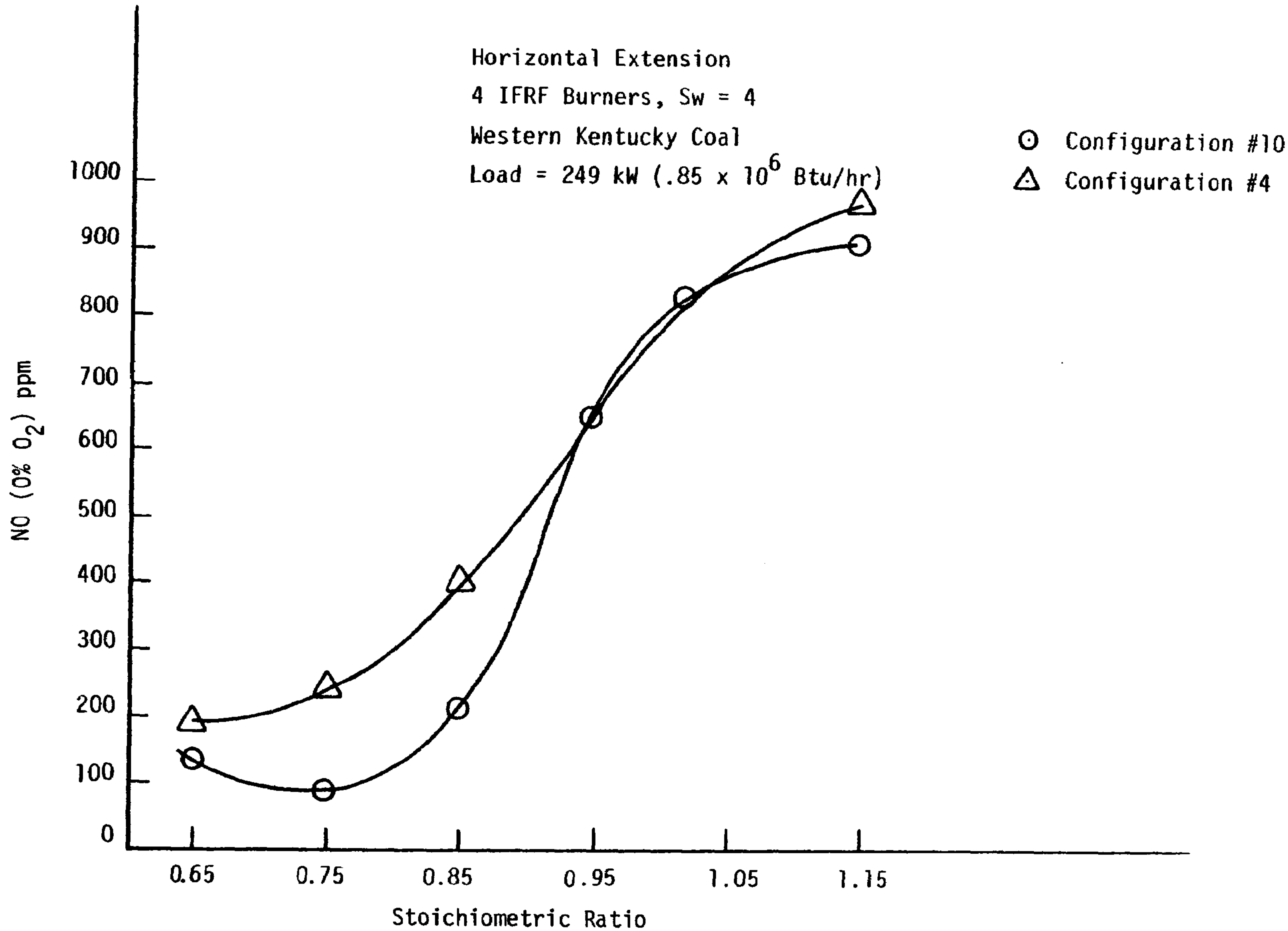


Figure 5-38. Effect of stoichiometry (horizontal extension).

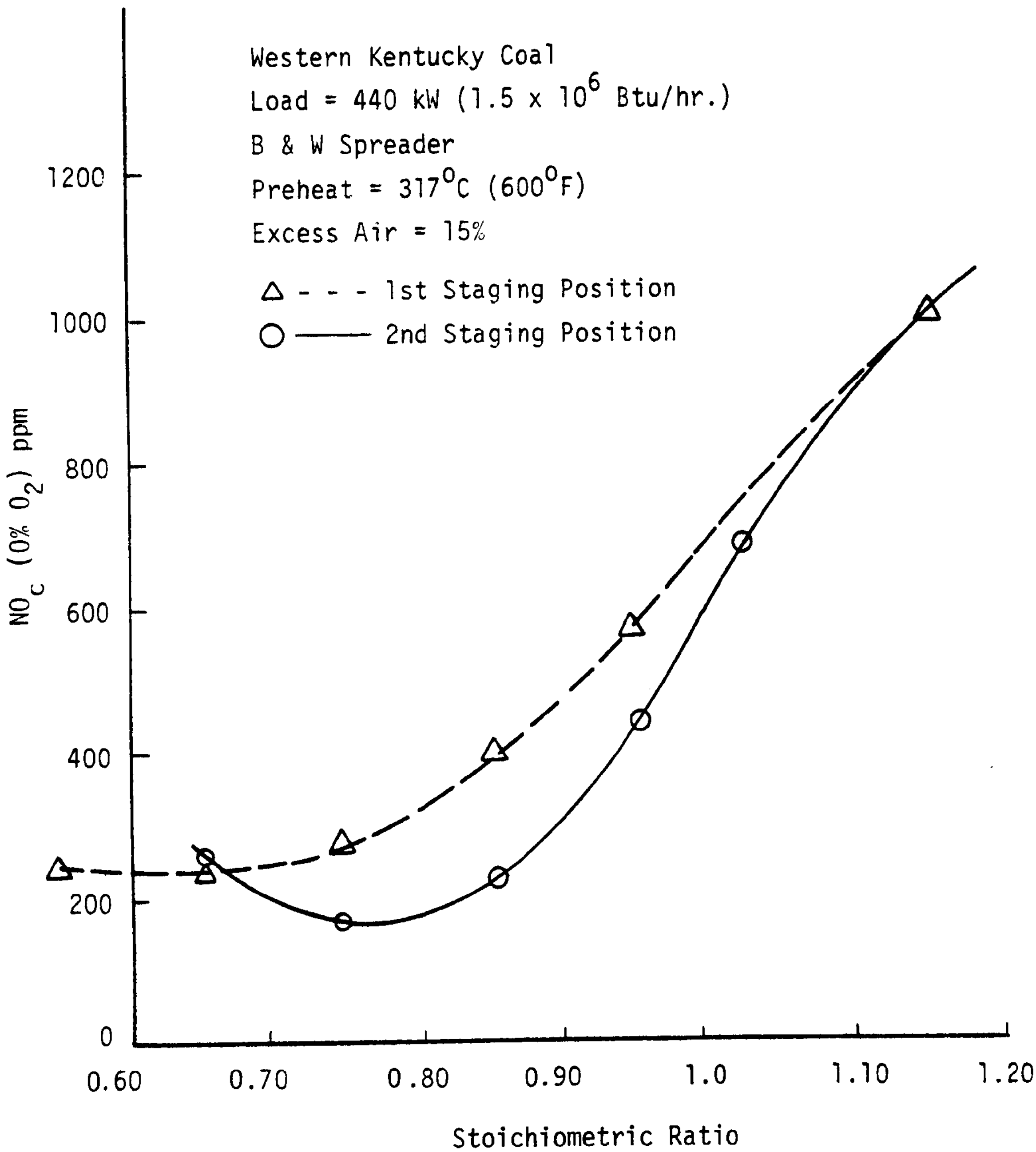


Figure 5-39. Effect of stoichiometry (front-wall-fired).

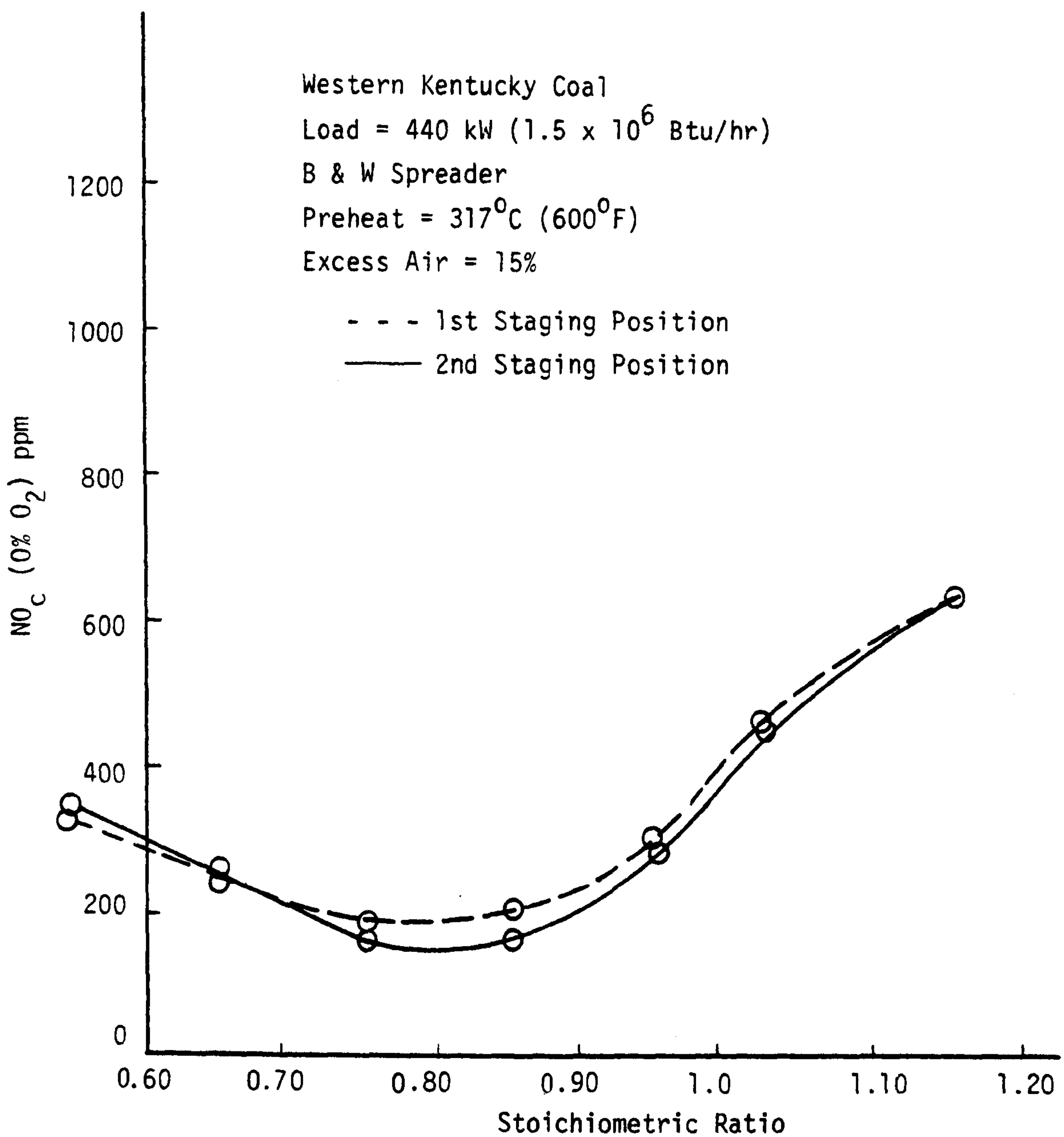
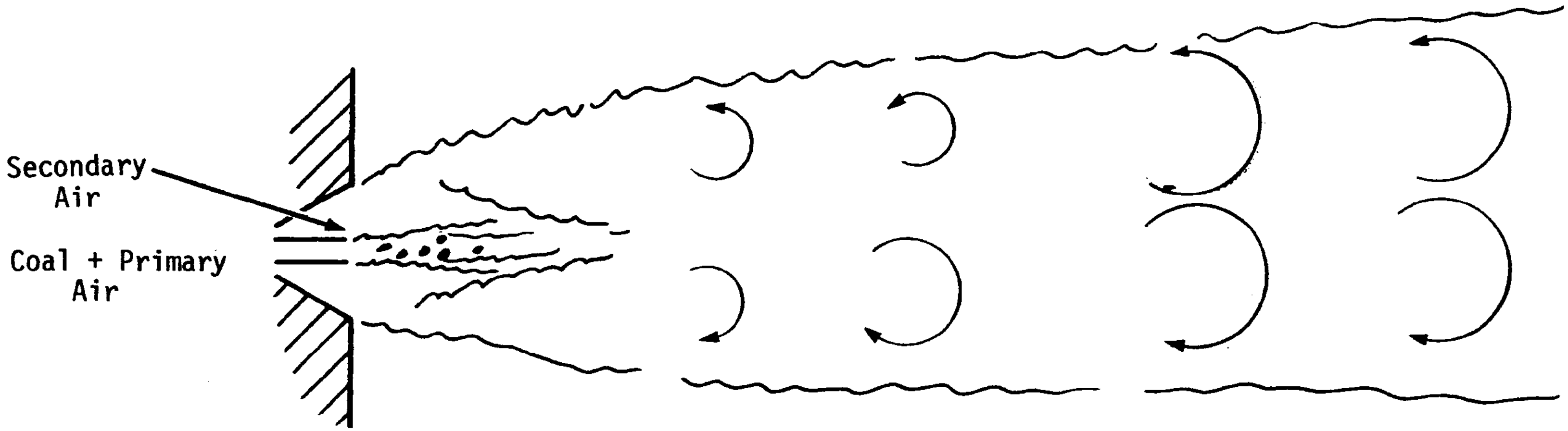


Figure 5-40. Effect of stoichiometry (tangentially fired).

FWF and HE data are more sensitive to residence time than tangentially-fired data.

Some of the difference between these firing systems may be due to actual versus bulk residence time effects. For example, the tangentially fired system probably has more of the combustion volume gases in motion than does the FWF or HE firing configurations. The actual residence time for the tangential system is then probably longer than the actual time for FWF and HE firing at the equivalent bulk residence time. Therefore, the tangential system stack NO data exhibits less sensitivity to residence time because it is further along in the decay process. Even though some differences between the results are due to correlating the data with bulk residence time rather than actual residence time, most of the differences are due to local stoichiometry, mixing and temperature differences in these systems.

The character of the stack NO results is a complex function of chemical and mixing processes. To help interpret these results, the combustion and pollutant formation events occurring in the first stage are conceptually separated into three zones as schematically shown in Figure 5-41. These zones, denoted as near, intermediate, and far, represent zones in a real pulverized coal combustion system in which the local stoichiometry has a significant change in character. Local stoichiometry is defined as the ratio of available fuel up to the end of the zone divided by the available air normalized by the stoichiometric fuel/air ratio. The local stoichiometry is continually changing character in these zones due to the evolving nature of coal combustion. For the coals burnt in this study, a considerable fraction of the fuel (greater than 40 percent) is volatilized during the combustion process and is burnt homogeneously in the gas phase. The time scale of



SR_1	mixing	near zone a	intermediate zone b	far zone c
~1	mixed	$SR_a > 1$	$SR_b \sim 1$	$SR_c \sim 1$
	stratified	$SRa > 1$	$SR_b < 1$	$SR_c \sim 1$
<1	mixed	$SR_a > 1$	$SR_b < 1$	$SR_c < 1$
	stratified	$SR_a > 1$	$SR_b < 1$	$SR_c < 1$

Figure 5-41. Schematic of local SR distributions in fully mixed and stratified combusting systems.

volatization depends on coal heating rate. An estimate of this time scale for the experiments carried out might be on the order of tens of milliseconds. During devolatilization, the oxygen in the combustion air is retarded from reaching the coal surface by the gases evolving from the coal. Heterogeneous combustion of the coal is then slowed during the devolatilization period. The availability of the fuel to the oxygen in the air or the local SR ratio is then a time dependent function whose time scale is roughly that of devolatilization or tens of milliseconds. Major gas phase combustion processes, including fuel-N conversion chemistry in combusting zones, occur on time scales shorter than tens of milliseconds.* Therefore, coal fuel availability to the oxygen in the combustion air is probably rate limiting in these systems.

In addition to fuel availability limitations, oxygen availability is varying in these systems due to the rate of mixing between the primary and secondary streams. If the burner is designed (i.e., injection velocities, swirl, etc.) to rapidly mix the primary and secondary streams, oxygen availability is not limiting and the local stoichiometry is primarily a function of fuel availability. However, if the burner is configured for slow mixing, oxygen availability as well as fuel availability can be rate limiting. Therefore, the relative rates of these processes determine the local stoichiometry and the spatial and time extent and uniformity of the near, intermediate and far zones as schematicized in Figure 5-41. Referring to Figure 5-41, the near zone local stoichiometry is shown to be fuel-lean for all first-stage stoichiometries and mixing rates. This is because the fuel initially available from the coal always sees an abundance of oxygen. Combustion of the initial concentration of fuel and fuel-N always occurs

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*Fuel sulfur might affect the homogeneous NO formation time scale to some extent depending on local conditions (see Reference 5-9).

under lean conditions and most of the fuel-N evolved will go immediately to NO. Very little fuel-N will be converted into N_2 within this zone. Therefore, volatile fuel-N conversion to NO will be very high in the near zone.

The intermediate zone is where most of the volatile fuel and fuel N components evolve and react. Depending on the overall first-stage SR and the mixing rate of primary and secondary air, combustion and pollutant formation processes can occur in a locally rich or lean environment in this zone. If the first-stage stoichiometry is rich, then combustion will probably occur under locally rich conditions for both fully mixed and stratified or unmixed conditions. Therefore, some of the fuel-N evolved in this region will be converted to N_2 rather than nitrogen intermediate or NO. In addition, NO generated in the near zone will be reduced to N_2 in the fuel-rich intermediate combustion zone.

For a first stage SR of approximately 1.0, the local intermediate zone SR can be either rich or lean depending on mixing rate. For a poorly mixed or stratified system, secondary air oxygen will only slowly mix into the fuel-rich primary stream. Combustion and pollutant formation will occur under locally fuel-rich conditions and the intermediate zone will have a character similar to that which occurs under a fuel-rich first-stage SR condition. For a rapidly mixed system, the overall intermediate zone SR ratio will be near 1.0 and most of the fuel-N evolved will be converted to NO_x. In summary, the intermediate zone processes will reduce near zone NO_x and convert fuel-N evolved in this zone to N_2 if either the overall first-stage SR is rich or the sytem is poorly mixed and highly stratified.

If the intermediate zone is very rich the evolved fuel-N can be converted to nitrogen intermediates rather than N_2. If it is lean, most of the fuel-N will be converted to NO.

The far zone is represented by a region sufficiently removed from the burner such that the SR achieved is characteristic of the overall first stage SR. In the far zone most of the available fuel has been exposed to the combustion air oxygen. If the overall first-stage stoichiometry is rich, processes in the far zone will tend to further reduce near zone NO to N_2 and some of the remaining fuel-N will be converted to N_2. However, if the overall first-stage stoichiometry is lean then fuel-N will be converted to NO_x and any nitrogen intermediate generated in a rich intermediate zone will be converted to NO_x.

In summary, for either rich or lean first-stage SRs, most of the fuel-N evolved in the near zone is converted into NO_x. For rapidly mixed systems and lean first-stage SRs, much of the fuel-N evolved in the intermediate zone is converted to NO_x. For rich SRs or stratified systems at lean SRs, the fuel-N evolved in the intermediate zone is partially converted into N_2 with some conversion to nitrogen intermediaries and NO_x. In addition, some of the NO_x formed in the near zone is reduced to N_2 in this locally rich zone. For rich SRs in mixed or stratified systems the fuel-N evolved in the far zone will be partially converted to N_2 as well as to nitrogen intermediaries and NO_x. Also, NO_x formed in the near zone will be further reduced to N_2 and nitrogen intermediaries in this rich combustion zone. For lean SRs in mixed or stratified systems the fuel-N evolved in the far zone will be converted to NO_x. In addition, the nitrogen intermediaries generated in the intermediate zone for the stratified system will be converted to NO_x in the fuel-lean far zone. It should be noted that the addition of rapidly mixed stage-air will have the same effect as an overall lean far zone.

The above conceptual model is simplistic and does not take into account "prompt NO" and fuel and thermal NO_x or fuel sulfur interactions. Also, the relative degree of N conversion and the rate of N devolatilization versus fuel devolatilization is not considered. However, these effects will govern the details of NO_x formation and will not alter the overall conclusions developed from this model.

The experimental data is now reexamined in light of the above conceptual model. Based on the model, initial NO should be high for all of the firing configurations and SRs tested. Both the FWF and HE stack NO data, presented in Figures 5-35 and 5-37 respectively, show fairly high early NO levels over the residence times measured. However, these results do not cover a sufficiently low range of residence times to draw any firm conclusion on near zone or early NO.

To gain additional insight into the formation and decay of NO in the first stage, prior to second stage air addition, sampling in the hot fuel-rich first stage in the horizontal extension configurations was performed using the probe shown in Figure 5-42. This is a water-cooled, water injection probe which rapidly quenches the hot gases and coal or char particles sampled from the first stage. The horizontal extensions were set up with the stage air introduced at the longest possible residence time and with samples taken at various distances (or residence times) from the burner. Figure 5-43 shows the NO levels as a function of residence time and stoichiometric ratio. These NO results confirm the existence of high levels of near zone or early NO which then decays in the fuel-rich intermediate zone. It appears that the maximum early NO level depends on SR ratio with

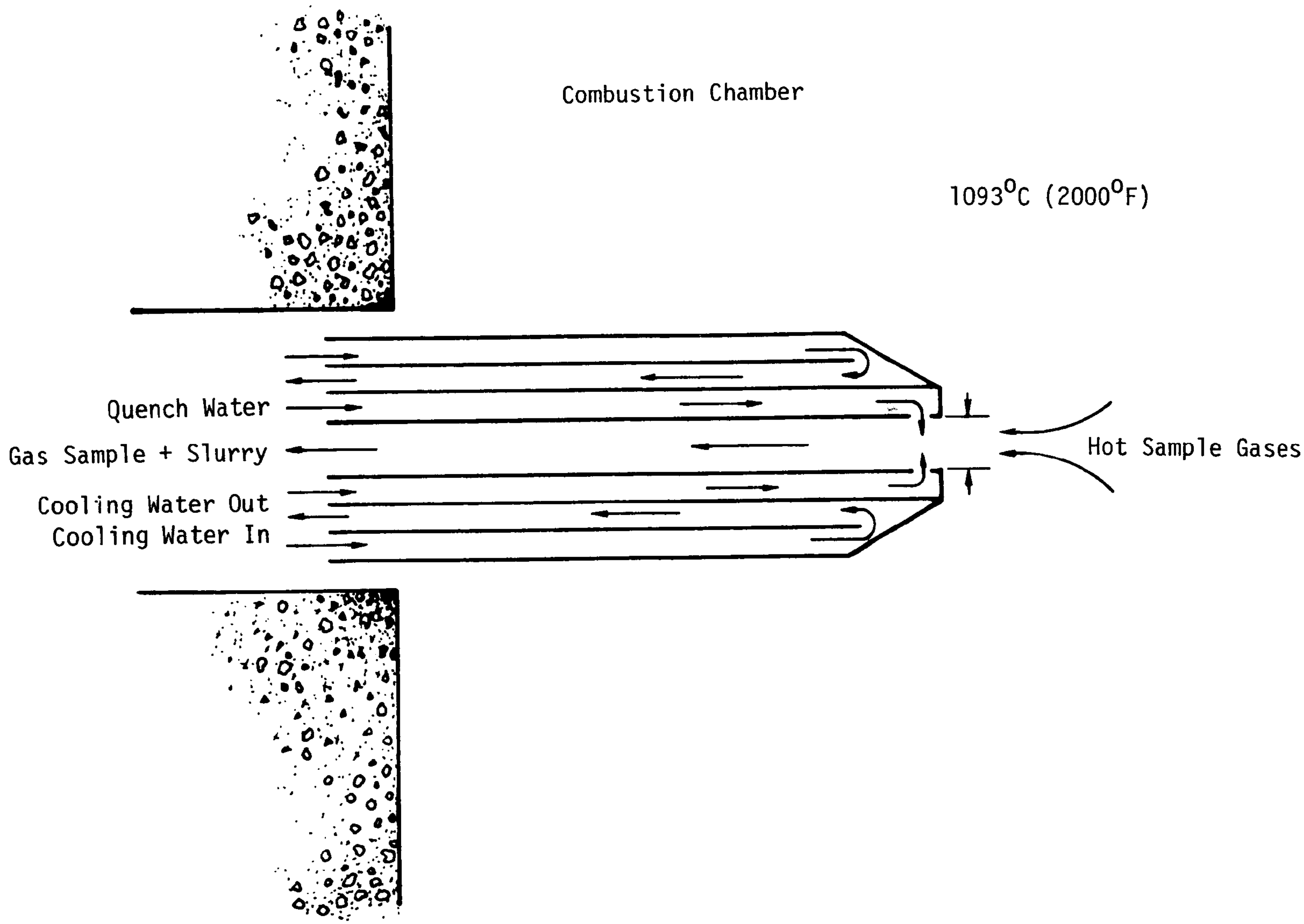


Figure 5-42. Schematic of hot sampling probe.

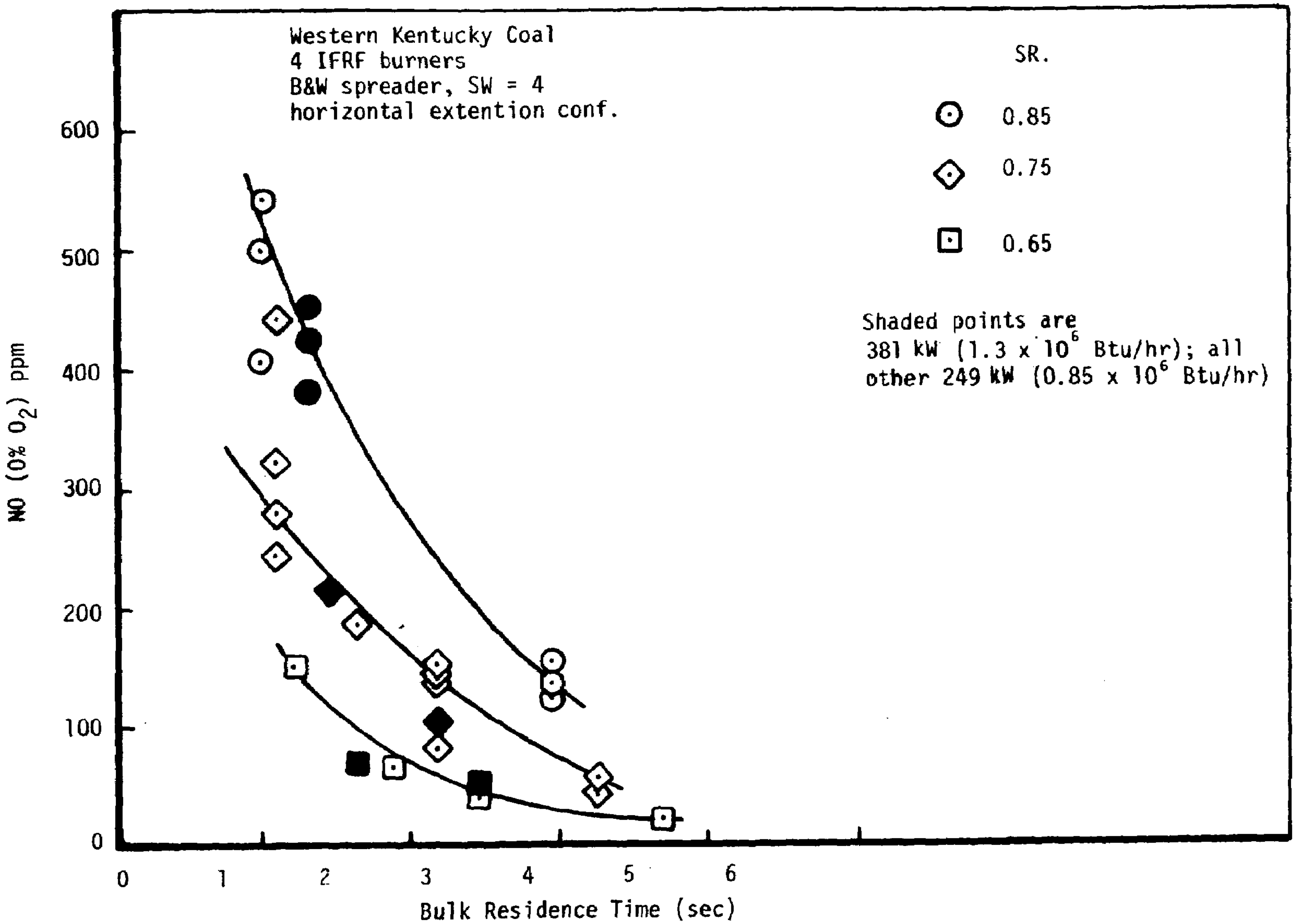


Figure 5-43. NO versus residence time in the first stage.

higher SR yielding higher early NO. However, measurements at earlier residence time were not possible to quantify the maximum early NO levels achieved as a function of SR. It should be noted again that the actual residence time can be 0.1 or less of the bulk residence time for this firing configuration. Therefore, actual residence times are probably on the order of tenths of seconds or less rather than seconds.

At sufficiently low SR and long residence time the local NO presented in Figure 5-43 appears to nearly vanish. Comparing this result to the stack NO results given in Figure 5-37 indicates that second-stage NO for low SRs is probably formed from the oxidation of first-stage nitrogen intermediates, such as HCN and NH_3 in the second stage. This adds further evidence to the concept of one optimal minimum-stack-NO SR at which maximum N_2 is produced and below which nitrogen intermediate production is favored. These intermediates can then be oxidized to NO in the oxygen rich second stage. Firm proof of this concept awaits the measurement of nitrogen intermediates in the first and second stages. Examining the FWF and HE results given in Figures 5-35 and 5-37, it can be seen that the rate of decay of stack NO is slower for the leaner SRs. This is consistent with the conceptual model where, reduction of near zone NO_x and generation of intermediate zone NO_x or N_2 depends on the overall richness of the first stage SR. For very lean systems no decay of NO should be observed. For a first-stage SR around 1, in this rapidly mixed system (i.e., high swirl, coal spreader) little N_2 and decay of first-stage NO_x is produced in the intermediate zone and stack NO levels are high. For lower SRs, production of N_2 and thereby the decay of NO with residence time is more rapid. For very low SRs, N_2 production is reduced in the intermediate zone and nitrogen intermediaries are increased. This will yield increased stack NO levels when the nitrogen intermediaries are oxidized in the second stage.

The tangential firing stack NO results given in Figure 5-36 show less sensitivity to residence time and do not exhibit high initial values noted in the FWF and HE results. The tangential system does not have swirl or a coal spreader device. Therefore, this mode of firing is of a slow mix nature. The low levels of NO observed in Figure 5-36 may be a result of the rich intermediate combustion zone reducing the early NO faster than is possible in the rapidly mixed FWF and HE systems. Also, actual residence time for the tangential system may be longer than that for the FWF and HE. If this is the case then we would be looking at the long residence time effect or far zone results for the tangential system in Figure 5-36.

In summary, high NO levels produced in the fuel-lean near zone are partially reduced in intermediate and far zone. The rate and extent of reduction depends on the local stoichiometry and the residence time at those conditions. Local stoichiometry is a function of the relative rates of coal devolatilization and mixing of secondary air with the primary coal stream. Once the near-zone NO is formed, it takes a considerable amount of bulk residence time to reduce it to low levels. It appears that a slowly mixed system, like the tangential firing configuration where local SRs are lower for a given first-stage SR, is more effective in decaying early NO than highly mixed systems. For a given bulk residence time to stage air addition, a mixing and thereby, local SR distribution could be found to yield minimum NO.

5.3.2.3 First-Stage Mixing

NO_x emissions from unstaged combustion and from staged combustion at

SRs near 1.0 and above are dominated by burner mixing (References 5-2, 5-7, 5-20, 5-21). Detailed study of NO_x control by burner modification is beyond the scope of this program and is covered elsewhere (Reference 5-21). However, the combined effect of mixing and staging was carried through the tests for two reasons. First, burner mixing is important in staging of boilers of conventional design where operation at SR < 0.95 is precluded by operational problems (References 5-2, 5-5). Second, the impact of mixing on NO_x production at low SRs, potentially achievable with new boiler designs, is expected to be insignificant. Therefore, the interaction of conventional burner mixing and staging was experimentally examined over a wide range of first-stage SRs to establish the importance of mixing on NO_x formation under staged combustion conditions.

Changes in the mixing rate between the primary and secondary air stream alter both the local oxygen environment and the heating and devolatilization rate of the coal particles. As discussed in the section on first stage residence time, mixing and the resulting intermediate zone local stoichiometry have a large impact on near zone NO_x reduction and intermediate zone NO_x production. In this study the impact of mixing on NO_x production was investigated by varying the angle of spread of the coal injector, swirl of secondary air and percent of air in primary stream for the FWF configuration. In addition, HE tests with variable coal spreader angles and number of burners were carried out to determine the impact of mixing on this firing configuration. Finally, mixing in the tangential system was just briefly investigated by altering the percent primary air and the angle of the burners.

The coal spreader applied in this study distributes the coal in a conical pattern whose apex is the injection point. The spreader also causes the primary air stream to have an initially diverging pattern. The diverging nature of the spreader flow helps to carry the coal into the secondary air stream. Thus the coal is rapidly mixed with both primary and secondary air. In contrast to this situation, at low swirl, the axial injector has a much slower mixing rate between coal and secondary air. Therefore, the impact of mixing on NO under staged combustion conditions should be clearly demonstrated by comparing results with and without the spreader. In Figure 5-44, stack NO levels under staged conditions with and without the spreader are presented. At a SR near 1.0, for both 293 and 440 kW (1 and 1.5 MBtu/hr) load, the difference in NO level between the axial injector and the spreader is substantial. As the SR decreases, this difference also decreases until, at a SR of around 0.8, the difference is negligible. Referring to the conceptual model presented in Figure 5-41, at a SR near 1.0 the axial injector gives a rich intermediate zone, where near-zone NO_x is reduced and fuel-N is converted to N_2. The spreader gives a leaner intermediate-zone SR; where near-zone NO_x is not reduced and most of the fuel-N goes to NO_x. As the SR is decreased, the far zone, for both the axial injector and spreader, becomes rich thus reducing NO_x formed in either the near or intermediate zone. Therefore, for low SRs and sufficiently long residence times the importance of intermediate-zone mixing decreases and the far-zone local SR dominates the results.

Adding stage-air at earlier times has an impact on NO_x, similar to a lean far zone because NO decay processes are interrupted. For earlier stage-air addition, intermediate zone mixing once again becomes important in determining final NO_x levels.

The higher load results presented in Figure 5-44 produced higher NO than the lower load cases over the entire SR range because of two effects.

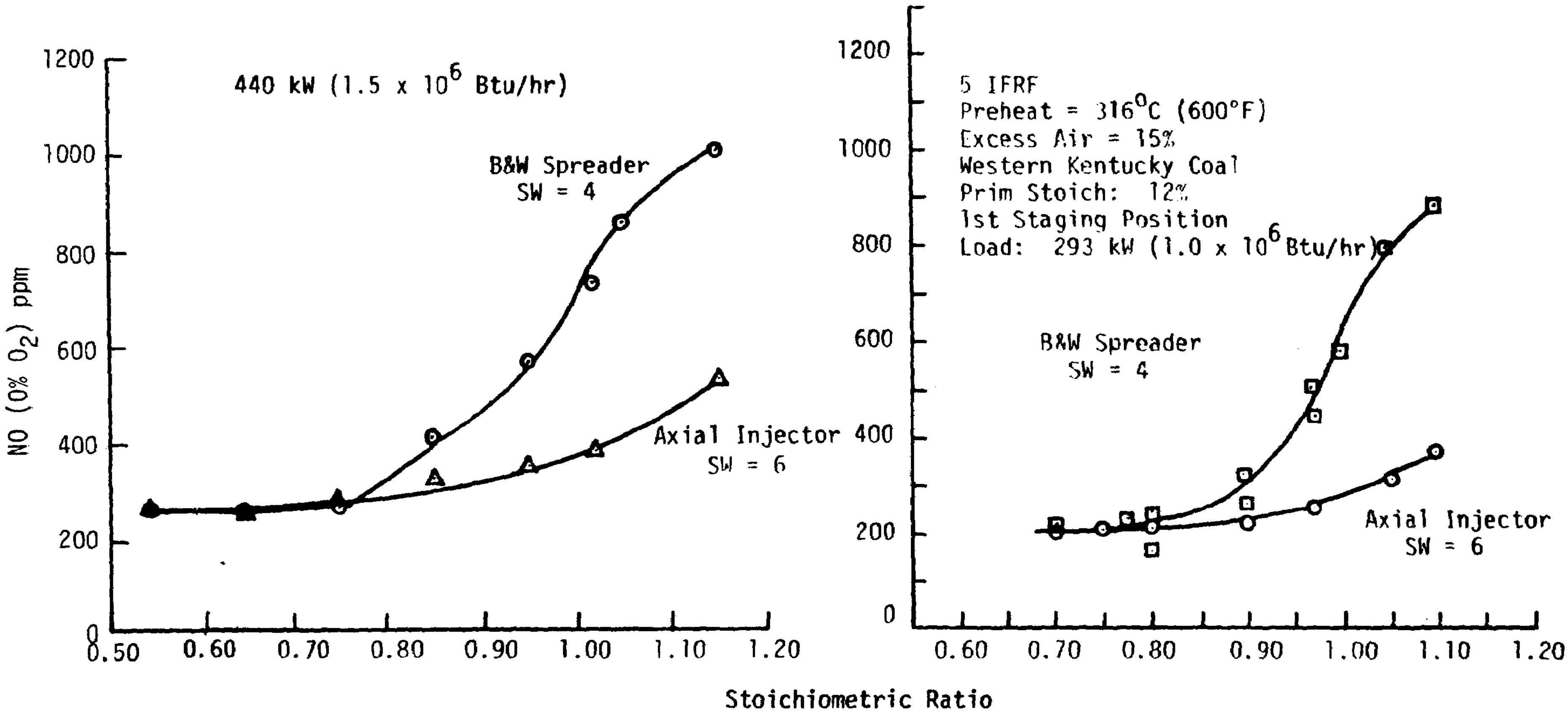


Figure 5-44. Effect of mixing (first stage).

First, at higher loads the injection velocities are greater and the mixing of the streams is improved. Second, temperature is increased at higher load altering the coal combustion rate and leading to additional thermal NO production.

In addition to coal injector design, the effect of mixing coal and combustion air on NO was further explored by varying secondary air swirl and percent primary air flow in the FWF firing configuration. Figure 5-45 shows the effect of secondary air swirl, including the coal spreader, for two stage-air addition positions. At SRs near 1.0, and the second staging position, swirl only has a moderate effect on NO. This is probably because the spreader has effectively mixed the coal and secondary air, and swirl does not enhance mixing significantly for this situation. At low SRs the effect of swirl becomes small, which is consistent with the hypothesis that far zone local SR dominates the NO level at long residence times. Also consistent with this picture at low SRs is the further flattening of the NO with swirl curve for the longer residence time 3rd staging position condition. In addition, the NO levels have decayed to lower levels due to a longer residence time in the locally fuel-rich far zone.

Figure 5-46 shows the effect of altering mixing by increasing primary air flow at both low and high secondary air swirl. Increasing the primary air increases the local oxygen level by increased secondary air entrainment due to higher primary air velocities. It also increases local oxygen by increasing the amount of premixed oxygen due to the greater primary air flow. In the unstaged modes (EA = 15%), increasing the primary air from 12 to 25 percent causes the flame to lift off the burner and the NO to increase dramatically. This is believed to be the result of increased local

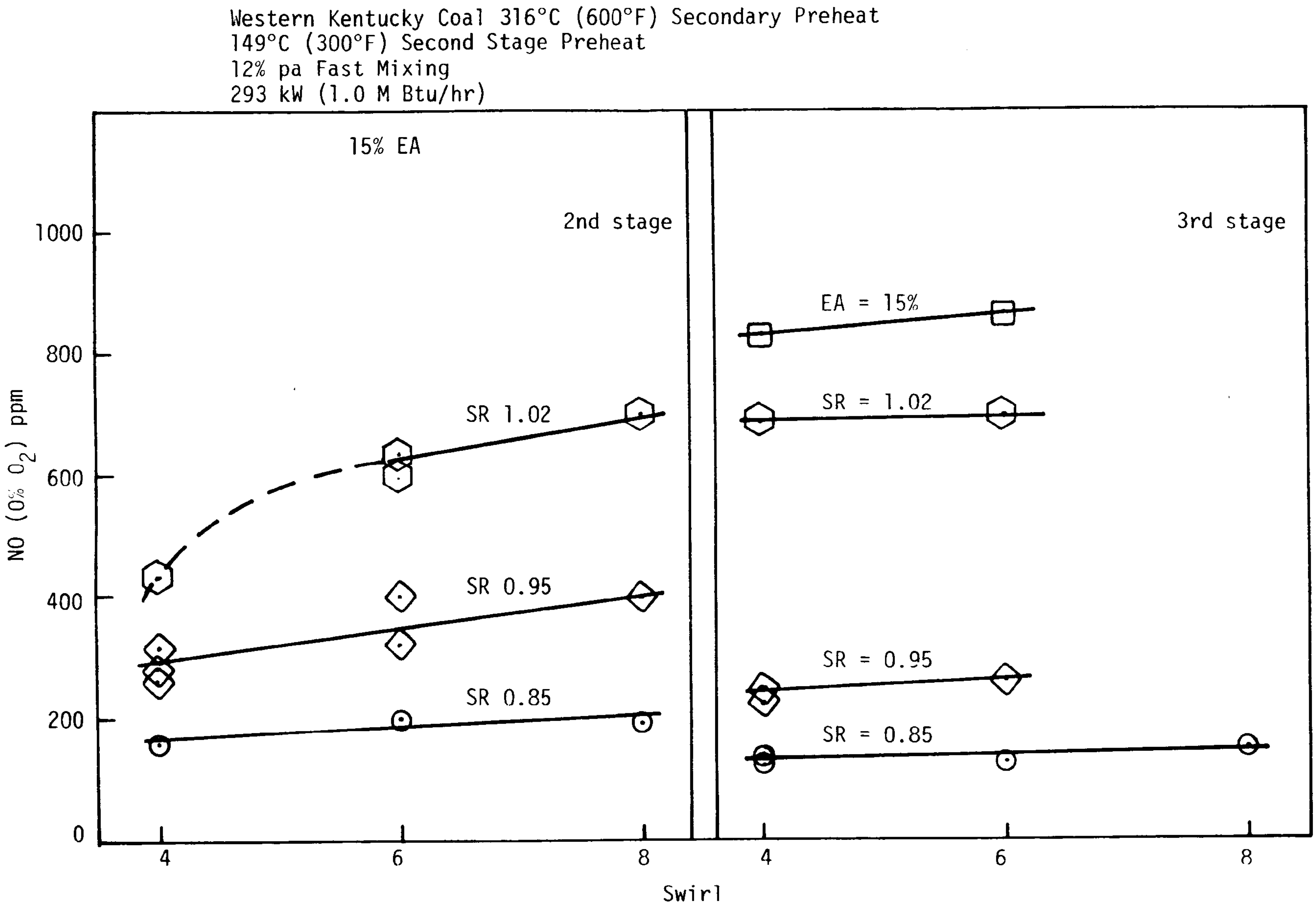


Figure 5-45. Effect of secondary air swirl.

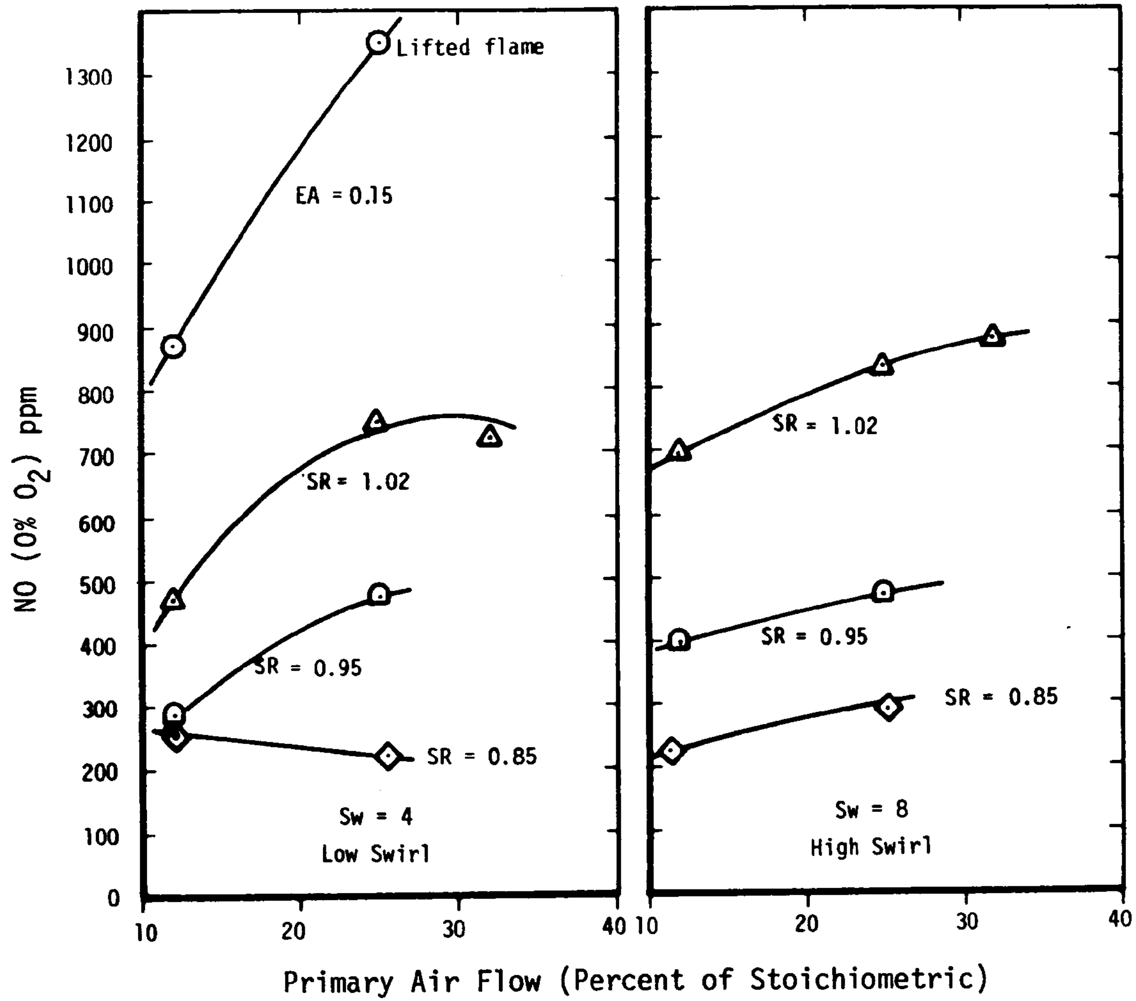


Figure 5-46. Effect of primary stoichiometry (load: 293 kW (1.0 x 10^6 Btu/hr), preheat: 316°C (600°F) first staging position).

oxygen availability at the point of volatile nitrogen evolution. In the lifted flame mode of operation, the primary and secondary air streams have sufficient time to mix with coal before any substantial fuel-nitrogen evolution. When fuel-nitrogen conversion does take place it does so in a locally lean environment and high levels of NO are produced.

Under staged combustion conditions, the increase in NO with percent primary air decreases as SR decreases. At a SR of 0.85 for both high and low swirl the change in NO with percent primary is small, and even negative in the case of small swirl. These results are also consistent with the hypothesis that at low SRs and long residence time, burner mixing does not impact NO significantly. What controls NO in these cases is far-zone local stoichiometry and residence time. For higher levels of swirl, the primary and secondary streams are more rapidly mixed and this gives higher NO levels for SRs of 1.02 and 0.95. The enhanced mixing by swirl reduces the impact of primary air flow changes.

Percent primary air variation results were also obtained for the nonswirling tangential firing configurations at a SR of 0.85. These results, which were obtained on Pittsburgh coal, showed very little change in NO as primary air increased from 10 to 25 percent. This behavior is consistent with the FWF results presented in Figure 5-46 and once again demonstrates that at low SR and sufficient long residence time, mixing does not significantly impact NO levels.

The effect of tangential burner yaw on staged tangential NO levels was also investigated. Yaw is defined as the angle between the diagonal across the firebox and the direction of the burner centerline. As can be seen in Table 5-6, varying the yaw from 0^0 to 9^0 had little effect on NO emissions. Since yaw impacts the way in which the corner-fired burner flames interact in the far zone, these results show that NO emissions are dominated by near- and intermediate-zone processes at SRs near 1.0. As indicated previously, given sufficient resident time at a SR of 0.85, the NO emissions are somewhat insensitive to mixing.

TABLE 5-6 EFFECT OF YAW - TANGENTIALLY FIRED

NO (0% O_2) PPM		
SR	0^o	9^o
1.15	500	550
0.95	197	202
0.85	120	106

Figures 5-47 and 5-48 show the effect of burner size and mixing on NO formation under staged conditions. These results were obtained in the horizontal extension at a firing rate of 249 kW (0.85 MBtu/hr). Burner design was similar with the large burner equivalent in capacity to four small burners. For the long residence time results shown in Figure 5-47, the large single burner has significantly lower NO under staged conditions above a SR of 0.8. Since the four smaller burners mix the primary and secondary streams more rapidly than the single burner, the intermediate zone for the large burner remains richer for a longer period of time than in the small burner case. This gives more near-zone NO reduction and higher

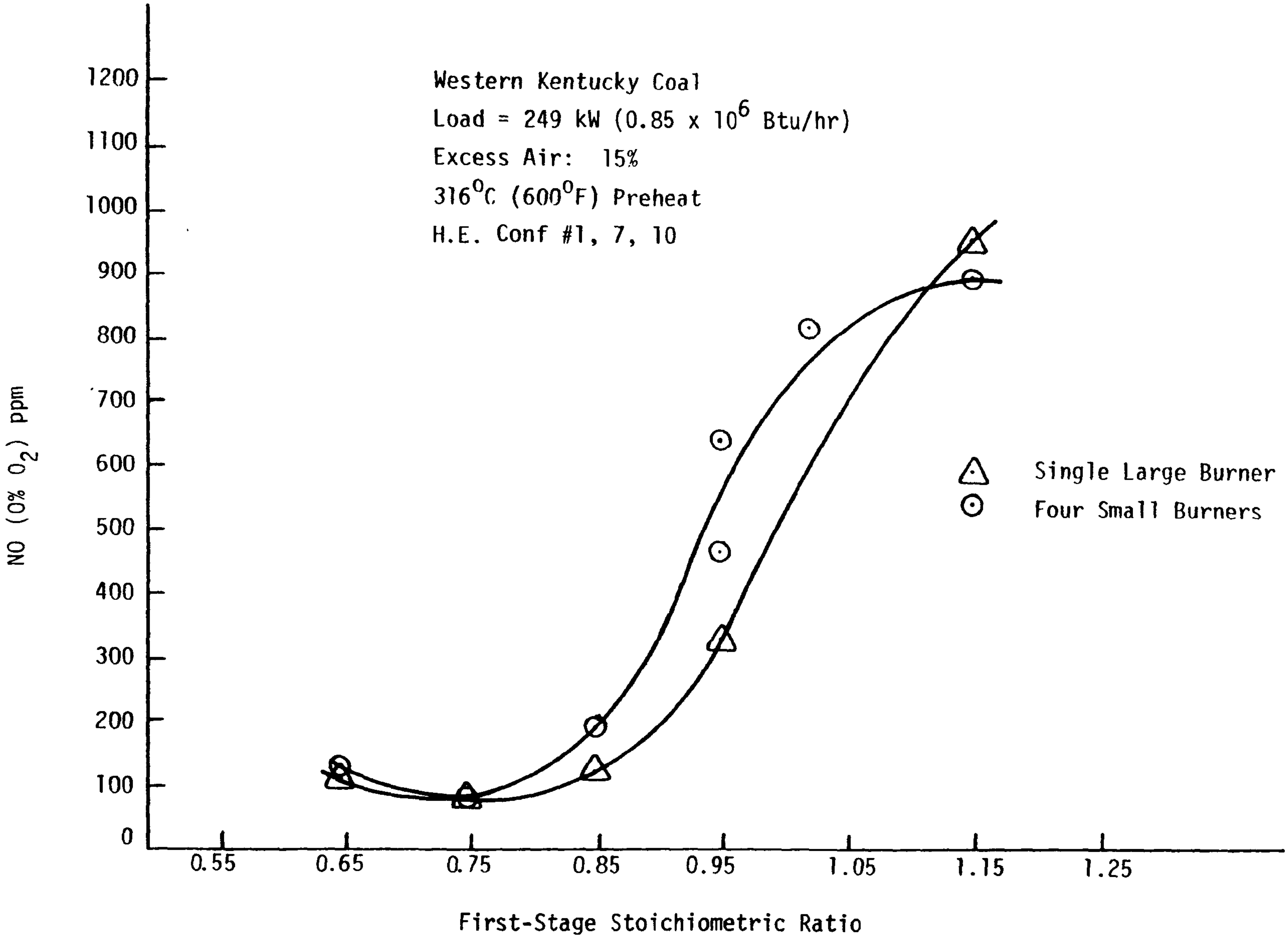


Figure 5-47. Effect of number of burners (long residence time).

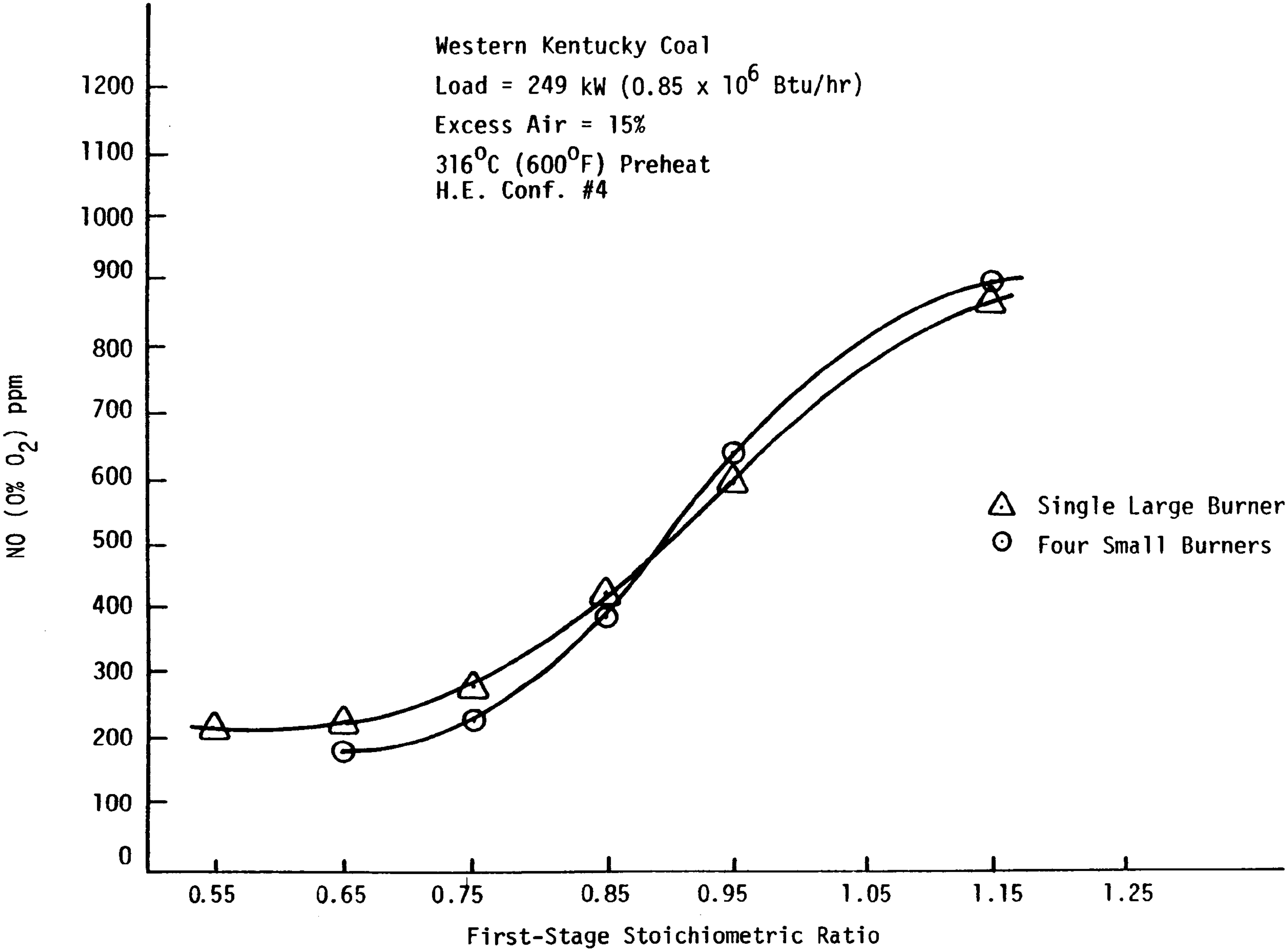


Figure 5-48. Effect of number of burners (short residence time).

conversion of fuel-N to N_2 which leads to lower NO levels. As in the FWF cases, at low SRS the far zone local SR dominates final NO values and the importance of mixing diminishes. Figure 5-48 shows the effect of reducing first-stage residence time under the same conditions as those in Figure 5-47. At SRs greater than 0.9, the single large burner gives lower NO. However, below a SR of 0.9 the four burners achieve lower NO. Besides having a slower mixing history, the large single burner also probably has a slower devolatization and combustion history. For the single large burner, addition of stage air earlier in the process probably interrupts the N_2 production and NO reduction processes before they are complete, resulting in higher NO levels. In the case of the four small burners, the N_2 formation process is more complete and earlier stage-air addition does not impact the NO results as strongly as in the single burner case. This is somewhat confirmed by comparing the four small burners short and long residence time NO results. Down to an SR of 0.95 the results are equivalent for the small burners whereas the large burner results are quite different. The same interruption of N_2 production for the slow-mixed case at short residence time can also be seen in Figure 5-49. These results show that the slow mixing, caused by employing the axial injector on four small burners, has produced lower NO only above 0.85. Below a SR of 0.85 the slow mixing has probably delayed combustion and fuel-N conversion sufficiently to cause the stage-air addition to interrput the N_2 production in the fuel-rich far zone.

These results show that, for long residence times and low SRs (near 0.8), mixing does not significantly impact NO levels. However, at shorter

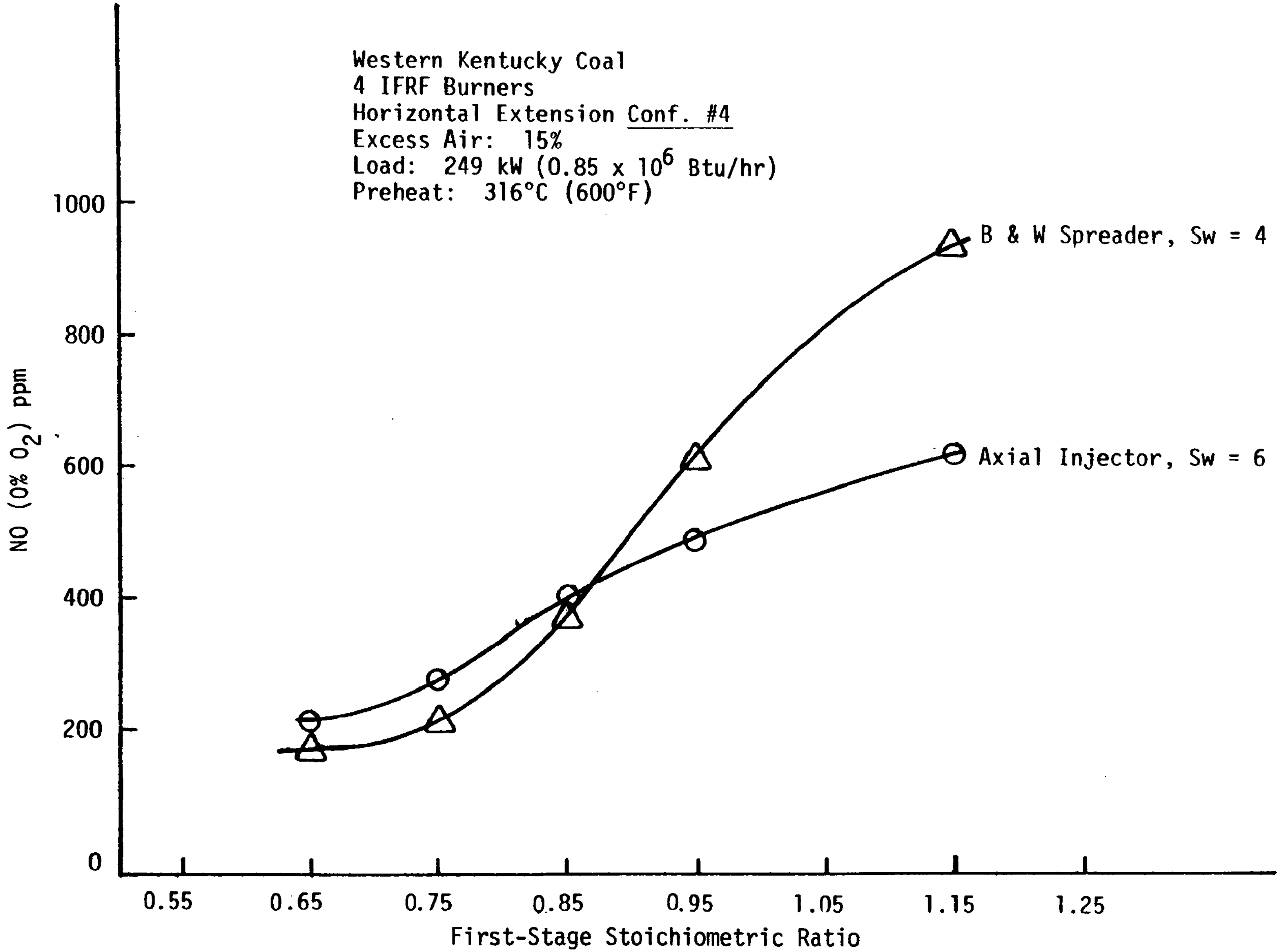


Figure 5-49. Effect of first-stage mixing (short residence time).

residence times and the same SRs, mixing does influence the NO levels because it determines the extent of combustion and fuel-N conversion in the first stage prior to stage-air addition. This can be made clear by referring to Figure 5-41. For a highly mixed system, the near and intermediate zones will be compressed spatially because of enhanced volatilization and combustion. Far-zone reactions will then have a considerable amount of time to decay near-zone NO before stage-air addition. For slow mixing, volatilization and combustion processes are delayed and far-zone reactions do not have sufficient time to decay near-zone NO before stage-air addition. This suggests that under staged condition at low SR, where residence time to stage air addition is limited, mixing in the near and intermediate zones must be carefully considered to minimize NO levels.

5.3.2.4 First-Stage Temperature

The influence of first-stage temperature on NO formation was established by considering extremes in thermal conditions. FWF, tangential and HE firing configuration data were obtained at the upper operating limit of the furnace, 371 - 427°C (700-800°F) secondary air preheat, and alternatively at the lower limit of stable combustion (no air preheat and 38 kW (0.1-0.13 MBtu/hr) additional wall cooling). As Figures 5-50 and 5-51 indicate, under normal combustion conditions (no staging), decreasing the combustion zone temperature reduces the NO emissions. This is almost certainly the result of a reduction in thermal NO formation. In fact, the unstaged NO emissions at low preheat are approximately the same as the fuel-NO measured by Pershing and Wendt (Reference 5-4) for this coal. This is further shown by the gas and coal fired tangential results presented in Figure 5-6 and repeated here as Figure 5-52. The slopes of NO concentration as a function of temperature

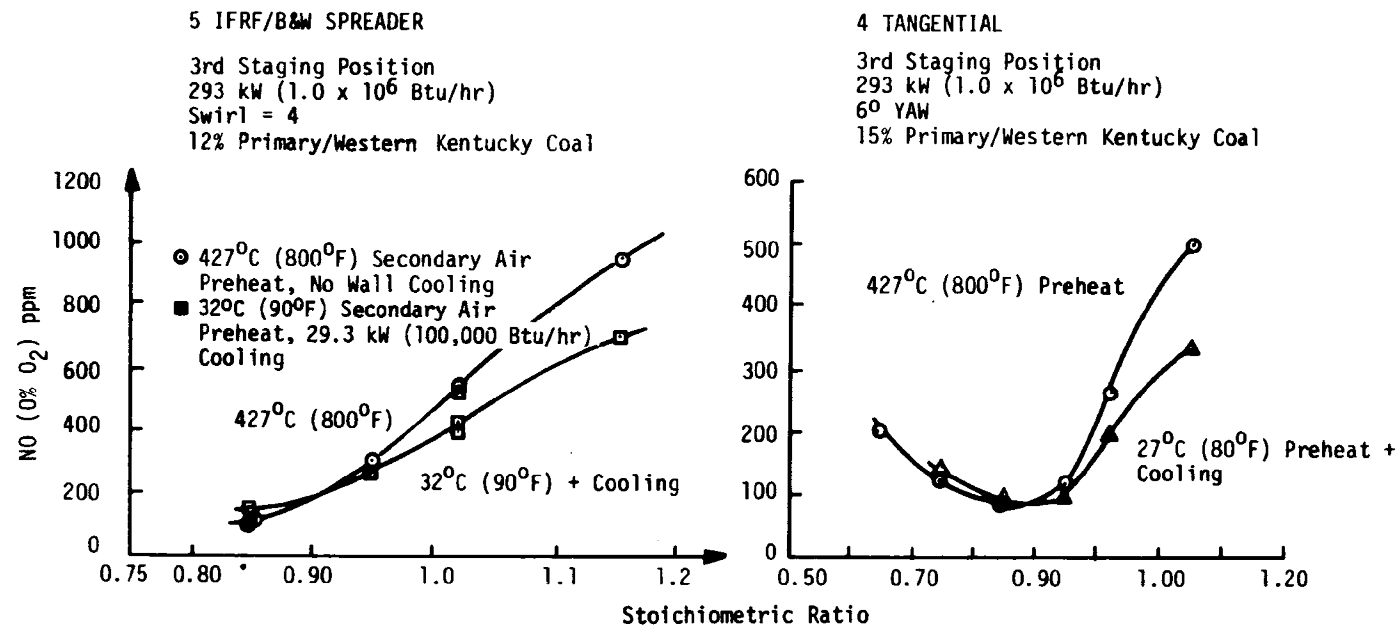


Figure 5-50. Effect of first-stage temperature (FWF and tangential).

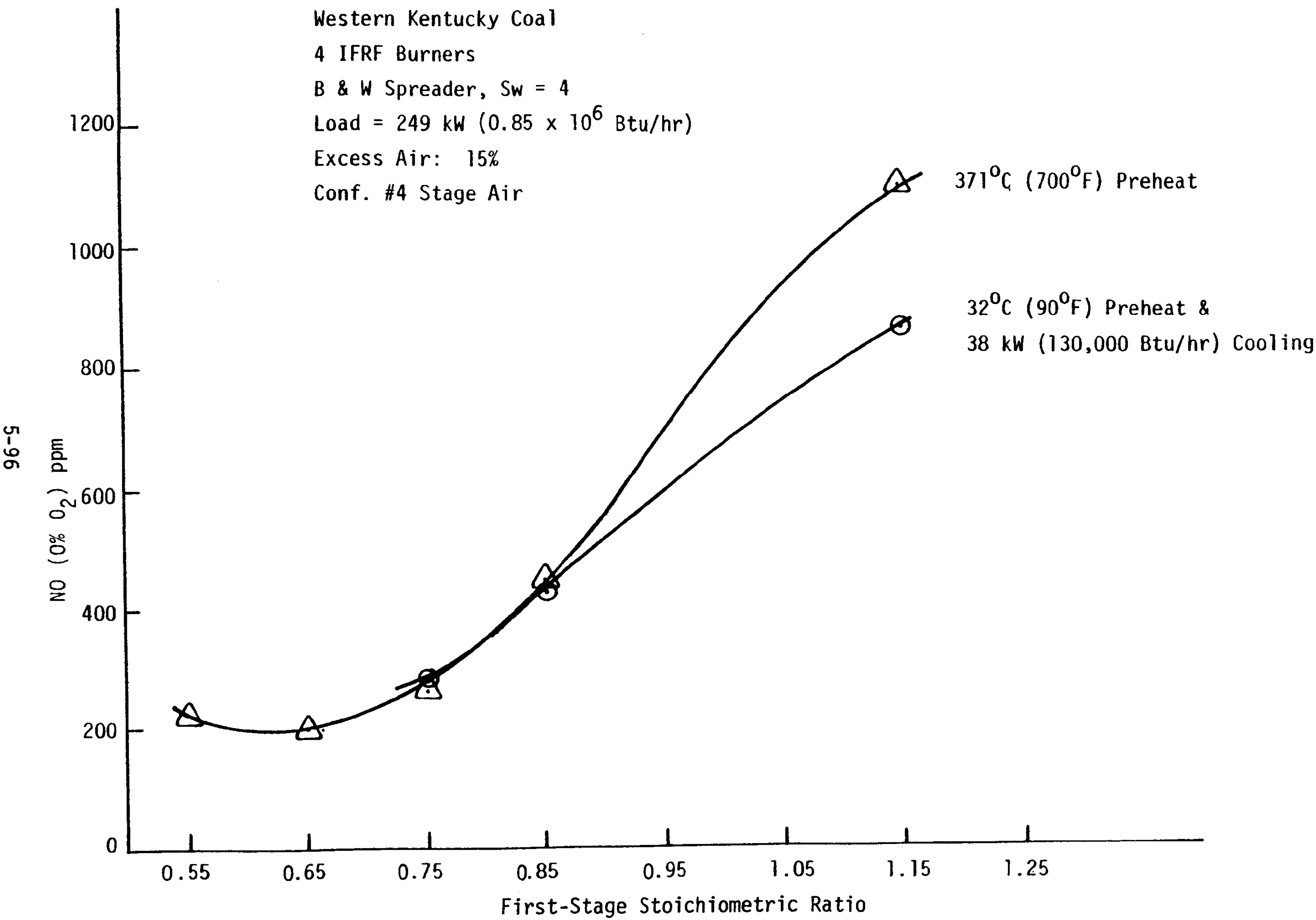


Figure 5-51. Effect of first-stage stoichiometry and preheat (horizontal extension).

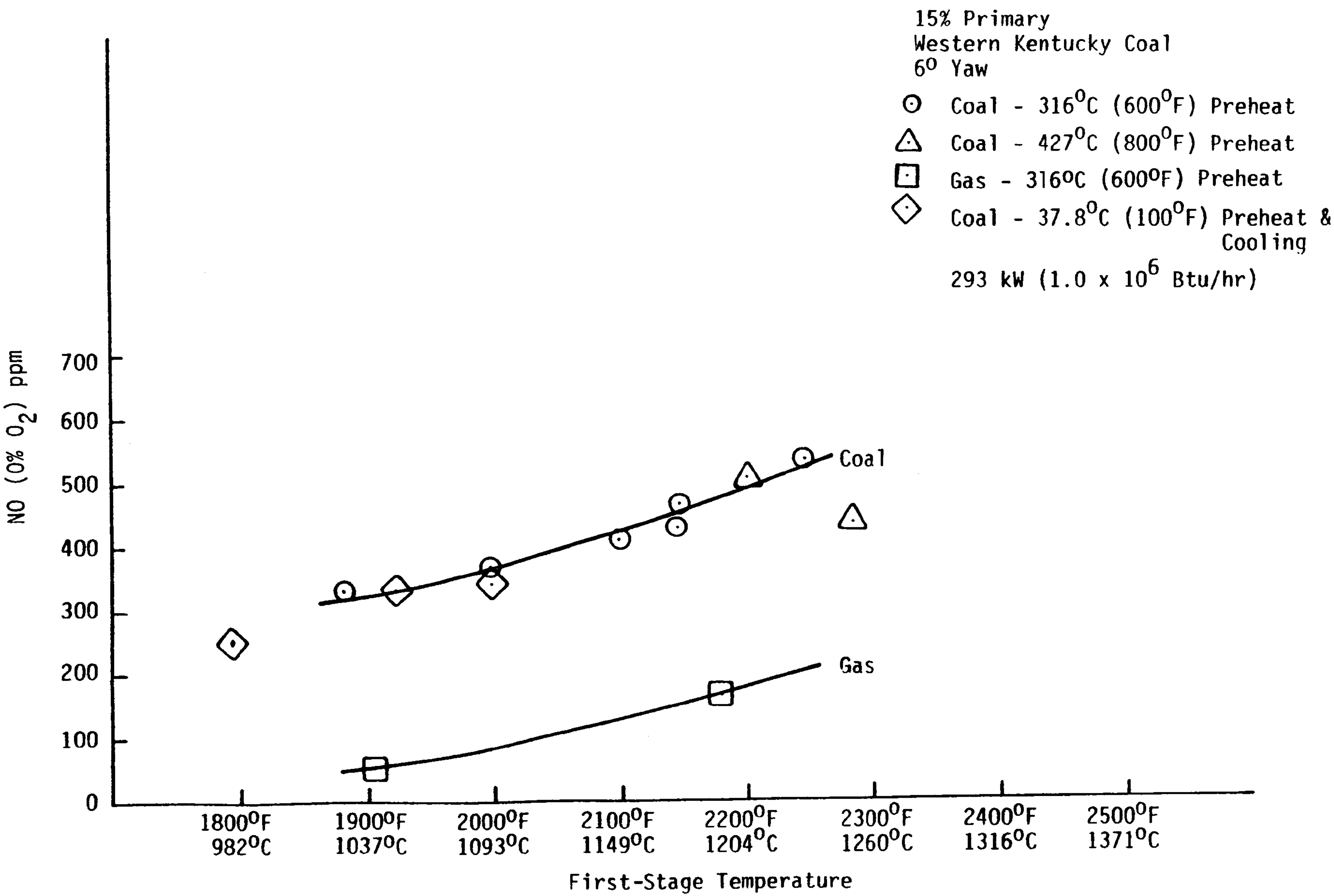


Figure 5-52. Effect of first-stage temperature (tangential).

are the same for gas and coal firing. This would seem to indicate that, near baseline conditions, the change in NO level with temperature is primarily associated with thermal NO rather than fuel-N derived NO. It should be noted that increasing the air preheat increases the injection velocity. Therefore, higher preheat results probably causes enhanced mixing.

Under staged conditions, the influence of combustion zone temperature is a function of first-stage stoichiometry. Near stoichiometric conditions, increasing temperature increased NO; however, at SR = 0.85, an inverse trend was noted. This is clearly shown by the FWF firing configuration data in Figure 5-53. These data were obtained at secondary air preheats of 32°C (90°F), 149°C (300°F), 316°C (600°F) and 427°C (800°F) and are reported in terms of the temperature measured at the end of the first stage using an unshielded Pt-Pt/Rh thermocouple. (Although the measurements cannot be assumed to represent the actual flame temperatures, they provide a means of correlating the data and summarizing the effect.) Blair et al., (Reference 5-22) and Pohl and Sarofim (Reference 5-11) have shown that under controlled pyrolysis conditions the yield of volatile nitrogen increases with increasing temperature. Under locally lean conditions this might convert more fuel-N to NO. However, under locally rich conditions, the evolved fuel-N might be more rapidly reduced to N_2 in the high temperature environment, giving lower final NO levels. This conjecture is consistent with the data presented in Figures 5-50, 5-51 and 5-53.

The above conclusions apply if the residence time before stage-air addition is sufficiently long to allow for the reactions to reduce as much fuel-N as possible to N_2. For shorter residence times, the far-zone processes are interrupted and the final NO results are altered. Figure 5-54

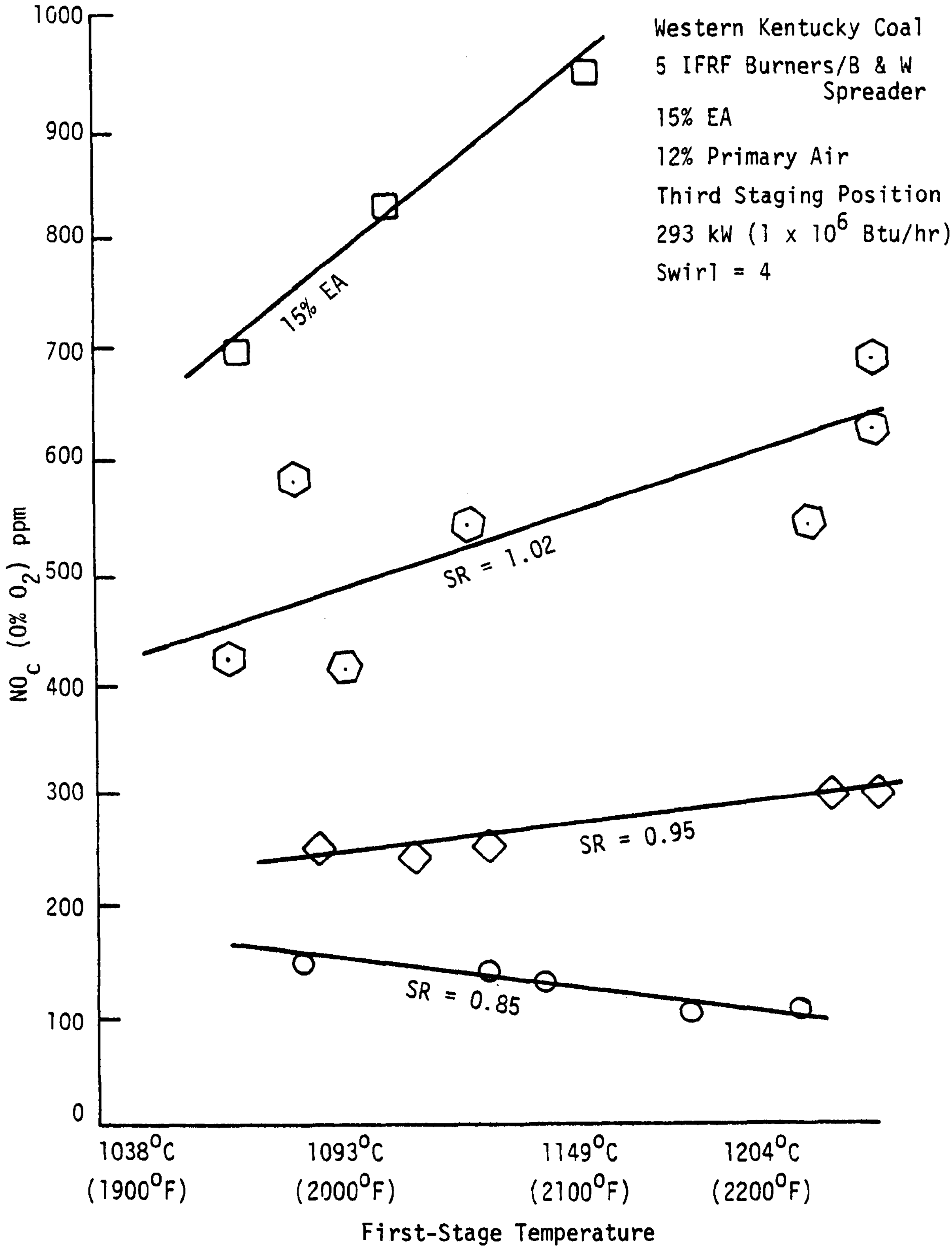


Figure 5-53. Effect of first-stage temperature and SR (front-wall-fired).

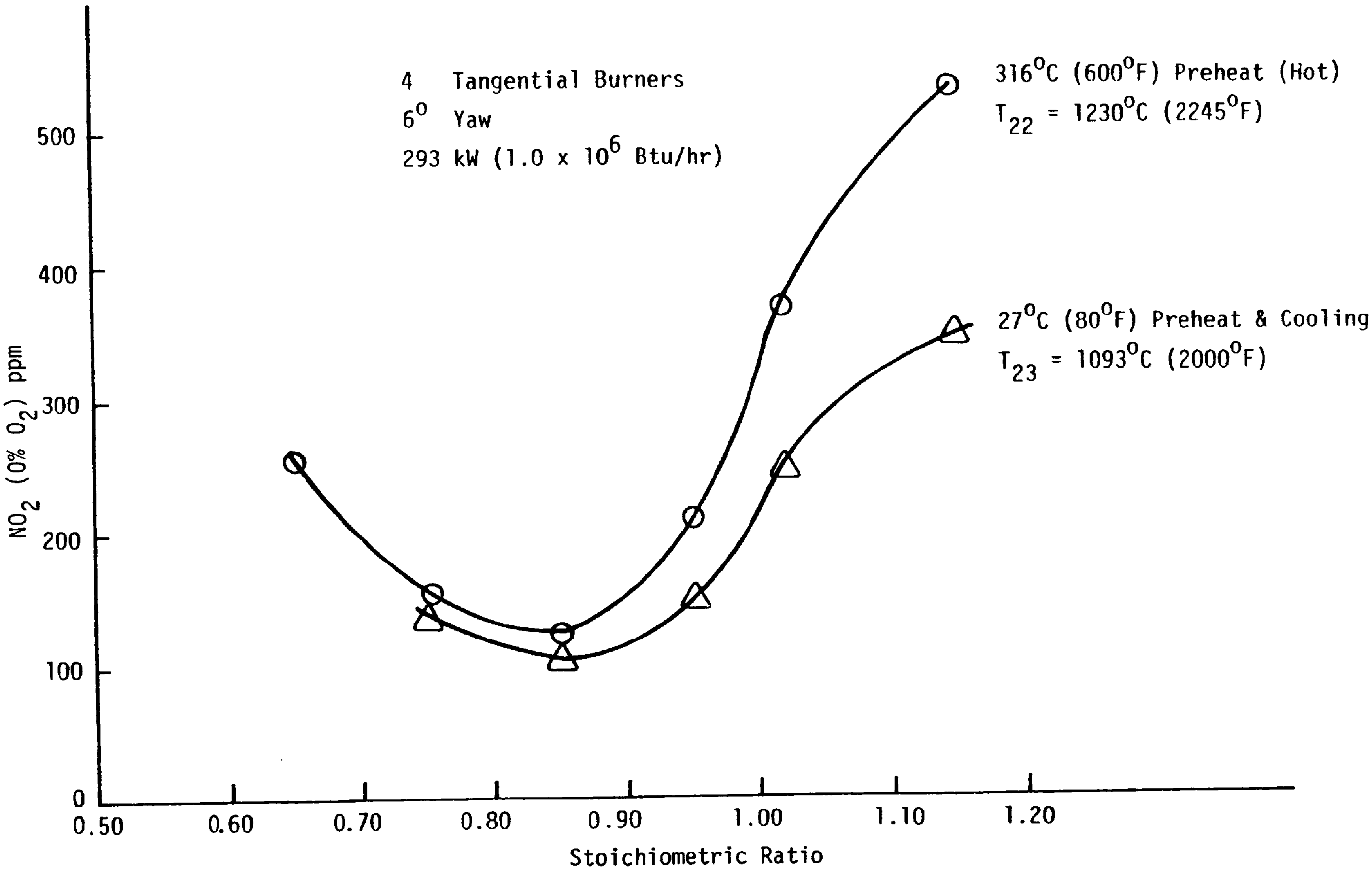


Figure 5-54. Effect of wall cooling at the mid-staging position.

gives NO level achieved at extreme thermal differences for tangential firing under the middle staging position. For SRs near the unstaged condition the results are comparable to those for the late staging position presented in Figure 5-50. However, at SRs near 0.8, the mid-staging position results show increased NO for higher temperature, which is opposite to the effect observed for the longer residence time third-staging position. This might be due to the high temperature enhancing volatilization to such an extent that very high near-zone NO is produced. Also, intermediate-zone combustion might become overly rich, producing nitrogen intermediates at the expense of N_2. Given sufficient residence time, these local processes would be masked by far-zone reduction processes. However, if stage-air is introduced early, the nitrogen intermediates and high early NO might become evident in the data as is shown in Figure 5-54. Of course, this is simply conjecture and to substantiate this requires measurement of NO and nitrogen intermediates throughout the first stage. What is important to note here is that the effect of temperature and mixing depends on residence time as was shown in the last section.

Load

Under normal operation, reduced load (volumetric heat release rate) and reduced air preheat tend to reduce NO_x emissions by suppressing thermal NO_x. Indeed, new boiler designs are using enlarged fireboxes partly to meet NO_x emissions standards (Reference 5-23). Under fuel-rich conditions, however, opposite effects may prevail. The work of Sarofim, et al., (References 5-11, 5-13 and 5-24) has suggested that high heat release rate and/or high preheat may reduce NO_x in two ways. First, high bulk temperature can accelerate the decay of bound-N intermediaries and near-zone NO in the first stage and thus reduce NO or the conversion to NO in the second stage.

Second, high first-stage temperature can reduce the amount of bound nitrogen carried into the second stage in the char. In addition, increased load and/or temperature enhances mixing in the present experimental setup.

The effects of load on NO under staged FWF, tangential and HE firing are presented in Figures 5-55 and 5-56. These results are very similar to the effects of preheat temperature and are consistent with the mechanisms discussed above and in the section on first-stage temperature. Visually, the intensity of combustion is increased as load is increased, giving sharply defined flames.

The effect of load on NO under staged conditions in the HE at reduced residence time is given in Figure 5-56. These results are also very similar to those achieved with preheat variation at several residence times. Arguments similar to those employed for preheat temperature variation might also be applied in this case.

5.3.3 Second-Stage Parameters

Following the first-stage parametric study the following second stage parameters were varied.

- Second-stage stoichiometry or excess air
- Residence time to quenching
- Stage-air mixing technique
- Stage-air preheat temperature

In general the first-stage parameters were held constant. However, in some cases the second-stage variables were also explored over a range of first-stage variables, such as SR, swirl etc. The nominal first-stage conditions during the second-stage tests were:

- 293 kW (1.0 x 10^6 Btu/hr) firing rate
- Western Kentucky Coal

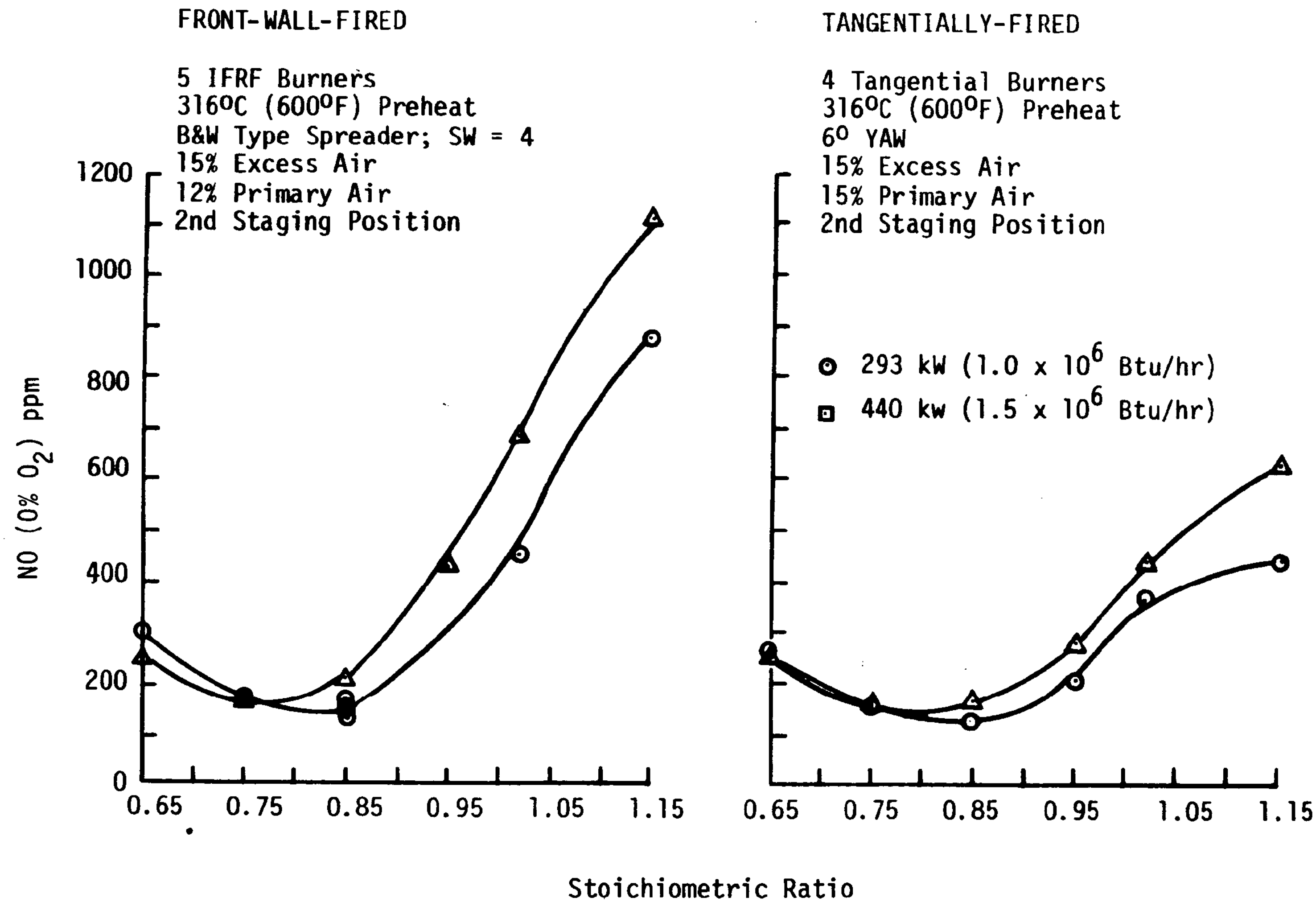


Figure 5-55. Effect of load (FWF and tangential).

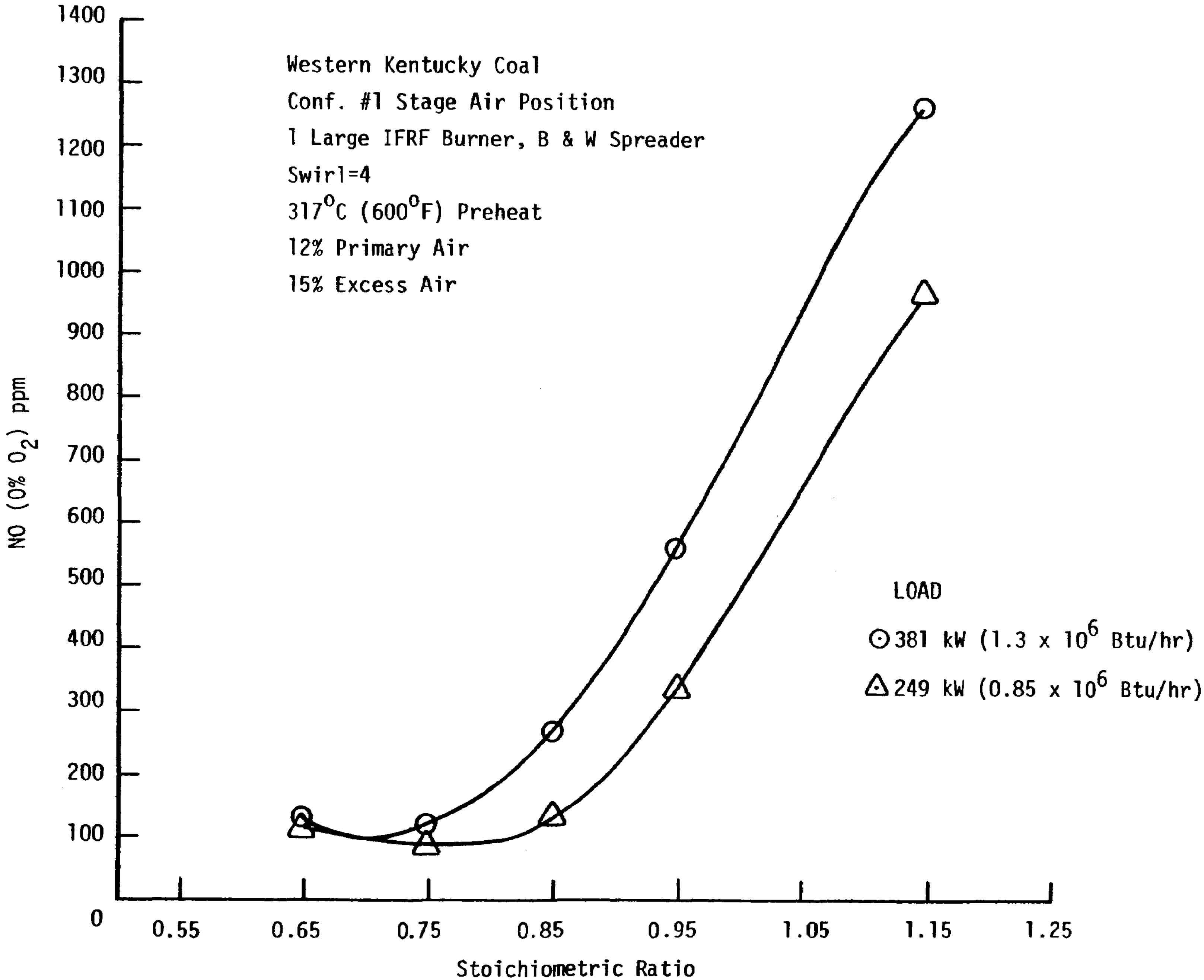


Figure 5-56. Effect of stoichiometry and load (one large IFRF burner).

- Babcock & Wilcox spreader at SW = 4
- 1st staging position
- Primary air: 12% of total @ 15% EA.

Results of tests on each of the second-stage variables is discussed in the following subsections.

5.3.3.1 Second-Stage Stoichiometry

Tests were conducted to determine the effect of second-stage stoichiometry on stack NO levels. Figure 5-57 shows several typical curves of NO versus overall excess air at various first-stage SRs. As shown, the overall NO does not seem to be a strong function of excess air, under staged conditions. The only significant effect is noted at SR = 0.65 between 15 and 5 percent excess air. At this SR, the NO decreased by 50 ppm at the lower excess air level. Similar results were obtained for the FWF configuration, for other loads, first stage mixing, coals, and staging positions. As shown in Figures 5-58 and 5-59, the general trend of these curves for various loads and mixing is that NO increases slightly as excess air is increased. This increase could be due to either increased availability of oxygen to oxidize first-stage nitrogen intermediates and produce second-stage NO or it could be due to backmixing of oxygen into the first stage as the stage-air velocity increases. This increase of first-stage oxygen would increase the effective first-stage SR and result in increased NO.

Excess air had a significant effect on CO and carbon loss if the second stage residence time was less than 1 second. In this case, 20 to 25 percent excess air was required to achieve CO levels below 100 ppm at SRs below 0.95. However, when the second-stage residence time was at least 1 second, the CO was always under 100 ppm and carbon loss was less than 0.5 percent of fuel input on a Btu basis.

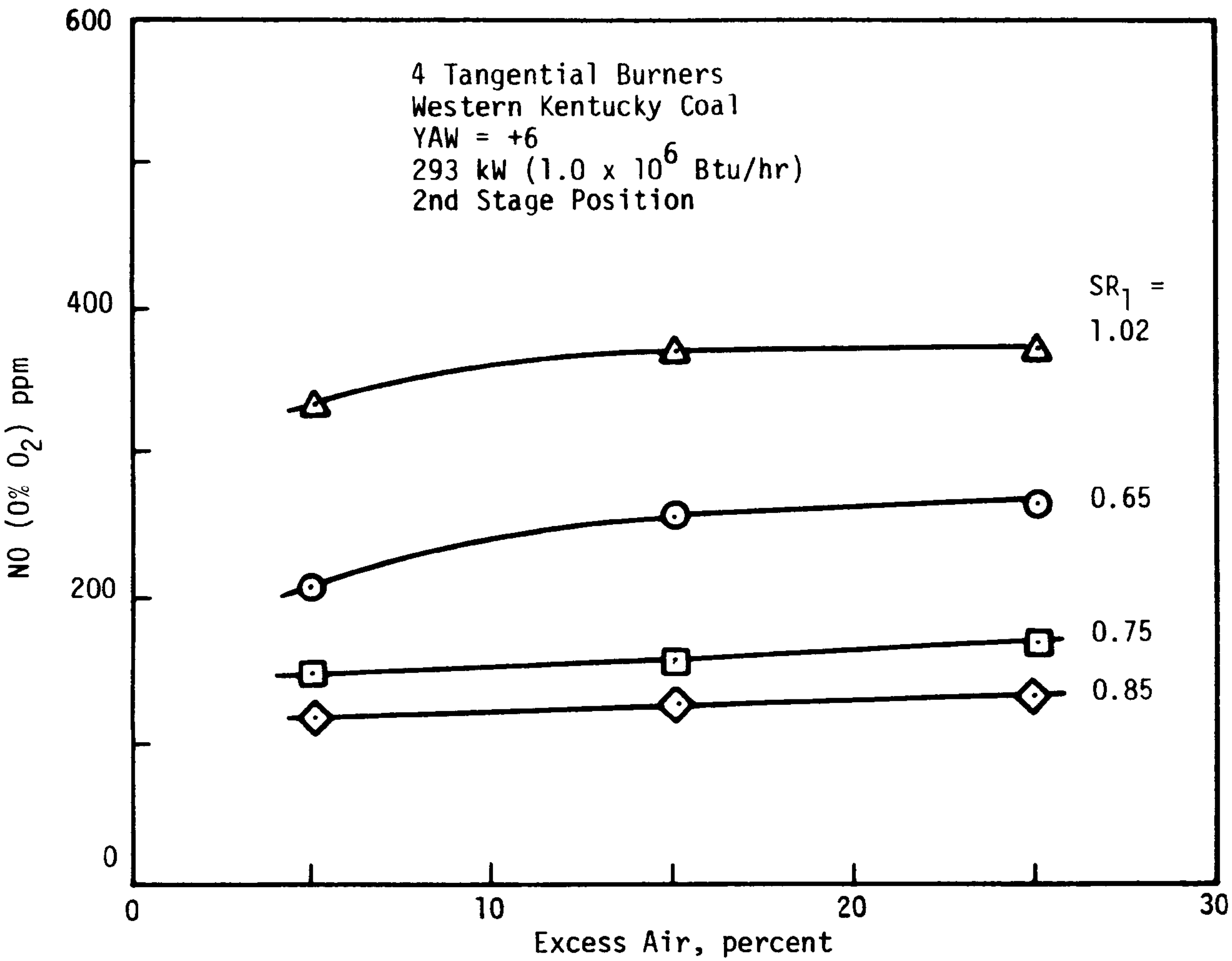


Figure 5-57. Effect of second-stage stoichiometry (tangential).

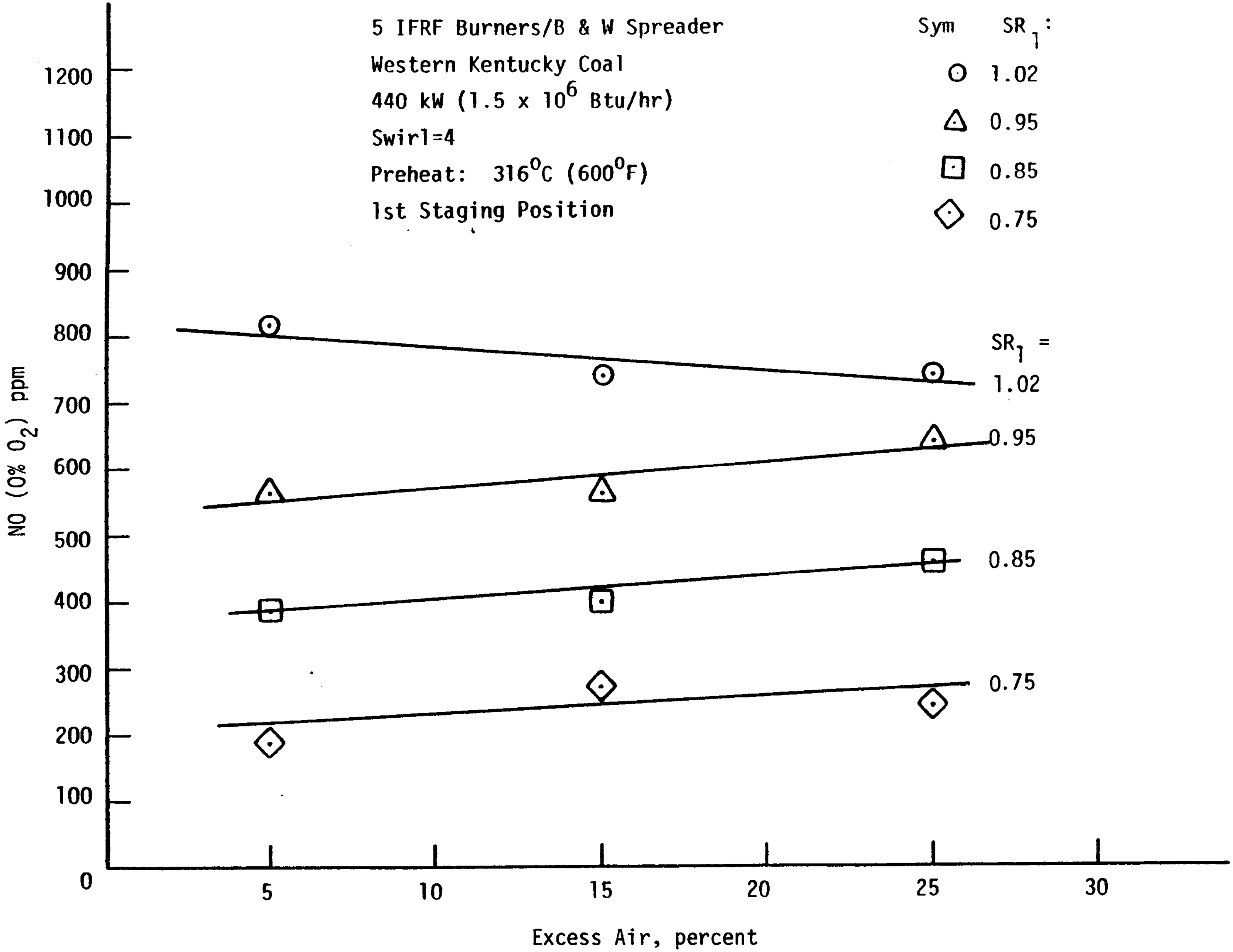


Figure 5-58. Effect of excess air (front-wall-fired).

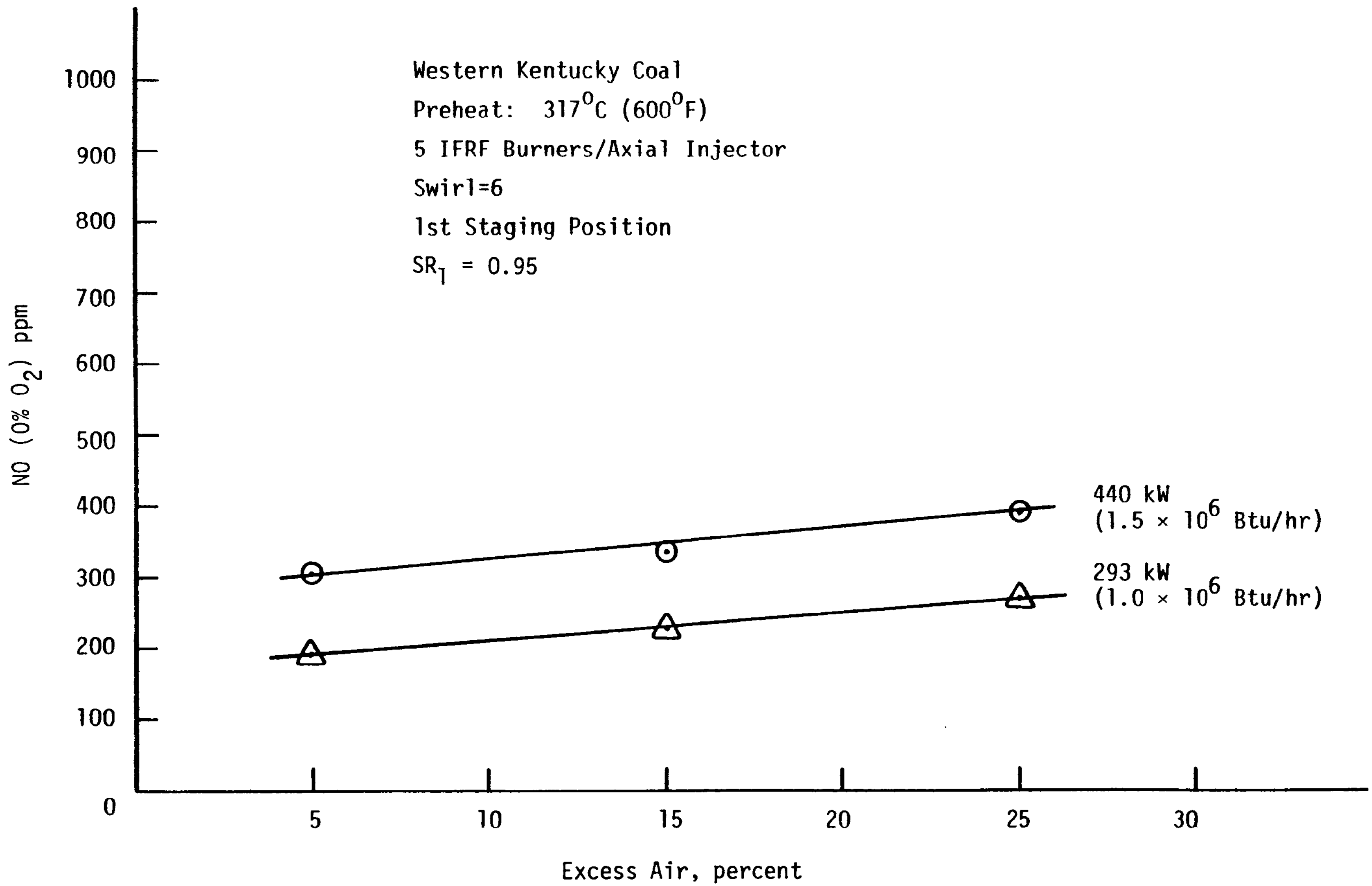


Figure 5-59. Effect of excess air (axial injector).

In summary, NO levels as low as 125 ppm can be achieved with the first-stage stoichiometry between an SR = 0.75 to 0.85 and an overall excess air of at least 15 percent to achieve CO and carbon burnout. The effect of excess air on NO emissions for most first-stage stoichiometries was not significant.

5.3.3.2 Second-Stage Residence Time

The effect of second-stage residence time was explored by keeping the stage-air location constant and moving the heat exchange surface. Figure 5-60 shows the effect of second-stage residence time as a function of SR and second-stage mixing technique. As can be seen, no substantial effect was observed indicating that for these SRs any second-stage NO that is being formed is produced very rapidly. This is expected for two reasons. First, the second stage is more well stirred and homogeneous than the first stage and homogeneous chemical reactions are sufficiently rapid compared to the residence time of the gases within the reactor. Second, most of the gas within the second stage is in motion and the bulk residence time is a good measure of the actual residence time. Therefore, bulk residence times of seconds within the second stage represent long actual residence times.

One practical limitation to staged combustion has been the occurrence of CO and carbon-in-flyash emissions at low stoichiometric and/or low second-stage residence times (References 5-1, 5-5 and 5-17 through 5-19). One objective of the present program was to identify the second-stage residence time required for CO and carbon burnout. This requirement impacts the feasibility of staging for NO_x control for application to both conventional and advanced designs. It was found that with 15 percent excess air and a second stage residence time of 1 second or longer, CO levels were below 100 ppm and carbon losses were below 0.5 percent of the heat input. The

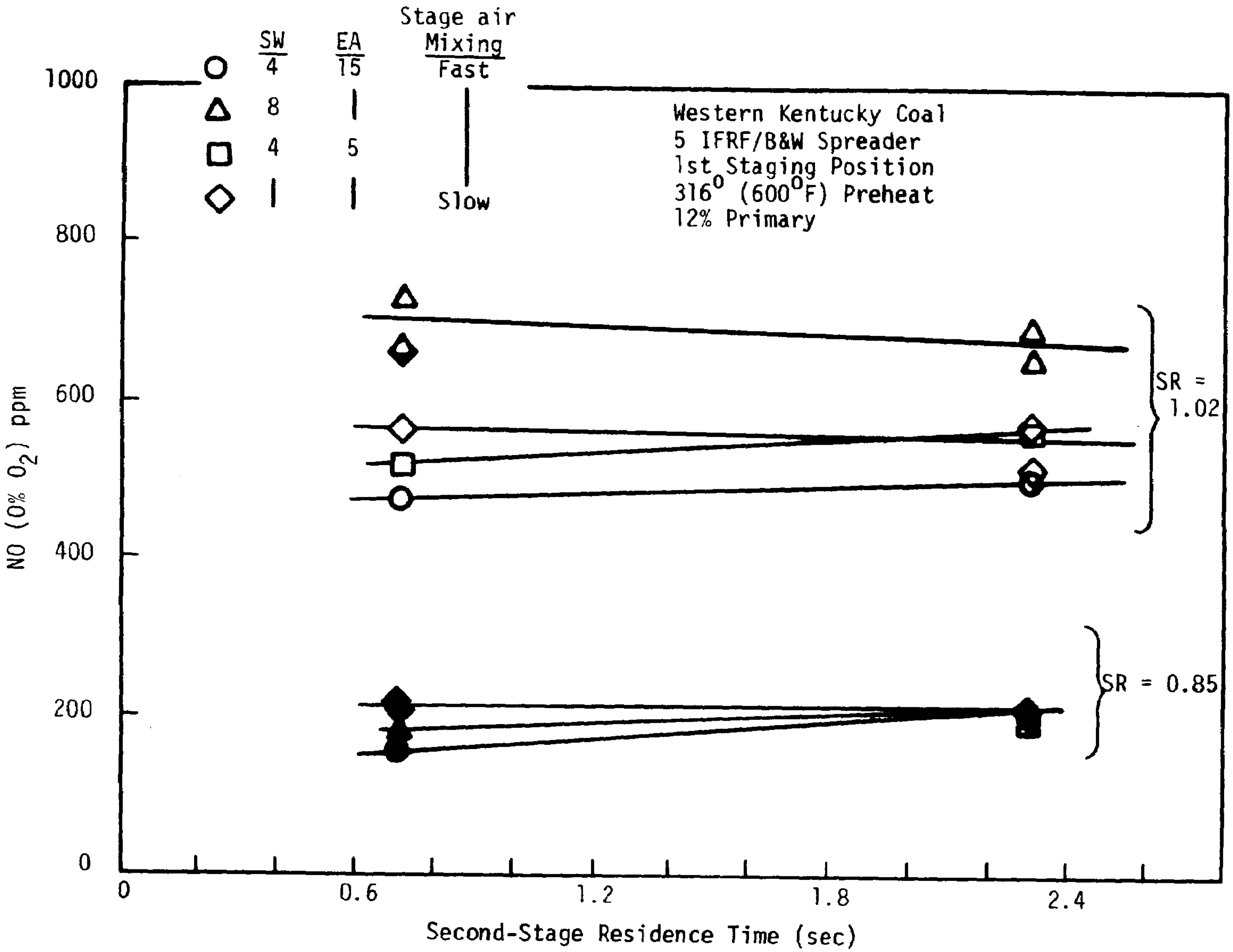


Figure 5-60. Effect of second-stage residence time (FWF).

minimum second stage residence time needed to reduce CO and carbon loss decreased at high levels of excess air.

5.3.3.3 Second-Stage Air Mixing

Nearly all prior studies of staged combustion have injected the stage-air so that a portion backmixes with the fuel-rich first stage. This backmixing makes it difficult to determine the independent effects of first stage SR, residence time and local fuel/air mixing on NO_x. Limited results have shown that directing stage-air away from the primary flame zone has a substantial effect on NO_x reduction (References 5-1 and 5-5). The present facility was therefore designed to achieve a minimum of backmixing into the first stage. The stage-air mixing technique was qualitatively studied using cold-flow smoke tests. Little backmixing was observed provided the opposed stage-air jet impinged at the center of the duct. If the jets impinged on the opposite wall, considerable backmixing was observed. Backmixing may account for some of the differences between the shape of the curves of stack NO versus SR given in Figure 5-31 and 5-44 for the two staging positions.

To illustrate the effect of backmixing and stage separation on NO_x, tests were run with biased-burner firing using the same burner flame stoichiometry as the staged tests. Also, the method of staged-air injection was perturbed to cause backmixing into the first stage and thereby reveal the consequences of backmixing on NO_x emissions. The stage-air injection technique was also varied to study the effects of second-stage mixing on CO and carbon burnout as well as any effect it may have on potential second stage NO.

Three mixing types were explored, fast, slow and downmixing (high backmixing). The fast mixing condition uses the normal four, 2.54-cm

(1-inch) diameter ports in which the opposing jets meet at the center of the duct under all condition. The slow mixing case utilized 5.08 cm (2-inch) diameter ports located in two vacant heat enchanger drawer windows as close to the first staging position as possible. Figure 5-61 is a schematic of the stage air injection configuration for slow mixing. Downmixing was achieved by introducing the stage-air from one side only at the first staging position.

Figure 5-62 shows that at a stoichiometric ratio of 0.85, there was virtually no impact of second-stage mixing conditions on NO. However, at a stoichiometric ratio of 1.02, the slow-mix condition gave consistently higher NO levels, with the spread in the data being greater with higher excess air. This result is believed attributable to greater backmixing, particularly into the first stage and especially with increased excess air. As can be seen in Figure 5-62 a similar result was obtained for the purposely back-mixed condition. As illustrated in Figure 5-31, NO is more sensitive to slight changes in the first-stage SR at a SR of 1.02 than at a SR of 0.85. Another consideration is the first-stage residence time. If the NO decay processes are not complete, backmixing will have a more substantial effect than if they are complete. The conclusion then, is that within the staging techniques and SRs tested, the second-stage mixing technique has very little influence on the NO except as it influences the first-stage SR. This effect can also be seen from the biased-fired data point shown on Figure 5-62. This represents the extreme case in backmixing where the lower three burners were operated at a SR = 0.85, with the excess air delivered through the upper burners. Staging tests in the HE with and without a baffle plate separating the first stage from the second stage air addition further demonstrated the impact of backmixing. As seen in Figure 5-63, removing the baffle plate (schematicized in Figure 5-33) causes an increase in NO level

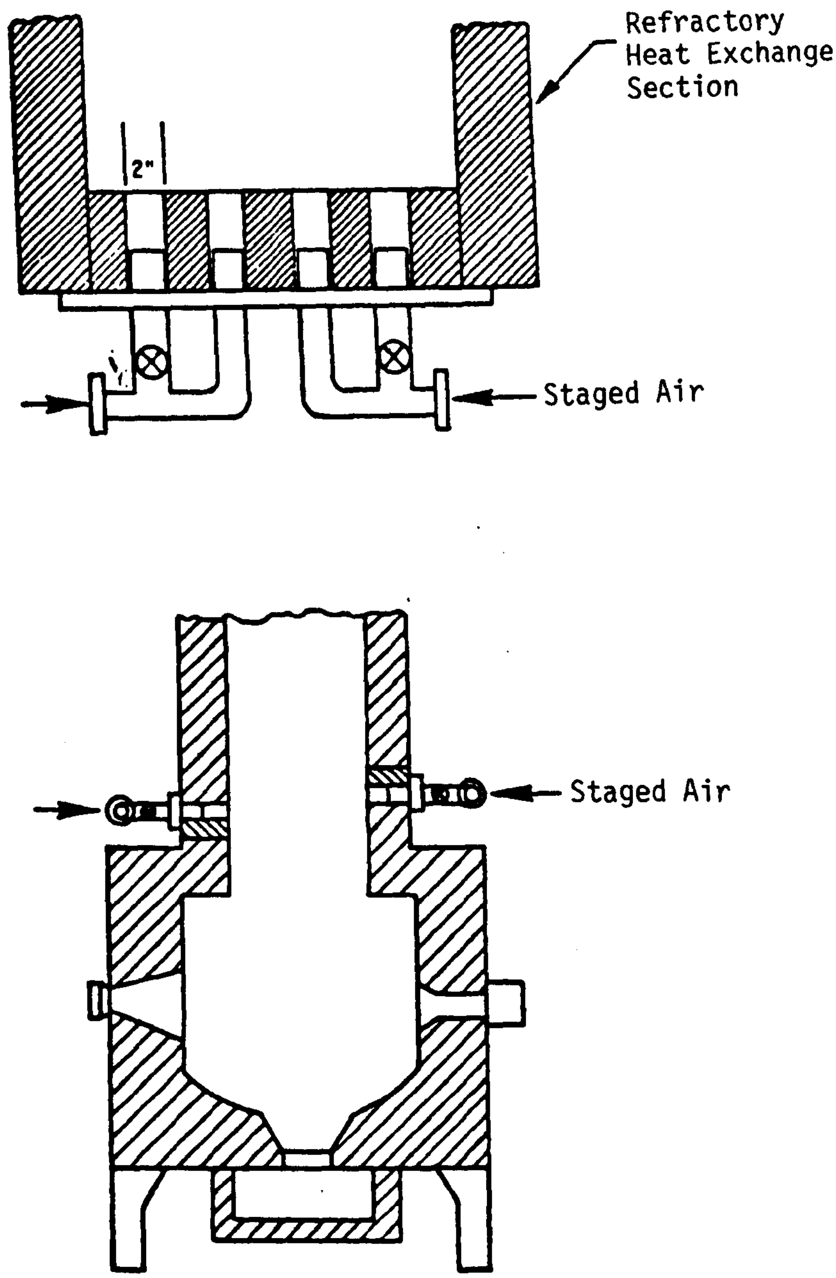


Figure 5-61. Slow mixing manifold location and configuration.

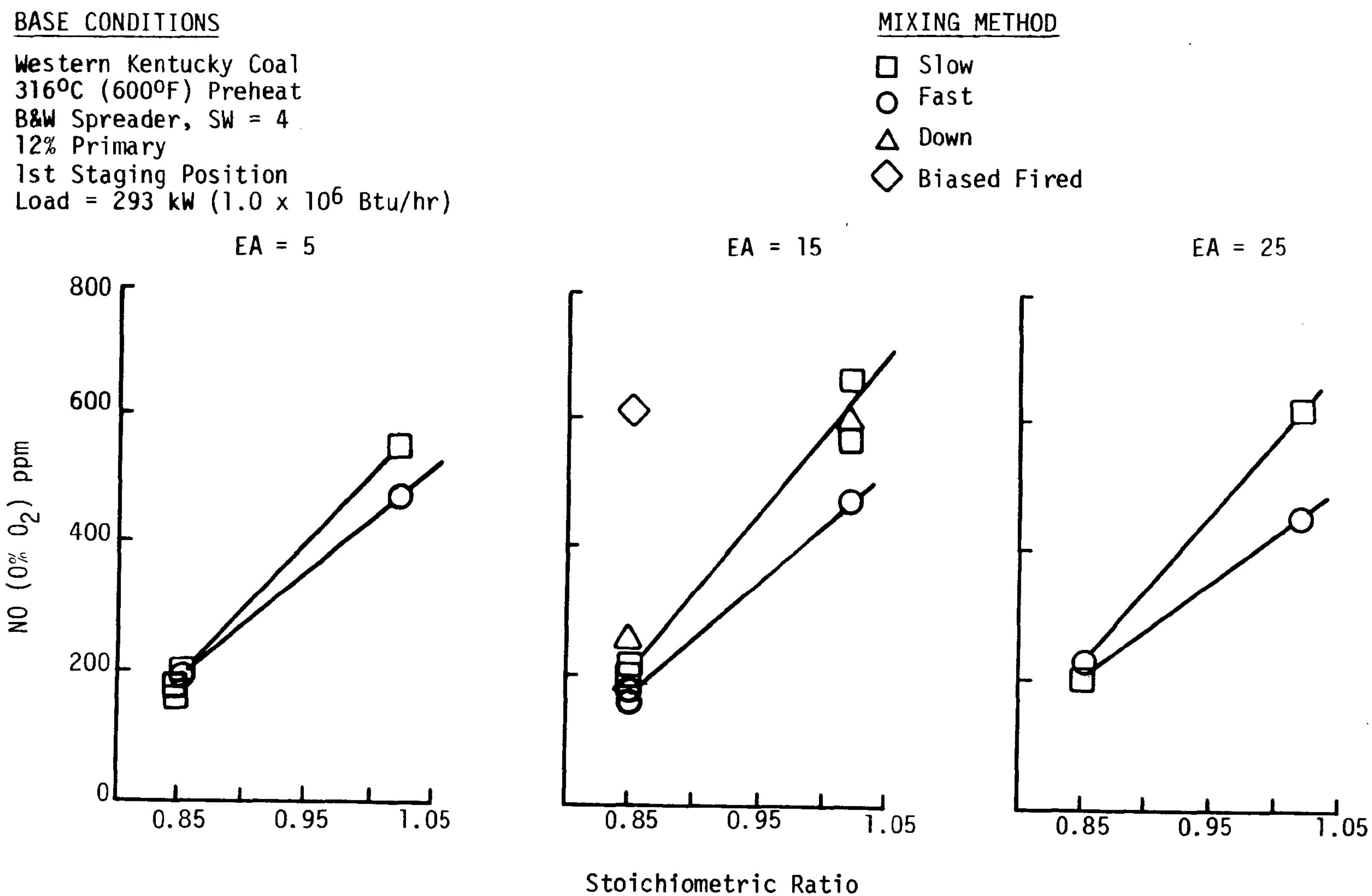


Figure 5-62. Effect of second-stage mixing.

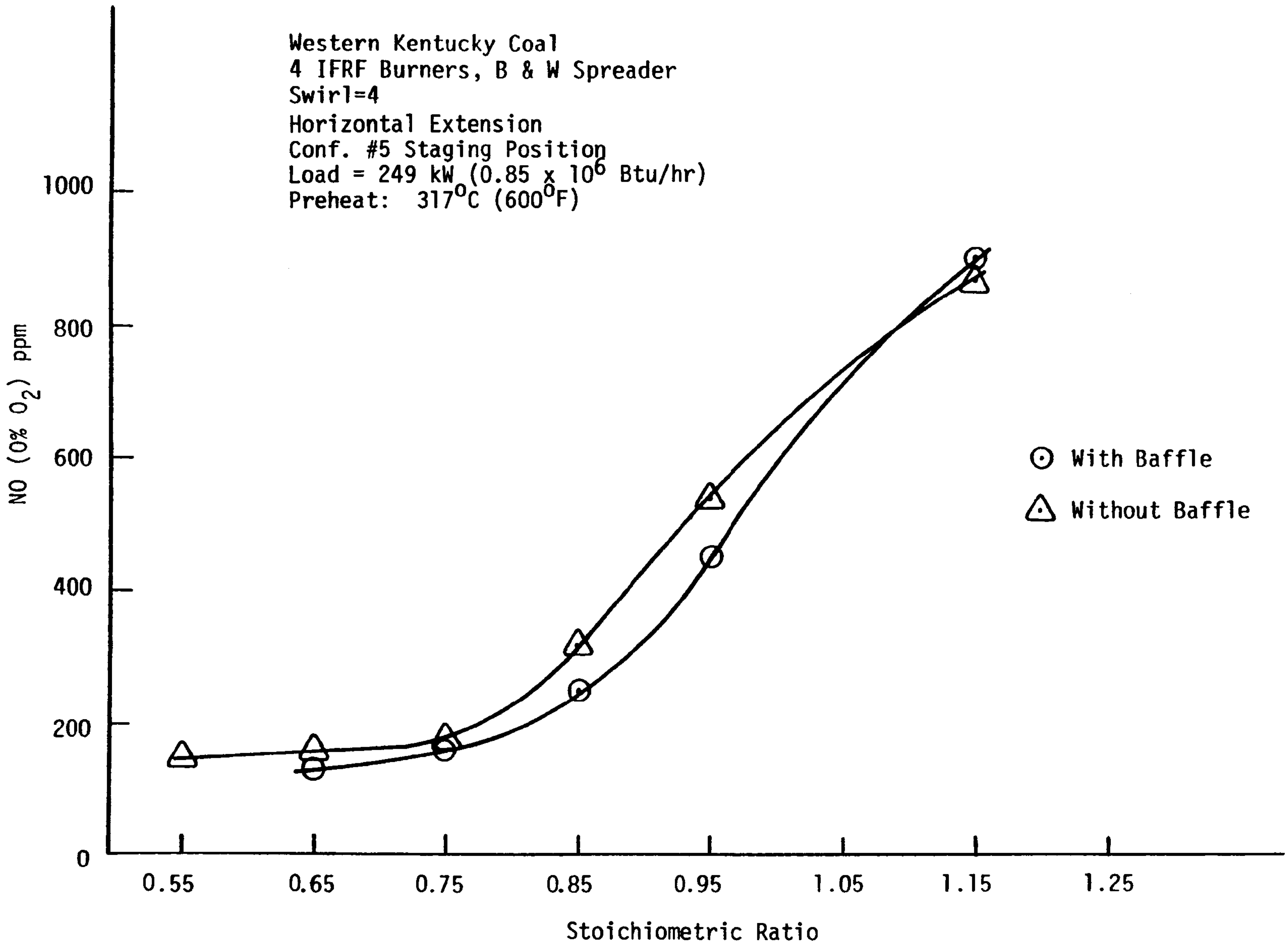


Figure 5-63. Effect of baffle.

over the range of SRs tested, with the most pronounced effect occuring at SRs around 0.95. The baffle plate was designed to reduce backmixing and results achieved without it indicate the impact of enhanced backmixing. These results show the importance of stage separation in achieving the lowest possible NO for any given first-stage SR.

An effect of the second-stage mixing technique was noted on CO and carbon loss, with the slower mix conditions producing higher CO and carbon (200 to 500 ppm CO and 1 to 2 percent carbon loss).

5.3.3.4 Second-Stage Temperature

Figure 5-64 shows the effect of increasing stage air temperature on stack NO for first-stage SRs of 0.85 and 1.02. A substantial increase of NO with temperature is observed at a SR of 1.02. At a SR of 0.85 the results are not clear. In Figure 5-65, the NO results given in Figure 5-64 are presented as a function of second-stage temperature. These results clearly show that NO increases with second-stage temperature for SR equal to 1.02 whereas temperature only has a small effect on NO at a SR of 0.85.

This behavior with SR is similar to that observed in the second stage mixing study and may partly be a result of enhanced backmixing as temperature is increased. Mixing increases as the stage-air temperature rises due to increased injection velocity for the same stage-air mass addition. For SR near 1.0, the high sensitivity of NO levels to backmixing, as discussed previously can give higher NO levels for small increases in first-stage SR.

In addition to the aerodynamic mixing effect discussed above, increase in stage temperature could affect the chemistry processes. At a SR of 0.85 significant amounts of unburned fuel and nitrogen intermediates exit the first stage. These quantities are greater than those achieved at a SR of 1.02. In addition, due to greater first stage N_2 production, less

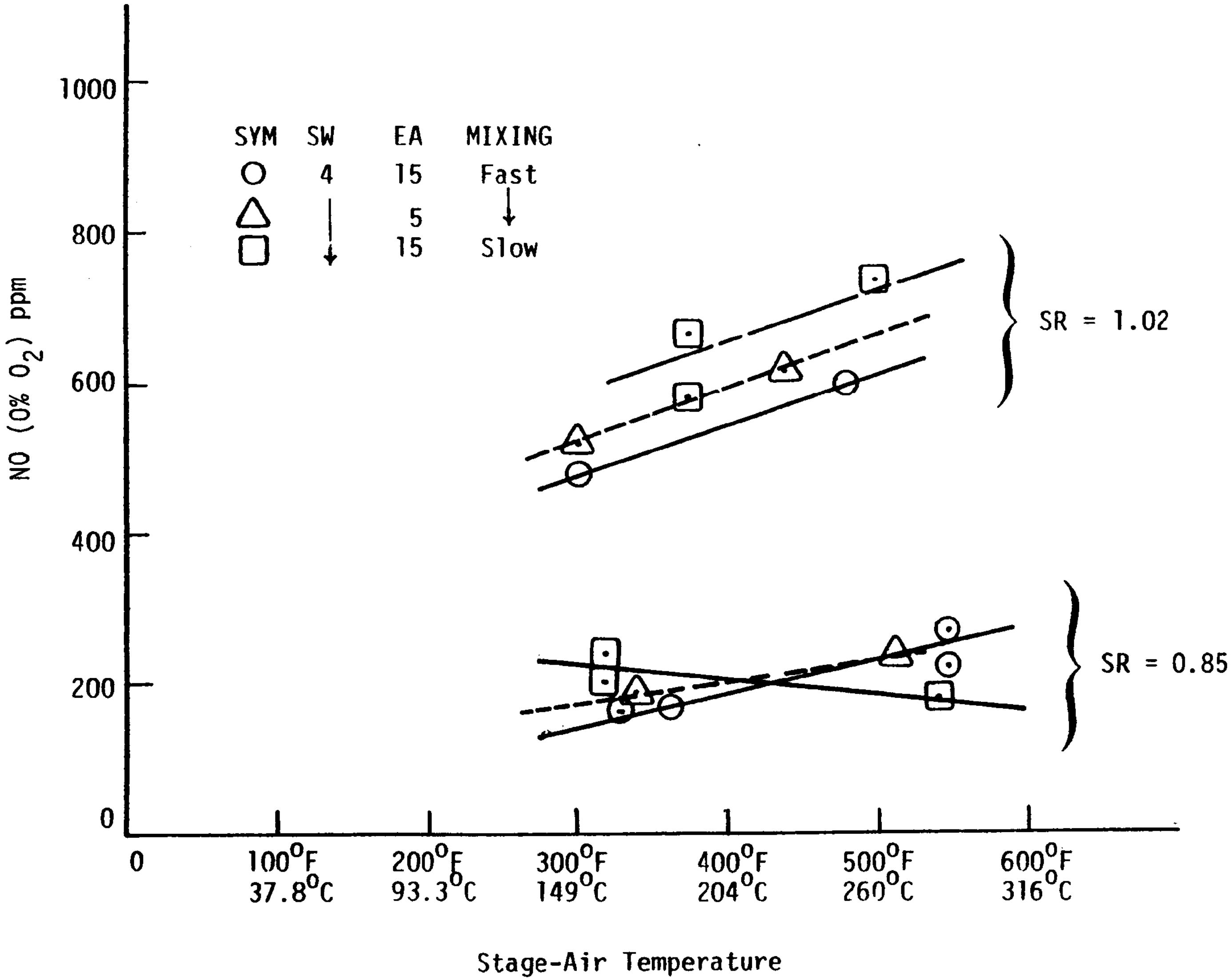


Figure 5-64. Effect of temperature.

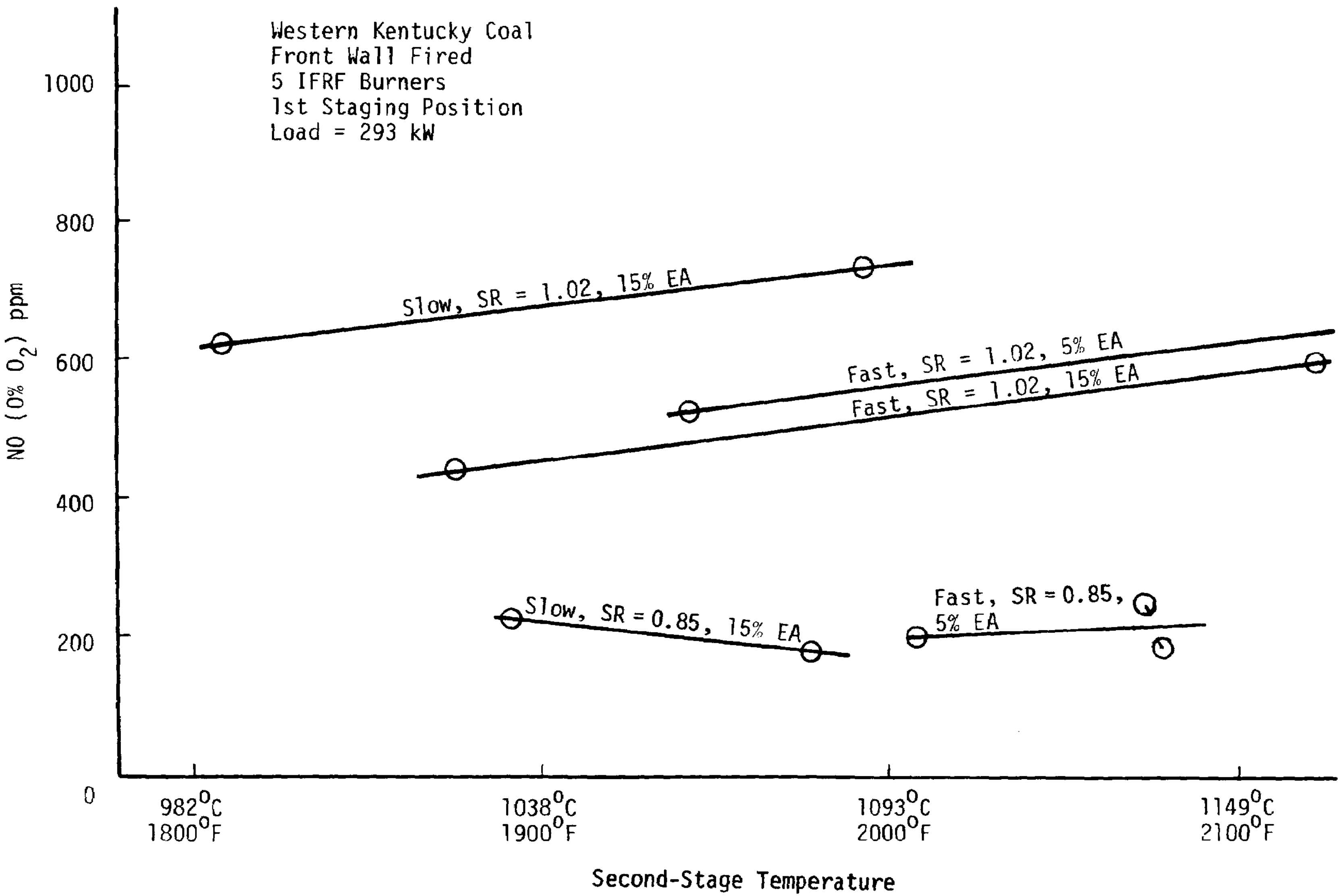


Figure 5-65. Effect of second-stage temperature.

total NO and nitrogen intermediates exit the first stage at a SR of 0.85 than at a SR of 1.02. Therefore, in contrast to SR equals 1.02 conditions, at SR equals 0.85, more fuel has to be burned in an environment which has less available NO and nitrogen intermediates to convert to NO. It can be hypothesized for the SR equals 0.85 case, that as the second stage air is mixed with the gases exiting the first stage, additional combustion will initially take place under rich conditions. The rich combustion zones will help to further reduce NO and bound-nitrogen intermediates to N_2 before the stage air is fully mixed with the first-stage exit gases. Thus the initial mixing zone in the second stage might be stratified and behave somewhat like a rich first stage which has a SR between 0.85 and 1.15.

The NO level for this case would then be fairly insensitive to temperature as is shown in the first-stage results presented in Figure 5-65. In addition, as also shown in Figure 5-65, temperature would strongly impact the NO levels at a SR of 1.02 due to thermal NO production. In fact, the increase in NO with second-stage gas temperature is identical to that achieved by increasing the first-stage temperature. Also, for the SR of 0.85 and 15 percent excess air case, the decrease in NO level, with increasing second-stage temperature is somewhat consistent with the decrease with first stage temperature. These consistencies support the hypothesis that first and second-stage processes have some similarities.

5.3.4 Effect of Coal Composition

Three different coals were tested to determine the effect of coal composition on NO emissions under staged conditions. Table 5-4 lists the principal properties, nitrogen content and the rationale behind selection of each of these coals. The effect of coal composition on NO under staged conditions is shown in Figure 5-66 for the FWF and tangential configurations.

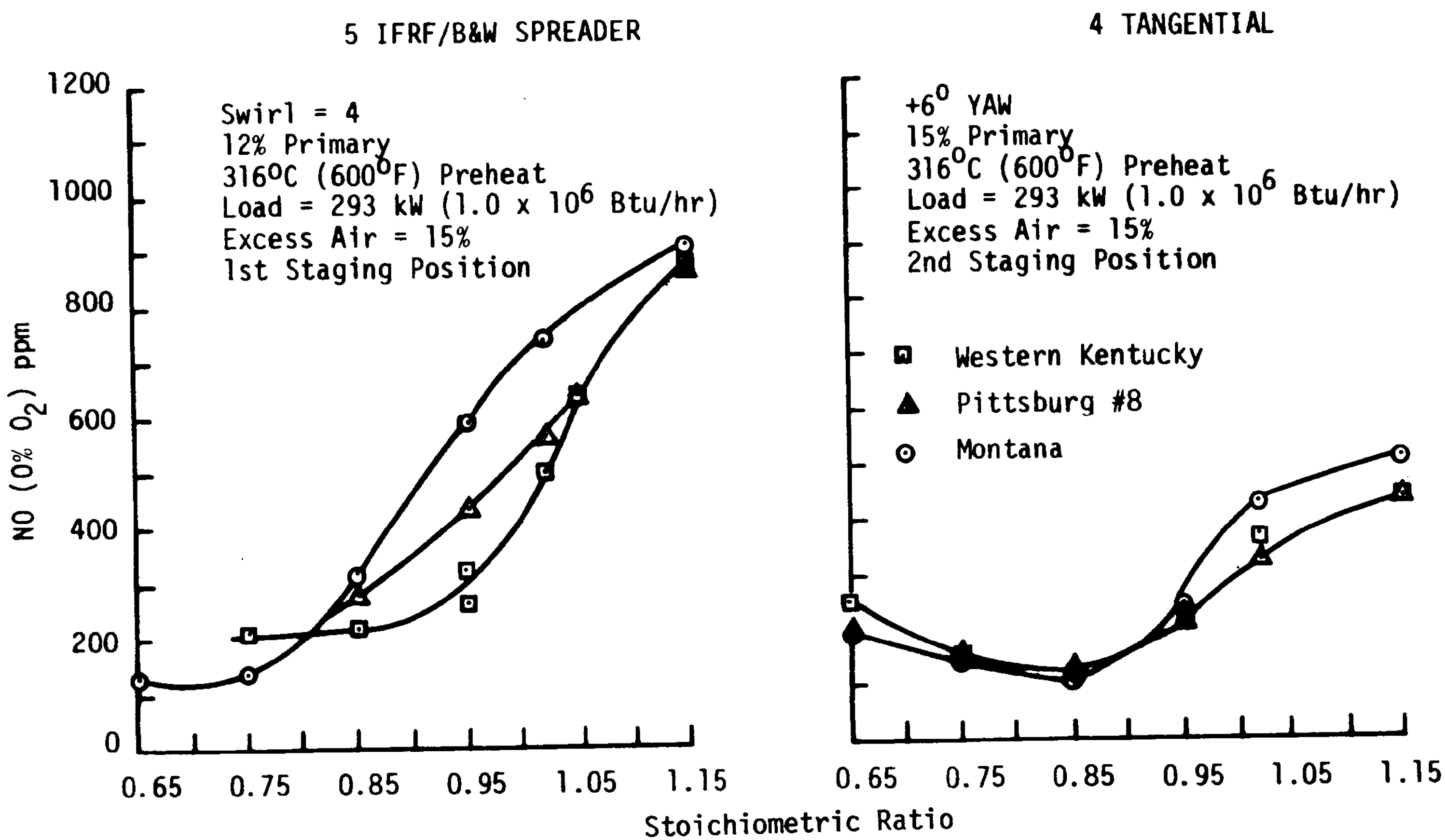


Figure 5-66. Effect of coal composition under staged conditions.

For the tangential configuration the Western Kentucky and Pittsburgh data agree closely. The Montana data is higher at baseline but is lower below SR = 0.90. At the rich conditions, NO emissions with the Pittsburgh coal did not increase with SR to the same extent as the Western Kentucky coal. The NO from the Montana coal reaches a lower minimum and does not exhibit as much nitrogen-intermediate-derived or second-stage NO as the Pittsburgh coal below a SR of 0.85. This suggests that at the low stoichiometric ratios the fuel-N intermediary products may be different for the three coals.

The staging data for the FWF configuration at 293 kW (1.0×10^6 Btu/hr) shows a similar trend to the tangential data. However, for the FWF configuration, the NO levels of the Western Kentucky and the Pittsburgh #8 coals differed at stoichiometric ratios of 1.0 to 0.85. On the other hand, as shown in Figure 5-67, at a firing rate of 440 kW (1.5×10^6 Btu/hr) no appreciable difference was observed between the NO levels of these two coals. It is possible that the difference in the 293 kW (1.0×10^6 Btu/hr) data was due to changes in mixing patterns caused by buildup of a sticky ash deposit on the fuel tip frequently encountered during the Pittsburgh #8 firing. The trend of the NO data for the Montana coal was consistent for all configurations and firing rates. For the Montana coal the NO levels are higher at baseline conditions and SRs greater than 0.80 to 0.85 and lower at SR < 0.85.

It appears that the combustion of Western Kentucky and Pittsburgh #8 coals yields quite similar results. The Montana coal acts differently under both baseline and staged conditions. This difference may be attributed to the lack of sulfur and high oxygen and water content of this coal.

As indicated in the baseline tests coal composition section (Section 5.2.4), Wendt (Reference 5-9) has shown that sulfur can either enhance or

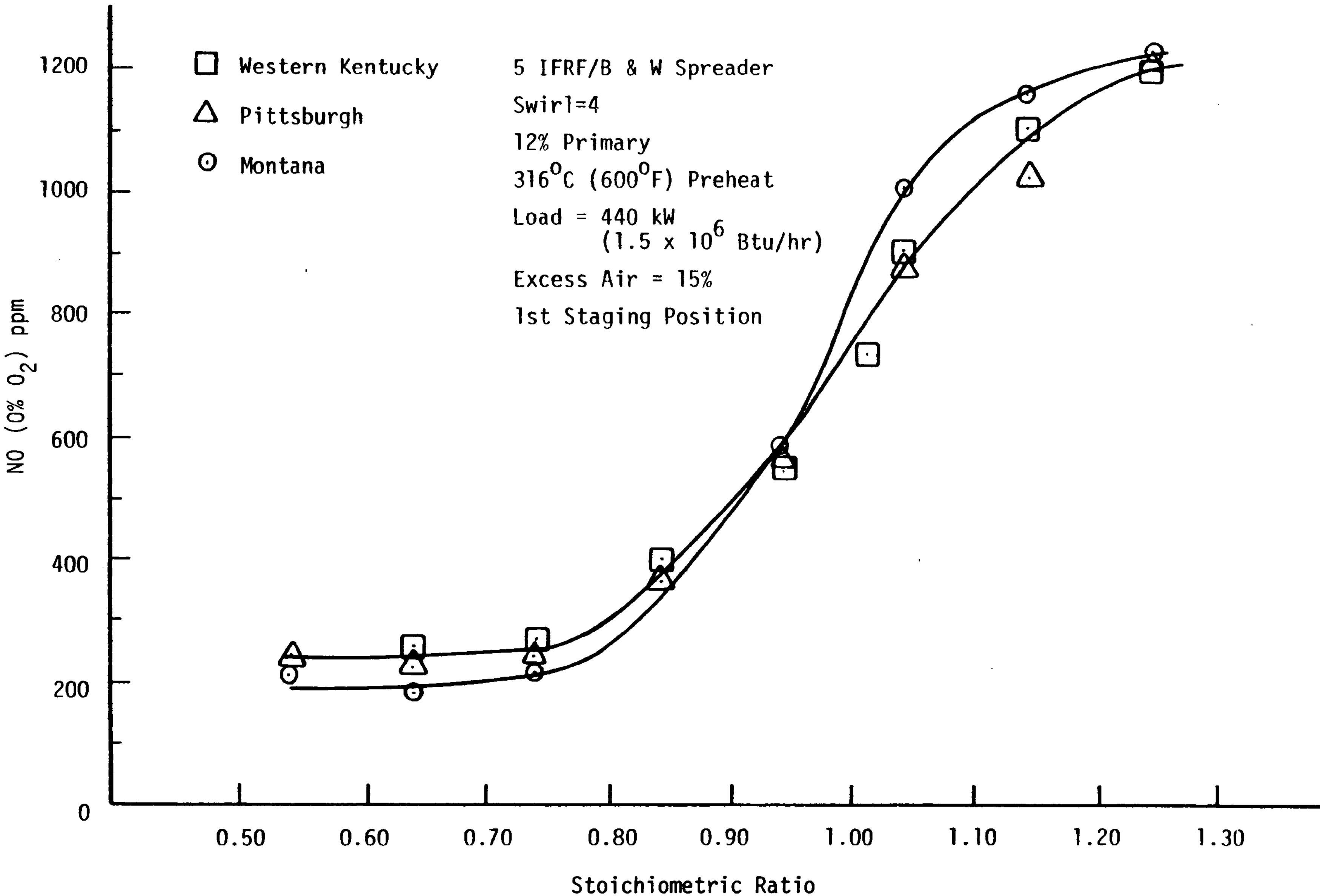
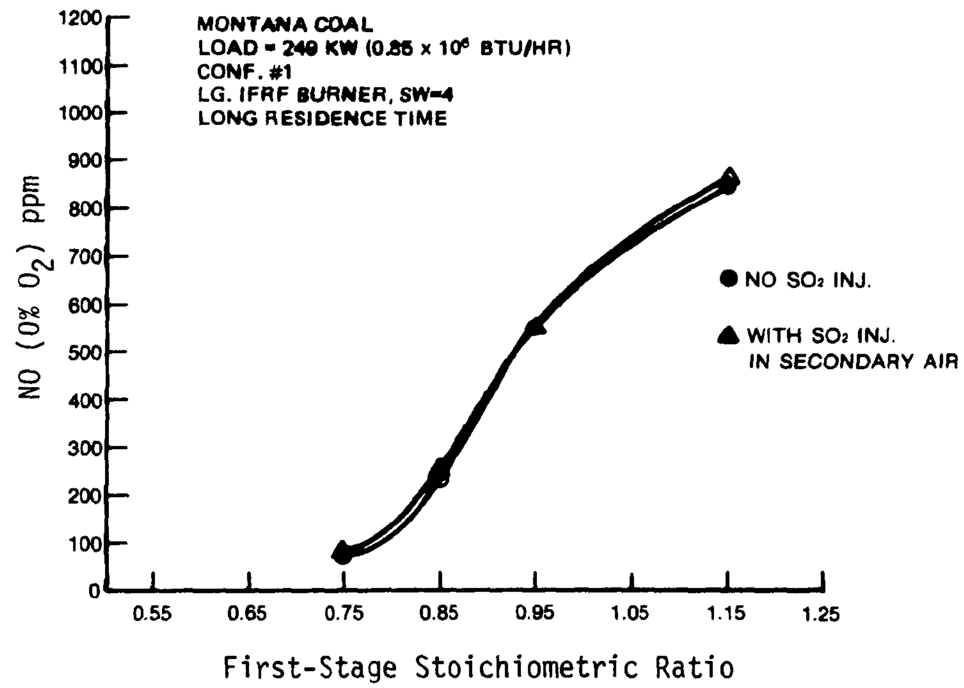


Figure 5-67. Effect of coal composition (440 kW).

reduce combustion-generated NO depending on temperature and local stoichiometry. In very rich hot combustion zones, where fuel-nitrogen is present, NO formation can be considerably enhanced by the addition of sulfur to the fuel. However, the addition of sulfur to well mixed overall lean flames can reduce thermal NO emissions. Therefore, at a SR near 1.0, where the combustion is overall lean, the low sulfur Montana coal should give higher NO levels than the other coals tested. This is clearly shown in Figure 5-66. In addition, as SR decreases to low values where the combustion occurs under rich conditions, the low sulfur Montana coal should have lower NO emissions than the other coals. This effect is also evident in Figure 5-66.

In summary, the difference in NO emissions between the Montana coal and the Pittsburgh #8 and Western Kentucky coals can be attributed partly to the difference in sulfur content between the coals. To further define the NO fuel sulfur interaction under staged conditions, several tests where SO_2 was injected into the air or fuel streams were carried out.

Figure 5-68 shows the effect of adding SO_2 to the secondary or primary air stream. Sufficient SO_2 was added to increase the stack SO_2 levels from roughly 1400-1500 ppm to 2400-2500 ppm. When SO_2 is added to the secondary air the effect of sulfur on NO is small even under rich conditions and long residence times. However, when SO_2 is added to the primary air or fuel stream, the sulfur enhances NO formation even at short residence times. These results show that for effective NO enhancement, the sulfur must be present in the primary stream or fuel-rich combustion zones. Figure 5-69 shows the effect of increasing the injection rate of SO_2 into the primary stream on NO at a SR of 0.65. Increasing SO_2 injection rate causes the stack NO levels to rise.



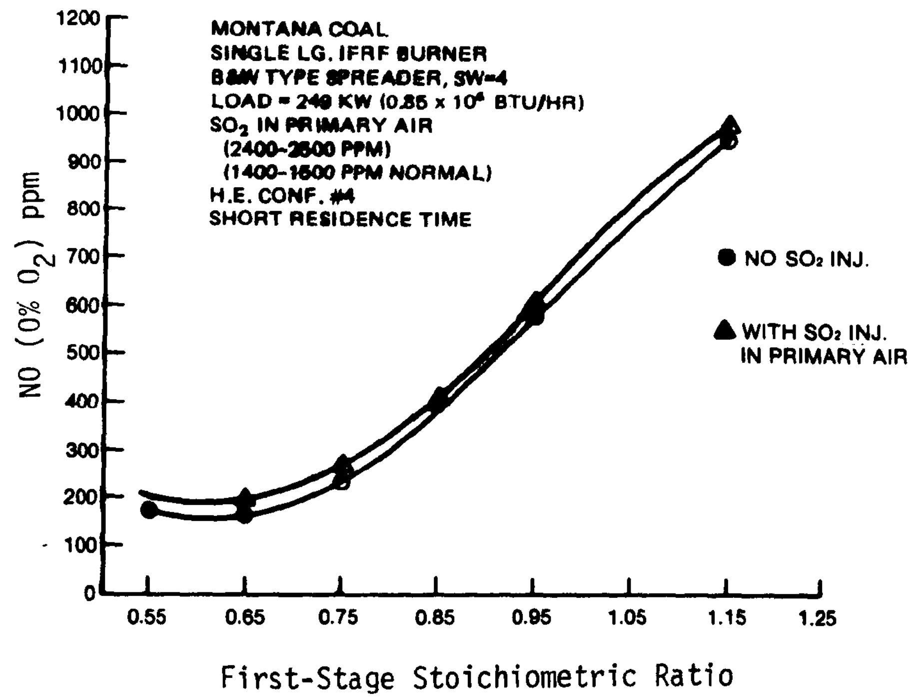


Figure 6-68. Effect of SO_2 doping (staged).

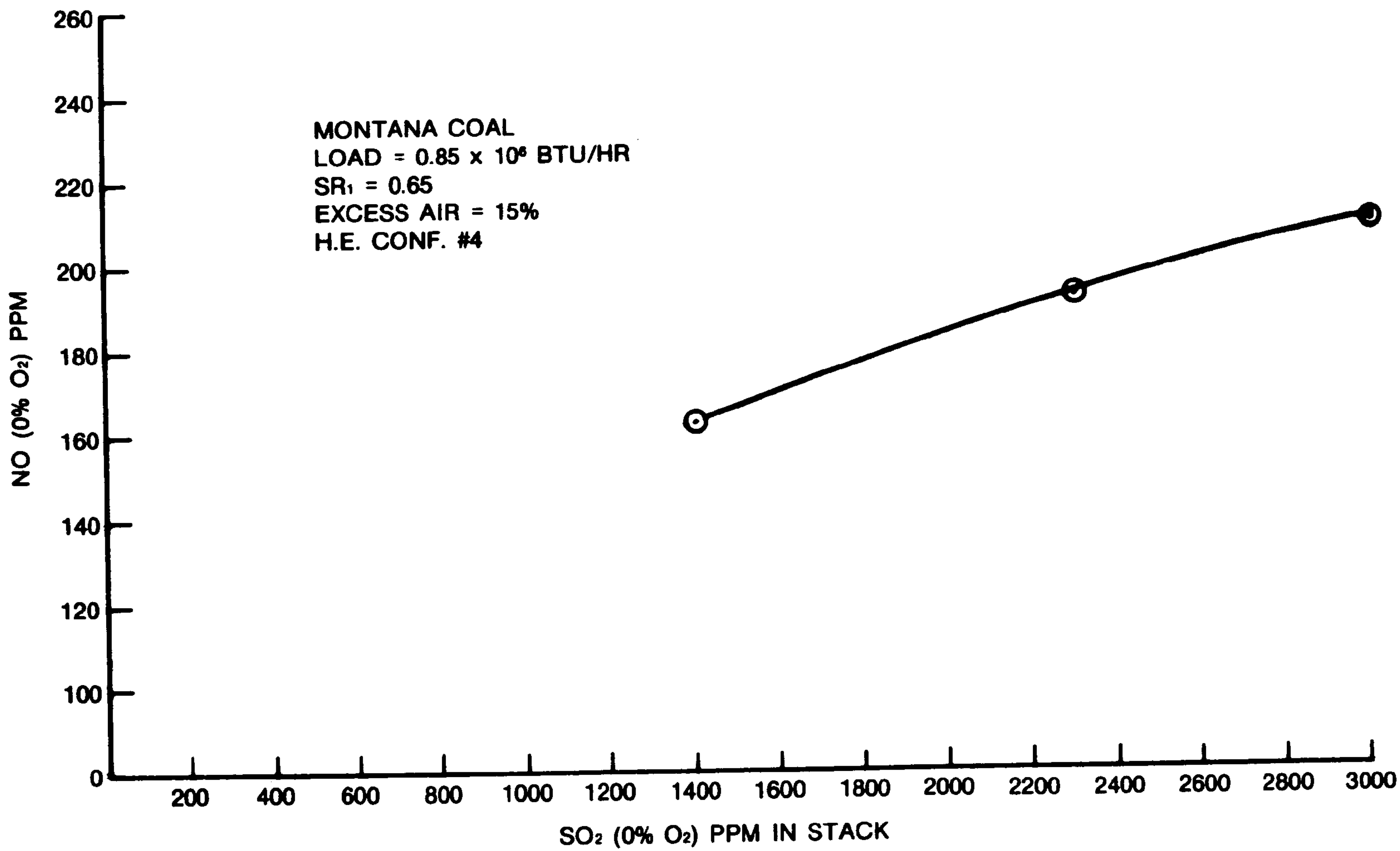


Figure 5-69. Effect of SO_2 concentration.

The SO_2 injection data show that there is a SO_x/NO_x interaction when the sulfur is present in fuel-rich combustion zones. This data implies that a lower sulfur coal will yield a lower NO under fuel-rich conditions as was shown in Figures 5-66 and 5-67. This is further shown in Figure 5-70 for the horizontal extension configuration where the lower sulfur Montana coal again gives lower values of NO than the Western Kentucky coal under low SR or fuel-rich conditions.

5.3.5 Flue Gas Recirculation

The impact of flue gas recirculation under baseline and staged combustion conditions was investigated for the tangentially-fired configuration. The flue gas was introduced into the secondary air supply ducts above and below the primary fuel stream. Ten and thirty percent of the exhaust gas was recirculated through the secondary air ports under baseline and staged-combustion conditions. The conditions of these tests and the stack NO results are given below.

TABLE 5-7. FLUE GAS RECIRCULATION

Tangentially fired -- 293 kW (1.0×10^6 Btu/hr)

600^oF preheat, 6^o yaw, 15% primary, 15% excess air, Western Kentucky Coal

SR	% FGR	NO (0% O_2) PPM	% Baseline
1.15	0	500	100
1.15	10	475	95
1.15	30	470	94
0.95	30	271 (214)[b]	54
0.85	30	150 (125)[b]	30

[b]Numbers in ( ) are NO levels w/o FGR; staged only

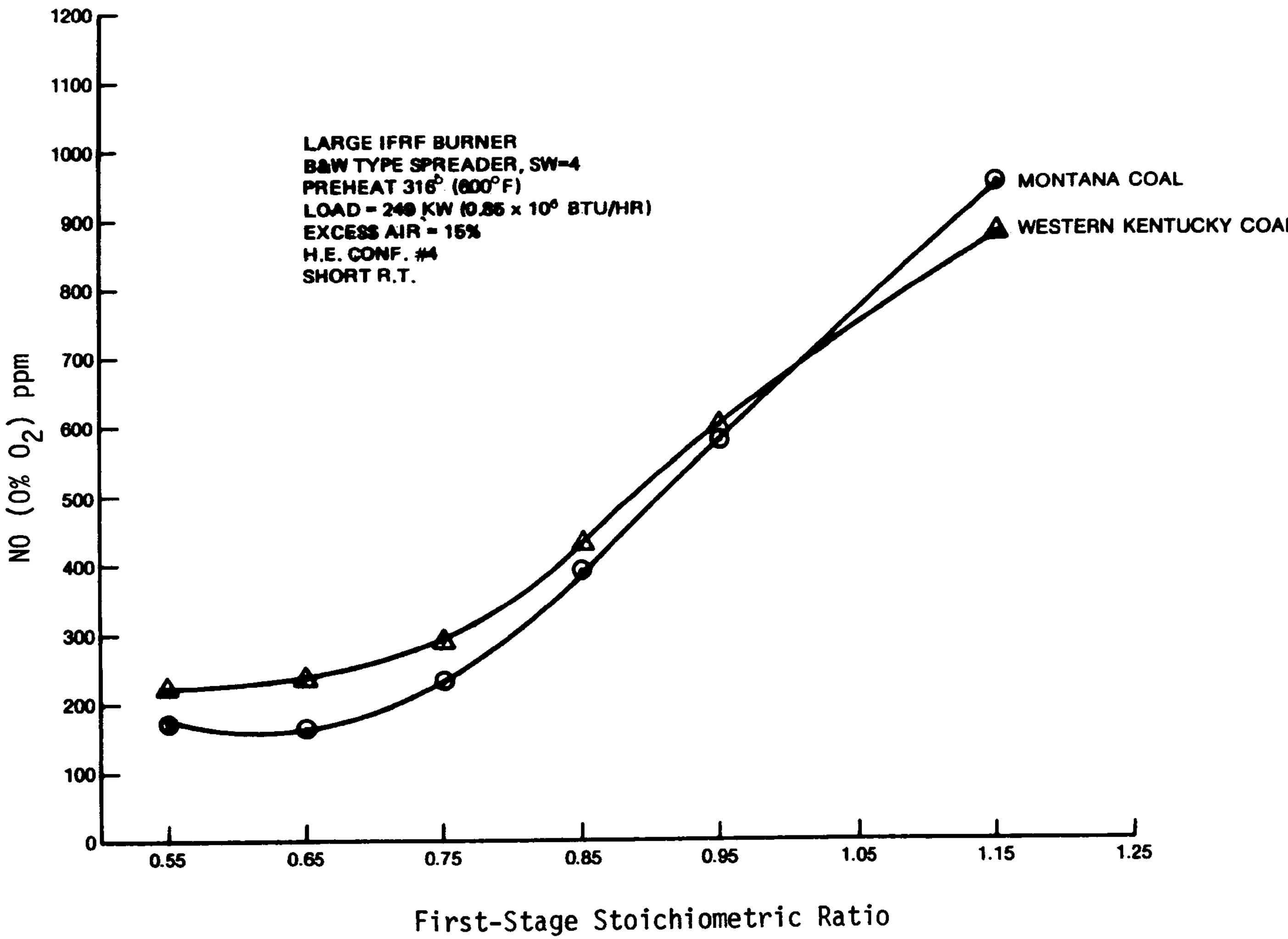


Figure 5-70. Effect of coal type.

From Table 5-7, flue gas recirculation is seen to be ineffective at baseline conditons, producing only a 6 percent reduction. At baseline conditions, FGR should reduce temperature and thereby thermal NO. However, the increased secondary air flow increases mixing which leads to increased NO in the normally stratified tangential firing configuration. Therefore, NO reduction due to the temperature effect is offset by mixing.

Under combined FGR addition and staging the NO levels were increased from their staged levels without FGR.

This loss in effectiveness of staging with FGR addition can be attributed to a number of reasons. First, at an SR of 0.95 mixing is still fairly important and FGR addition could increase mixing sufficiently to cause a rise in NO. Second, at a SR of 0.85, reductions in temperature by FGR addition could slow down the reducing reactions and lead to higher NO levels. Third, FGR addition reduces the overall residence time, which leads to increased stack NO levels. Finally, additional NO is introduced into the first stage with the FGR. This could have an impact on stack NO levels.

In conclusion, the introduction of FGR into the secondary air is not an effective method of NO reduction under baseline and staged conditions. When used in this manner, FGR has very little beneficial impact on fuel-N derived NO which is the primary source of NO in coal-fired systems.

5.3.6 Biased-Fired Results

Biased firing tests were performed to establish the effect on NO and to determine if the pilot-scale facility NO results compare with full-scale biased-firing tests. Both FWF and tangential configuration biased-firing tests were conducted. Figure 5-71 is a schematic

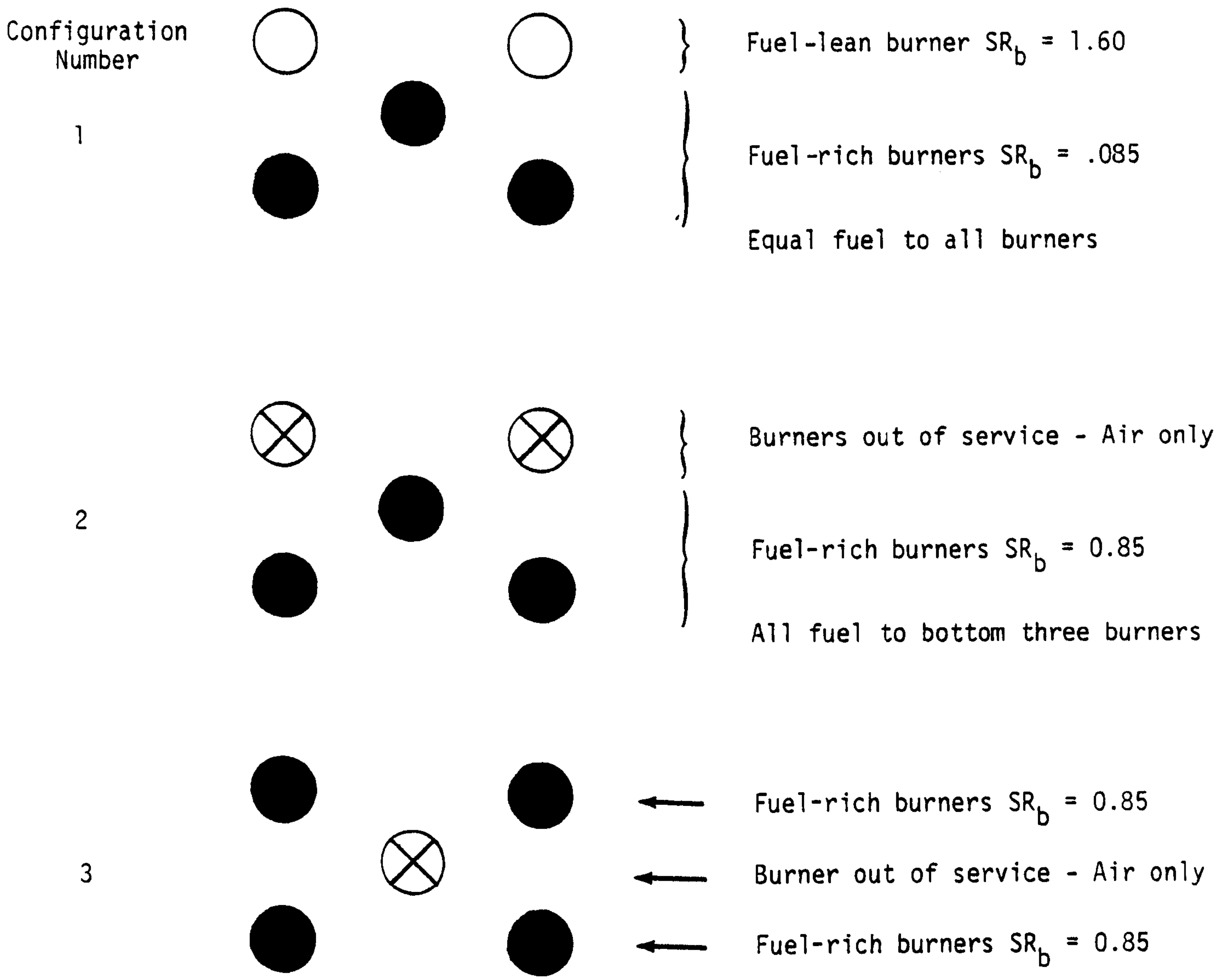


Figure 5-71. Biased-firing configurations.

of the three FWF biased-firing configurations investigated. A summary of burner conditions during the tests is also listed on this figure.

While burning Western Kentucky coal at a load of 293 kW (1.0 x 10^6 Btu/hr), a preheat of 316°C (600°F) and the burner swirl set at 4, the biased-firing configurations gave the following results.

Conf	NO ($0\%O_2$)ppm	% Baseline
Baseline	875	100
1	615	70
2	875	100
3	645	74

For configurations 1 and 3 shown in Figure 5-71, the results are typical of emission reductions in biased-firing in full-scale equipment. Configuration 2 resulted in no decrease in NO. This might be because the load for the burners firing fuel was increased by a factor of 1.67, resulting in very rapid mixing of the stage-air introduced in the nearby out-of-service burners with the burners firing fuel.

At a load of 352 kW (1.2 x 10^6 Btu/hr) and 15% primary stoichiometry the following results were obtained.

SR	Biased-Firing Configuration	NO ($0\%O_2$)ppm	% Baseline
1.15	Baseline	1135	100
0.95	1	1035	91
0.85	1	995	88
0.85	2	1035	91

The NO reduction achived at this firing rate and primary air was not as great as that achieved at the lower load. The higher primary stoichiometry and load may have resulted in greater mixing of the nearby staging air giving less NO reduction for this biased-firing case.

One additional test was performed to compare the NO in four burners to the NO from the normal five burner array under staged conditions, both at a load of 293 kW (1.0×10^6 Btu/hr).

The fifth burner had both the air and fuel turned off. Figure 5-72 shows the NO versus SR for the four and five burner array configuration. No significant differences in NO levels can be seen between these results. At a SR <1 these results are consistent with the tests of increased mixing at constant load presented in the section on first-stage mixing. The higher mixing produced by increased individual burner load when firing on four burners gives higher NO under staged conditions and SR near 1.0. At low SRs the difference in mixing becomes less important.

Two biased-firing configurations were tested in the tangential firing mode. In the overfire air biased-firing mode, the stage air was introduced through the upper burner tier locations at the same yaw angle ($+6^o$) as the burner air. In the diagonally or same side biased-firing mode, the stage-air was introduced in diagonally opposite or same side corners respectively with the other corners containing burners firing at SR = 0.85. These results, achieved at the same conditions as the overfire air tests, are presented below:

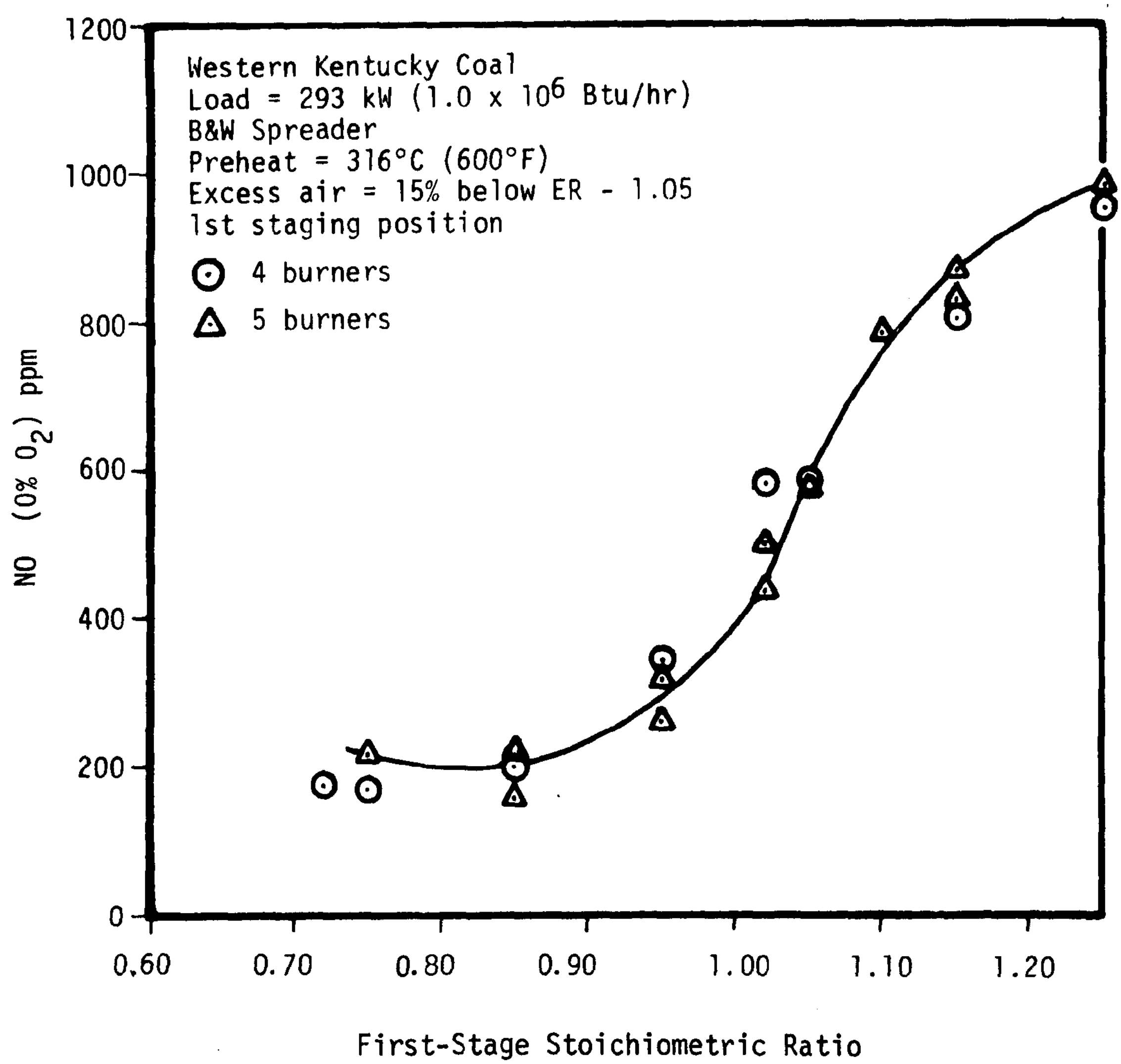


Figure 5-72. NO vs. first-stage stoichiometric ratio (4 vs. 5 burners).

Biased-Fired Tangential

Configurations	NO ($0\%O_2$) ppm	% Baseline
Baseline	485	100
Diagonal Opposed	485	100
Same Side	495	102

These results indicate that stage separation by this effect is probably negligible. As indicated earlier in the section on first-stage residence time, reduction of early NO requires a substantial time at low SR. Introducing stage air into the firebox enhances mixing and reduces residence time. This gives a first stage with a reduced residence time and an effectively higher SR than burner settings would indicate. Both of these effects work counter to NO reduction.

5.3.7 Staged-Combustion -- Natural Gas

Staging tests were performed with natural gas firing at 293kW (1.0×10^6 Btu/hr) to investigate in this facility the effect of staging on clean fuels. The five IFRF burners were set up in the following manner:

- 6 hole radial/axial nozzle
- Swirl setting of 2 to produce a clear blue flame under baseline conditions
- Axial fuel tube position
- Water cooled quarl - same as in the coal fired tests

Stage-air was introduced in the first and second staging positions in two separate tests. When the second staging position was utilized, a water-cooled stainless steel sampling probe was inserted in the first staging port to sample first-stage emission levels. At both staging positions, the emissions were also sampled at the normal port with the staged-air off (substoichiometric firing). Figure 5-73 gives the NO versus SR found

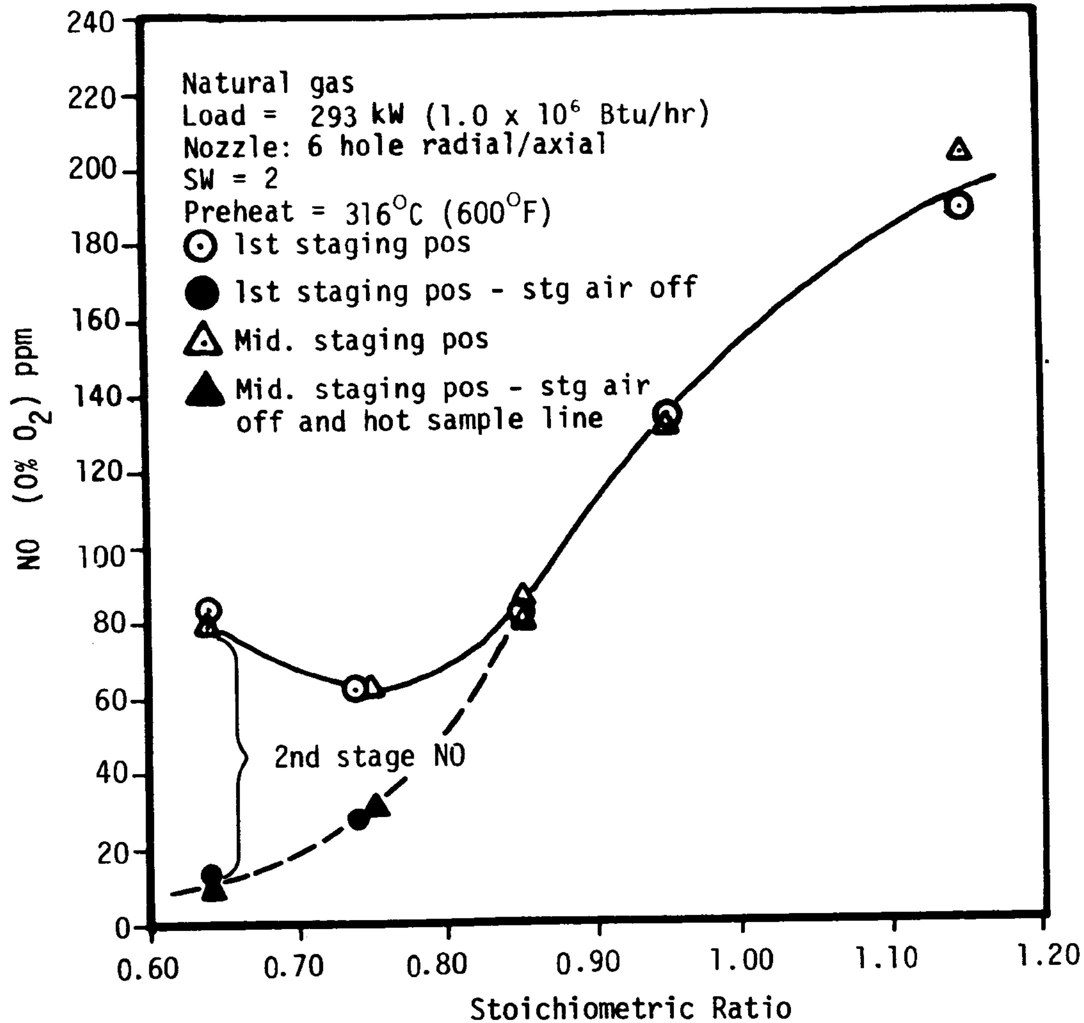


Figure 5-73. Natural gas fired NO vs. SR.

for this test series. The shapes of these curves are very similar to the coal-fired results. However, unlike the coal-firing cases, there was no difference between the first-stage and second-stage position results. In addition, hot sampling in the first stage gave the same NO levels as stack values while running substoichometrically at a SR above 0.85. Below a SR of 0.85, the NO levels within the first stage steadily decayed reaching 10-12 ppm at a SR = 0.65. These results suggest that above SRs of 0.85, the bulk of the NO is produced in the first stage. Below SRs of 0.85, increasing amounts of NO are produced in the second stage until at around 0.65 the bulk of the NO is formed in the second stage.

As was hypothesized for coal-firing at long residence time, the shape of the NO vs SR curve is primarily due to chemical processes. DeSoete (Reference 5-25) has suggested that atmospheric N_2 acts like a fuel-nitrogen species at low SR, yielding nitrogen intermediate species which can potentially be converted to NO in the fuel-lean second stage. Comparing hot sampling and stack NO results at low SR adds some support to the hypothesis that nitrogen intermediates are being oxidized in the second stage. The close similarity between the gas- and coal-fired NO vs SR curve shapes for fuels, which have widely dissimilar mixing and combustion characteristics, lends support to the hypothesis that chemical effects are dominating the shapes of the curves. It is interesting to note that stage position did not impact gas-firing results, whereas it has a significant impact on coal-fired results. This difference could be a result of several processes. First, during gas firing the fuel is mixed and combusted on a shorter time scale than coal combustion. For gas-firing, the combustion volume may be sufficient to complete all chemical processes whereas coal processes may be continuing at the point of stage-air addition. Second, near zone NO produced during coal firing will probably not be present when firing on gas. Finally coal contains bound-nitrogen and sulfur compounds which can interact and which are not expected to yield NO formation levels and rates similar to gas fired results. Therefore, the decay processes and long residence times needed to reduce this early NO during coal firing are not needed for gas combustion.

The gas-fired results give an indication of the NO levels achieved when firing clean fuels under staged condition. These results can be used as a rough measure of the effectiveness of staging when burning fuels containing bound nitrogen.

REFERENCES

5-1. McCann, C., Demeter, J., Snedden, R., and Bienstock, D., "Combustion Control of Pollutants from Multi-Burner Coal-Fired Systems," U.S. Bureau of Mines, EPA-650/2-74-038, May 1974.

5-2. Crawford, A. R., et al., "The Effect of Combustion Modification on Pollutants and Equipment Performance of Power Generation Equipment," Exxon Research and Engineering Co., EPA-600/2-76-152c, prepared for the Stationary Source Combustion Symposium, September 24-26, 1975.

5-3. Armento, W. J., "Effects of Design and Operating Variables on NO_x from Coal Fired Furnaces -- Phase II, " EPA-650-2-74/002b, February, 1975.

5-4. Pershing, D. W. and Wendt, J. O. L., "Pulverized Coal Combustion: The Influence of Flame Temperatures and Coal Composition on Thermal and Fuel NO_x," presented at the Sixteenth Symposium (International) on Combustion, M.I.T., August 15, 1976.

5-5. Selker, A. P., "Program for Reduction of NO_x from Tangential Coal-Fired Boilers, Phase II and IIa," EPA-650/2-73-005a and b, June 1975.

5-6. Heap, M. P., Proceedings, Coal Combustion Seminar, June 19-20, 1973, Research Triangle Park, North Carolina 27711, EPA-650/2-73-021, September 1973.

5-7. Pershing, D. W., et al., "Influence of Design Variables on the Production of Thermal and Fuel NO from Residual Oil and Coal Combustion," AIChE Symposium Series, No. 148, Vol. 71, 1975, pp. 19-29.

5-8. Habelt, W. W. and Selker, A. P., "Operating Procedures and Prediction for NO_x Control in Steam Power Plants", presented at Central States Section of the Combustion Institute, Spring Technical Meeting, Madison, WI, March 26-27, 1974.

5-9. Wendt, J. O. L., Corley, T. L. and Morcomb, J. T., "Interactions Between Sulfur Oxides and Nitrogen Oxides in Combustion Processes," Proceedings of the Second Stationary Source Combustion Symposium, Vol. IV, Fundamental Combustion Research, EPA-600/7-77-073d, July 1977.

5-10. Hardgrove, R. M., "Method for Burning Fuel," U.S. Patent 3,048,131, August 7, 1962.

5-11. Pohl, J. H. and Sarofin, A. F., "Devolatilization and Oxidation of Coal Nitrogen", Sixteenth Symposium (International) on Combustion, The Combustion Institute, 1976, p. 491.

5-12. Corlett, R. C. and Monteith, L. E., "Molecular Nitrogen Yields from Fuel Nitrogen in Backmixed Combustion", Western States Section Combustion Institute Paper WSS/CI 77-47, Stanford University, Palo Alto, CA, October 1977.

5-13. Sarofim, A. F., et al., "Mechanisms and Kinetics of NO_x Formation: Recent Developments," presented at 69th Annual Meeting, AIChE, Chicago, November 30, 1976.

5-14. Folsom, B.A., Evaluation of Combustor Design Concepts for Advanced Energy Conversion Systems, Proceedings of the Second Stationary Source Combustion Symposium, Vol. V, EPA-600/7-77-073e, July, 1977.

5-15. Axworthy, A. E., et al., "Chemical Reactions in the Conversion of Fuel Nitrogen to NO_x," in Proceedings of the Stationary Source Combustion Symposium, Volume I, EPA 600/2-76-152a, June 1976.

5-16. Yamagishi, K., et al., "A Study of NO_x Emission Characteristics in Two Stage Combustion," Fifteenth Symposium (International) on Combustion, The Combustion Institute, p. 1156, 1974.

5-17. Heap, M. P., et al., "The Control of Pollutant Emissions from Package Boilers," ASME paper 75-WA/F4-4, December 4, 1975.

5-18. Siegmund, C. W. and Turner, D. W., "NO_x Emissions from Industrial Boilers: Potential Control Methods," ASME Journal of Engineering for Power p.1, January 1974.

5-19. Cato, G. A., et al., "Field Testing: Application of Combustion Modification to Control Pollutant Emissions from Industrial Boilers -- Phase 2," KVB Engineering, Environmental Protection Technology Series, EPA-600/2-76-086a, April 1976.

5-20. Martin, G. B., and Berkau, E. E., "An Investigation of the Conversion of Various Fuel Nitrogen Compounds to Nitrogen Oxides in Oil Combustion," presented at 70th National AIChE Meeting, Atlantic City, NJ, August, 1971.

5-21. Heap, M. P., et al., "Burner Criteria for NO_x Control -- Volume I. Influence of Burner Variables on NO_x in Pulverized Coal Flames," EPA-600/2-76-061a, March 1976.

5-22. Blair, D. W., Wendt., J. O. L., and Bartok, W., "Evolution of Nitrogen and Other Species During Controled Pyrolyns of Coal," Sixteenth Symposium (International) on Combustion, The Combustion Institute, 1976, p. 475.

5-23. Copeland, J. D., "An Investigation of the Best System of Emission Reduction for Nitrogen Oxides from Large Coal-Fired Steam Generators," Standards Support and Environmental Impact Statement, Office of Air Quality Planning and Standards, October 1976.

5-24. Pohl, J. H. and Sarofim, A. F., "Fate of Coal Nitrogen During Pyrolysis and Oxidation," in Proceedings of the Stationary Source Combustion Symposium, Vol. I, Fundamental Research, EPA-600/2-76-152a, June 1976.

5-25. DeSoete, G. G., "Overall Reaction Rates of NO and N_2 Formation from Fuel Nitrogen," Fifteenth Symposium (International) on Combustion, the Combustion Institute, p. 1093, August 1974.

SECTION 6

SUMMARY AND CONCLUSIONS

The conclusions derived from the previous section are summarized for the baseline and control technology tests in Tables 6-1 and 6-2 respectively. In general, these conclusions apply equally well to the front-wall-fired, tangentially-fired or horizontal extension fired configurations.

Staged combustion as a technique for controlling NO_x emissions is limited in its application due to the long residence times and very fuel-rich conditions (0.75 to 0.85 SR) required to achieve low NO_x levels (400 ppm). Unfortunately, to achieve less than 100 ppm it would require nearly 2/3 of the volume of present conventional utility boilers. This would present severe corrosion slagging and flame stability/detection problems. However it is possible that a combination of low-NO_x burners plus staging at higher SRs (0.90 to 1.02) may be suitable for either new boiler design or retrofit of existing boilers.

Table 6-3 summarizes the impact of the major parameters, both under low and medium first-stage SR conditions. An indication is given for each test parameter whether it has a major, moderate or minor effect on NO and preferred value or direction for that parameter.

TABLE 6-1. SUMMARY AND CONCLUSIONS

Baseline Testing

- Facility simulates full-scale units with hot refractory walls
- NO increases with excess air
- Axial type injector on front-wall-fired burners yields NO levels similar to tangential results; both are lower than front wall-fired spreader coal injector results
- NO levels increase slightly with temperature due to thermal NO contribution
- An optimum swirl and axial fuel tube position was found for minimum NO levels for front-wall-fired units
- NO increases with increasing primary air and very high NO levels may be achieved if the flame becomes detached from the burner
- Increases in firing rate increased both temperature and air/fuel mixing and thereby NO levels
- The Western Kentucky Coal and Pittsburgh #8 Coal yielded very similar results for each firing mode. The Montana Coal with higher H_2O and ash levels but low S levels consistently yielded higher NO levels

TABLE 6-2. SUMMARY AND CONCLUSIONS

Evaluation of Control Technology

- Minimum NO levels were achieved at stoichiometric ratios of 0.75 to 0.85; the minimum NO and SR was not dependent on the type of firing
- Chemical rather than physical processes dominate under fuel-rich long residence time conditions
- Under fuel-rich conditions, NO levels decay with increasing residence time; 3 to 5 seconds at the minimum SR are required to achieve NO levels less than 100 ppm
- Increased temperature at the minimum SR and long residence times resulted in slighly lower NO levels possibly due to greater devolatilization under fuel-rich conditions and/or greater decay of NO
- Higher firing rates had effects on NO similar to temperature
- At short residence times and SRs greater than the minimum, increases both in temperature and firing rate produced higher NO levels
- Mixing in the 1st stage becomes more important as the residence time is decreased and/or the SR is increased
- Second-stage parameters (excess air, mixing, temperature or residence time) did not have a strong influence on the NO levels unless they impacted back-mixing of stage-air into the first stage

APPENDIX A

NOTES TO TEST AND PARTICULATE DATA SUMMARY SHEETS

TEST SUMMARY SHEETS

Fuel:	1 = Western Kentucky Coal
	2 = Pittsburg #8
	3 = Montana Coal
	4 = Virginia Coal
	G = Natural Gas
SR:	Stoichiometric Ratio
EA:	Excess Air (%)
Load:	Firing Rate x 10^6 Btu/hr
Preheat:	Sec. = secondary air preheat
	Stg. = stage air preheat
	W.C. = indicates addition water cooling in the 1st stage
Burner:	5 IFRF = five small IFRF swirl block burners
	Tang = tangentially fired burner
SW/Inj. or Yaw:	SW = swirl index on burner, 0 to 8
	Inj. = injector type
(No indication):	B&W type spreader
Rad/Ax	radial/axial gas nozzle
AX	axial injection stright open pipe
Prim. Stoich:	Primary stoichiometry; percent of total air at 15 percent EA
Stg. Air Mixing Location:	Fast -- four 1-inch hole injectors
	Slow -- eight 2-inch hole injectors
	Down -- air injected one side only
	4/1 = indicates injected through four holes at first staging position

H-#	See text for horizontal extension configuration
Nominal Residence Time, τ	1st = first stage
	Short = staged at first staging position
	Med = staged at second staging position
	Long = staged at third staging position
	2nd = second stage
	Short = one heat exchanger length
	Long = one and one-half or more heat exchanger lengths
Temperature:	Bare Pt/Pt-Rh thermocouple measurement
	T_{23} = measured at the exit of the firebox
	T_{24} = measured in the second stage
NO_c:	NO level in ppm corrected to 0% O_2
CO_c:	NO level in ppm corrected to 0% O_2
m_f:	fuel flow, lbs/hr
m_t:	total air flow, lbs/hr
m_T:	total air plus fuel flow, $m_f + m_t = m_T$, lbs/hr
TR:	total residue from cyclones and filter, grams
Vg:	volume of flue sample collected, ft^3
GL:	grain loading, grains/ft^3
CP:	percent combustibles in residue collected, %
AF:	lbs of dry refuse per lb of as-fired fuel
CL:	combustible loss as carbon or a percentage of heat input, %
Comments:	Axial fuel tube position -- distance from end of fuel tube to burner body in inches, outside the burner. Used as reference measurement.

APPENDIX A.1

DATA SUMMARY SHEETS

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
100a	G	1.25	25	2.4	300	5 IFRF	2/rad/ax	--	--	--	--	2263	--	205	--	5.15[b]
b	G	1.10	10	2.4	300	5 IFRF	2/rad/ax	--	--	--	--	2345	--	216	--	5.15
c	G	1.05	5	2.4	300	5 IFRF	2/rad/ax	--	--	--	--	2500	--	218	--	5.15
d	G	1.10	10	2.4	300	5 IFRF	2/rad/ax	--	--	--	--	2486	--	255	--	5.15
e	G	1.25	25	2.4	300	5 IFRF	2/rad/ax	--	--	--	--	2444	--	253	--	5.15
f	G	1.15	15	1.5	600	5 IFRF	2/rad/ax	--	--	--	--	2322	--	241	--	5.15
g	G	1.35	35	1.5	600	5 IFRF	2/rad/ax	--	--	--	--	2275	--	242	--	5.15
h	G	1.05	5	1.5	600	5 IFRF	2/rad/ax	--	--	--	--	--	--	195	--	5.15
102a	G	1.15	15	2.5	182 w.c.	5 IFRF	2/rad/ax	--	--	--	--	--	--	93	--	5.15
b	G	1.05	5	2.5	182 w.c.	5 IFRF	2/rad/ax	--	--	--	--	--	--	88	--	5.15
c	G	1.35	35	2.5	182 w.c.	5 IFRF	2/rad/ax	--	--	--	--	--	--	107	--	5.15
103a	G	1.25	25	2.5	300 w.c.	5 IFRF	2/rad/ax	--	--	--	--	2063	--	116	--	5.15
b	G	1.10	10	2.5	300 w.c.	5 IFRF	2/rad/ax	--	--	--	--	2120	--	117	--	5.15
c	G	1.05	5	2.5	300 w.c.	5 IFRF	2/rad/ax	--	--	--	--	2173	--	115	--	5.15
d	G	1.30	30	2.5	600 w.c.	5 IFRF	2/rad/ax	--	--	--	--	2104	--	177	--	5.15
e	G	1.15	15	2.5	600 w.c.	5 IFRF	2/rad/ax	--	--	--	--	2154	--	189	--	5.15
f	G	1.05	5	2.5	600 w.c.	5 IFRF	2/rad/ax	--	--	--	--	2217	--	173	--	5.15
g	G	1.35	35	1.5	600 w.c.	5 IFRF	2/rad/ax	--	--	--	--	1952	--	137	--	5.15
h	G	1.15	15	1.5	600 w.c.	5 IFRF	2/rad/ax	--	--	--	--	1991	--	128	--	5.15
i	G	1.02	2	1.5	600 w.c.	5 IFRF	2/rad/ax	--	--	--	--	2019	--	117	--	5.15
105a	1	1.40	40	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2026	--	1240	--	4.65
b	1	1.35	35	1.5	600 w.c.	5 IFRF	2	12	--	--	--	2060	--	1300	--	4.65
c	1	1.35	35	1.5	600 w.c.	5 IFRF	6	12				2062	--	1400	--	4.65
d	1	1.40	40	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2142	--	1310	--	4.65
e	1	1.25	25	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2170	--	1210	85	4.65
106a	1	1.30	30	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2181	--	1110	54	4.65
107a	G	1.15	15	2.5	600 w.c.	5 IFRF	2/rad/ax	12	--	--	--	2215	--	274.4	9	5.15
b	1	1.20	20	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2132	--	880	17	5.15
c	1	1.20	20	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2043	--	980	35	4.65
d	1	1.20	20	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2206	--	1175	52	4.15
e	1	1.15	15	1.0	600 w.c.	5 IFRF	4	25	--	--	--	1961	--	1300	47	4.65
f	1	1.25	25	1.0	600 w.c.	5 IFRF	4	25	--	--	--	1950	--	1440	34	4.65
g	1	1.10	10	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2147	--	1010	107	4.65
h	1	1.00	0	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2226	--	660	168	5.15
i	1	1.01	1	1.5	600 w.c.	5 IFRF	4	12	--	--	--	2229	--	720	56	5.15
j	1	1.25	25	1.5	300 w.c.	5 IFRF	4	12	--	--	--	2225	--	1100	95	4.65
k	1	1.15	15	1.5	300 w.c.	5 IFRF	4	12	--	--	--	2238	--	935	69	4.65
108a	G	1.25	25	2.4	600	5 IFRF	2/rad/ax	--	--	--	--	1538[a]	--	233	--	5.15
b	1	1.10	10	1.5	600	5 IFRF	4	12	--	--	--	1818	--	1128	--	5.15
c	1	1.25	25	1.5	600	5 IFRF	6	12	--	--	--	1984	--	1350	--	5.5
d	1	1.25	25	1.5	600	5 IFRF	4	12	--	--	--	2026	--	1300	--	5.5

[a] T_{23} out; wall T/C instead
[b] Numbers -- Axial fuel tube position

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT Temperature 1st	Nom. RT Temperature 2nd	T_{23} (°F)	T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
108e	1	1.10	10	1.5	600	--	5 IFRF	4	12	--	--	--	2081	--	1280	--	6.0[b]
f	1	1.15	15	1.5	600	--	5 IFRF	4	25	--	--	--	2137	--	1551	--	5.15
g	1	1.25	25	1.5	600	--	5 IFRF	4	25	--	--	--	2184	--	1790	--	4.15
h	1	1.15	15	1.5	600	--	5 IFRF	4	12	--	--	--	2202	--	1068	--	4.15
i	1	1.15	15	1.5	600	--	5 IFRF	4	12	--	--	--	2198	--	975	--	4.15
j	1	1.05	5	1.5	600	--	5 IFRF	4	12	--	--	--	2199	--	890	--	4.15
k	1	1.15	15	1.5	600	--	5 IFRF	4	12	--	--	--	2213	--	1040	--	4.15
l	1	1.25	25	1.5	600	--	5 IFRF	4	12	--	--	--	--	--	1130	--	4.15
109a	G	1.02	2	1.82	600	--	5 IFRF	2/rad/ax	--	--	--	--	2570	1969	333	--	CO meter out
b	G	1.11	11	2.4	600	--	5 IFRF	2/rad/ax	--	--	--	--	2547	2027	388	--	CO meter out
c	G	1.23	23	2.4	600	--	5 IFRF	2/rad/ax	--	--	--	--	2482	2068	392	--	CO meter out
d	G	1.14	13.5	2.4	600	--	5 IFRF	2/rad/ax	--	--	--	--	2563	2135	464	--	CO meter out
e	G	1.06	5.5	2.4	600	--	5 IFRF	2/rad/ax	--	--	--	--	2605	2158	430	--	CO meter out
f	G	1.24	23.5	2.4	600	--	5 IFRF	2/rad/ax	--	--	--	--	2531	2191	411	--	CO meter out
g	G	1.13	13	2.4	600	--	5 IFRF	2/rad/ax	--	--	--	--	2583	2203	468	--	CO meter out
h	G	1.15	15	2.2	600	--	5 IFRF	4/rad/ax	--	--	--	--	2554	2225	414	--	CO meter out
i	G	1.06	6	2.2	600	--	5 IFRF	4/rad/ax	--	--	--	--	2581	2239	386	--	CO meter out
j	G	1.24	23.5	2.2	600	--	5 IFRF	4/rad/ax	--	--	--	--	2556	2256	363	--	CO meter out
110a	1	1.30	30.0	1.5	600	--	5 IFRF	4	12	--	--	--	2298	1834	1270	--	CO meter out
111a	1	1.28	28.0	1.5	600	--	5 IFRF	4	12	--	--	--	2256	--	1260	--	CO meter out
b	1	1.12	12.0	1.5	600	--	5 IFRF	4	12	--	--	--	2336	--	1150	--	CO meter out
113a	1	1.06	5.6	1.5	620	--	5 IFRF	4	12	--	--	--	2494	--	875	--	CO meter out
b	1	1.11	11.1	1.5	620	--	5 IFRF	4	12	--	--	--	2556	--	1075	--	CO meter out
114a	1	1.12	11.6	1.5	600	--	5 IFRF	4	12	--	--	--	2006	--	940	--	CO meter out
b	1	1.25	25.2	1.5	600	--	5 IFRF	4	21.6	--	--	--	2120	--	1680	--	CO meter out
c	1	1.12	11.7	1.5	600	--	5 IFRF	4	12	--	--	--	2088	--	910	--	CO meter out
d	1	1.12	11.7	1.5	600	--	5 IFRF	4	12	--	--	--	2123	--	950	--	CO meter out
e	1	1.03	2.8	1.5	600	--	5 IFRF	4	12	--	--	--	2194	--	820	--	CO meter out
f	1	1.17	16.9	1.5	600	--	5 IFRF	4	12	--	--	--	2230	--	1170	--	CO meter out
115a	1	1.19	19.9	1.5	300	--	5 IFRF	4	12	--	--	--	2156	--	1020	--	CO meter out
b	1	1.13	13.5	1.5	300	--	5 IFRF	4	12	--	--	--	2260	--	1050	--	CO meter out
c	1	1.06	6.2	1.5	300	--	5 IFRF	4	12	--	--	--	2292	--	840	--	CO meter out
d	1	1.26	26.0	1.5	300	--	5 IFRF	4	12	--	--	--	2304	--	1075	--	CO meter out
e	1	1.13	13.3	1.5	300	--	5 IFRF	4	12	--	--	--	2349	--	950	--	CO meter out
116a	1	1.38	38.2	1.0	600	--	5 IFRF	4	12	--	--	--	2058	--	1025	--	CO meter out
b	1	1.24	24.4	1.0	600	--	5 IFRF	4	12	--	--	--	2117	--	975	--	CO meter out
c	1	1.18	17.9	1.0	600	--	5 IFRF	4	12	--	--	--	2188	--	910	--	CO meter out
d	1	1.12	11.7	1.0	600	--	5 IFRF	4	12	--	--	--	2247	--	820	--	CO meter out
e	1	1.05	5.1	1.0	600	--	5 IFRF	4	12	--	--	--	2266	--	675	--	CO meter out
118a	1	1.44	44.2	1.0	300	--	5 IFRF	4	12	--	--	--	1970	--	940	24	
b	1	1.25	25.0	1.0	300	--	5 IFRF	4	12	--	--	--	2039	--	840	24	

[b]Numbers -- Axial fuel tube position

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
118c	1	1.17	17.3	1.0	300	--	5 IFRF	4	12	--	--	--	2167	--	770	75	
d	1	1.03	2.9	1.0	300	--	5 IFRF	4	12	--	--	--	2240	--	510	238	
e	1	1.45	44.7	1.0	300	--	5 IFRF	4	12	--	--	--	2255	--	1030	42	
120a	G	1.32	32.0	0.89	600	--	5 IFRF	4	--	--	--	--	1897	--	191	0	Note gas thru coal nozzle
b	G	1.18	18.1	0.90	600	--	5 IFRF	4	--	--	--	--	1935	--	168	0	Note gas thru coal nozzle
c	G	1.165	16.5	0.92	588	--	5 IFRF	4	--	--	--	--	1973	--	176	0	Note gas thru coal nozzle
d	G	1.165	16.5	0.92	588	--	5 IFRF	4	--	--	--	--	1984	--	185	0	Note gas thru coal nozzle
e	G	1.045	4.5	0.93	584	--	5 IFRF	4	--	--	--	--	2032	--	150	0	Note gas thru coal nozzle
f	G	1.282	28.2	0.88	589	--	5 IFRF	4	--	--	--	--	2006	--	216	0	Note gas thru coal nozzle
g	G	1.282	28.2	0.88	591	--	5 IFRF	6	--	--	--	--	--	--	197	0	Note gas thru coal nozzle
121a	G	1.38	38.0	0.90	300	--	5 IFRF	4	--	--	--	--	1819	--	139	0	Note gas thru coal nozzle
b	G	1.19	19.2	0.92	300	--	5 IFRF	4	--	--	--	--	1889.6	--	126	0	Note gas thru coal nozzle
c	G	1.05	5.0	0.92	300	--	5 IFRF	4	--	--	--	--	1950.4	--	99	30	Note gas thru coal nozzle
d	G	1.145	14.5	0.90	300	--	5 IFRF	4	--	--	--	--	1946	--	126	0	Note gas thru coal nozzle
e	G	1.22	22.0	0.91	300	--	5 IFRF	4	--	--	--	--	1935	--	146	0	Note gas thru coal nozzle

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
120f	G	1.16	16.0	1.58	300	--	5 IFRF	4	--	--	--	--	2136	--	210	0	Note gas thru coal nozzle
g	G	1.095	9.5	1.47	300	--	5 IFRF	4	--	--	--	--	2198	--	185	0	Note gas thru coal nozzle
122a	1	1.05	15	1.0	600	300	5 IFRF	4	12	Fast 4/1	Short	Short	--	1820	575	21	
b	1	1.02	15	1.0	600	--	5 IFRF	4	12	Fast 4/1	Short	Short	--	1879	435	54	
123a	1	0.95	15	1.0	600	335	5 IFRF	6	12	Fast 4/1	Short	Short	--	1961	280	84	
b	1	0.95	15	1.0	600	--	5 IFRF	6	12	Fast 4/1	Short	Short	--	2020	310	250	
124a	1	1.05	15	1.0	600	--	5 IFRF	6	12	Fast 4/1	Short	Short	--	1915	720	99	
b	1	1.02	15	1.0	600	--	5 IFRF	6	12	Fast 4/1	Short	Short	--	1929	610	90	
c	1	0.95	15	1.0	600	350	5 IFRF	6	12	Fast 4/1	Short	Short	--	1940	400	67	
d	1	1.02	15	1.0	300	300	5 IFRF	4	12	Fast 4/1	Short	Short	--	1991	515	60	
e	1	0.95	15	1.0	300	--	5 IFRF	4	12	Fast 4/1	Short	Short	--	2062	385	60	
f	1	0.95	15	1.0	300	--	5 IFRF	6	12	Fast 4/1	Short	Short	--	2081	335	60	
g	1	1.02	15	1.0	300	--	5 IFRF	6	12	Fast 4/1	Short	Short	--	2027	600	60	
125a	1	1.02	25	1.0	600	342	5 IFRF	6	12	Fast 4/1	Short	Short	--	1775	465	74	
b	1	0.95	25	1.0	600	351	5 IFRF	6	12	Fast 4/1	Short	Short	--	1805	285	150	
c	1	0.95	25	1.0	600	350	5 IFRF	4	12	Fast 4/1	Short	Short	--	1891	270	150	
d	1	0.95	20	1.0	600	350	5 IFRF	4	12	Fast 4/1	Short	Short	--	1928	310	70	
e	1	0.95	15	1.0	600	360	5 IFRF	4	12	Fast 4/1	Short	Short	--	1945	315	125	
126a	1	1.05	15	1.0	600	300	5 IFRF	6	12	Fast 4/1	Short	Short	--	1909	625	35	
b	1	1.02	15	1.0	600	315	5 IFRF	6	12	Fast 4/1	Short	Short	--	2006	635	39	
c	1	0.95	15	1.0	600	340	5 IFRF	6	12	Fast 4/1	Short	Short	--	2022	315	73	
127a	1	0.95	15	1.0	600	328	5 IFRF	4	12	Fast 4/1	Short	Short	--	2000	260	150	
b	1	0.85	15	1.0	600	331	5 IFRF	4	12	Fast 4/1	Short	Short	--	2084	160	1160	
c	1	0.95	15	1.0	300	300	5 IFRF	4	12	Fast 4/1	Short	Short	--	2085	290	400	
d	1	0.95	15	1.0	300	300	5 IFRF	6	12	Fast 4/1	Short	Short	--	2051	330	200	
e	1	1.02	15	1.0	300	271	5 IFRF	6	12	Fast 4/1	Short	Short	--	2089	490	100	
f	1	1.02	15	1.0	300	270	5 IFRF	4	12	Fast 4/1	Short	Short	--	2124	490	130	
128a	1	0.85	15	1.0	600	300	5 IFRF	6	12	Fast 4/1	Short	Short	--	2096	195	100	
b	1	1.02	15	1.0	600	344	5 IFRF	4	33	Fast 4/1	Short	Short	--	2062	650	72	
c	1	1.02	15	1.0	600	350	5 IFRF	8	33	Fast 4/1	Short	Short	--	2105	850	50	
d	1	1.02	15	1.0	600	350	5 IFRF	8	25	Fast 4/1	Short	Short	--	2115	835	50	
e	1	1.02	15	1.0	600	340	5 IFRF	4	25	Fast 4/1	Short	Short	--	2131	750	42	
f	1	0.95	15	1.0	600	330	5 IFRF	4	25	Fast 4/1	Short	Short	--	2139	470	141	
g	1	0.95	15	1.0	600	310	5 IFRF	8	25	Fast 4/1	Short	Short	--	2139	475	59	
h	1	0.95	15	1.0	600	297	5 IFRF	8	12	Fast 4/1	Short	Short	--	2125	400	111	
i	1	1.02	15	1.0	600	288	5 IFRF	8	12	Fast 4/1	Short	Short	--	2138	700	51	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
129a	1	0.80	15	1.0	600	360	5 IFRF	6	12	Fast 4/1	Short	Short	--	2063	190	273	
b	1	0.80	15	1.0	600	355	5 IFRF	8	12	Fast 4/1	Short	Short	--	2126	195	240	
c	1	0.80	15	1.0	800	330	5 IFRF	8	12	Fast 4/1	Short	Short	--	2136	180	2000	
d	1	0.80	35	1.0	800	330	5 IFRF	8	12	Fast 4/1	Short	Short	--	2157	160	100	
e	1	0.82	15	1.0	800	330	5 IFRF	8	12	Fast 4/1	Short	Short	--	--	170	117	
131a	1	1.15	25	1.0	600	--	5 IFRF	4	12	Fast 4/3	Long	Short	2085	1637	835	31	
b	1	0.95	15	1.0	600	282	5 IFRF	4	12	Fast 4/3	Long	Short	2078	1612	240	215	
c	1	0.95	15	1.0	600	343	5 IFRF	6	12	Fast 4/3	Long	Short	2102	1649	260	180	
d	1	0.85	15	1.0	600	360	5 IFRF	6	12	Fast 4/3	Long	Short	2093	1733	130	175	
e	1	0.85	15	1.0	600	360	5 IFRF	4	12	Fast 4/3	Long	Short	2100	1779	130	175	
132a	1	1.05	15	1.0	600	312	5 IFRF	4	12	Fast 4/3	Long	Short	2210	1756	745	31	
b	1	1.05	15	1.0	600	312	5 IFRF	6	12	Fast 4/3	Long	Short	2220	1762	735	26	
c	1	1.02	15	1.0	600	309	5 IFRF	6	12	Fast 4/3	Long	Short	2237	1768	695	41	
d	1	1.02	15	1.0	600	310	5 IFRF	4	12	Fast 4/3	Long	Short	2252	1784	690	41	
e	1	1.02	15	1.0	300	256	5 IFRF	4	12	Fast 4/3	Long	Short	2267	1814	625	35	
f	1	1.02	15	1.0	300	250	5 IFRF	6	12	Fast 4/3	Long	Short	2275	1825	565	50	
g	1	0.95	15	1.0	300	236	5 IFRF	6	12	Fast 4/3	Long	Short	2261	1853	300	162	
h	1	0.95	15	1.0	300	236	5 IFRF	4	12	Fast 4/3	Long	Short	2267	1852	300	220	
i	1	0.95	25	1.0	300	237	5 IFRF	4	12	Fast 4/3	Long	Short	2263	1867	270	85	
134a	1	1.15	25	1.0	600	--	5 IFRF	4	12	Fast 4/3	Long	Short	2110	1703	815	55	
b	1	0.85	15	1.0	600	333	5 IFRF	4	12	Fast 4/3	Long	Short	2074	1771	140	300	
c	1	0.85	15	1.0	600	397	5 IFRF	8	12	Fast 4/3	Long	Short	2067	1807	154	300	
d	1	0.85	25	1.0	600	427	5 IFRF	4	12	Fast 4/3	Long	Short	2065	1754	162	170	
135a	1	1.15	15	1.0	600	--	5 IFRF	4	12	Fast 4/3	Long	Short	2032	1672	830	15	
b	1	1.15	15	1.0	600	--	5 IFRF	6	12	Fast 4/3	Long	Short	2011	1668	865	15	
c	1	1.15	15	1.0	800	--	5 IFRF	6	12	Fast 4/3	Long	Short	2079	1732	1000	10	
d	1	1.15	15	1.0	800	--	5 IFRF	4	12	Fast 4/3	Long	Short	2123	1762	950	10	
e	1	1.02	15	1.0	800	335	5 IFRF	4	12	Fast 4/3	Long	Short	2220	1779	540	40	
f	1	0.95	15	1.0	800	371	5 IFRF	4	12	Fast 4/3	Long	Short	2231	1837	300	210	
g	1	0.85	15	1.0	800	424	5 IFRF	4	12	Fast 4/3	Long	Short	2215	1922	105	210	
g'	1	0.85	15	1.0	800	424	5 IFRF	4	12	Fast 4/3	Long	Short	2211	1950	85	158	NO_x meter on low cal
h	1	0.85	15	1.0	800	400	5 IFRF	8	12	Fast 4/3	Long	Short	2201	1958	95	175	84 ppm
i	1	0.75	15	1.0	800	400	5 IFRF	8	12	Fast 4/3	Long	Short	2163	2050	110	100	84 ppm
j	1	0.75	15	1.0	800	400	5 IFRF	4	12	Fast 4/3	Long	Short	2159	2033	110	60	84 ppm
k	1	0.85	15	1.0	800	400	5 IFRF	4	12	Fast 4/3	Long	Short	2172	1982	78	53	84 ppm
137a	1	0.85	15	1.0	800	458	5 IFRF	4	12	Fast 4/3	Long	Short	2086	1760	100	--	84 ppm
a'	1	0.85	15	1.0	800	458	5 IFRF	4	12	Fast 4/3	Long	Short	--	--	122	260	Normal cal
138a	1	1.02	15	1.0	600	296	5 IFRF	4	12	Fast 4/3	Long	Short	1992	1529	580	110	Normal cal
b	1	0.95	15	1.0	600	340	5 IFRF	4	12	Fast 4/3	Long	Short	2042	1589	240	275	Normal cal

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
138b'	1	0.95	25	1.0	600	340	5 IFRF	4	12	Fast 4/3	Long	Short	(2042)	(1589)	200	184	Normal cal
c	1	0.85	25	1.0	600	358	5 IFRF	4	12	Fast 4/3	Long	Short	2059	1717	125	440	Normal cal
c'	1	0.85	25	1.0	600	357	5 IFRF	4	12	Fast 4/3	Long	Short	2059	1764	95	530	NO_x meter on low cal
d	1	0.85	25	1.0	600	362	5 IFRF	4	12	Fast 4/3	Long	Short	2060	1763	103	257	NO_x meter on low cal
d'	1	0.85	25	1.0	600	362	5 IFRF	4	12	Fast 4/3	Long	Short	2070	1754	120	260	Normal cal
e	1	0.85	15	1.0	800	423	5 IFRF	4	12	Fast 4/3	Long	Short	2164	1817	100	625	Normal cal
e'	1	0.85	15	1.0	800	423	5 IFRF	4	12	Fast 4/3	Long	Short	2162	1856	92	600	NO_x meter on low cal
f	1	0.85	25	1.0	800	425	5 IFRF	4	12	Fast 4/3	Long	Short	2164	1856	95	325	NO_x meter on low cal
f'	1	0.85	25	1.0	800	425	5 IFRF	4	12	Fast 4/3	Long	Short	2167	1843	119	290	Normal cal
g	1	0.85	25	1.0	800	414	5 IFRF	Clinkers off	12	Fast 4/3	Long	Short	2172	1817	110	325	Normal cal
g'	1	0.85	25	1.0	800	414	5 IFRF	Clinkers off	12	Fast 4/3	Long	Short	(2172)	(1817)	88	452	NO_x meter on low cal
139a	1	1.02	15	1.0	95+ cool	95	5 IFRF	Clinkers off	12	Fast 4/3	Long	Short	1960	1540	420	215	Normal cal
b	1	0.95	15	1.0	95+ cool	95	5 IFRF	4	12	Fast 4/3	Long	Short	2001	1555	250	405	
c	1	0.85	15	1.0	95+ cool	95	5 IFRF	4	12	Fast 4/3	Long	Short	1992	1729	145	900	
c'	1	0.85	15	1.0	95+ cool	95	5 IFRF	4	12	Fast 4/3	Long	Short	1995	1777	120	785	NO_x meter on low cal
d	1	1.02	15	1.0	95+ cool	95	5 IFRF	4	12	Fast 4/3	Long	Short	2068	1682	540	155	
140a	1	1.15	15	1.0	90	--	5 IFRF	4	12	Fast 4/3	Long	Short	1965	1605	700	30	
b	1	1.02	15	1.0	90	90	5 IFRF	4	12	Fast 4/3	Long	Short	2026	1617	410	70	
c	1	1.15	15	1.0	600+ cool	--	5 IFRF	4	12	Fast 4/3	Long	Short	2070	1736	785	28	
d	1	1.02	15	1.0	600+ cool	280	5 IFRF	4	12	Fast 4/3	Long	Short	2114	1707	400	97	
e	1	0.85	15	1.0	600+ cool	328	5 IFRF	4	12	Fast 4/3	Long	Short	2114	1825	155	435	
143a	1	1.02	15	1.0	600	300	5 IFRF	4	12	Fast 4/1	Short	Long	2035	1653	510	41	
b	1	1.02	15	1.0	600	300	5 IFRF	8	12	Fast 4/1	Short	Long	2081	1736	675	40	
c	1	1.02	5	1.0	600	281	5 IFRF	4	12	Fast 4/1	Short	Long	2152	1791	550	33	
d	1	0.85	5	1.0	580	317	5 IFRF	4	12	Fast 4/1	Short	Long	2265	1902	185	61	
e	1	0.85	15	1.0	580	350	5 IFRF	4	12	Fast 4/1	Short	Long	2237	1904	220	35	
f	1	0.85	15	1.0	580	384	5 IFRF	8	12	Fast 4/1	Short	Long	2217	1890	215	35	
144a	1	1.02	15	1.0	600	260	5 IFRF	4	12	Slow 6/1	Short	Long	1960	1629	530	50	
b	1	1.02	5	1.0	600	270	5 IFRF	4	12	Slow 4/1	Short	Long	(1960)	(1629)	580	100	
c	1	0.85	15	1.0	590	308	5 IFRF	4	12	Slow 8/1	Short	Long	2129	1823	220	75	
d	1	0.85	5	1.0	580	(308)	5 IFRF	4	12	Slow 8/1	Short	Long	2173	1861	190	1400	
145a	1	1.02	15	1.0	600	373	5 IFRF	4	12	Slow 6/1	Short	Short	--	1812	620	31	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
145b	1	1.02	25	1.0	590	343	5 IFRF	4	12	Slow 8/1	Short	Short	--	1824	630	39	
c	1	1.02	5	1.0	590	329	5 IFRF	4	12	Slow 4/1	Short	Short	--	1878	550	47	
d	1	0.85	15	1.0	580	318	5 IFRF	4	12	Slow 8/1	Short	Short	--	1895	218	400	
e	1	0.85	25	1.0	580	319	5 IFRF	4	12	Slow 8/1	Short	Short	--	1867	210	220	
f	1	0.85	5	1.0	580	318	5 IFRF	4	12	Slow 8/1	Short	Short	--	1948	175	1300	
g	1	0.85	15	1.0	620	543	5 IFRF	4	12	Slow 8/1	Short	Short	--	1982	168	170	
h	1	1.02	15	1.0	600	500	5 IFRF	4	12	Slow 8/1	Short	Short	--	1998	720	50	
146a	1	1.02	25	1.0	600	333	5 IFRF	4	12	Fast 4/1	Short	Short	--	1885	450	37	
b	1	1.02	5	1.0	600	300	5 IFRF	4	12	Fast 4/1	Short	Short	--	1947	515	26	
c	1	0.85	25	1.0	600	329	5 IFRF	4	12	Fast 4/1	Short	Short	--	1973	233	40	
d	1	0.85	5	1.0	600	339	5 IFRF	4	12	Fast 4/1	Short	Short	--	2013	190	61	
e	1	0.85	15	1.0	600	333	5 IFRF	4	12	Down 2/1	Short	Short	--	2009	257	49	
f	1	1.02	15	1.0	600	326	5 IFRF	4	12	Down 2/1	Short	Short	--	2007	600	37	
g	1	0.85	15	1.0	600	545	5 IFRF	4	12	Fast 4/1	Short	Short	--	2079	236	37	
h	1	0.85	5	1.0	600	510	5 IFRF	4	12	Fast 4/1	Short	Short	--	2157	212	207	
i	1	1.02	15	1.0	600	478	5 IFRF	4	12	Fast 4/1	Short	Short	--	2129	575	31	
j	1	1.02	5	1.0	600	436	5 IFRF	4	12	Fast 4/1	Short	Short	--	2170	640	20	
148a	1	0.95	15	1.0	600	240	5 IFRF	6 axial	12	Fast 4/1	Short	Long	1951	1477	225	58	
b	1	0.85	15	1.0	580	331	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2067	1574	225	53	
c	1	1.02	15	1.0	600	336	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2076	1612	250	69	
d	1	1.15	18	1.0	600	293	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2095	1650	360	63	
149a	1	0.85	15	1.0	600	400	5 IFRF	4	12	Fast 4/1	Short	Long	2118	1685	243	55	
b	1	0.75	15	1.0	600	400	5 IFRF	4	12	Fast 4/1	Short	Long	2137	1733	230	54	
150a	1	0.85	15	1.0	580	325	5 IFRF	4	12	Fast 4/1	Short	Long	2168	1798	205	54	
b	1	0.80	15	1.0	575	325	5 IFRF	4	12	Fast 4/1	Short	Long	2177	1824	207	41	
c	1	0.75	15	1.0	575	325	5 IFRF	4	12	Fast 4/1	Short	Long	2234	1881	212	38	
d	1	0.75	15	1.0	575	325	5 IFRF	2	12	Fast 4/1	Short	Long	2230	1895	229	39	
e	1	0.75	15	1.0	575	325	5 IFRF	8	12	Fast 4/1	Short	Long	2230	1909	223	41	
f	1	0.75	15	1.0	575	325	5 IFRF	2	10	Fast 4/1	Short	Long	2259	1925	210	43	
g	1	0.75	15	1.0	750	325	5 IFRF	4	12	Fast 4/1	Short	Long	2315	1942	187	37	
h	1	0.75	15	1.0	750	325	5 IFRF	2	12	Fast 4/1	Short	Long	(2315)	(1942)	207	34	
152a	1	1.15	15	1.0	600	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	1947	1728	340	31	
b	1	1.25	25	1.0	600	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2070	1860	410	22	
c	1	1.05	5	1.0	600	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2132	1903	280	300	
d	1	1.15	15	1.2	600	--	5 IFRF	6 axial	15	Fast 4/1	Short	Long	2131	1931	480	116	
e	1	1.05	5	1.2	600	--	5 IFRF	6 axial	15	Fast 4/1	Short	Long	2266	2241	290	216	
f	1	1.25	25	1.2	600	--	5 IFRF	6 axial	15	Fast	Short	Long	2241	2055	560	57	
153a	1	0.95	5	1.0	600	335	5 IFRF	6 axial	12	Fast	Short	Long	2030	1780	190	931	
b	1	0.95	25	1.0	600	335	5 IFRF	6 axial	12	Fast	Short	Long	2056	1854	270	135	
c	1	1.02	15	1.2	600	300	5 IFRF	6 axial	15	Fast	Short	Long	2081	1884	310	104	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
154a	1	0.95	15	1.2	585	343	5 IFRF	6 axial	15	Fast	Short	Long	2079	1894	270	58	
b	1	0.95	5	1.2	585	324	5 IFRF	6 axial	15	Fast	Short	Long	2189	1999	230	575	
c	1	0.95	25	1.2	580	367	5 IFRF	6 axial	15	Fast	Short	Long	2231	2075	285	39	
d	1	0.85	15	1.2	580	376	5 IFRF	6 axial	15	Fast	Short	Long	2301	2159	220	47	
e	1	0.75	15	1.2	570	362	5 IFRF	6 axial	15	Fast	Short	Long	2336	2194	205	52	
f	1	0.95	15	1.2	580	(362)	5 IFRF	6 axial	15	Fast	Short	Long	2352	2213	255	25	
g	1	0.75	15	1.0	570	398	5 IFRF	6 axial	12	Fast	Short	Long	2340	2185	205	60	
155a	1	1.02	5	1.2	600	250	5 IFRF	4	15	Fast	Short	Long	2253	2094	865	42	
b	1	1.02	15	1.2	600	257	5 IFRF	4	15	Fast	Short	Long	2275	2125	900	52	
c	1	1.02	25	1.2	600	297	5 IFRF	4	15	Fast	Short	Long	2238	2095	955	60	
d	1	0.95	5	1.2	590	290	5 IFRF	4	15	Fast	Short	Long	2308	2152	720	80	
e	1	0.95	15	1.2	590	303	5 IFRF	4	15	Fast	Short	Long	2320	2172	765	48	
f	1	0.85	5	1.2	580	300	5 IFRF	4	15	Fast	Short	Long	2367	2231	410	113	
156a	1	0.95	25	1.2	600	400	5 IFRF	4	15	Fast	Short	Long	2074	1924	695	70	
b	1	0.85	15	1.2	595	378	5 IFRF	4	15	Fast	Short	Long	2129	1972	425	62	
c	1	0.85	25	1.2	590	373	5 IFRF	4	15	Fast	Short	Long	2117	1973	430	76	
d	1	0.75	15	1.2	580	372	5 IFRF	4	15	Fast	Short	Long	2151	2003	235	58	
e	1	0.75	5	1.2	580	367	5 IFRF	4	15	Fast	Short	Long	2245	2084	175	1650	
f	1	0.75	23	1.2	580	344	5 IFRF	4	15	Fast	Short	Long	2192	2062	240	96	
g	1	0.65	15	1.2	570	320	5 IFRF	4	15	Fast	Short	Long	2242	2114	210	68	
h	1	0.65	7.5	1.2	570	314	5 IFRF	4	15	Fast	Short	Long	2322	2189	180	100	
i	1	1.15	15	1.2	600	--	5 IFRF	4	15	Fast	Short	Long	2263	2150	1135	50	
j	1	1.25	25	1.2	600	--	5 IFRF	4	15	Fast	Short	Long	2306	2197	1310	76	
k	1	1.25	25	1.2	600	--	5 IFRF	4	15	Fast	Short	Long	2307	2202	1180	71	
l	1	1.15	15	1.2	600	--	5 IFRF	4	15	Fast	Short	Long	2318	2204	1170	40	
m	1	1.05	5	1.2	600	--	5 IFRF	4 SPRDR	15	Fast 4/1	Short	Long	2348	2227	1010	35	
n	1	1.15	15	1.0	600	--	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2335	2216	1015	32	
o	1	SR_1 = 0.95	15	1.2	600	--	5 IFRF	4 SPRDR	15	Fast 4/1	Cont:[c] = 1	--	2395	2290	1035	34	Biased fired
p	1	SR_1 = 0.85	15	1.2	600	--	5 IFRF	4 SPRDR	15	Fast 4/1	Cont:[c] = 1	--	2412	2311	995	34	Biased fired
q	1	SR_1 = 0.85	15	1.2	600	--	5 IFRF	4 SPRDR	15	Fast 4/1	Cont:[c] = 3	--	2373	2293	1035	52	Biased fired
157a	2	1.15	15	1.0	600	--	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2087	1930	845	34	
b	2	1.05	5	1.0	600	--	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2118	--	700	38	
c	2	1.25	25	1.0	600	--	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2130	--	990	48	
d	2	1.15	15	1.5	600	--	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2281	2051	1020	198	
e	2	1.05	5	1.5	600	--	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2333	2080	875	70	

[c]See chart for biased firing

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NOc ppm	COc ppm	Comments
157f	2	1.25	25	1.5	600	--	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2370	2130	1210	251	
g	2	0.95	15	1.5	600	240	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2331	2089	570	62	
h	2	0.85	5	1.5	600	292	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2408	2159	370	49	
i	2	0.95	5	1.5	600	310	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2425	2175	495	50	
j	2	1.02	15	1.0	590	308	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2344	2081	550	34	
k	2	1.02	5	1.0	590	280	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2320	2048	520	40	
l	2	0.95	15	1.0	585	311	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2280	2031	450	33	
m	2	0.95	5	1.0	580	320	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2305	2046	375	42	
n	2	0.95	25	1.0	580	330	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2262	2022	404	37	
o	2	0.85	15	1.0	575	347	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2280	2025	275	35	
p	2	0.85	5	1.0	575	345	5 IFRF	4 SPRDR	12	Fast 4/1	Short	Long	2316	2055	240	51	
q	2	0.85	5	1.0	575	323	5 IFRF	6 axial	15	Fast 4/1	Short	Long	2266	2010	170	171	4.65[b]
r	2	0.85	5	1.0	575	323	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2318	2069	170	194	5.00
s	2	0.85	5	1.0	575	323	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2354	2094	185	163	4.65
t	2	0.85	15	1.0	575	320	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2319	2071	210	98	5.00
u	2	1.15	15	1.0	585	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2295	2058	570	63	5.00
v	2	1.05	5	1.0	590	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2327	2078	400	270	5.00
158a	2	1.02	15	1.0	595	278	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2007	1777	275	110	5.00
b	2	0.95	15	1.0	590	296	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2036	1813	230	89	5.00
c	2	0.95	5	1.0	590	303	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2045	1820	210	612	5.00
d	2	0.75	15	1.0	580	324	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2137	1898	165	100	5.00
e	2	0.85	15	1.0	600	378	5 IFRF	4	12	Fast 4/1	Short	Long	2122	1921	365	170	5.00
f	2	0.65	15	1.5	600	370	5 IFRF	4	12	Fast 4/1	Short	Long	2303	2082	235	194	5.00
g	2	0.75	15	1.5	590	368	5 IFRF	4	12	Fast 4/1	Short	Long	2317	2093	240	149	5.00
h	2	0.55	15	1.5	580	380	5 IFRF	4	12	Fast 4/1	Short	Long	2417	2173	245	160	5.00
i	3	1.15	15	1.5	600	--	5 IFRF	4	12	Fast 4/1	Short	Long	2290	2098	1155	102	4.65
j	3	1.05	5	1.5	600	--	5 IFRF	4	12	Fast 4/1	Short	Long	2389	2178	1005	82	
159a	3	1.25	25	1.5	600		5 IFRF	4	12	Fast 4/1	Short	Long	2033	--	1215	--	
b	3	0.95	15	1.5	600	400	5 IFRF	4	12	Fast 4/1	Short	Long	2139	--	650	20	
c	3	0.75	15	1.5	600	400	5 IFRF	4	12	Fast 4/1	Short	Long	2214	--	215	21	
d	3	0.65	15	1.5	590	393	5 IFRF	4	12	Fast 4/1	Short	Long	2299	--	180	21	
e	3	0.55	15	1.5	580	388	5 IFRF	4	12	Fast 4/1	Short	Long	2329	--	210	22	
f	3	0.75	15	1.0	575	392	5 IFRF	4	12	Fast 4/1	Short	Long	2232	--	140	14	
g	3	0.65	15	1.0	570	398	5 IFRF	4	12	Fast 4/1	Short	Long	2198	--	135	13	
h	3	1.15	15	1.0	590	--	5 IFRF	4	12	Fast 4/1	Short	Long	2102	--	925	13	
i	3	1.25	25	1.0	595	--	5 IFRF	4	12	Fast 4/1	Short	Long	2142	--	1095	14	
j	3	1.05	5	1.0	590	--	5 IFRF	4	12	Fast 4/1	Short	Long	2150	--	760	20	
k	3	1.02	15	1.0	590	--	5 IFRF	4	12	Fast 4/1	Short	Long	2186	--	730	11	
l	3	1.02	5	1.0	590	--	5 IFRF	4	12	Fast 4/1	Short	Long	2190	--	800	50	
m	3	0.95	15	1.0	585	--	5 IFRF	4	12	Fast 4/1	Short	Long	2168	--	590	36	

[b]Number -- axial fuel tube position

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
159n	3	0.95	15	1.0	590	--	5 IFRF	4	12	Fast 4/1	Short	Long	2234	--	555	330	
o	3	0.85	15	1.0	585	307	5 IFRF	4	12	Fast 4/1	Short	Long	2213	--	320	56	
p	3	0.85	15	1.0	585	320	5 IFRF	4	12	Fast 4/1	Short	Long	2254	--	300	240	
q	3	0.95	5	1.5	600	331	5 IFRF	4	12	Fast 4/1	Short	Long	2422	--	640	41	
r	3	1.15	15	1.0	600	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2268	--	550	38	
s	3	1.05	5	1.0	600	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2327	--	455	--	
t	3	0.95	15	1.0	600	266	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2336	--	385	18	
u	3	0.85	15	1.0	590	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2329	--	250	20	
v	3	0.75	15	1.0	580	335	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2329	--	210	30	
w	3	0.65	15	1.0	580	367	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2311	--	180	85	
x	3	0.55	15	1.0	580	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2416	--	170	56	
160a	1	1.02	15	1.5	600	303	5 IFRF	4	12	Fast 4/1	Short	Long	2251	--	735	37	
b	1	1.02	5	1.5	600	279	5 IFRF	4	12	Fast 4/1	Short	Long	2349	--	815	29	
c	1	0.95	15	1.5	600	290	5 IFRF	4	12	Fast 4/1	Short	Long	2327	--	560	38	
d	1	0.95	5	1.5	600	290	5 IFRF	4	12	Fast 4/1	Short	Long	2391	--	560	48	
e	1	0.95	25	1.5	600	289	5 IFRF	4	12	Fast 4/1	Short	Long	2388	--	635	38	
f	1	0.85	15	1.5	595	289	5 IFRF	4	12	Fast 4/1	Short	Long	2432	--	400	29	
g	1	0.85	5	1.5	595	292	5 IFRF	4	12	Fast 4/1	Short	Long	2479	--	385	57	
h	1	0.85	25	1.5	600	337	5 IFRF	4	12	Fast 4/1	Short	Long	2397	--	455	54	
i	1	0.75	15	1.5	600	343	5 IFRF	4	12	Fast 4/1	Short	Long	2432	--	265	32	
j	1	0.65	15	1.5	600	353	5 IFRF	4	12	Fast 4/1	Short	Long	2536	--	255	32	
k	1	0.55	15	1.5	600	?	5 IFRF	4	12	Fast 4/1	Short	Long	2596	--	250	62	
161a	1	1.02	25	1.5	600	300	5 IFRF	4	12	Fast 4/1	Short	Long	2071	--	735	40	
b	1	0.75	25	1.5	600	370	5 IFRF	4	12	Fast 4/1	Short	Long	2249		245	35	
c	1	0.75	5	1.5	600	380	5 IFRF	4	12	Fast 4/1	Short	Long	2312		190	54	
d	1	1.15	15	1.5	600	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2356		515	75	
e	1	1.25	25	1.5	615	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2367		720	75	
f	1	1.05	5	1.5	612	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2437		315	1750	
g	1	1.02	15	1.5	608	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2512		375	335	
h	1	0.95	15	1.5	607	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2494		335	40	
i	1	0.95	5	1.5	607	--	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2538		310	1880	
j	1	0.95	25	1.5	606	300	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2510		390	60	
k	1	0.85	15	1.5	600	332	5 IFRF	6 axial	12	Fast 4/1	Short	Long	2538		320	33	
l	1	0.75	15	1.5	600	350	5 IFRF	6 axial	12	Fast 4/1	Short	Long	--	2497	275	26	
m	1	0.65	15	1.5	590	372	5 IFRF	6 axial	12	Fast 4/1	Short	Long	--	2534	245	33	
n	1	0.55	15	1.5	590	380	5 IFRF	6 axial	12	Fast 4/1	Short	Long	--	2588	257	50	
162a	1	1.15	15	1.5	621	--	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2321	--	985	20.4	
b	1	--	15	1.0	600	--	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2322	--	825	20	
c	1	0.85	15	1.0	600	280	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2276	--	145	20.3	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat		Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT		Temperature		NO_c ppm	CO_c ppm	Comments
					Sec. °F	Stg. °F					1st	2nd	T_{23} (°F)	T_{24} (°F)			
162d	1	0.75	15	1.0	600	282	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2263	--	175	20.2	
e	1	0.95	15	1.0	600	297	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2286	--	345	20.2	
f	1	0.85	15	1.0	760	329	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2322	--	150	19.8	
g	1	0.85	15	1.5	800	383	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2401	--	255	20.4	
h	1	0.75	15	1.5	800	--	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2432	--	165	19.1	
164a	1	0.80	15	1.0	580	445	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2119	--	165	75	
b	1	0.65	15	1.0	570	475	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2104	--	290	85	
c	1	0.85	15	1.0	580	480	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2142	--	170	70	
d	1	0.85	15	1.5	600	446	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2269	--	2.10	104	
e	1	0.75	15	1.5	600	400	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2375	--	155	89	
f	1	0.65	15	1.5	590	403	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2356	--	255	80	
g	1	0.95	15	1.5	600	412	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2459	--	430	145	
h	1	1.02	15	1.0	575	235	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2161	--	460	22	
i	1	0.95	15	1.0	570	257	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2231	--	320	48	
j	1	0.85	15	1.0	560	308	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2237	--	145	705	
k	1	1.02	15	1.5	600	332	5 IFRF	4 SPRDR	12	Fast 4/2	Med	Long	2362	--	710	40	
l	G	1.15	15	1.0	600	--	5 IFRF	2 radial	--	Fast 4/2	Med	Long	2242	--	228	2	
m	G	0.92	15	1.0	600	327	5 IFRF	2 radial	--	Fast 4/2	Med	Long	2236	--	118	16	
n	G	0.83	15	1.0	600	348	5 IFRF	2 radial	--	Fast 4/2	Med	Long	2216	--	58	440	
165a	1	0.85	15	1.0	570	378	5 IFRF	4	12	Fast 4/1	Short	Long	--	1998	204	130	
b	1	0.75	15	1.0	560	385	5 IFRF	4	12	Fast 4/1	Short	Long	--	2033	216	90	
c	1	Bias #1 ERb = 0.85	15	1.0	580	--	5 IFRF	4	12	--	--	--	--	2013	646	59	Biased fired
d	1	Bias #3 ERb = 0.85	15	1.0	585	--	5 IFRF	4	12	--	--	--	--	1972	872	40	Biased fired
e	1	Bias #4 ERb = 0.85	15	1.0	580	--	5 IFRF	SW = 2 B #5	12	--	--	--	--	2067	645	126	Biased fired
f	1	Bias ERb = 0.85	15	1.0	585	--	5 IFRF	SW = 2 B #5	12	--	--	--	--	2085	660	82	Biased fired

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
165g	1	1.15	15	1.0	595	--	4 IFRF	4	12	--	--	--	--	2119	805	77	
h	1	1.25	25	1.0	595	--	4 IFRF	4	12	--	--	--	--	2139	955	87	
i	1	1.05	5	1.0	590	--	4 IFRF	4	12	--	--	--	--	2158	585	40	
j	1	1.02	15	1.0	585	222	4 IFRF	4	12	Fast 4/1	Short	Long	--	2142	585	46	
k	1	0.95	15	1.0	585	239	4 IFRF	4	12	Fast 4/1	Short	Long	--	2135	345	47	
l	1	0.85	15	1.0	580	296	4 IFRF	4	12	Fast 4/1	Short	Long	--	2205	200	44	
m	1	0.75	15	1.0	575	340	4 IFRF	4	12	Fast 4/1	Short	Long	--	2253	170	43	
n	G	1.15	15	1.0	600	--	5 IFRF	2 rad/ax	--	--	Short	Long	--	2109	187	22	
o	G	0.95	15	1.0	600	317	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2158	133	19	
p	G	0.85	15	1.0	600	341	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2193	93	19	
q	G	0.75	15	1.0	580	365	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2221	60	21	
r	G	0.65	15	1.0	570	379	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2266	81	43	
r'	G	0.65	--	1.0	570	--	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2132	13		Staged air off
s	G	0.85	15	1.0	580	326	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2158	82	60	
s'	G	0.85	--	1.0	580	--	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2140	79		Staged air off
t	G	0.75	15	1.0	575	311	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2205	62	78	
t'	G	0.75	--	1.0	575	--	5 IFRF	2 rad/ax	12	Fast 4/1	Short	Long	--	2122	28		Staged air off
166a	G	1.15	15	1.0	600	--	5 IFRF	2 rad/ax	12	Fast 4/2	Med	Long	2192	--	203	9	
a'	G	1.15	15	1.0	600	--	5 IFRF	2 rad/ax	12	Fast 4/2	Med	Long	2192	--	191	15	
b	G	0.95	15	1.0	590	318	5 IFRF	2 rad/ax	12	Fast 4/2	Med	Long	2172	--	131	9	
b'	G	0.95	15	1.0	590	318	5 IFRF	2 rad/ax	12	Fast 4/2	Med	Long	2172	--	130	>2000	
c	G	0.85	15	1.0	585	324	5 IFRF	2 rad/ax	12	Fast 4/2	Med	Long	2148	--	78	11	
c'	G	0.85	15	1.0	585	324	5 IFRF	2 rad/ax	12	Fast 4/2	Med	Long	2148	--	74	>2000	
d	G	0.85	10	1.0	580	330	5 IFRF	2 rad/ax	12	Fast 4/2	Med	Long	2138	--	78	23	
d'	G	0.85	10	1.0	580	330	5 IFRF	2 rad/ax	12	Fast 4/2	Med	Long	2138	--	71	>2000	
e	G	0.85	5	1.0	580	333	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2136		75	172	
$^{d}e'$	G	0.85	5	1.0	580	333	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2136		73	>2000	
$^{d}e''$	G	0.85	--	1.0	580	--	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2136		73	>2000	
f	G	0.75	15	1.0	575	319	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2115		60	34	
$^{d}f'$	G	0.75	15	1.0	575	319	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2115		25	>2000	
g	G	0.75	10	1.0	570	291	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2091		76	47	
$^{d}g'$	G	0.75	10	1.0	570	291	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2091		25	>2000	
h	G	0.75	5	1.0	570	281	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2088		59	229	
$^{d}h'$	G	0.75	5	1.0	570	281	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2088		25	>2000	
i	G	0.65	15	1.0	560	284	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2074		79	38	

d' indicates sample at end of first state.
'' staged air off-flue sample
''' staged air off -- sample at end of first stage

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
d166i'	G	0.65	15	1.0	560	284	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2074		6	2000	
j	G	0.65	10	1.0	550	300	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2057		76	61	
dj'	G	0.65	10	1.0	550	300	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2057		7	>2000	
k	G	0.65	5	1.0	550	303	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2054	2212	73	1300	
dk'	G	0.65	5	1.0	550	303	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2054	2212	7	>2000	
dk''	G	0.65	--	1.0	550	303	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2054	1961	9	>2000	
l	G	0.65	25	1.0	550	301	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2030.6	2131.1	79	87	
dl'	G	0.65	25	1.0	550	301	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2030.6	2131.1	6.5	>2000	
m	G	0.75	15	1.0	550	342	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2044.8	2136	63	96	
dm'	G	0.75	15	1.0	550	342	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2044.8	2136	23	>2000	
dm''	G	0.75	--	1.0	550	--	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2020	1898	22	>2000	
dm'''	G	0.75	--	1.0	550	--	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2020	1898	24	>2000	
n	G	0.85	15	1.0	560	333	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2061	2083	69	94	
dn'	G	0.85	15	1.0	560	333	5 IFRF	2 rad/ax	--	Fast 4/2	Med	Long	2061	2083	74	>2000	
168a	1	1.15	15	1.0	600	--	4 tang	+6	20	--	--	--	2050	1700	454	--	
b	1	1.15	15	1.0	600	--	4 tang	+6	12	--	--	--	2125	1775	415	--	
c	1	1.25	25	1.0	600	--	4 tang	+6	12	--	--	--	2143	1808	520	--	
d	1	1.05	5	1.0	600	--	4 tang	+6	12	--	--	--	2182	1826	290	--	
e	1	1.15	15	1.0	600	--	4 tang	+6	20	--	--	--	2171	1823	518	--	
f	1	1.25	25	1.0	600	--	4 tang	+6	20	--	--	--	2174	1837	626	--	
g	1	1.05	5	1.0	600	--	4 tang	+6	20	--	--	--	2156	1843	359	--	
h	1	0.75	15	1.0	600	300	4 tang	+6	20	Fast 4/2	Med	Long	2161	1947	--	--	
169a	1	1.15	15	1.0	580	--	4 tang	+6	15	--	--	--	2050	1716	417	20	
b	1	1.25	25	1.0	580	--	4 tang	+6	15	--	--	--	2102	1774	540	16	
169c	1	1.05	5	1.0	580	--	4 tang	+6	15	--	--	--	2149	1811	250	50	
d	1	1.02	25	1.0	560	288	4 tang	+6	15	Fast 4/2	Med	Long	2169	1769	--	46	
e	1	0.85	15	1.0	580	355	4 tang	+6	15	Fast 4/2	Med	Long	2151	1825	120	55	
f	1	0.75	5	1.0	580	388	4 tang	+6	15	Fast 4/2	Med	Long	2152	1999.6	148	1259	
g	1	0.75	15	1.0	580	410	4 tang	+6	15	Fast 4/2	Med	Long	2148	1993	150	168	
h	1	0.75	25	1.0	580	420	4 tang	+6	15	Fast 4/2	Med	Long	2140	1936	165	73	
i	1	0.65	15	1.0	580	415	4 tang	+6	15	Fast 4/2	Med	Long	2127	2062	249	55	
j	1	0.65	25	1.0	580	415	4 tang	+6	15	Fast 4/2	Med	Long	2114	2012	261	55	
k	1	0.65	5	1.0	580	416	4 tang	+6	15	Fast 4/2	Med	Long	2114	2121	210	1063	
l	1	0.85	25	1.0	580	450	4 tang	+6	15	Fast 4/2	Med	Long	2160	1871	131	112	
m	1	0.85	5	1.0	580	400	4 tang	+6	15	Fast 4/2	Med	Long	2194.7	2005	117	237	
n	1	0.95	15	1.0	580	388	4 tang	+6	15	Fast 4/2	Med	Long	2213	1928	200	62	
o	1	1.02	15	1.0	580	370	4 tang	+6	15	Fast 4/2	Med	Long	2236	1935	347	43	
p	1	1.02	25	1.0	580	373	4 tang	+6	15	Fast 4/2	Med	Long	2246	1915	350	45	

d' indicates sample at end of first state.
'' staged air off-flue sample
''' staged air off -- sample at end of first stage

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
169q	1	1.02	5	1.0	580	356	4 tang	+6	15	Fast 4/2	Med	Long	2260	1966	330	33	
r	1	1.15	15	1.0	580	--	4 tang	+6	15	--	--	--	2245	1979	528	24	
s	1	1.25	25	1.0	580	--	4 tang	+6	15	--	--	--	2239	1984	648	32	
t	1	1.05	5	1.0	580	--	4 tang	+6	15	--	--	--	2265	1989	360	22	
170a	1	1.15	15	1.5	600	--	4 tang	+6	15	--	--	--	2196	1907	607	--	
b	1	1.25	25	1.5	600	--	4 tang	+6	15	--	--	--	2253	1972	726	--	
c	1	1.05	5	1.5	600	--	4 tang	+6	15	--	--	--	2304	2022	463	--	
d	1	1.02	15	1.5	600	--	4 tang	+6	15	Fast 4/2	Med	Long	2349	2047	437	--	
e	1	1.02	5	1.5	600	--	4 tang	+6	15	Fast 4/2	Med	Long	2382.8	2095.5	442	--	
f	1	0.95	15	1.5	600	--	4 tang	+6	15	Fast 4/2	Med	Long	2363	2110	262	--	
g	1	1.02	25	1.5	600	--	4 tang	+6	15	Fast 4/2	Med	Long	2363	1987	448	--	
h	1	0.85	15	1.5	600	350	4 tang	+6	15	Fast 4/2	Med	Long	2326	2098.9	147	--	
i	1	0.75	15	1.5	600	370	4 tang	+6	15	Fast 4/2	Med	Long	2276	2179	170	--	
j	1	0.65	5	1.5	600	380	4 tang	+6	15	Fast 4/2	Med	Long	2264	2327	200	--	
k	1	0.65	15	1.5	600	381	4 tang	+6	15	Fast 4/2	Med	Long	2241	2332	222	--	
l	1	0.65	25	1.5	600	381	4 tang	+6	15	Fast 4/2	Med	Long	2227	2256	235	--	
m	1	0.55	15	1.5	600	395	4 tang	+6	15	Fast 4/2	Med	Long	2185	2322	305	--	
n	2	1.15	15	1.5	600	--	4 tang	+6	15	--	--	--	2298	2114	630	--	
o	2	1.25	25	1.5	600	--	4 tang	+6	15	--	--	--	2358	2141	738	--	
p	2	1.05	5	1.5	600	--	4 tang	+6	15	--	--	--	2381	2099	475	--	
q	2	1.02	25	1.5	600	320	4 tang	+6	15	Fast 4/2	Med	Long	2357	2045	428	--	
r	2	0.95	15	1.5	600	358	4 tang	+6	15	Fast 4/2	Med	Long	2336	2071	272	--	
s	2	0.85	15	1.5	600	390	4 tang	+6	15	Fast 4/2	Med	Long	2308	2134	146	--	
t	2	0.75	15	1.5	600	398	4 tang	+6	15	Fast 4/2	Med	Long	2276	2181	146	--	
u	2	0.65	5	1.5	600	397	4 tang	+6	15	Fast 4/2	Med	Long	2273	2336	162	--	
v	2	0.65	15	1.5	600	398	4 tang	+6	15	Fast 4/2	Med	Long	2258	2319	177	--	
w	2	0.65	25	1.5	600	398	4 tang	+6	15	Fast 4/2	Med	Long	2245	2225	186	--	
x	2	0.55	15	1.5	600	391	4 tang	+6	15	Fast 4/2	Med	Long	2204	2315	246	--	
y	2	1.02	15	1.5	600	362	4 tang	+6	15	Fast 4/2	Med	Long	2289	2124	427	--	
z	2	1.02	5	1.5	600	--	4 tang	+6	15	Fast 4/2	Med	Long	2301	2147	418	--	
171a	2	1.15	15	1.0	600	--	4 tang	+6	15	--	--	--	2035	1856	410	--	
b	2	1.25	25	1.0	600	--	4 tang	+6	15	--	--	--	2054	1873	520	--	
c	2	1.05	5	1.0	600	--	4 tang	+6	15	--	--	--	2076	1887	310	--	
d	2	1.02	15	1.0	600	211	4 tang	+6	15	Fast 4/2	Med	Long	2109	1887	324	--	
e	2	1.02	5	1.0	600	200	4 tang	+6	15	Fast 4/2	Med	Long	2109	1907	306	--	
f	2	1.02	25	1.0	600	243	4 tang	+6	15	Fast 4/2	Med	Long	2124	1873	319	--	
g	2	0.95	15	1.0	600	278	4 tang	+6	15	Fast 4/2	Med	Long	2116	1873	188	--	
h	2	0.85	15	1.0	600	324	4 tang	+6	15	Fast 4/2	Med	Long	1939	2068	135	--	
i	2	0.75	15	1.0	600	323	4 tang	+6	15	Fast 4/2	Med	Long	2063	2029.8	155	--	
j	2	0.65	15	1.0	600	352	4 tang	+6	15	Fast 4/2	Med	Long	2941	2068	200	--	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
171k	2	0.65	25	1.0	600	369	4 tang	+6	15	Fast 4/2	Med	Long	--	2039.6	210	--	
l	2	0.65	5	1.0	600	380	4 tang	+6	15	Fast 4/2	Med	Long	3513	2064	181	--	
m	2	0.85	15	1.0	600	396	4 tang	+6	10	Fast 4/2	Med	Long		--	129	--	
n	2	0.85	15	1.0	600	396	4 tang	+6	25	Fast 4/2	Med	Long		1985	141	--	
o	3	1.15	15	1.0	600	--	4 tang	+6	15	--	--	--		1928	476	--	
p	3	1.25	25	1.0	600	--	4 tang	+6	15	--	--	--		1944	625	--	
q	3	1.05	5	1.0	600	--	4 tang	+6	15	--	--	--	--	1942	384	--	
r	3	0.85	15	1.0	600	336	4 tang	+6	15	Fast 4/2	Med	Long	--	2054	102	--	
s	3	0.75	15	1.0	600	392	4 tang	+6	15	Fast 4/2	Med	Long	--	2075	147	--	
t	3	0.65	15	1.0	600	420	4 tang	+6	15	Fast 4/2	Med	Long	--	2136	200	--	
u	3	0.65	25	1.0	600	422	4 tang	+6	15	Fast 4/2	Med	Long	--	2077	215	--	
v	3	0.65	5	1.0	600	422	4 tang	+6	15	Fast 4/2	Med	Long	--	2140	177	--	
w	3	0.95	15	1.0	600	390	4 tang	+6	15	Fast 4/2	Med	Long	2236	1902	231	--	
x	3	1.02	15	1.0	600	376	4 tang	+6	15	Fast 4/2	Med	Long	2255	1901	380	--	
z	3	1.02	5	1.0	600	357	4 tang	+6	15	Fast 4/2	Med	Long	2263	1926	347	--	
aa	3	1.15	15	1.5	600	--	4 tang	+6	15	--	--	--	2375	2078	713	--	
bb	3	1.25	25	1.5	600	--	4 tang	+6	15	--	--	--	2399	2119	828	--	
cc	3	1.05	5	1.0	600	--	4 tang	+6	15	--	--	--	2410	2129	526	--	
dd	3	1.02	15	1.0	600	304	4 tang	+6	15	Fast 4/2	Med	Long	2473	2148	525	--	
ee	3	1.02	5	1.5	600	304	4 tang	+6	15	Fast 4/2	Med	Long	2476	2177	509	--	
ff	3	0.95	15	1.5	600	303	4 tang	+6	15	Fast 4/2	Med	Long	2463	2182	315	--	
gg	3	0.85	15	1.5	600	321	4 tang	+6	15	Fast 4/2	Med	Long	2311	2135	101	--	
hh	3	0.75	15	1.5	600	358	4 tang	+6	15	Fast 4/2	Med	Long	2286	2202	115	--	
ii	3	0.65	15	1.5	600	368	4 tang	+6	15	Fast 4/2	Med	Long	2249	2236	170	--	
171jj	3	0.65	25	1.5	600	381	4 tang	+6	15	Fast 4/2	Med	Long	2237	2241	185	--	
kk	3	0.65	5	1.5	600	400	4 tang	+6	15	Fast 4/2	Med	Long	2207	2256	145	--	
ll	3	0.55	15	1.5	600	455	4 tang	+6	15	Fast 4/2	Med	Long	2197	2313	188	--	
mm	3	1.02	25	1.5	600	423	4 tang	+6	15	Fast 4/2	Med	Long	2300	2044	386	--	
nn	3	0.85	15/ 25	1.5	600	--	4 tang	+6	15	Fast 4/2	Med	Long	2275	2175	97	--	
172a	G	1.15	15	--	600	--	4 tang	+6	15	--	--	--	1907	1730	56	--	Water in box
b	G	0.95	15	--	600	--	4 tang	+6	15	Fast 4/1	Short	Long	1927	1762	27	13	Water in box
c	G	0.85	15	--	600	--	4 tang	+6	15	Fast 4/1	Short	Long	1946	1788	23	61	Water in box
d	G	0.65	15	--	600	--	4 tang	+6	15	Fast 4/1	Short	Long	2006	1841	25	240	Water in box

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
172e	1	1.02	15	1.0	600	273	4 tang	+6	15	Fast 4/1	Short	Long	1884	1745	216	39	Water in box
f	1	0.95	15	1.0	600	284	4 tang	+6	15	Fast 4/1	Short	Long	1865	1730	165	41	Water in box
g	1	0.85	15	1.0	600	343	4 tang	+6	15	Fast 4/1	Short	Long	1967	1824	171	40	Water in box
h	1	0.75	15	1.0	600	377	4 tang	+6	15	Fast 4/1	Short	Long	2013	1868	210	34	Water in box
i	1	0.65	15	1.0	600	407	4 tang	+6	15	Fast 4/1	Short	Long	2092	1926	281	32	Water in box
173a	1	0.85	15	1.0	600	285	4 tang	+6	15	Fast 4/1	Short	Long	2056	1907	153	37.5	
b	1	0.75	15	1.0	580	364	4 tang	+6	15	Fast 4/1	Short	Long	2081	1933	176	37.5	
c	1	0.65	15	1.0	570	412	4 tang	+6	15	Fast 4/1	Short	Long	2129	1972	243	34.0	
d	1	0.85	15	1.5	600	443	4 tang	+6	15	Fast 4/1	Short	Long	2132	1994	184	46.5	
e	1	0.75	15	1.5	600	443	4 tang	+6	15	Fast 4/1	Short	Long	2261	2106	180	57.0	
f	1	0.65	15	1.5	600	438	4 tang	+6	15	Fast 4/1	Short	Long	2357	2200	222	39.8	
g	1	0.55	15	1.5	600	--	4 tang	+6	15	Fast 4/1	Short	Long	2470	2318	303	47.2	
h	1	0.95	15	1.5	600	397	4 tang	+6	15	Fast 4/1	Short	Long	2264	2147	269	35.3	
i	1	1.02	15	1.5	600	371	4 tang	+6	15	Fast 4/1	Short	Long	2273	2143	428	30.0	
j	1	0.95	15	1.0	600	358	4 tang	+6	15	Fast 4/1	Short	Long	2179	2048	217	58.8	
k	1	1.02	15	1.0	600	354	4 tang	+6	15	Fast 4/1	Short	Long	2150	2016	329	46.0	
174a	1	0.95	15	1.0	600	259	4 tang	+6	15	Fast 4/3	Long	Short	2142	1736	127	176	
b	1	0.85	15	1.0	600	302	4 tang	+6	15	Fast 4/3	Long	Short	2138	1800	105	348	
c	1	1.02	15	1.0	600	333	4 tang	+6	15	Fast 4/3	Long	Short	2179	1778	268	40	
d	1	0.75	15	1.0	600	330	4 tang	+6	15	Fast 4/3	Long	Short	2137	1957	166	416	
e	1	0.75	25	1.0	600	325	4 tang	+6	15	Fast 4/3	Long	Short	2125	1952	170	177	
f	1	0.65	15	1.0	600	322	4 tang	+6	15	Fast 4/3	Long	Short	2088	2039	236	265	
g	1	1.15	15	1.0	600	--	4 tang	+6	15	--	--	--	2148	1869	444	46	
h	1	1.25	25	1.0	600	--	4 tang	+6	15	--	--	--	2163	1867	565	58	
i	1	1.05	5	1.0	600	--	4 tang	+6	15	--	--	--	2214	1879	295	35	
j	1	0.85	15	1.5	600	280	4 tang	+6	15	Fast 4/3	Long	Short	2256	2023	98	607	
k	1	1.15	15	1.0	800	--	4 tang	+6	15	--	--	--	2283	1964	427	24	
l	1	0.85	15	1.0	800	306	4 tang	+6	15	Fast 4/3	Long	Short	2232	1996	85	217	
m	1	0.75	15	1.0	800	372	4 tang	+6	15	Fast 4/3	Long	Short	2200	2024	125	82	
n	1	0.65	15	1.0	800	447	4 tang	+6	15	Fast 4/3	Long	Short	2159	2128	207	179	
o	1	0.95	15	1.0	800	413	4 tang	+6	15	Fast 4/3	Long	Short	2227	1966	125	83	
p	1	1.02	15	1.0	800	413	4 tang	+6	15	Fast 4/3	Long	Short	2236	1957	255	40	
175a	1	1.15	15	1.0	600	--	4 tang	+6	15	--	--	--	2127	1850	401	5	
b	1	1.25	25	1.0	600	--	4 tang	+6	15	--	--	--	2135	1865	503	2	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
175c		1.15	15	1.0	600	--	4 tang	+6	15	--	--	--	2145	1872	428	2	
d	1	1.25	25	1.0	600	--	4 tang	+6	15	--	--	--	2145	1877	549	1	
e	1	1.05	5	1.0	600	--	4 tang	+6	15	--	--	--	2174	1879	315	12	
f	1	0.85	15	1.0	600	--	4 tang	+6	15	Fast 4/3	Long	Short	2141	1920	98	386	
g	1	1.15	15	1.0	800	--	4 tang	+6	15	--	--	--	2201	1942	507	20	
h	1	0.85	15	1.0	800	300	4 tang	+6	15	Fast 4/3	Long	Short	2158	1929	86	352	
176a	1	1.15	15	1.0	117	--	4 tang	+6	15	--	--	--	1788	1587	251	44	
b	1	1.02	15	1.0	101	--	4 tang	+6	15	Fast 4/3	Long	Short	1864	1592	170	77	
c	1	0.95	15	1.0	90	104	4 tang	+6	15	Fast 4/3	Long	Short	1864	1614	101	488	
d	1	0.85	15	1.0	83	86	4 tang	+6	15	Fast 4/3	Long	Short	1878	1788	94	637	
e	1	0.75	15	1.0	82	84	4 tang	+6	15	Fast 4/3	Long	Short	1867	--	142	623	
f	1	0.95	15	1.0	82	84	4 tang	+6	15	Fast 4/3	Long	Short	1890	--	99	620	
g	1	1.02	15	1.0	81	83	4 tang	+6	15	Fast 4/3	Long	Short	1911	--	201	190	
h	1	1.15	15	1.0	81	--	4 tang	+6	15	--	Long	Short	1923	--	336	182	
177a	1	1.15	15	1.0	100	--	4 tang	+6	15	--			2001	1856	345	6.0	
b	1	1.02	15	1.0	100	92	4 tang	+6	15	Fast 4/2	Med	Long	2019	1826	242	16.5	
c	1	0.95	15	1.0	90	90	4 tang	+6	15	Fast 4/2	Med	Long	2024	1816	147	45.6	
d	1	0.85	15	1.0	88	90	4 tang	+6	15	Fast 4/2	Med	Long	2017	1837	102	61.2	
e	1	0.75	15	1.0	85	87	4 tang	+6	15	Fast 4/2	Med	Long	2007	1911	120	53.8	
178a	1	0.95	15	1.0	600	453	4 tang	+6	15	Upper tier 3/4	Short	Long	2189	2031	397	39.7	Overfire air
b	1	0.85	15	1.0	600	384	4 tang	+6	15	Upper tier 3/4	Short	Long	2274	2114	430	35.1	Overfire air
c	1	0.75	15	1.0	600	406	4 tang	+6	15	Upper tier 3/4	Short	Long	2284	2133	400	67.2	Overfire air
d	1	1.15	15	1.0	600	--	4 tang	+6	15	--	--	--	2290	2152	473	45.5	--
e	1	0.85	15	1.0	600	--	4 tang	+6	15	Biased diago-nally opposite	--	--	2315	2179	527	43.5	Biased fired
f	1	0.85	15	1.0	600	--	4 tang	+6	15	Biased same side	--	--	2334	2191	543	38.0	Biased fired
g	1	1.15	15	1.0	600	--	4 tang	+6		Baseline	--	--	--	--	--	--	Biased fired
g'	1	1.15	15	1.0	600	--	4 tang	+6		No annu-lar air	--	--	--	--	--	--	Biased fired
179a	1	1.02	15	1.0	600	--	4 tang	+6	15	--	--	--	2133	2000	458	12.0	
b	1	1.02	15	1.0	600	166	4 tang	+6	15	Fast 4/2	Med	Long	2201	2018	303	21.4	
c	1	0.95	15	1.0	600	216	4 tang	+6	15	Fast 4/2	Med	Long	2227	2027	210	34.3	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T (F)	Temperature T (F)	NO ppm	CO ppm	Comments
179d	1	0.85	15	1.0	600	280	4 tang	+6	15	Fast 4/2	Med	Long	2216	2040	120	35.0	
e	1	0.75	15	1.0	600	296	4 tang	+6	15	Fast 4/2	Med	Long	2211	2093	152	29.2	
f	1	0.65	15	1.0	600	345	4 tang	+6	15	Fast 4/2	Med	Long	2215	2193	216	24.6	
g	1	1.15	15	1.0	800	--	4 tang	+6	15	--	--	--	2298	2149	510	40.5	
h	1	0.95	15	1.0	800	--	4 tang	+6	15	4/2	Med	Long	2344	2149	220	55.7	
i	1	0.85	15	1.0	800	446	4 tang	+6	15	4/2	Med	Long	2332	2205	119	64.6	
j	1	0.75	15	1.0	800	500	4 tang	+6	15	Fast 4/2	Med	Long	2338	2263	118	40.9	
k	1	0.65	15	1.0	800	491	4 tang	+6	15	Fast 4/2	Med	Long	2328	2351	155	39.8	
l	1	1.02	15	1.0	800	464	4 tang	+6	15	Fast 4/2	Med	Long	2366	2209	352	38.7	
180a	1	1.15	15	1.0	600	--	4 tang	+6	15	--	--	--	2182	1969	413	9.1	FGR = 0%
b	1	1.15	15	1.0	600	120	4 tang	+6	15	--	--	--	2228	2029	--	11	FGR = 10%
c	1	1.15	15	1.0	600	204	4 tang	+6	15	--	--	--	2208	2043	--	16	FGR = 30%
d	1	0.95	15	1.0	600	275/ 210	4 tang	+6	15	Fast 4/2	Med	Long	2212	1999	-- --	59	FGR = 30%
e	1	0.95	15	1.0	600	333	4 tang	+6	15	Fast 4/2	Med	Long	2260	2019	213	45.0	FGR = 0%
f	1	0.85	15	1.0	600	422/ 194	4 tang	6	15	Fast 4/2	Med	Long	2185	1993	--	64	FGR = 30%
g	1	0.85	15	1.0	600	428	4 tang	0	15	Fast 4/2	Med	Long	2261	2077	120	51.5	
h	1	0.95	15	1.0	600	--	4 tang	0	15	Fast 4/2	Med	Long	2287	2070	194	40.6	
i	1	1.15	15	1.0	600	--	4 tang	0	15	--	--	--	2317	2121	512	13.2	
j	1	1.15	15	1.0	600	--	4 tang	9	15	--	--	--	2334	2140	551	8.8	
k	1	0.95	15	1.0	600	305	4 tang	9	15	--	--	--	2345	2108	218	37.3	
l	1	0.85	15	1.0	600	300	4 tang	9	15	--	--	--	2331	2141	108	33.1	
181a	1	1.15	15	1.0	600	--	5 IFRF	6 ax	15	--	--	--	2158	2020	290	143	
b	1	1.02	15	1.0	600	192	5 IFRF	6 ax	15	Fast 4/2	Med	Long	2204	2020	195	80	
c	1	0.95	15	1.0	600	221	5 IFRF	6 ax	15	Fast 4/2	Med	Long	2196	2011	185	92	
d	1	0.85	15	1.0	600	273	5 IFRF	6 ax	15	Fast 4/2	Med	Long	2216	2067	191	104	
e	1	0.75	15	1.0	600	313	5 IFRF	6 ax	15	Fast 4/2	Med	Long	2206	2090	210	72.5	
f	1	0.65	15	1.0	600	353	5 IFRF	6 ax	15	Fast 4/2	Med	Long	2156	2173	272	82	
g	1	0.85	15	1.0	600	400	5 IFRF	6 ax	15	Fast 4/2	Med	Long	2111	1993	178	94.7	
182a	1	1.15	15	1.0	600	--	5 IFRF	6 ax	15	--			1931	1908	280	52	
b	1	0.85	15	1.0	600	332	5 IFRF	6 ax	15	Fast 4/1	Short	Long	2018	1992	192	38.4	
c	1	0.75	15	1.0	580	330	5 IFRF	6 ax	15	Fast 4/1	Short	Long	2107	2086	231	35	
d	1	0.65	15	1.0	570	328	5 IFRF	6 ax	15	Fast 4/1	Short	Long	2151	2132	258	37	
e	1	0.95	15	1.0	590	289	5 IFRF	6 ax	15	Fast 4/1	Short	Long	2068	2054	208	44.4	
f	1	1.02	15	1.0	590	292	5 IFRF	6 ax	15	Fast 4/1	Short	Long	2062	2048	240	94	
g	1	1.15	15	1.0	600	--	5 IFRF	4	15	Fast 4/1	Short	Long	2131	2112	789	24	
h	1	0.95	15	1.0	600	--	5 IFRF	4	15	Fast 4/1	Short	Long	2109	2096	392	33.4	
i	1	0.85	15	1.0	590	250	5 IFRF	4	15	Fast 4/1	Short	Long	2106	2092	233	37.2	
j	1	0.75	15	1.0	580	297	5 IFRF	4	15	Fast 4/1	Short	Long	2182	2165	184	31.5	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat: Sec. °F	Preheat: Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT: 1st	Nom. RT: 2nd	Temperature: T_{23} (°F)	Temperature: T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
182k	1	0.65	15	1.0	580	325	5 IFRF	4	15	Fast 4/1	Short	Long	2234	2213	219	38	
l	1	0.85	15	1.0	570	341	5 IFRF	4	15	Fast 4/1	Shor	Long	2142	2124	238	42	
183a	1	1.15	15	1.0	600	--	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2156	1621	646	12	
b	1	0.85	15	1.0	600	256	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2158	1662	137	108	
c	1	0.75	15	1.0	600	316	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2131	1764	162	73	
d	1	0.65	15	1.0	570	348	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2081	1805	237	88	
e	1	0.95	15	1.0	530	314	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2186	1645	239	87	
f	1	1.02	15	1.0	590	301	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2207	1656	417	54	
g	1	1.15	15	1.0	840	--	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2262	1739	690	90	
h	1	1.02	15	1.0	840	237	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2284	1721	475	73	
i	1	0.95	15	1.0	840	265	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2297	1728	290	104	
j	1	0.85	15	1.0	840	300	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2283	1796	120	190	
k	1	0.75	15	1.0	840	328	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2244	1819	150	219	
l	1	0.65	15	1.0	830	378	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2213	1905	187	158	
m	1	0.85	15	1.5	600	363	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2356	1928	170	588	
n	1	0.75	15	1.5	580	355	5 IFRF	4 SPRDR	15	Fast 4/3	Long	Short	2357	1999	120	641	
186a	NG	1.15	15	1.3	580	--	4 IFRF Hor ext	2	12	---	--	--	2574	2252	244	0.0	
b	1	1.15	15	0.85	560	--	4 IFRF Hor ext	4	12	---	--	--	2517	2211	908	29.5	
c	1	1.25	25	0.85	560	--	4 IFRF Hor ext	4	12	---	--	--	2499	2219	1026	26.4	
d	1	1.05	5	0.85	560	--	4 IFRF Hor ext	4	12	---	--	--	2541	2234	765	10.2	
e	1	0.85	15	0.85	540	286	4 IFRF Hor ext	4	12	H-10	--	--	2445	2235	209	14.3	
f	1	0.75	15	0.85	520	404	4 IFRF Hor ext	4	12	H-10	--	--	2317	2187	90	41.3	
g	1	0.65	15	0.85	520	365	4 IFRF Hor ext	4	12	H-10	--	--	2290	2231	131	24.8	
h	1	0.75	15	0.85	500	434	4 IFRF Hor ext	4	12	H-10	--	--	2222	2181	100	41.2	
i	1	0.95	15	0.85	530	307	4 IFRF Hor ext	4	12	H-10	--	--	2291	2204	664	15.6	
j	1	1.02	15	0.85	530	302	4 IFRF Hor ext	4	12	H-10	--	--	2281	2223	830	10.1	
k	1	1.15	15	1.3	570	--	4 IFRF Hor ext	4	12	--	--	--	2494	2404	1300	5.8	
l	1	1.25	25	1.3	580	--	4 IFRF Hor ext	4	12	--	--	--	2528	2442	1423	6.8	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
186m	1	1.05	5	1.3	580	--	4 IFRF Hor ext	4	12	--	--	--	2590	2477	1120	3.5	
n	1	1.02	15	1.3	580	201	4 IFRF Hor ext	4	12	H-10	--	--	2637	2523	1188	6.9	
o	1	0.95	15	1.3	570	225	4 IFRF Hor ext	4	12	H-10	--	--	2600	2531	932	9.0	
187a	1	0.85	15	1.3	596	266	4 IFRF Hor ext	4	12	H-10	--	--	2204	2368	380	16.0	
b	1	0.75	15	1.3	585	341	4 IFRF Hor ext	4	12	H-10	--	--	2199	2391	110	30.0	
c	1	0.65	15	1.3	570	359	4 IFRF Hor ext	4	12	H-10	--	--	2262	2380	135	57.5	
d	1	1.15	15	1.3	780	--	4 IFRF Hor ext	4	12	--	--	--	2729	2495	1355	16.8	
e	1	0.75	15	1.3	800	317	4 IFRF Hor ext	4	12	H-10	--	--	2591	2484	91	23.7	
f	1	1.15	15	0.85	800	--	4 IFRF Hor ext	4	12	--	--	--	2595	2484	950	18.0	
g	1	0.75	15	0.85	770	400	4 IFRF Hor ext	4	12	H-10	--	--	2539	2432	107	18.8	
188a	1	1.15	15	0.85	80	--	4 IFRF Hor ext	4	12	--			2333	1689	609	12.8	
b	1	0.75	15	0.85	80	80	4 IFRF Hor ext	4	12	H-10			2246	1853	102	91.6	
c	1	1.15	15	1.3	80	--	4 IFRF Hor ext	4	12	--			2486	1876	945	11.8	
d	1	0.75	15	1.3	80	--	4 IFRF Hor ext	4	12	H-10			2415	2091	110	76.2	
e	1	1.15	15	1.3	300	--	4 IFRF Hor ext	4	12	--			2581	2034	1043	28.0	
f	1	0.75	15	1.3	300	184	4 IFRF Hor ext	4	12	H-10			2483	2164	101	38.6	
g	1	1.15	15	0.85	300	--	4 IFRF Hor ext	4	12	--			2482	1997	696	29.8	
h	1	0.75	15	0.85	300	254	4 IFRF Hor ext	4	12	H-10			2346	2017	98	92.7	
189a	1	1.15	15	0.85	580	--	4 IFRF Hor ext	4	12	--			2405	1780	788	48.2	

DATA SUMMARY SHEETS

					Preheat						Nom. RT		Temperature				
Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Sec. °F	Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	1st	2nd	T_{23} (°F)	T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
189b	1	1.15	15	0.85	580	--	4 IFRF Hor ext	4	12	--			2608	1888	852	13.2	
c	1	0.95	15	0.85	580	250	4 IFRF Hor ext	4	12	H-7			2586	1883	480	21.3	
d	1	0.85	15	0.85	580	297	4 IFRF Hor ext	4	12	H-7			2544	1935	172	17.5	
e	1	0.75	15	0.85	570	327	4 IFRF Hor ext	4	12	H-7			2566	2005	108	21.0	
f	1	0.65	15	0.85	540	344	4 IFRF Hor ext	4	12	H-7			2477	2144	168	89.2	
g	1	0.65	15	0.85	520	348	4 IFRF Hor ext	4	12	H-7			2457	2150	158	62.8	w/cooling
h	1	0.75	15	0.85	530	340	4 IFRF Hor ext	4	12	H-7			2502	1998	109	46.6	w/cooling
i	1	0.85	15	0.85	540	324	4 IFRF Hor ext	4	12	H-7			2610	1936	252	37.5	w/cooling
j	1	0.95	15	0.85	560	315	4 IFRF Hor ext	4	12	H-7			2589	1877	684	35.0	w/cooling
k	1	0.95	15	1.3	600	232	4 IFRF Hor ext	4	12	H-7			2743	1975	857	48.0	w/cooling
l	1	0.85	15	1.3	600	276	4 IFRF Hor ext	4	12	H-7			2733	2043	358	47.0	w/cooling
m	1	0.75	15	1.3	590	275	4 IFRF Hor ext	4	12	H-7			2661	2135	126	47.5	w/cooling
n	1	0.65	15	1.3	580	273	4 IFRF Hor ext	4	12	H-7			2612	2193	132	51.3	w/cooling
o	1	0.65	15	1.3	580	272	4 IFRF Hor ext	4	12	H-7			2607	2252	134	42.0	
p	1	0.75	15	1.3	580	264	4 IFRF Hor ext	4	12	H-7			2663	2225	136	36.2	
q	1	0.85	15	1.3	580	257	4 IFRF Hor ext	4	12	H-7			2552	2181	--	--	
190a	1	0.85	15	1.3	530	280	4 IFRF Hor ext	SP-4	12	H-7			2641	2001	366	34.8	
b	1	0.95	15	1.3	530	281	4 IFRF Hor ext	SP-4	12	H-7			2665	2034	832	31.1	
c	1	0.75	15	1.3	580	282	4 IFRF Hor ext	SP-4	12	H-4			2564	2137	347	8.6	
d	1	0.85	15	1.3	580	288	4 IFRF Hor ext	SP-4	12	H-4			2469	2136	572	11.9	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
190e	1	0.95	15	1.3	580	286	4 IFRF Hor ext	SP-4	12	H-4			2512	2179	904	--	
f	1	0.65	15	1.3	580	321	4 IFRF Hor ext	SP-4	12	H-4			2496	2239	262	15.9	
g	1	0.55	15	1.3	570	325	4 IFRF Hor ext	SP-4	12	H-4			2446	2277	245	16.0	
h	1	0.95	15	0.85	570	202	4 IFRF Hor ext	SP-4	12	H-4			2469	2161	665	16.3	
i	1	0.85	15	0.85	561	255	4 IFRF Hor ext	SP-4	12	H-4			2458	2127	432	17.4	
j	1	0.75	15	0.85	554	285	4 IFRF Hor ext	SP-4	12	H-4			2442	2113	250	19.3	
k	1	0.65	15	0.85	540	319	4 IFRF Hor ext	SP-4	12	H-4			2401	2137	202	21.7	
l	1	0.85	15	0.85	565	295	4 IFRF Hor ext	SP-4	12	H-7			2449	2094	290	41.2	
191a	1	0.95	15	0.85	580	214	4 IFRF Hor ext	SP-4	12	H-6			2407	1804	453	18.0	
b	1	0.85	15	0.85	570	311	4 IFRF Hor ext	SP-4	12	H-6			2401	1844	214	33.6	
c	1	0.75	15	0.85	560	345	4 IFRF Hor ext	SP-4	12	H-6			2287	1892	126	49.7	
d	1	0.65	15	0.85	545	356	4 IFRF Hor ext	SP-4	12	H-6			2268	1928	127	58.6	
e	1	0.95	15	1.3	600	284	4 IFRF Hor ext	SP-4	12	H-6			2323	2049	737	53.0	
f	1	0.85	15	1.3	600	324	4 IFRF Hor ext	SP-4	12	H-6			2762	2107	370	50.0	
g	1	0.75	15	1.3	580	335	4 IFRF Hor ext	SP-4	12	H-6			2597	2181	149	52.0	
h	1	0.65	15	1.3	580	302	4 IFRF Hor ext	SP-4	12	H-6			2485	2237	110	55.2	
i	1	0.55	15	1.3	570	283	4 IFRF Hor ext	SP-4	12	H-6			2394	2241	135	54.5	
192a	1	0.95	15	0.85	570	229	4 IFRF Hor ext	SP-4	12	H-8			2453	1896	538	18.7	
b	1	0.85	15	0.85	560	306	4 IFRF Hor ext	SP-4	12	H-8			2460	1922	228	--	
c	1	0.75	15	0.85	550	353	4 IFRF Hor ext	SP-4	12	H-8			2405	1987	161	--	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
194c	1	0.75	15	0.85	550	286	4 IFRF Hor ext	SP-4	12	H-5 w/o B			2264	2231	170	53.7	
d	1	0.65	15	0.85	550	311	4 IFRF Hor ext	SP-4	12	H-5 w/o B			2229	2282	157	50.0	
e	1	0.55	15	0.85	520	335	4 IFRF Hor ext	SP-4	12	H-5 w/o B			2182	2313	142	47.0	
f	1	0.95	15	0.85	570	232	4 IFRF Hor ext	SP-4	12	H-7			2367	2263	525	26.0	
g	1	0.85	15	0.85	540	284	4 IFRF Hor ext	SP-4	12	H-7			2436	2309	322	23.4	
h	1	0.75	15	0.85	550	299	4 IFRF Hor ext	SP-4	12	H-7			2392	2263	100	30.0	
i	1	0.65	15	0.85	530	305	4 IFRF Hor ext	SP-4	12	H-7			2393	2249	117	146.8	
195a	1	0.65	15	0.85	550	200	4 IFRF Hor ext	SP-4	12	H-5			2252	2118	133	88.8	
b	1	0.75	15	0.85	530	271	4 IFRF Hor ext	SP-4	12	H-5			2256	2171	155	65.5	
c	1	0.85	15	0.85	530	267	4 IFRF Hor ext	SP-4	12	H-5			2317	2144	252	47.2	
d	1	0.95	15	0.85	550	249	4 IFRF Hor ext	SP-4	12	H-5			2362	2102	456	42.8	
e	1	0.95	15	1.3	590	226	4 IFRF Hor ext	SP-4	12	H-5			2507	2275	656	96.3	
f	1	0.85	15	1.3	590	212	4 IFRF Hor ext	SP-4	12	H-5			2534	2388	388	94.0	
g	1	0.75	15	1.3	590	309	4 IFRF Hor ext	SP-4	12	H-5			2508	2428	194	79.2	
h	1	0.65	15	1.3	574	306	4 IFRF Hor ext	SP-4	12	H-5			2456	2464	156	81.4	
i	1	0.55	15	1.3	560	297	4 IFRF Hor ext	SP-4	12	H-5			2780	2486	188	83.0	
203a	4	1.15	15	1.35	600	--	Sgl lg IFRF w/4" sleeve	4	12	--			2262	2309	1127	--	
b	4	1.05	5	1.35	590	--	Sgl lg IFRF w/4" sleeve	4	12	--			2418	2462	890	--	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat: Sec. °F	Preheat: Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT: 1st	Nom. RT: 2nd	Temperature: T_{23} (°F)	Temperature: T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
203c	4	1.25	25	1.35	600	--	Sgl lg IFRF w/4" sleeve	4	12				2423	2457	1317	--	
d	1	1.25	25	1.3	600	--	Sgl lg IFRF w/4" sleeve	4	12	--			2494	2514	1420	--	
e	1	1.15	15	1.3	595	--	Sgl lg IFRF w/4" sleeve	4	12	--			2396	2412	1265	57.4	
f	1	1.05	5	1.3	590	--	Sgl lg IFRF w/4" sleeve	4	12	--			2479	2479	956	18.0	
g	1	1.25	25	0.85	580	--	Sgl lg IFRF w/4" sleeve	4	12	--			2420	2412	1191	16.4	
h	1	1.15	15	0.85	580	--	Sgl lg IFRF w/4" sleeve	4	12	--			2394	2379	970	--	
i	1	1.05	5	0.85	570	--	Sgl lg IFRF w/4" sleeve	4	12	--			2406	2384	646	--	
203j	1	0.75	15	0.85	550	300	Sgl lg IFRF w/4" sleeve	4	12	Hor #1			2435	2307	95	16.0	
k	1	0.65	15	0.85	550	300	Sgl lg IFRF w/4" sleeve	4	12	Hor #1			2398	2239	116	25.2	
l	1	0.85	15	0.85	540	300	Sgl lg IFRF w/4" sleeve	4	12	Hor #1			2404	2259	132	20.0	
m	1	0.95	15	0.85	550	300	Sgl lg IFRF w/4" sleeve	4	12	Hor #1			2422	2303	387	16.7	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
204a	1	1.25	25	1.3	600	--	Lg IFRF no sleeve	4	12	--			2467	2341	1177	37.0	
b	1	1.15	15	1.3	600	--	Lg IFRF no sleeve	4	12	--			2541	2422	1038	20.0	
c	1	1.05	5	1.3	590	--	Lg IFRF no sleeve	4	12	--			2616	2476	825	9.0	
d	1	1.25	25	0.85	580	--	Lg IFRF no sleeve	4	12	--			2481	2382	890	5.0	
e	1	1.15	15	0.85	580	--	Lg IFRF no sleeve	4	12	--			2491	2383	736	9.0	
f	1	1.05	5	0.85	560	--	Lg IFRF no sleeve	4	12	--			2502	2385	469	1.0	
g	1	0.75	15	0.85	550	250	Lg IFRF no sleeve	4	12	Hor #1			--	--	75	30.0	
205a	1	1.25	25	1.3	600	--	Sgl w/ sleeve	4	12	--			2449	2360	1423	16.8	
b	1	1.15	15	1.3	600	--	Sgl w/ sleeve	4	12	--			2512	2411	1239	16.3	
c	1	1.05	5	1.3	600	--	Sgl w/ sleeve	4	12	--			2587	2476	776	15.4	
d	1	1.05	5	0.85	570	--	Sgl w/ sleeve	4	12	--			2473	2364	584	34.5	
e	1	1.15	15	0.85	590	--	Sgl w/ sleeve	4	12	--			2447	2350	969	17.2	
f	1	1.25	25	0.85	590	--	Sgl w/ sleeve	4	12	--			2412	2323	1208	16.9	
206a	1	0.95	15	1.3	600	240	Sgl w/ sleeve	4	12	Hor #1			2430	2245	194	22	
b	1	0.95	15	1.3	600	270	Sgl w/ sleeve	4	12	Hor #1			2522	2375	564	68	
206c	1	0.85	15	1.3	600	290	Sgl w/ sleeve	4	12	Hor #1			2546	2391	217	66	
d	1	0.75	15	1.3	590	330	Sgl w/ sleeve	4	12	Hor #1			2411	2227	122	87	
e	1	0.65	15	1.3	580	316	Sgl w/ sleeve	4	12	Hor #1			2449	2265	129	90	
f	3	1.25	25	1.3	600	--	Sgl w/ sleeve	4	12	--			2477	2425	1559	70	
g	3	1.25	25	1.3	600	--	Sgl w/ sleeve	4	12	--			2555	2486	1570	71	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
206h	3	1.15	15	1.3	590	--	Sgl w/ sleeve	4	12	--			2517	2458	1407	59	
i	3	1.15	15	1.3	590	--	Sgl w/ sleeve	4	12	--			2559	2500	1432	104	
j	3	1.05	5	1.3	590	--	Sgl w/ sleeve	4	12	--			2618	2556	1173	38	
k	3	1.05	5	1.3	590	--	Sgl w/ sleeve	4	12	--			2630	2584	1152	32	
l	3	0.95	15	1.3	--	--	Sgl w/ sleeve	4	12	Hor #1			--	--			
m	3	0.95	15	1.3	--	--	Sgl w/ sleeve	4	12	Hor #1			--	--			
n	3	0.85	15	1.3	600	255	Sgl w/ sleeve	4	12	Hor #1			2671	2570	1026	45	
o	3	0.85	15	1.3	600	260	Sgl w/ sleeve	4	12	Hor #1			2679	2586	1030	110	
p	3	0.75	15	1.3	590	306	Sgl w/ sleeve	4	12	Hor #1			2668	2536	410	72	
q	3	0.75	15	1.3	590	350	Sgl w/ sleeve	4	12	Hor #1			2673	2520	462	61	
r	3	0.65	15	1.3	580	360	Sgl w/ sleeve	4	12	Hor #1			2621	2479	112	62	
s	3	0.65	15	1.3	--	--	Sgl w/ sleeve	4	12	Hor #1			2608	2458	91	62	
t	3	0.65	15	0.85	580	300	Sgl w/ sleeve	4	12	Hor #1			2543	2400	78	100	
u	3	0.65	15	0.85	580	280	Sgl w/ sleeve	4	12	Hor #1			2502	2341	79	69	
206v	3	0.75	15	0.85	580	262	Sgl w/ sleeve	4	12	Hor #1			2545	2353	230	67	
w	3	0.75	15	0.85	590	250	Sgl w/ sleeve	4	12	Hor #1			2561	2364	244	76	
x	3	0.85	15	0.85	600	240	Sgl w/ sleeve	4	12	Hor #1			2589	2391	565	67	
y	3	0.85	15	0.85	600	230	Sgl w/ sleeve	4	12	Hor #1			2589	2403	590	65	
z	3	0.95	15	0.85	--	--	Sgl w/ sleeve	4	12	Hor #1			--	--			
aa	3	0.95	15	0.85	--	--	Sgl w/ sleeve	4	12	Hor #1			--	--			

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
206bb	3	1.05	5	0.85	600	--	Sgl w/ sleeve	4	12	--			2572	2410	844	42	
cc	3	1.05	5	0.85	620	--	Sgl w/ sleeve	4	12	--			2574	2408	872	50	
dd	3	1.15	15	0.85	620	--	Sgl w/ sleeve	4	12	--			2563	2384	960	60	
ff	3	1.25	25	0.85	620	--	Sgl w/ sleeve	4	12	--			2538	2391	1161	107	
gg	3	1.25	25	0.85	--	--	Sgl w/ sleeve	4	12	--			2508	2343	1110	58	
207a	3	1.15	15	0.85	580	--	Lg IFRF	4	12	--			2135	2158	968	--	
b	3	1.15	15	0.85	580	--	Lg IFRF	4	12	--			2135	2158	989	--	
c	3	0.95	15	0.85	560	152	Lg IFRF	4	12	Hor-4			2207	2170	567	--	
d	3	0.95	15	0.85	560	152	Lg IFRF	4	12	Hor-4			2207	2170	615	--	
e	3	0.85	15	0.85	560	193	Lg IFRF	4	12	Hor-4			2237	2183	376	--	
f	3	0.85	15	0.85	560	193	Lg IFRF	4	12	Hor-4			2237	2183	395	--	
g	3	0.75	15	0.85	530	275	Lg IFRF	4	12	Hor-4			2236	2193	225	--	
h	3	0.75	15	0.85	530	275	Lg IFRF	4	12	Hor-4			2236	2193	257	16.1	
i	3	0.65	15	0.85	500	340	Lg IFRF	4	12	Hor-4			2217	2167	171	1.2	
j	3	0.65	15	0.85	500	340	Lg IFRF	4	12	Hor-4			2217	2167	196	--	
k	3	0.65	15	0.85	500	340	Lg IFRF	4	12	Hor-4			2217	2167	201	--	
l	3	0.65	15	0.85	500	340	Lg IFRF	4	12	Hor-4			2217	2167	213	--	
m	3	0.55	15	0.85	500	348	Lg IFRF	4	12	Hor-4			--	--	166	--	
n	1	0.55	15	0.85	500	367	Lg IFRF	4	12	Hor-4			2182	2251	230	6.9	
o	1	0.65	15	0.85	500	356	Lg IFRF	4	12	Hor-4			2224	2254	227	9.4	
p	1	0.75	15	0.85	500	341	Lg IFRF	4	12	Hor-4			2279	2236	286	9.4	
q	1	0.85	15	0.85	500	302	Lg IFRF	4	12	Hor-4			2334	2228	431	12.5	
r	1	0.95	15	0.85	520	275	Lg IFRF	4	12	Hor-4			2361	2237	600	12.2	
s	1	0.95	15	1.3	580	236	Lg IFRF	4	12	Hor-4			2441	2314	896	28.3	
t	1	0.85	15	1.3	580	314	Lg IFRF	4	12	Hor-4			2488	2343	628	28.4	
u	1	0.75	15	1.3	580	347	Lg IFRF	4	12	Hor-4			2514	2389	391	32.5	
v	1	0.65	15	1.3	550	346	Lg IFRF	4	12	Hor-4			2501	2422	305	30.3	
w	1	0.55	15	1.3	540	330	Lg IFRF	4	12	Hor-4			2473	2479	296	28.3	
208a	1	0.95	15	0.85	570	163	Lg IFRF w/4" sleeve	4	12	Hor-3			1899	1841	436	24	
b	1	0.85	15	0.85	550	189	Lg IFRF w/4" sleeve	4	12	Hor-3			1906	1834	264	34	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
208c	1	0.75	15	0.85	560	249	Lg IFRF w/4" sleeve	4	12	Hor-3			1930	1852	156	35	
d	1	0.65	15	0.85	530	293	Lg IFRF w/4" sleeve	4	12	Hor-3			1958	1873	138	56	
e	1	0.55	15	0.85	500	335	Lg IFRF w/4" sleeve	4	12	Hor-3			1996	1904	146	80	
f	1	0.95	15	1.3	590	241	Lg IFRF w/4" sleeve	4	12	Hor-3			2046	2013	683	69	
g	1	0.85	15	1.3	580	291	Lg IFRF w/4" sleeve	4	12	Hor-3			2094	2050	405	67	
h	1	0.75	15	1.3	580	335	Lg IFRF w/4" sleeve	4	12	Hor-3			2145	2078	230	71	
i	1	0.65	15	1.3	560	332	Lg IFRF w/4" sleeve	4	12	Hor-3			2213	2142	171	107	
j	1	0.55	15	1.3	545	297	Lg IFRF w/4" sleeve	4	12	Hor-3			2297	2232	207	90	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
181g'	1	0.85	15	1.0	600		5 IFRF -2nd	8 ax	12						181	90	
g"	1	0.85	15	1.0	600		5 IFRF	0 ax	12						184	89	
182i'	1	0.85	15	1.0	600		5 IFRF	4 SPRDR 8 ax	12						219	43	
i"	1	0.85	15	1.0	600		5 IFRF	4 SPRDR 0 ax	12						265	50	
j'	1	0.75	15	1.0	600		5 IFRF	4 SPRDR 0 ax	12						191	37	
j"	1	0.75	15	1.0	600		5 IFRF	4 SPRDR 8 ax	12						193	39	
l'	1	0.85	15	1.0	600		5 IFRF	4 SPRDR 0 ax	25						233	42	
l"	1	0.85	15	1.0	600		5 IFRF	4 SPRDR 8 ax	25						235	44	
187x	1	1.15	15	1.3	600		4 IFRF	4	12	H-10					1200	23	
189j'	1	0.95	15	1.3	600 w.c.		4 IFRF	4	12	H-7					1088	27	
190x	1	1.15	15	1.3	600		4 IFRF	4	12	H-7					1139	25	
y	1	1.15	15	0.85	600		4 IFRF	4	12	H-4					950	15	
191 (B1)	1	1.15	15	0.85	600		4 IFRF	4	12	H-6					845	38	
(B2)	1	1.15	15	1.3	600		4 IFRF	4	12	H-6					104	43	
192 (B1)	1	1.15	15	0.85	600		4 IFRF	4	12	H-8					909	21	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Locatio	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
192 (B2)	1	1.15	15	1.3	600		4 IFRF	4	12	H-8					1190	42	
193 (B1)	1	1.15	15	0.85	100	w/cooling	4 IFRF	4	12	H-4					853	5	
(B2)	1	1.15	15	0.85	800		4 IFRF	4	12	H-4					1085	--	
194 (B1)	1	1.15	15	0.85	600		4 IFRF	4	12	H-5 w/o B					823	57	
195 (B1)	1	1.15	15	0.85	600		4 IFRF	4	12	H-5					889	49	
(B2)	1	1.15	15	1.3	600		4 IFRF	4	12	H-5					1017	132	
(B3)	1	1.15	15	1.3	600		4 IFRF	4	12	H-5					1192	76	
207 (B1)	1	1.15	15	1.3	600		Lg IFRF-4	4	12	(4HE) Dist air					515	28	
208 (B1)	1	1.15	15	0.85	600		Lg IFRF w/4" sleeve -4	4	12	3HE					887	22	
(B2)	1	1.15	15	1.3	600		Lg IFRF w/4" sleeve -4	4	12	3HE					1067	59	
209 (B1)	1	1.15	15	0.85	100		4 IFRF-4 Hor 6	4	12						720	17	
207 (B2)	1	1.15	15	0.85	600		Lg IFRF -4	4	12	4HE Dist. air					940	16	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
170m'	1	0.55		1.5	600		4 tang, 2nd	+6	15	Stack w/o staged air					39	--	
152a'	1	1.15		1.5	600		5 IFRF -8	8	12	Stack w/o staged air					429	19	
131c'	1	0.95	25	1.0	600	343	5 IFRF	6	12	Fast 4/3	5.0	0.65	2102	1649	240	95	
135f'	1	0.95	25	1.0	800	371	5 IFRF -4	4	12	Fast 4/3	5.0	0.65	2231	1837	272	65	
143f'	1	0.75	5	1.0	600	384	5 IFRF -8	8	12	Fast 4/1	3.5	2.3	2217	1890	151	43	
144d'	1	0.85	5	1.0	600	308	5 IFRF -4	4	12	Slow 6/1	3.5	2.3	2173	1861	181	100	
d"	1	0.85	5	1.0	600	308	5 IFRF -4	4	12	Slow 7/1	3.5	2.3	2173	1861	195	150	
146f'	1	1.02	15	1.0	600		5 IFRF -4 (down)	4	12						594	36	
146x1	1	0.92	35				5 IFRF -4 (down)	4	12	Down Mix					473	74	
x2	1	0.98	45						12	Fast Mix					551	65	
169k'	1	0.65		1.0	600		4 tang, 2nd	+6	15	w/o staged air					21	--	
l'	1	0.85		1.0	600		4 tang, 2nd	+6	15	w/o staged air					99	--	
n'	1	0.95		1.0	600		4 tang, 2nd	+6	15	w/o staged air					226	354	
170f'	1	1.15	15	1.5	600		4 tang, 2nd	+6	15	Baseline					668	--	
l'	1	0.65	--	1.5	600		4 tang, 2nd	+6	15	w/o staged air					47	--	
i'	1	0.75	--	1.5	600		4 tang, 2nd	+6	15	w/o staged air					63	--	
x'	2	1.15	15	1.5	600		4 tang, 2nd	+6	15	Baseline					594	--	

DATA SUMMARY SHEETS

Test No.	Fuel	SR	EA (%)	Load x 10^6 Btu/hr	Preheat Sec. °F	Preheat Stg. °F	Burners	SW/Inj. or Yaw	Prim. Stoich. (%)	Stg. Air Mixing/ Location	Nom. RT 1st	Nom. RT 2nd	Temperature T_{23} (°F)	Temperature T_{24} (°F)	NO_c ppm	CO_c ppm	Comments
171hh'	3	0.75	25	1.5	600		4 tang, 2nd	+6	15	Baseline					132	--	
171nn'	3	0.85	25	1.5	600		4 tang, 2nd	+6	15	w/o Staged air					95	--	
172d'	1	1.15	15	1.0	600		4 tang, 1st	+6	15	w/o Staged air					338	17	(d' Baseline)
172g'	1	1.15	15	1.0	600		4 tang, 1st	+6	15	w/o Staged air					95	158	(g' Baseline)
172i'	1	1.15	15	1.0	600		4 tang, 1st	+6	15	w/o Staged air					316	29	(i' Baseline)
174b'	1	0.85	25	1.0	600		4 tang, 3rd	+6	15	w/o Staged air					129	95	

APPENDIX A.2

PARTICULATE DATA SUMMARY SHEETS

PARTICULATE DATA SUMMARY SHEET

Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
125b		Coal #1	1.0	6 ax	25	0.95	993.0	80.6	1073.6	0.05545	3.43	0.244	14.36	0.463×10^{-3}	0.10397
125c-1		Coal #1	1.0	4 SPRDR	25	0.95	993.0	80.6	1073.6	0.07606	3.42	0.336	24.40	0.637×10^{-3}	0.24299
125c-2		Coal #1	1.0	4 SPRDR	25	0.95	993.0	80.6	1073.6	0.13167	6.84	0.291	21.92	0.551×10^{-3}	0.18897
125d-1		Coal #1	1.0	4 SPRDR	20	0.95	941.0	80.6	1021.6	0.12079	6.87	0.266	15.66	0.504×10^{-3}	0.11734
125d-2		Coal #1	1.0	4 SPRDR	20	0.95	941.0	80.6	1021.6	0.29432	6.90	0.645	23.92	1.221×10^{-3}	0.43450
125e		Coal #1	1.0	4 SPRDR	15	0.95	904.0	80.6	984.6	0.10742	6.84	0.237	16.96	0.450×10^{-3}	0.10940
126a		Coal #1	1.0	6 ax	15	1.05	922.8	80.6	1003.4	0.33790	6.75	0.757	3.80	1.432×10^{-3}	0.07955
126b		Coal #1	1.0	6 ax	15	1.02	931.0	80.6	1011.6	0.34876	7.05	0.748	4.08	1.415×10^{-3}	0.08509
126c-1		Coal #1	1.0	6 ax	15	0.95	933.0	80.6	1013.6	0.41395	3.82	1.638	6.05	3.095×10^{-3}	0.27648
126c-2		Coal #1	1.0	6 ax	15	0.95	933.0	80.6	1013.6	0.28074	3.73	1.138	7.79	2.152×10^{-3}	0.24750
127a		Coal #1	1.0	4 SPRDR	15	0.95	914.7	80.6	995.3	0.23809	3.41	1.056	2.37	1.997×10^{-3}	0.06860
127b		Coal #1	1.0	4 SPRDR	15	0.85	929.6	80.6	1010.2	0.26386	3.15	1.267	8.54	0.632×10^{-3}	0.07930
127c		Coal #1	1.0	4 SPRDR	15	0.95	918.0	80.6	998.6	0.29392	3.52	1.263	8.58	2.387×10^{-3}	0.29788
127d		Coal #1	1.0	6 ax	15	0.95	918.0	80.6	998.6	0.17693	3.46	0.773	3.38	1.463×10^{-3}	0.07193
127e		Coal #1	1.0	6 ax	15	1.02	925.6	80.6	1006.2	0.15789	3.56	0.671	3.46	1.269×10^{-3}	0.06436
127f		Coal #1	1.0	4 SPRDR	15	1.02	925.6	80.6	1006.2	0.18809	3.34	0.851	4.18	1.611×10^{-3}	0.09869
128a		Coal #1	1.0	6 ax	15	0.85	923.4	80.6	1004.0	0.21390	3.55	0.911	4.58	1.723×10^{-3}	0.11544
128b		Coal #1	1.0	4 SPRDR	15	1.02	1004.0	80.6	1084.6	0.17157	3.51	0.739	3.53	1.399×10^{-3}	0.07800
128c		Coal #1	1.0	8 SPRDR	15	1.02	1004.0	80.6	1084.6	0.20753	3.52	0.891	3.73	1.686×10^{-3}	0.09938
128d		Coal #1	1.0	8 SPRDR	15	1.02	920.5	80.6	1001.1	0.30971	3.41	1.373	5.45	2.596×10^{-3}	0.20628
128f		Coal #1	1.0	4 SPRDR	15	0.95	919.0	80.6	999.6	0.28750	3.65	1.191	3.77	2.252×10^{-3}	0.12361
128g		Coal #1	1.0	8 SPRDR	15	0.95	922.0	80.6	1002.6	0.29061	3.29	1.336	1.37	2.525×10^{-3}	0.05051
128h		Coal #1	1.0	8 SPRDR	15	0.95	931.0	80.6	1011.6	0.31311	3.40	1.392	5.85	2.632×10^{-3}	0.22685
129a		Coal #1	1.0	6 ax	15	0.80	932.3	80.6	1012.9	0.15088	3.19	0.715	8.17	1.353×10^{-3}	0.16314
129b		Coal #1	1.0	8 SPRDR	15	0.80	932.3	80.6	1012.9	0.15584	3.39	0.695	12.08	1.315×10^{-3}	0.23445
134a		Coal #1	1.0	4 SPRDR	23	1.15	977.0	80.6	1057.6	0.33414	18.76	0.269	3.64	0.510×10^{-3}	0.02860
134b		Coal #1	1.0	4 SPRDR	15	0.85	898.0	80.6	978.6	2.58692	15.35	2.548	26.55	4.806×10^{-3}	1.81869
134c		Coal #1	1.0	8 SPRDR	15	0.85	898.0	80.6	878.6	1.46561	12.44	1.781	29.89	3.364×10^{-3}	1.43342
134d		Coal #1	1.0	4 SPRDR	25	0.85	983.0	80.6	1063.6	2.46443	13.76	2.708	26.80	5.106×10^{-3}	2.11980
135a	142-53	Coal #1	1.0	4 SPRDR	15	1.15	931.7	80.6	1012.3	1.921	11.189	2.596	2.45	4.895×10^{-3}	0.17684
135b	142-62	Coal #1	1.0	6 ax	15	1.15	931.7	80.6	1012.3	2.285	12.395	2.787	2.75	5.254×10^{-3}	0.21306
135c	142-66	Coal #1	1.0	6 ax	15	1.15	912.6	80.6	993.2	2.760	12.944	3.224	1.81	6.073×10^{-3}	0.15901
135d	142-63	Coal #1	1.0	4 SPRDR	15	1.15	912.6	80.6	993.2	2.611	13.411	2.944	1.83	5.548×10^{-3}	0.14687
135e	142-60	Coal #1	1.0	4 SPRDR	15	1.02	927.8	80.6	1008.4	2.357	11.487	3.102	12.93	5.845×10^{-3}	1.11006
135f	142-68	Coal #1	1.0	4 SPRDR	15	0.95	911.9	80.6	991.9	2.802	15.290	2.771	19.13	5.223×10^{-3}	1.44370

PARTICULATE DATA SUMMARY SHEET

Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
138a	142-54	Coal #1	1.0	4 SPRDR	15	1.02	915.3	80.6	995.9	2.06298	13.25	2.354	23.15	4.441×10^{-3}	1.49149
138b	142-65	Coal #1	1.0	4 SPRDR	15	0.95	916.7	80.6	1077.3	2.65349	12.40	3.236	28.39	6.094×10^{-3}	2.71488
138c	142-51	Coal #1	1.0	4 SPRDR	15	0.85	911.1	80.6	991.7	3.79631	13.81	4.156	49.81	7.815×10^{-3}	5.62296
138e	142-61	Coal #1	1.0	4 SPRDR	15	0.85	905.6	80.6	986.2	6.81555	28.36	3.634	22.79	6.839×10^{-3}	2.23888
140a	--	Coal #1	1.0	4 SPRDR	15	1.15	925.7	80.6	1005.3	--	--	--	--	--	--
140b	142-101	Coal #1	1.0	4 SPRDR	15	1.02	914.0	80.6	994.6	6.48264	29.88	3.280	23.29	6.178×10^{-3}	2.08452
140c	142-102	Coal #1	1.0	4 SPRDR	15	1.15	927.0	80.6	1007.6	2.02398	15.56	1.967	2.01	3.713×10^{-3}	0.10954
140d	142-103	Coal #1	1.0	4 SPRDR	15	1.02	915.7	80.6	996.3	2.30075	14.09	2.469	17.00	4.657×10^{-3}	1.14889
140e	142-104	Coal #1	1.0	4 SPRDR	15	0.85	913.7	80.6	994.3	2.17639	13.86	2.374	29.20	4.479×10^{-3}	1.89423
143a	142-105	Coal #1	1.0	4 SPRDR	15	1.02	927.4	80.6	1008.0	1.83445	15.33	1.809	3.29	3.417×10^{-3}	0.16506
143b	142-114	Coal #1	1.0	8 SPRDR	15	1.02	927.4	80.6	1008.0	1.75391	14.38	1.844	3.65	0.483×10^{-3}	0.18664
143c	142-113	Coal #1	1.0	4 SPRDR	5	1.02	859.6	80.6	940.2	3.84895	12.68	4.590	6.31	8.623×10^{-3}	0.74511
$143d_1$	142-109	Coal #1	1.0	4 SPRDR	5	0.85	830.9	80.6	911.5	2.11443	12.17	2.627	9.53	4.954×10^{-3}	0.62676
$143d_2$	142-108	Coal #1	1.0	4 SPRDR	5	0.85	830.9	80.6	911.5	2.40665	11.28	3.226	5.67	6.076×10^{-3}	0.45741
143e	142-107	Coal #1	1.0	4 SPRDR	15	0.85	920.7	80.6	1001.3	2.71210	13.72	2.989	2.38	5.632×10^{-3}	0.19550
143f	142-106	Coal #1	1.0	8 SPRDR	15	0.85	920.7	80.6	1001.3	1.67876	13.45	1.887	2.01	3.564×10^{-3}	0.10447
144c	142-111	Coal #1	1.0	4 SPRDR	15	0.85	916.7	80.6	997.3	3.73138	11.14	5.064	11.49	9.506×10^{-3}	1.58668
144d	142-110	Coal #1	1.0	4 SPRDR	5	0.85	840.7	80.6	921.3	13.16115	13.00	15.307	25.44	28.191×10^{-3}	9.62404
145a	142-123	Coal #1	1.0	4 SPRDR	15	1.02	931.5	80.6	1012.1	1.963	13.00	2.283	6.36	4.308×10^{-3}	0.40392
145b	142-127	Coal #1	1.0	4 SPRDR	25	1.02	1009.2	80.6	1089.8	1.634	13.00	1.900	6.98	3.589×10^{-3}	0.39761
145c	142-124	Coal #1	1.0	4 SPRDR	5	1.02	855.3	80.6	935.9	2.1158	13.00	2.461	8.13	4.642×10^{-3}	0.51444
145d	142-119	Coal #1	1.0	4 SPRDR	15	0.85	915.0	80.6	995.6	1.2981	13.00	1.510	29.18	2.853×10^{-3}	1.20726
145e	142-122	Coal #1	1.0	4 SPRDR	25	0.85	997.0	80.6	1077.6	2.3134	13.00	2.691	17.58	5.073×10^{-3}	1.39985
145f	142-126	Coal #1	1.0	4 SPRDR	5	0.85	835.0	80.6	915.6	0.9522	13.00	1.107	39.60	2.094×10^{-3}	1.10607
145g	142-120	Coal #1	1.0	4 SPRDR	15	0.85	920.9	80.6	1001.5	2.03[illegible]	13.00	2.361	23.80	4.454×10^{-3}	1.54650
146a	142-125	Coal #1	1.0	4 SPRDR	25	1.02	994.0	80.6	1074.6	5.6338	13.09	6.507	11.74	12.182×10^{-3}	2.23852
146b	142-118	Coal #1	1.0	4 SPRDR	5	1.02	837.3	80.6	917.9	1.83347	11.44	2.423	8.88	4.571×10^{-3}	0.54272
146c	142-116	Coal #1	1.0	4 SPRDR	25	0.85	992.0	80.6	1072.6	1.64251	11.49	2.161	10.23	4.079×10^{-3}	0.65198
146d	142-121	Coal #1	1.0	4 SPRDR	5	0.85	838.4	80.6	919.0	1.63910	9.64	2.571	17.55	4.848×10^{-3}	1.13898
146e	142-117	Coal #1	1.0	4 SPRDR	15	0.85	918.8	80.6	999.4	0.88522	8.46	1.582	19.47	2.989×10^{-3}	0.84722
146f	--	Coal #1	1.0	4 SPRDR	15	1.02	915.5	80.6	896.1	1.46896	13.10	1.695	7.34	3.203×10^{-3}	0.30684
146g	142-128	Coal #1	1.0	4 SPRDR	15	0.85	913.8	80.6	994.4	2.08792	9.89	3.192	8.45	6.013×10^{-3}	0.73591

PARTICULATE DATA SUMMARY SHEET

Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
148a	142-131	Coal #1	1.0	6 ax	15	0.95	927	80.6	1007.6	2.67371	19.94	2.0274	9.94	3.829×10^{-3}	0.559
148b	142-130	Coal #1	1.0	6 ax	15	0.85	917	80.6	997.6	2.02244	18.38	1.6637	5.81	3.143×10^{-3}	0.265
149a	142-132	Coal #1	1.0	4 SPRDR	15	0.85	911.6	80.6	992.2	1.26821	12.34	1.5539	7.95	2.936×10^{-3}	0.337
149b	142-129	Coal #1	1.0	4 SPRDR	15	0.75	928.6	80.6	1009.2	1.43718	12.29	1.7681	6.91	3.340×10^{-3}	0.339
152a	142-145	Coal #1	1.0	6 ax	15	1.15	920	80.6	1000.6	1.09898	9.42	1.764	9.95	3.330×10^{-3}	0.483
152b	142-146	Coal #1	1.0	6 ax	25	1.25	998.4	80.6	1079	2.1130	11.87	2.6915	4.77	5.075×10^{-3}	0.380
152c	142-144	Coal #1	1.0	6 ax	5	1.05	870	80.6	950.6	1.0725	10.36	1.5653	16.43	2.958×10^{-3}	0.673
152d	142-139	Coal #1	1.2	6 ax	15	1.15	1057.8	121	1178.8	2.37678	13.5	2.662	3.26	5.019×10^{-3}	0.187
152e	142-138	Coal #1	1.2	6 ax	5	1.05	955.5	121	1076.5	2.16799	10.99	2.9827	7.11	5.621×10^{-3}	0.417
152f	142-137	Coal #1	1.2	6 ax	25	1.25	1149.5	121	1270.5	1.85883	15.38	1.8274	3.58	3.451×10^{-3}	
153a	135	Coal #1	1.0	6 ax	5	0.95	837.9	80.6	918.5	0.75251	7.5	1.5171	32.31	2.867×10^{-3}	1.239
153b	134	Coal #1	1.0	6 ax	25	0.95	997.7	80.6	1078.3	1.01864	9.78	1.5748	10.10	2.976×10^{-3}	0.472
153c	133	Coal #1	1.2	6 ax	15	1.02	1053	120	1173	1.73469			6.36		
154a	157	Coal #1	1.2	6 ax	15	0.95	1045.5	120	1165.5	1.28184	12	1.6151	13.78	3.051×10^{-3}	0.475
154b	156	Coal #1	1.2	6 ax	5	0.95	951.8	120	1071.8	1.03842	10.48	1.4982	18.68	2.831×10^{-3}	0.550
154c	155	Coal #1	1.2	6 ax	25	0.95	1123.6	120	1243.6	1.50657	15.05	1.0615	5.06	2.860×10^{-3}	0.175
154d	154	Coal #1	1.2	6 ax	25	0.85	1056.9	120	1176.9	1.09370	11.84	1.3967	10.22	2.640×10^{-3}	0.308
154e	153	Coal #1	1.2	6 ax	25	0.75	1059.9	120	1179.9	0.93733	11.02	1.2861	9.54	2.430×10^{-3}	0.265
154f	152	Coal #1	1.2	6 ax	25	0.95	1055.5	120	1175.5	0.76518	10.38	1.1146	9.62	2.108×10^{-3}	0.231
154g	151	Coal #1	1.0	6 ax	25	0.75	911	80.6	991.6	0.96855	10.22	1.4329	7.71	2.708×10^{-3}	0.302
155a	150	Coal #1	1.2	4 SPRDR	5	1.02	972	120	1092	0.59188	9.78	0.91505	8.33	1.731×10^{-3}	0.153
155b	149	Coal #1	1.2	4 SPRDR	15		1061	120	1181	0.74035	11.66	0.96004	3.74		
155c	148	Coal #1	1.2	4 SPRDR	25		1154	120	1274	0.82038	12.48	0.99392	--		
155d	142	Coal #1	1.2	4 SPRDR	5	0.95	955.7	120	1075.7	0.71351	10.79	0.9998	5.87	1.891×10^{-3}	0.116

PARTICULATE DATA SUMMARY SHEET

Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
155e	141	Coal #1	1.2	4 SPRDR	15	0.95	1050.3	120	1170.3	0.84902	10.64	1.2065	8.46	2.281×10^{-3}	0.219
155f	159	Coal #1	1.2	4 SPRDR	5	0.85	--	120		0.61090	10.8	0.8553	8.90	1.618×10^{-3}	
156a	158	Coal #1	1.2	4 SPRDR	25	0.95	1154.5	120	1274.5	0.78361	10.59	1.1188	9.54	2.116×10^{-3}	0.250
156b	153	Coal #1	1.2	4 SPRDR	15	0.85	1048.4	120	1168.4	0.66047	10.71	0.9324	12.42	1.764×10^{-3}	0.248
156c	152	Coal #1	1.2	4 SPRDR	25	0.85	1143.2	120	1263.2	0.79488	12.22	0.98352	6.68	1.853×10^{-3}	0.152
156d	151	Coal #1	1.2	4 SPRDR	15	0.75	1036	120	1156	0.86594	12.32	1.0527	7.55	2.010×10^{-3}	0.170
156e	150	Coal #1	1.2	4 SPRDR	5	0.75	941.2	120	1061.2	0.90260	10.9	1.1133	18.82	2.367×10^{-3}	0.459
156f	149	Coal #1	1.2	4 SPRDR	23	0.75	1117.9	120	1237.9	0.76020	12.39	0.92770	9.33	1.755×10^{-3}	0.197
156g	148	Coal #1	1.2	4 SPRDR	15	0.65	1054	120	1174	0.71005	12.46	0.86163	6.74	1.630×10^{-3}	0.125
156h	157	Coal #1	1.2	4 SPRDR	7.5	0.65	975	120	1095	0.54067	--		17.64		
157e	155	Coal #2	1.5	4 SPRDR	5	1.05	1191	109	1300	0.93065	16.23	0.8670	6.67	1.640×10^{-3}	0.153
157f	156	Coal #2	1.5	4 SPRDR	25	1.25	1414	109	1523	1.48316	19.02	1.179	2.10	2.230×10^{-3}	0.0768
157g	154	Coal #2	1.5	4 SPRDR	15	0.95	1306	109	1415	0.96405	16.59	0.8786	6.27	1.662×10^{-3}	0.159
157h	50	Coal #2	1.5	4 SPRDR	5	0.85	1198	109	1307	0.56484	16.18	0.52784	10.89	0.999×10^{-3}	0.153
157i	165	Coal #2	1.5	4 SPRDR	5	0.95	1185	109	1294	1.00259	16.22	0.9346	7.53	1.768×10^{-3}	0.186
157j	164	Coal #2	1.0	4 SPRDR	15	1.02	869.6	73	942.6	0.57285	8.06	1.0746	4.89	2.032×10^{-3}	0.151
157k	163	Coal #2	1.0	4 SPRDR	5	1.02	796.2	73	869.2	0.57971	4.74	1.8492	2.10	3.492×10^{-3}	0.1025
157l	162	Coal #2	1.0	4 SPRDR	15	0.95	870.6	73	943.6	0.32654	6.78	0.7282	6.84	1.378×10^{-3}	0.143
157m	161	Coal #2	1.0	4 SPRDR	5	0.95	796	73	869	0.36758	4.84	1.1483	10.93	2.171×10^{-3}	0.332
157n	160	Coal #2	1.0	4 SPRDR	25	0.95	950.5	73	1023.5	0.42403	7.78	0.8241	5.14	1.559×10^{-3}	0.132
157o	55	Coal #2	1.0	4 SPRDR	15	0.85	878.8	73	951.8	0.37783	6.52	0.87619	6.99	1.658×10^{-3}	0.177
157p	52	Coal #2	1.0	4 SPRDR	5	0.85	799.6	73	872.6	0.20739	4.9	0.63995	13.94	1.211×10^{-3}	0.237
157q	58	Coal #2	1.0	4 SPRDR	5	0.85	793	73	866	2.02346	6.69	4.5732	10.36	8.592×10^{-3}	0.1240

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Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
158a	168	Coal #2	1.0	6 ax	15	1.02	871	73	944	1.94409	13.95	2.1071	11.78	3.977×10^{-3}	0.711
158b	167	Coal #2	1.0	6 ax	15	0.95	863.8	73	936.8	0.95373	13.81	1.0442	42.95	1.975×10^{-3}	1.278
158c	166	Coal #2	1.0	6 ax	5	0.95	791	73	864	2.09213	13.7	2.309	28.45	4.356×10^{-3}	1.724
158d	178	Coal #2	1.0	6 ax	15	0.75	876	73	949	1.21947	14.84	1.2425	13.04	2.349×10^{-3}	0.4675
158e	177	Coal #2	1.5	4 SPRDR	15	0.85	1322	109	1431	1.53615	21	1.1060	17.68	2.092×10^{-3}	0.570
158f	192	Coal #2	1.5	4 SPRDR	15	0.65	1302.7	109	1411.7	0.77416	8.84	1.3241	15.81	2.503×10^{-3}	0.602
158g	191	Coal #2	1.5	4 SPRDR	15	0.75	1302.6	109	1411.6	0.53613	15.85	0.5114	10.39	9.683×10^{-4}	0.153
158h	190	Coal #2	1.5	4 SPRDR	15	0.55	1295.2	109	1404.2	0.87311	16.36	0.80693	8.24	1.527×10^{-3}	0.190
159a	189	Coal #3	1.5	4 SPRDR	25	1.25	1434.7	168	1602.7	3.33174	14.81	3.4015	2.24	6.405×10^{-3}	0.161
159b	188	Coal #3	1.5	4 SPRDR	15	0.95	1315	168	1483	3.78299	15.13	3.7805	0.70	7.113×10^{-3}	0.0516
159c	179	Coal #3	1.5	4 SPRDR	15	0.75	1316.6	168	1484.6	2.74672	15.39	2.6985	0.52	5.088×10^{-3}	0.0274
159d	174	Coal #3	1.5	4 SPRDR	15	0.65	1305.9	168	1473.9	2.36112	15.74	2.2681	0.39	4.280×10^{-3}	0.0172
159f	173	Coal #3	1.0	4 SPRDR	15	0.75	886	112	998	2.07275	15.39	2.0364	0.30	3.844×10^{-3}	0.0121
159g	172	Coal #3	1.0	4 SPRDR	15	0.65	881	112	993	1.75923	15.11	1.7604	0.26	3.325×10^{-3}	0.00900
159h	171	Coal #3	1.0	4 SPRDR	15	1.15	891	112	1003	3.20806	15.97	3.0373	0.27	5.723×10^{-3}	0.0162
159i	170	Coal #3	1.0	4 SPRDR	25	1.25	969	112	1081	2.91512	16.65	2.6472	0.36	4.992×10^{-3}	0.0204
159j	176	Coal #3	1.0	4 SPRDR	5	1.05	805	112	917	2.73231	14.69	2.8123	0.42	5.301×10^{-3}	0.0214
159k	187	Coal #3	1.0	4 SPRDR	15	1.02	890.7	112	1002.7	3.17544	15.89	3.02156	0.45	5.693×10^{-3}	0.0269
159l	186	Coal #3	1.0	4 SPRDR	5	1.02	818	112	930	3.53583	15.2	3.5172	0.36	6.671×10^{-3}	0.0232
159m	185	Coal #3	1.0	4 SPRDR	15	0.95	883.5	112	995.5	2.30814	16.01	2.1798	0.50	4.114×10^{-3}	0.0215
159n	184	Coal #3	1.0	4 SPRDR	5	0.95	803.5	112	915.5	1.91648	15.24	2.8935	0.39	5.453×10^{-3}	0.0204
159o	183	Coal #3	1.0	4 SPRDR	15	0.85	883.3	112	995.3	2.89894	15.77	2.7794	0.28	5.240×10^{-3}	0.0153
159p	182	Coal #3	1.0	4 SPRDR	5	0.85	803.6	112	915.6	2.37378	20.97	1.7115	0.18	3.233×10^{-3}	0.00558
159q	181	Coal #3	1.5	4 SPRDR	5	0.95	1195.9	168	1363.9	4.01263	17.08	3.5522	0.44	6.687×10^{-3}	0.0280
159r	180	Coal #3	1.0	6 ax	15	1.15	888	112	1000	4.50679	15.17	4.492	0.41	8.441×10^{-3}	0.0363
159s	202	Coal #3	1.0	6 ax	5	1.05	801.4	112	913.4	3.07512	13.31	3.4933	0.44	6.576×10^{-3}	0.0277
159t	201	Coal #3	1.0	6 ax	15	0.95	882.5	112	994.5	1.88930	17.41	1.6408	0.06	3.100×10^{-3}	0.00194
159u	200	Coal #3	1.0	6 ax	15	0.85	877	112	989	2.28192	10.69	3.2276	0.03	6.079×10^{-3}	0.00189
159v	199	Coal #3	1.0	6 ax	15	0.75	--	112		2.6052	12.61	3.1238	0.19	5.885×10^{-3}	
160a	198	Coal #1	1.5	4 SPRDR	15	1.02	1374.3	120	1494.3	0.03147	21.42	0.02221	--	4.210×10^{-5}	
160b	196	Coal #1	1.5	4 SPRDR	5	1.02	1250.3	120	1370	0.01547	19.99	0.01170	--	2.220×10^{-5}	
160c	197	Coal #1	1.5	4 SPRDR	15	0.95	1359.6	120	1479.6	0.01125	21.29	0.00799	--	1.514×10^{-5}	

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Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
160e	195	Coal #1	1.5	4 SPRDR	25	0.95	1481.1	120	1601.1	4.37288	18.07	3.6590	1.54	6.886×10^{-3}	0.165
160f	194	Coal #1	1.5	4 SPRDR	15	0.85	1363.9	120	1483.9	1.1224	18.41	0.92182	3.08	1.744×10^{-3}	0.0774
160g	211	Coal #1	1.5	4 SPRDR	5	0.85	1241	120	1361	0.96360	17.64	0.82594	6.77	1.563×10^{-3}	0.140
160h	210	Coal #1	1.5	4 SPRDR	25	0.85	1484.7	120	1604.7	1.47019	17.44	1.2746	1.92	2.410×10^{-3}	0.0720
160i	209	Coal #1	1.5	4 SPRDR	15	0.75	1355.4	120	1475.4	0.74774	17.45	0.64789	2.84	1.226×10^{-3}	0.0498
160j	208	Coal #1	1.5	4 SPRDR	15	0.65	1377.8	120	1497.8	0.63042	17.31	0.55066	1.29	1.042×10^{-3}	0.0196
160k	206	Coal #1	1.5	4 SPRDR	15	0.55	1367.9	120	1487.9	0.35211	16.94	0.31428	4.57	5.952×10^{-4}	0.0393
161a	205	Coal #1	1.5	4 SPRDR	25	1.02	1500.9	120	1620.9	2.28869	16.85	2.0537	4.97	3.877×10^{-3}	0.303
161b	203	Coal #1	1.5	4 SPRDR	25	0.75	1478.4	120	1598.4	1.86912	16.85	1.6772	3.59	3.168×10^{-3}	0.176
161c	204	Coal #1	1.5	4 SPRDR	5	0.75	1243.6	120	1363.6	1.94374	16.56	1.7747	6.41	3.352×10^{-3}	0.2843
161d	226	Coal #1	1.5	6 ax	15	1.15	1372	120	1492	2.80149	16.77	2.52585	7.22	4.764×10^{-3}	0.498
161e	225	Coal #1	1.5	6 ax	25	1.25	1490	120	1610	1.89559	17.15	1.6712	1.47	3.157×10^{-3}	0.0725
161f	224	Coal #1	1.5	6 ax	5	1.05	1251	120	1371	1.77083	16.49	1.6237	16.16	3.068×10^{-3}	0.660
161g	223	Coal #1	1.5	6 ax	15	1.02	1368	120	1488	1.88132	16.99	1.6742	10.56	3.163×10^{-3}	0.482
161h	222	Coal #1	1.5	6 ax	15	0.95	1356.7	120	1476.7	1.32004	13.85	1.4411	3.00	2.724×10^{-3}	0.117
161i	221	Coal #1	1.5	6 ax	5	0.95	1247.3	120	1367.3	1.07207	14.1	1.1496	4.21	2.174×10^{-3}	0.121
161j	220	Coal #1	1.5	6 ax	25	0.95	1488.3	120	1608.3	0.55988	14.53	0.58261	3.81	1.103×10^{-3}	0.0656
161k	218	Coal #1	1.5	6 ax	15	0.85	1357.1	120	1477.1	0.42643	14.19	0.45431	3.73	0.860×10^{-3}	0.0460
161l	217	Coal #1	1.5	6 ax	15	0.75	1366	120	1486	0.19992	14.88	0.20241	4.07	3.850×10^{-4}	0.0225
161m	216	Coal #1	1.5	6 ax	15	0.65	1374	120	1494	0.33058	14.86	0.33636	3.13	6.370×10^{-4}	0.0289
161n		Coal #1	1.5	6 ax	15	0.55		120							
162c	215	Coal #1	1.0	4 SPRDR	15	0.85	910	80	990	1.67412	13.41	0.2232	7.03	0.423×10^{-3}	
162d	214	Coal #1	1.0	4 SPRDR	15	0.75	903.5	80.6	984.1	1.41820	13.72	1.5629	9.35	2.953×10^{-3}	0.396
162e		Coal #1	1.0	4 SPRDR	15	0.95	909	80.6	989.6						
162f	213	Coal #1	1.0	4 SPRDR	15	0.85	923.1	80.6	1003.7	1.70702	14.34	1.8000	7.32	3.399×10^{-3}	0.364
162g	212	Coal #1	1.5	4 SPRDR	15	0.85	1376	120	1496	1.76299	14.36	1.8563	9.34	3.505×10^{-3}	0.475
162h		Coal #1	1.5	4 SPRDR	15	0.75	1360.6	120	1480.6						
164a	142-236	Coal #1	1.0	4 SPRDR	15	0.80	899.2	80.6	979.8	1.7045	11.82	2.1804	18.18	4.10×10^{-3}	1.0638
164b	142.235	Coal #1	1.0	4 SPRDR	15	0.65	895.5	80.6	976.1	1.30005	11.98	1.6408	11.26	3.10×10^{-3}	0.4963
164c	142.234	Coal #1	1.0	4 SPRDR	15	0.85	913.6	80.6	994.2	1.6202	9.60	2.5518	17.10	4.80×10^{-3}	1.1886
164d	142-233	Coal #1	1.5	4 SPRDR	15	0.85	1375	120	1495	1.71067	10.13	2.5533	14.40	4.80×10^{-3}	1.5051
164e	142-232	Coal #1		4 SPRDR	15	0.75	1370	120	1490	1.0808	9.25	1.7667	25.24	3.30×10^{-3}	1.8077
164f	142-231	Coal #1		4 SPRDR	15	0.65	1365.2	120	1485.2	1.2984	11.46	1.7131	13.05	3.20×10^{-3}	0.9034
164g	142-230	Coal #1		4 SPRDR	15	0.95	1377.3	120	1497.3	2.2819	10.71	3.2215	7.79	6.10×10^{-3}	1.0364
164h	142-229	Coal #1	1.0	4 SPRDR	15	1.02	922.9	80.6	1003.5	1.8452	6.72	4.1517	7.33	7.80×10^{-3}	0.8357
164i	142-228	Coal #1	1.0	4 SPRDR	15	0.95	914	80.6	994.6	1.9527	8.57	3.4451	7.95	6.50×10^{-3}	0.7486

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Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
165a	142-227	Coal #1	1.0	4 SPRDR	15	0.85	915.7	80.6	996.3	1.9196	12.25	2.3693	16.51	4.50×10^{-3}	1.0782
165b	142-251	Coal #1	1.0	4 SPRDR	15	0.75	924.0	80.6	1004.6	1.0934	12.30	1.3441	11.25	2.50×10^{-3}	0.4115
165c	142-250	Coal #1	1.0	4 SPRDR	15	0.85/	928.7	80.6	1009.3	1.7961	13.17	2.0620	3.40	3.90×10^{-3}	0.1949
				4 SPRDR		1.6									
165d	142-249	Coal #1	1.0	4 SPRDR	15	0.85	920.9	80.6	1001.5	1.8103	13.54	2.0215	4.41	3.80×10^{-3}	0.2445
165e	142-248	Coal #1	1.0	4 SPRDR	15	0.85	907.0	80.6	987.6	2.5415	13.72	2.8008	23.17	5.30×10^{-3}	1.7665
165f	--	Coal #1	1.0	4 SPRDR	15	0.85	907.0	80.6	987.6	--	--		--		
165g	142-247	Coal #1	1.0	4 SPRDR	15	1.15	915.0	80.6	995.6	1.9987	13.59	2.2237	1.92	4.20×10^{-3}	0.1169
165h	142-267	Coal #1	1.0	4 SPRDR	25	1.25	991.2	80.6	1071.8	1.5919	13.96	1.7242	2.19	3.30×10^{-3}	0.1128
165i	142-266	Coal #1	1.0	4 SPRDR	5	1.05	840.6	80.6	921.2	1.7880	12.44	2.1732	3.27	4.10×10^{-3}	0.1799
165j	142-265	Coal #1	1.0	4 SPRDR	15	1.02	906.6	80.6	987.2	1.8473	12.53	2.2291	3.58	4.20×10^{-3}	0.2162
165k	142-264	Coal #1	1.0	4 SPRDR	15	0.95	913.9	80.6	994.5	1.7000	12.72	2.0208	5.87	3.80×10^{-3}	0.3231
165l	142-263	Coal #1	1.0	4 SPRDR	15	0.85	911.7	80.6	992.3	1.4656	12.82	1.7172	2.93	3.30×10^{-3}	0.1398
169a	142-262	Coal #1	1.0	4 tang	15	1.15	889.9	80.9	970.8	1.64651	13.29	1.873	3.13	3.50×10^{-3}	0.1543
169b	142-295	Coal #1	1.0	4 tang	25	1.25	955.4	80.9	1036.3	1.73536	14.24	1.843	1.27	3.70×10^{-3}	0.0726
169c	142-294	Coal #1	1.0	4 tang	5	1.05	782.1	80.9	863.0	2.47392	12.78	2.927	13.04	5.50×10^{-3}	0.8982
169d	142-293	Coal #1	1.0	4 tang	25	1.02	940.5	80.9	1021.4	1.84790	14.15	1.975	10.34	3.70×10^{-3}	0.5671
169e	142-292	Coal #1	1.0	4 tang	15	0.85	885.2	80.9	966.1	2.17358	13.18	2.494	15.45	4.70×10^{-3}	1.0180
169f	142-291	Coal #1	1.0	4 tang	5	0.75	797.1	80.9	878.0	1.90114	12.16	2.364	21.04	4.50×10^{-3}	1.2063
169g	142-290	Coal #1	1.0	4 tang	15	0.75	878.6	80.9	959.5	1.79441	13.01	2.0854	14.79	3.90×10^{-3}	0.8032
169h	142-289	Coal #1	1.0	4 tang	25	0.75	959.6	80.9	1040.5	1.97130	14.58	2.0443	9.06	3.90×10^{-3}	0.5335
169i	142-288	Coal #1	1.0	4 tang	15	0.65	866.4	80.9	947.3	1.67960	13.76	1.8456	7.43	3.50×10^{-3}	0.3575
169j	142-287	Coal #1	1.0	4 tang	25	0.65	934.4	80.9	1015.3	1.37969	14.33	1.4558	5.03	2.80×10^{-3}	0.2075
169k	142-286	Coal #1	1.0	4 tang	5	0.65	776.4	80.9	857.3	1.76711	12.39	2.1565	14.81	4.10×10^{-3}	0.7554
169l	142-285	Coal #1	1.0	4 tang	25	0.85	960.3	80.9	1041.2	1.87927	14.79	1.9212	8.60	3.60×10^{-3}	0.4678
169m	142-272	Coal #1	1.0	4 tang	5	0.85	799.5	80.9	880.4	2.19191	12.49	2.6534	12.96	4.90×10^{-3}	0.8113
169n	142-270	Coal #1	1.0	4 tang	15	0.95	881.7	80.9	962.6	1.78252	12.99	2.0748	7.89	3.90×10^{-3}	0.4298
169o	142-271	Coal #1	1.0	4 tang	15	1.02	878.5	80.9	959.4	1.60613	13.24	1.8342	4.97	3.50×10^{-3}	0.2422
169q	142-269	Coal #1	1.0	4 tang	5	1.02	807.5	80.9	888.4	1.79032	12.92	2.0952	4.58	3.95×10^{-3}	0.2332
170a	142-268	Coal #1	1.5	4 tang	15	1.15	1331.0	121	1452.0	3.41846	14.57	3.5475	5.35	6.70×10^{-3}	0.5050

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Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vq ft^3	GL grains/ft^3	CP %	AF	CL %
170b	142-278	Coal #1	1.5	4 tang	25	1.25	1424.0	121	1545.0	2.21930	16.12	2.0816	2.16	3.90×10^{-3}	0.1263
170c	142-275	Coal #1	1.5	4 tang	5	1.05	1199.1	121	1320.1	2.02055	16.27	1.8777	3.30	3.50×10^{-3}	0.1479
170d	142-279	Coal #1	1.5	4 tang	15	1.02	1299.2	121	1420.2	1.94243	16.31	1.8007	3.46	3.40×10^{-3}	0.1621
170e	142-254	Coal #1	1.5	4 tang	5	1.02	1186.2	121	1307.2	2.00419	16.33	1.8557	3.21	3.50×10^{-3}	0.1425
170f	142-253	Coal #1	1.5	4 tang	15	0.95	1296.0	121	1417.0	1.57895	16.42	1.4539	4.81	2.70×10^{-3}	0.1786
170g	142-252	Coal #1	1.5	4 tang	25	1.02	1396.7	121	1517.7	3.66049	16.71	3.3122	5.13	6.20×10^{-3}	0.4684
170h	142-280	Coal #1	1.5	4 tang	15	0.85	1310.8	121	1431.8	2.71939	12.77	3.2198	8.01	6.10×10^{-3}	0.6788
170i	142-277	Coal #1	1.5	4 tang	15	0.75	1304.2	121	1425.2	1.66939	13.23	1.9079	24.06	3.60×10^{-3}	1.1977
170j	142-282	Coal #1	1.5	4 tang	5	0.65	1183.6	121	1304.6	2.35463	12.91	2.7577	12.18	5.20×10^{-3}	0.8017
170k	142-281	Coal #1	1.5	4 tang	15	0.65	1299.6	121	1420.6	1.59921	13.34	1.8167	11.54	3.40×10^{-3}	0.5408
170l	142-283	Coal #1	1.5	4 tang	25	0.65	1410.6	121	1531.6	1.71096	13.34	1.9393	5.38	3.70×10^{-3}	0.2958
170m	142-284	Coal #1	1.5	4 tang	15	0.55	1321.3	121	1442.3	1.66102	13.39	1.8756	5.71	3.50×10^{-3}	0.2797
170n	--	Coal #2	1.5	4 tang	15	1.15	1301.9	121	1422.9						
170o	--	Coal #2	1.5	4 tang	25	1.25	1403.0	121	1524.0						
170p	142-276	Coal #2	1.5	4 tang	5	1.05	1197.9	121	1318.9	1.79940	13.40	2.0304	8.05	3.80×10^{-3}	0.3914
170q	142-261	Coal #2	1.5	4 tang	25	1.02	1409.1	121	1530.1	1.38456	13.51	1.5496	9.67	2.90×10^{-3}	0.4163
170r	142-260	Coal #2	1.5	4 tang	15	0.95	1295.7	121	1416.7	1.51008	13.44	1.6988	10.01	3.20×10^{-3}	0.4403
170s	142-259	Coal #2	1.5	4 tang	15	0.85	1296.0	121	1417.0	1.77486	13.44	1.9968	11.28	3.80×10^{-3}	0.5893
170t	142-246	Coal #2	1.5	4 tang	15	0.75	1293.9	121	1414.9	1.24650	11.43	1.6489	14.67	3.10×10^{-3}	0.6243
170u	142-245	Coal #2	1.5	4 tang	5	0.65	1166.5	121	1287.5	1.19730	11.32	1.5992	33.67	3.00×10^{-3}	1.2618
170v	142-244	Coal #2	1.5	4 tang	15	0.65	1272.5	121	1393.5	0.93920	11.37	1.2490	10.96	2.40×10^{-3}	0.3556
171a	142-243	Coal #2	1.0	4 tang	15	1.15	870.7	81	951.7	0.9339	11.84	1.1926	17.23	2.30×10^{-3}	0.5466
171b	142-257	Coal #2	1.0	4 tang	25	1.25	961.0	81	1042.0	1.1784	13.05	1.3653	1.89	2.60×10^{-3}	0.0742
171c	--	Coal #2	1.0	4 tang	5	1.05	793.0	81	874.0	--	--		--		
171d	142-255	Coal #2	1.0	4 tang	15	1.02	869.1	81	950.1	1.2628	12.74	1.4987	11.28	2.80×10^{-3}	0.4349
171e	142-241	Coal #2	1.0	4 tang	5	1.02	797.1	81	878.1	1.5138	12.01	1.9058	18.42	3.60×10^{-3}	0.8440
171f	142-240	Coal #2	1.0	4 tang	25	1.02	940.1	81	1021.1	1.3488	13.32	1.5311	9.90	2.90×10^{-3}	0.4249
171g	142-258	Coal #2	1.0	4 tang	15	0.95	860.5	81	941.5	1.5106	11.83	1.9307	14.54	3.60×10^{-3}	0.7143
171h	142-239	Coal #2	1.0	4 tang	15	0.85	878.0	81	959.0	1.7793	12.40	2.1696	17.55	4.10×10^{-3}	1.0001
171i	142-238	Coal #2	1.0	4 tang	15	0.75	878.8	81	959.8	1.5319	11.62	1.9933	13.59	3.80×10^{-3}	0.7184
171j	142-237	Coal #2	1.0	4 tang	15	0.65	872.7	81	953.7	1.3491	11.67	1.7479	11.38	3.30×10^{-3}	0.5191
171k	142-274	Coal #2	1.0	4 tang	25	0.65	949.7	81	1030.7	1.1028	12.71	1.3119	6.60	2.50×10^{-3}	0.2465
171l	142-310	Coal #2	1.0	4 tang	5	0.65	791.7	81	872.7	1.4345	11.32	1.9160	21.44	3.60×10^{-3}	0.9763
171o	142-273	Coal #3	1.0	4 tang	15	1.15	886.3	116	967.3	1.8909	11.28	2.5346	5.23	4.80×10^{-3}	0.2458

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Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
171p	142-306	Coal #3	1.0	4 tang	25	1.15	973.0	116	1054.0	2.0041	12.90	2.3490	2.22	4.40×10^{-3}	0.1042
171q	142-296	Coal #3	1.0	4 tang	5	1.05	806.8	116	922.8	2.3156	11.22	3.1205	4.08	5.90×10^{-3}	0.2248
171r	142-297	Coal #3	1.0	4 tang	15	0.85	883.9	116	999.9	2.5230	12.88	2.9618	2.96	5.60×10^{-3}	0.1677
171s	142-305	Coal #3	1.0	4 tang	15	0.75	884.0	116	1000.0	1.9203	12.02	2.4156	3.90	4.60×10^{-3}	0.1816
171t	142-307	Coal #3	1.0	4 tang	15	0.65	874.3	116	990.3	1.9494	11.36	2.5946	2.05	4.90×10^{-3}	0.1007
171u	142-302	Coal #3	1.0	4 tang	25	0.65	949.3	116	1065.3	2.0571	12.63	2.4627	2.07	4.60×10^{-3}	0.1027
171v	142-309	Coal #3	1.0	4 tang	5	0.65	786.3	116	902.3	2.8016	11.24	3.7687	2.48	7.10×10^{-3}	0.1608
171w	142-298	Coal #3	1.0	4 tang	15	0.95	906.5	116	1022.5	3.1742	12.33	3.8924	2.04	7.30×10^{-3}	0.15410
171x	142-299	Coal #3	1.0	4 tang	15	1.02	884.8	116	1000.8	2.6633	11.56	3.4835	1.59	6.60×10^{-3}	0.1063
171y	142-312	Coal #3	1.0	4 tang	25	1.02	1004.8	116	1120.8	2.6719	12.80	3.1562	1.02	5.90×10^{-3}	0.0683
171z	142-313	Coal #3	1.0	4 tang	5	1.02	859.8	116	975.8	3.0083	11.35	4.0075	1.23	7.50×10^{-3}	0.0911
171aa	142-301	Coal #3	1.5	4 tang	15	1.15	1344.7	163	1507.7	3.2539	18.33	2.6841	1.05	5.10×10^{-3}	0.0582
171bb	142-311	Coal #3	1.5	4 tang	25	1.25	1436.5	163	1599.5	2.8572	20.70	2.0870	0.80	3.90×10^{-3}	0.0359
171cc	142-308	Coal #3	1.5	4 tang	5	1.05	1186.2	163	1349.2	3.0822	16.82	2.7709	0.62	5.20×10^{-3}	0.0313
171dd	142-304	Coal #3	1.5	4 tang	15	1.02	1320.4	163	1483.4	2.0485	18.37	1.6861	--	3.20×10^{-3}	0.0342
171ee	142-303	Coal #3	1.5	4 tang	5	1.02	1202.4	163	1365.4	3.8740	17.17	3.4115	0.39	6.40×10^{-3}	0.0245
171ff	142-332	Coal #3	1.5	4 tang	15	0.95	1323.0	163	1468.0	2.5712	18.88	2.0591	0.74	3.90×10^{-3}	0.0305
171gg	142-324	Coal #3	1.5	4 tang	15	0.85	1320.7	163	1483.7	3.5815	18.05	3.0001	0.72	5.70×10^{-3}	0.0439
171hh	142-323	Coal #3	1.5	4 tang	15	0.75	1330.1	163	1493.1	4.3265	18.32	3.5708	0.74	6.70×10^{-3}	0.0533
171ii	142-322	Coal #3	1.5	4 tang	15	0.65	1331.3	163	1494.3	4.0865	18.36	3.3654	0.83	6.30×10^{-3}	0.0563
171jj	142-321	Coal #3	1.5	4 tang	25	0.65	1428.3	163	1591.3	3.5325	19.20	2.7818	0.77	5.30×10^{-3}	0.0468
171kk	142-320	Coal #3	1.5	4 tang	5	0.65	1190.6	163	1353.6	3.8567	16.68	3.4960	1.16	6.60×10^{-3}	0.0746
171ll	142-319	Coal #3	1.5	4 tang	15	0.55	1273.6	163	1436.6	3.1905	17.77	2.7147	0.91	5.10×10^{-3}	0.0480
171mm	142-330	Coal #3	1.5	4 tang	25	1.02	2620.0	163	2783.0	3.6803	19.79	2.8118	0.97	5.30×10^{-3}	0.0586
173a	142-331	Coal #1	1.0	4 tang	15	0.85	876.6	81	957.6	1.2925	9.96	1.9621	18.30	3.70×10^{-3}	0.9398
173b	142-329	Coal #1	1.0	4 tang	15	0.75	889.4	81	970.4	0.5536	9.76	0.8576	26.74	1.60×10^{-3}	0.6017
173c	142-328	Coal #1	1.0	4 tang	15	0.65	882.5	81	963.5	1.7534	9.85	2.6915	16.30	5.10×10^{-3}	1.1609
173d	142-327	Coal #1	1.5	4 tang	15	0.85	1302.8	121	1423.8	2.5652	14.82	2.6171	17.52	4.90×10^{-3}	1.1859
173e	142-326	Coal #1	1.5	4 tang	15	0.75	1320.9	121	1441.9	2.1852	15.04	2.1968	16.53	4.10×10^{-3}	0.9481
173f	142-325	Coal #1	1.5	4 tang	15	0.65	1309.9	121	1430.9	3.3955	30.87	1.6631	13.56	3.10×10^{-3}	0.5836
173g	142-318	Coal #1	1.5	4 tang	15	0.55	1323.7	121	1444.7	1.8958	17.04	1.6822	13.75	3.20×10^{-3}	0.6168
173h	142-317	Coal #1	1.5	4 tang	15	0.95	1310.3	121	1431.3	1.6057	17.75	1.3678	13.31	2.60×10^{-3}	0.4806
173i	142-316	Coal #1	1.5	4 tang	15	1.02	1318.4	121	1439.4	3.1396	17.16	2.7664	10.40	5.20×10^{-3}	0.7553
173j	142-314	Coal #1	1.0	4 tang	15	0.95	880.5	81	961.5	1.4697	10.87	2.0443	11.89	3.90×10^{-3}	0.6462
173k	142-343	Coal #1	1.0	4 tang	15	1.02	889.4	81	970.4	1.3196	10.76	1.8543	18.56	3.50×10^{-3}	0.9137
174a	142-342	Coal #1	1.0	4 tang	15	0.95	888.2	81	969.2	2.9311	12.36	3.5856	38.40	6.70×10^{-3}	3.6141
174b	142-353	Coal #1	1.0	4 tang	15	0.85	891.0	81	972.0	2.9478	12.80	3.4821	40.85	6.60×10^{-3}	3.7983

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Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m- lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
174c	142-352	Coal #1	1.0	4 tang	15	1.02	889.7	81	970.7	2.5476	13.30	2.8962	25.71	5.50×10^{-3}	1.9894
174d	142-351	Coal #1	1.0	4 tang	15	0.75	886.5	81	966.5	2.5700	12.94	3.0030	31.27	5.70×10^{-3}	2.4994
174e	142-350	Coal #1	1.0	4 tang	25	0.75	960.5	81	1041.5	2.5031	14.38	2.6319	30.31	5.00×10^{-3}	2.2877
174f	142-349	Coal #1	1.0	4 tang	15	0.65	882.3	81	963.3	2.5566	13.54	2.8549	33.45	5.40×10^{-3}	2.5219
174g	142-336	Coal #1	1.0	4 tang	15	1.15	883.8	81	964.8	1.9024	13.26	2.1693	9.95	4.10×10^{-3}	0.5705
174h	142-335	Coal #1	1.0	4 tang	25	1.25	965.1	81	1046.1	1.9233	14.50	2.0055	2.67	3.80×10^{-3}	0.1521
174i	142-334	Coal #1	1.0	4 tang	5	1.05	813.0	81	894.0	2.4247	12.47	2.9400	8.34	5.50×10^{-3}	0.5944
174j	142-339	Coal #1	1.5	4 tang	15	0.85	1310.0	123	1433.0	5.0515	19.15	3.9884	22.46	7.50×10^{-3}	2.3040
174k	142-338	Coal #1	1.0	4 tang	15	1.15	883.4	81	964.4	1.8133	12.38	2.2146	6.78	4.20×10^{-3}	0.3980
174l	142-337	Coal #1	1.0	4 tang	15	0.85	875.2	81	956.2	2.0541	11.93	2.6034	18.39	4.90×10^{-3}	1.2488
174m	142-348	Coal #1	1.0	4 tang	15	0.75	887.2	81	968.2	2.2117	12.44	2.6882	18.50	5.10×10^{-3}	1.3240
174n	142-347	Coal #1	1.0	4 tang	15	0.65	866.7	81	947.7	1.6430	12.13	2.0480	16.79	3.90×10^{-3}	0.8994
174o	142-346	Coal #1	1.0	4 tang	15	0.95	887.3	81	968.3	2.2576	12.35	2.7640	13.57	5.20×10^{-3}	0.9903
174p	142-345	Coal #1	1.0	4 tang	15	1.02	892.9	81	973.9	1.5192	12.51	1.8362	8.93	3.50×10^{-3}	0.4412
176a	142-344	Coal #1	1.0	4 tang	15	1.15	873.5	81	954.5	2.0854	12.84	2.4557	11.20	4.60×10^{-3}	0.7127
176b	142-340	Coal #1	1.0	4 tang	15	1.02	869.6	81	950.6	2.7574	12.45	3.3487	30.72	6.30×10^{-3}	2.6665
176c	142-341	Coal #1	1.0	4 tang	15	0.95	867.2	81	948.2	6.2808	11.45	8.2939	46.23	1.55×10^{-2}	9.8478
176d	142-360	Coal #1	1.0	4 tang	15	0.85	869.0	81	950.0	4.3179	13.06	4.9990	51.12	9.40×10^{-3}	6.6165
176e	142-359	Coal #1	1.0	4 tang	15	0.75	878.3	81	959.3	3.6304	12.17	4.5104	50.78	8.50×10^{-3}	6.0014
177a	142-358	Coal #1	1.0	4 tang	15	1.15	876.3	81	957.3	38.3058	13.01	44.5183	14.48	7.78×10^{-2}	15.6307
177b	142-357	Coal #1	1.0	4 tang	15	1.02	869.7	81	950.7	4.3323	11.93	5.4907	15.65	1.03×10^{-2}	2.2212
177c	142-356	Coal #1	1.0	4 tang	15	0.95	864.2	81	945.2	5.1759	13.19	5.9333	20.65	1.11×10^{-2}	3.1401
177d	142-354	Coal #1	1.0	4 tang	15	0.85	865.7	81	946.7	4.2300	13.19	4.8489	24.63	9.10×10^{-3}	3.0754
177e	142-355	Coal #1	1.0	4 tang	15	0.75	860.7	81	941.7	3.2007	13.20	3.6663	24.49	6.90×10^{-3}	2.3064
178a	142-367	Coal #1	1.0	4 tang	15	0.95	890.6	81	971.6	1.5957	11.00	2.1934	3.69	4.10×10^{-3}	0.2130
178b	142-366	Coal #1	1.0	4 tang	15	0.95	866.3	81	947.3	1.8248	11.45	2.4097	1.09	4.50×10^{-3}	0.0673
178c	142-365	Coal #1	1.0	4 tang	15	0.75	871.2	81	952.2	1.5583	10.87	2.1676	8.04	4.10×10^{-3}	0.4549
178e	142-364	Coal #1	1.0	4 tang	15	0.85	892.5	81	973.5	2.0753	12.39	2.5326	7.00	4.80×10^{-3}	0.4741
178f	142-363	Coal #1	1.0	4 tang	15	0.85	895.3	81	976.3	0.3228	12.51	0.3901	1.86	0.70×10^{-3}	0.0184
179b	142-362	Coal #1	1.0	4 tang	15	1.02	876.4	81	957.4	3.2113	13.12	3.7008	3.27	7.00×10^{-3}	0.3176
179c	142-361	Coal #1	1.0	4 tang	15	0.95	874.7	81	955.7	1.7833	13.49	1.9988	12.08	3.80×10^{-3}	0.6359
179d	142-437	Coal #1	1.0	4 tang	15	0.85	867.9	81	948.9	1.1955	13.67	1.3223	24.02	2.50×10^{-3}	0.8259

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Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
179e	142-436	Coal #1	1.0	4 tang	15	0.75	876.6	81	957.6	3.7990	22.25	2.5816	6.39	4.90×10^{-3}	0.4346
179f	142-435	Coal #1	1.0	4 tang	15	0.65	881.4	81	962.4	2.3132	22.10	1.5826	3.98	3.00×10^{-3}	0.1665
179g	--	Coal #1	1.0	4 tang	15	1.15	887.5	81	968.5	--			--		
179h	142-434	Coal #1	1.0	4 tang	15	0.95	863.2	81	944.2	1.9920	12.38	2.4329	3.57	4.60×10^{-3}	0.2247
179i	142-433	Coal #1	1.0	4 tang	15	0.85	892.4	81	973.4	1.8587	12.16	2.311	3.74	4.40×10^{-3}	0.2322
179j	142-432	Coal #1	1.0	4 tang	15	0.75	865.8	81	946.8	1.6971	12.01	2.1366	3.61	4.00×10^{-3}	0.1982
179k	142-425	Coal #1	1.0	4 tang	15	0.65	874.1	81	955.1	1.4569	12.12	1.8175	2.21	3.40×10^{-3}	0.1040
179l	142-427	Coal #1	1.0	4 tang	15	1.02	894.5	81	975.5	0.7743	12.99	0.9013	4.02	1.70×10^{-3}	0.0966
181a	142-423	Coal #1	1.0	6 ax	15	1.15	901.5	81	982.5	1.2776	10.44	1.850	21.51	3.494×10^{-3}	1.07030
181b	142-422	Coal #1	1.0	6 ax	15	1.02	872.8	81	953.8	1.9291	12.35	2.362	12.38	4.456×10^{-3}	0.76258
181c	142-421	Coal #1	1.0	6 ax	15	0.95	887.0	81	968.0	2.1763	14.96	2.200	18.11	4.151×10^{-3}	1.05471
181d	142-420	Coal #1	1.0	6 ax	15	0.85	887.1	81	968.1	1.7637	12.48	2.137	16.62	4.033×10^{-3}	0.94051
181e	142-418	Coal #1	1.0	6 ax	15	0.75	887.1	81	968.1	1.8418	12.31	2.262	15.24	4.269×10^{-3}	0.91283
181f	142-419	Coal #1	1.0	6 ax	15	0.65	869.9	81	950.9	0.7831	12.13	0.976	15.42	1.846×10^{-3}	0.39240
182a	142-389	Coal #1	1.0	6 ax	15	1.15	876.0	81	957.0	1.8936	12.83	2.232	12.55	4.211×10^{-3}	0.73306
182b	142-392	Coal #1	1.0	6 ax	15	0.85	875.4	81	956.4	1.8021	13.11	2.078	7.60	3.923×10^{-3}	0.41331
182c	142-387	Coal #1	1.0	6 ax	15	0.75	880.6	81	961.6	1.5490	12.59	1.860	7.00	3.513×10^{-3}	0.34273
182d	142-390	Coal #1	1.0	6 ax	15	0.65	884.4	81	965.4	1.5246	13.07	1.764	5.46	3.331×10^{-3}	0.25450
182e	142-393	Coal #1	1.0	6 ax	15	0.95	876.4	81	957.4	1.9980	13.08	2.310	9.05	4.358×10^{-3}	0.54726
182f	142-386	Coal #1	1.0	6 ax	15	1.02	888.4	81	969.4	1.7255	12.28	2.125	12.60	4.010×10^{-3}	0.70991
182g	142-375	Coal #1	1.0	4 SPRDR	15	1.15	873.1	81	954.1	2.1408	12.33	2.625	5.69	4.950×10^{-3}	0.38951
182h	142-372	Coal #1	1.0	4 SPRDR	15	0.95	871.2	81	952.2	1.8700	12.23	2.312	4.30	4.362×10^{-3}	0.25886
182i	142-398	Coal #1	1.0	4 SPRDR	15	0.85	878.4	81	959.4	1.7213	12.28	2.119	3.83	4.000×10^{-3}	0.21305
182j	142-383	Coal #1	1.0	4 SPRDR	15	0.75	879.6	81	960.6	2.3539	11.99	2.968	4.57	5.594×10^{-3}	0.35592
182k	142-382	Coal #1	1.0	4 SPRDR	15	0.65	879.0	81	960.0	0.6870	11.39	0.912	5.02	1.725×10^{-3}	0.12051
183c	142-385	Coal #1	1.0	4 SPRDR	15	0.75	889.3	81	970.3	2.8790	17.10	2.546	15.86	4.801×10^{-3}	1.07083
183d	142-413	Coal #1	1.0	4 SPRDR	15	0.65	883.7	81	964.7	2.2346	15.62	2.163	12.23	4.082×10^{-3}	0.69810
183e	142-412	Coal #1	1.0	4 SPRDR	15	0.95	883.3	81	964.3	2.9177	16.11	2.738	14.79	5.163×10^{-3}	1.06717
183f	142-405	Coal #1	1.0	4 SPRDR	15	1.02	886.0	81	967.0	2.9992	15.63	2.901	6.03	5.468×10^{-3}	0.46213
183h	142-403	Coal #1	1.0	4 SPRDR	15	1.02	876.1	81	957.1	3.3141	14.55	3.444	4.61	6.484×10^{-3}	0.41466
183i	142-369	Coal #1	1.0	4 SPRDR	15	0.95	877.0	81	958.0	2.7113	14.23	2.881	9.63	5.430×10^{-3}	0.72604
183j	142-368	Coal #1	1.0	4 SPRDR	15	0.85	877.3	81	958.3	3.0769	14.42	3.226	10.33	6.077×10^{-3}	0.87189
183k	142-404	Coal #1	1.0	4 SPRDR	15	0.75	886.5	81	967.5	2.7884	13.78	3.060	15.15	5.765×10^{-3}	1.22466
183l	142-417	Coal #1	1.0	4 SPRDR	15	0.65	889.8	81	970.8	2.1239	13.10	2.451	19.69	4.624×10^{-3}	1.28110
186e	142-415	Coal #1	0.85	4 SPRDR	15	0.85	744.0	69	813.0	1.0849	10.38	1.580	5.60	2.986×10^{-3}	0.23129
186f	142-414	Coal #1	0.85	4 SPRDR	15	0.75	745.0	69	814.0	0.5815	8.99	0.978	4.20	1.850×10^{-3}	0.10761
186g	142-370	Coal #1	0.85	4 SPRDR	15	0.65	754.0	69	823.0	1.5863	10.31	2.326	3.29	4.389×10^{-3}	0.20221

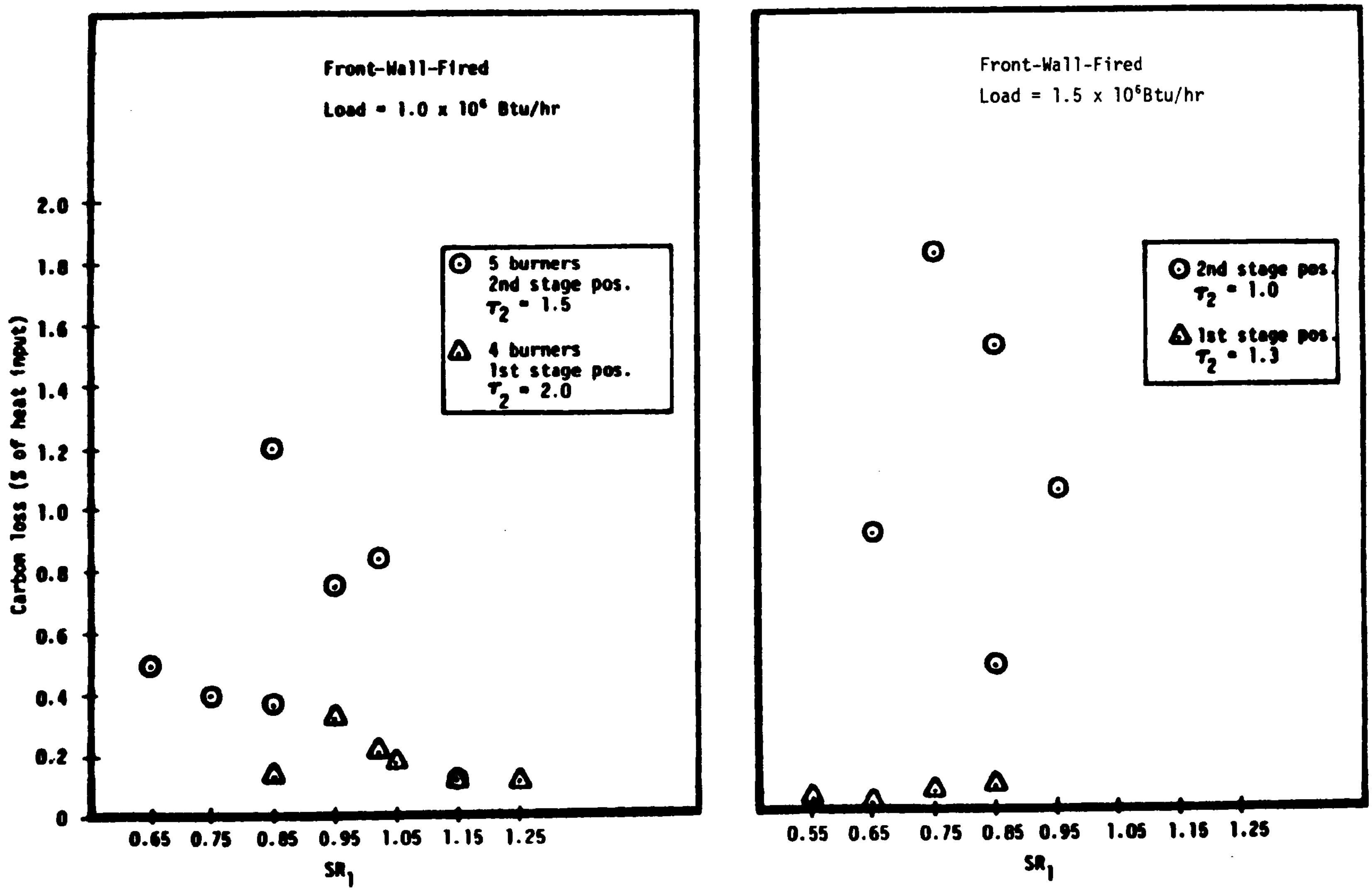
PARTICULATE DATA SUMMARY SHEET

Test No.	Filter No.	Fuel	Load x 10^6 Btu/hr	Inj	EA %	SR	m_t lbs/hr	m_f lbs/hr	m_T lbs/hr	TR grams	Vg ft^3	GL grains/ft^3	CP %	AF	CL %
186i	142-377	Coal #1	0.85	4 SPRDR	15	0.95	749.0	69	818.0	0.8475	9.05	1.416	3.11	2.676×10^{-3}	0.11583
186j	142-376	Coal #1	0.85	4 SPRDR	15	1.02	752.0	69	821.0	0.7749	10.34	1.133	2.19	2.143×10^{-3}	0.06555
186k	142-388	Coal #1	1.3	4 SPRDR	15	1.15	1133.6	105.3	1238.9	2.6321	12.26	3.246	2.50	6.114×10^{-3}	0.21112
186l	142-411	Coal #1	1.3	4 SPRDR	25	1.25	1244.8	105.3	1350.1	1.0880	13.25	1.242	1.40	2.347×10^{-3}	0.04947
186m	142-410	Coal #1	1.3	4 SPRDR	5	1.05	1028.7	105.3	1134.0	1.7027	12.67	2.032	1.05	3.836×10^{-3}	0.05092
186n	142-409	Coal #1	1.3	4 SPRDR	15	1.02	1141.7	105.3	1247.0	0.5938	14.00	0.641	0.89	1.214×10^{-3}	0.01502
186n	142-408	Coal #1	1.3	4 SPRDR	15	0.95	1129.7	105.3	1235.0	1.5636	13.14	1.799	0.87	3.398×10^{-3}	0.04071
187a	142-446	Coal #1	1.3	4 SPRDR	15	0.85	1134.2	103.5	1237.7	1.2623	15.16	1.259	1.82	2.380×10^{-3}	0.06082
187b	142-407	Coal #1	1.3	4 SPRDR	15	0.75	1134.5	103.5	1238.0	1.2444	13.70	1.373	1.73	2.596×10^{-3}	0.06306
187c	142-401	Coal #1	1.3	4 SPRDR	15	0.65	1127.3	103.5	1230.8	2.1604	13.76	2.374	1.99	4.479×10^{-3}	0.12443
187e	142-400	Coal #1	1.3	4 SPRDR	15	0.75	1126.9	103.5	1230.4	2.0035	15.51	1.953	1.29	3.688×10^{-3}	0.06639
187f	142-399	Coal #1	1.3	4 SPRDR	15	1.15	744.0	69	813.0	2.3407	12.20	2.901	0.94	5.467×10^{-3}	0.07109
187g	142-406	Coal #1	1.3	4 SPRDR	15	0.75	739.5	69	808.5	1.5891	9.96	2.412	2.77	4.551×10^{-3}	0.17341
188a	142-384	Coal #1	0.85	4 SPRDR	15	1.15	746.6	69	815.6	0.3953	12.20	0.490	3.81	0.928×10^{-3}	0.04904
188b	142-374	Coal #1	0.85	4 SPRDR	15	0.75	770.9	69	839.9	0.3027	9.79	0.467	27.50	0.885×10^{-3}	0.34786
188c	142-378	Coal #1	1.3	4 SPRDR	15	1.15	1174.0	105.3	1279.3	4.2529	16.06	4.004	8.03	7.531×10^{-3}	0.86250
188d	142-379	Coal #1	1.3	4 SPRDR	15	0.75	1119.8	105.3	1225.1	1.7675	15.96	1.674	7.84	3.163×10^{-3}	0.33873
188e	142-380	Coal #1	1.3	4 SPRDR	15	1.15	1147.3	105.3	1252.6	1.3970	18.06	1.170	1.77	2.212×10^{-3}	0.05467
188f	142-381	Coal #1	1.3	4 SPRDR	15	0.75	1126.9	105.3	1232.2	1.8275	17.82	1.551	3.26	2.930×10^{-3}	0.13122
188g	142-395	Coal #1	0.85	4 SPRDR	15	1.15	756.0	69	825.0	0.5808	13.95	0.630	2.28	1.192×10^{-3}	0.03813
188h	142-396	Coal #1	0.85	4 SPRDR	15	0.75	742.0	69	811.0	1.1586	11.19	1.566	12.70	2.958×10^{-3}	0.51836

APPENDIX A.3

CO PLOTS AND CONCLUSIONS

EFFECT OF STOICHIOMETRY: FIRST STAGE



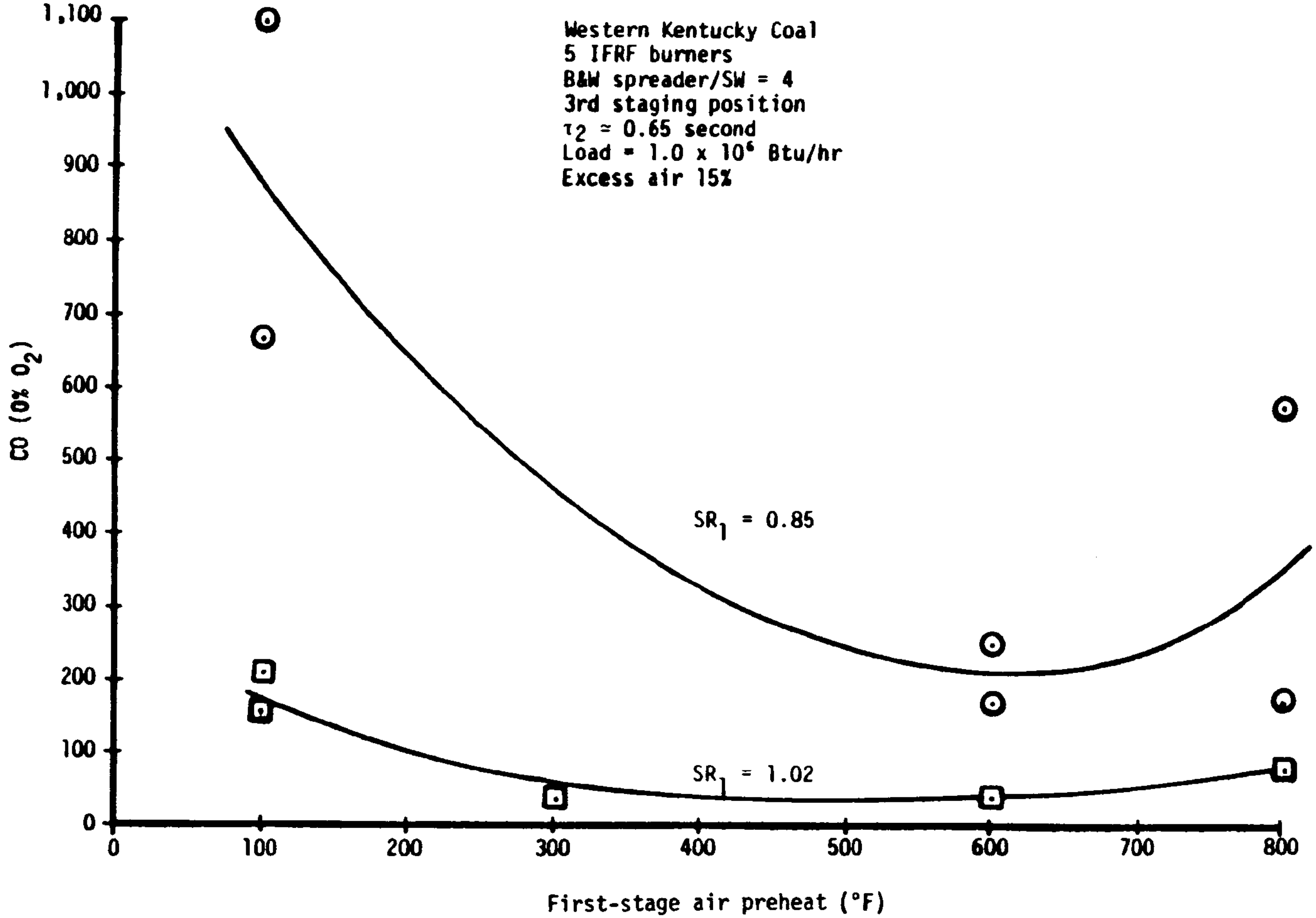
CO CONCLUSIONS

TEMPERATURE

- CO LEVELS DECREASED WITH INCREASING TEMPERATURE FOR BOTH FWF AND TANGENTIAL CONFIGURATIONS AT τ_2 = 0.65 SEC
- FOR $\tau_2 > 0.65$ NO EFFECT WAS OBSERVED

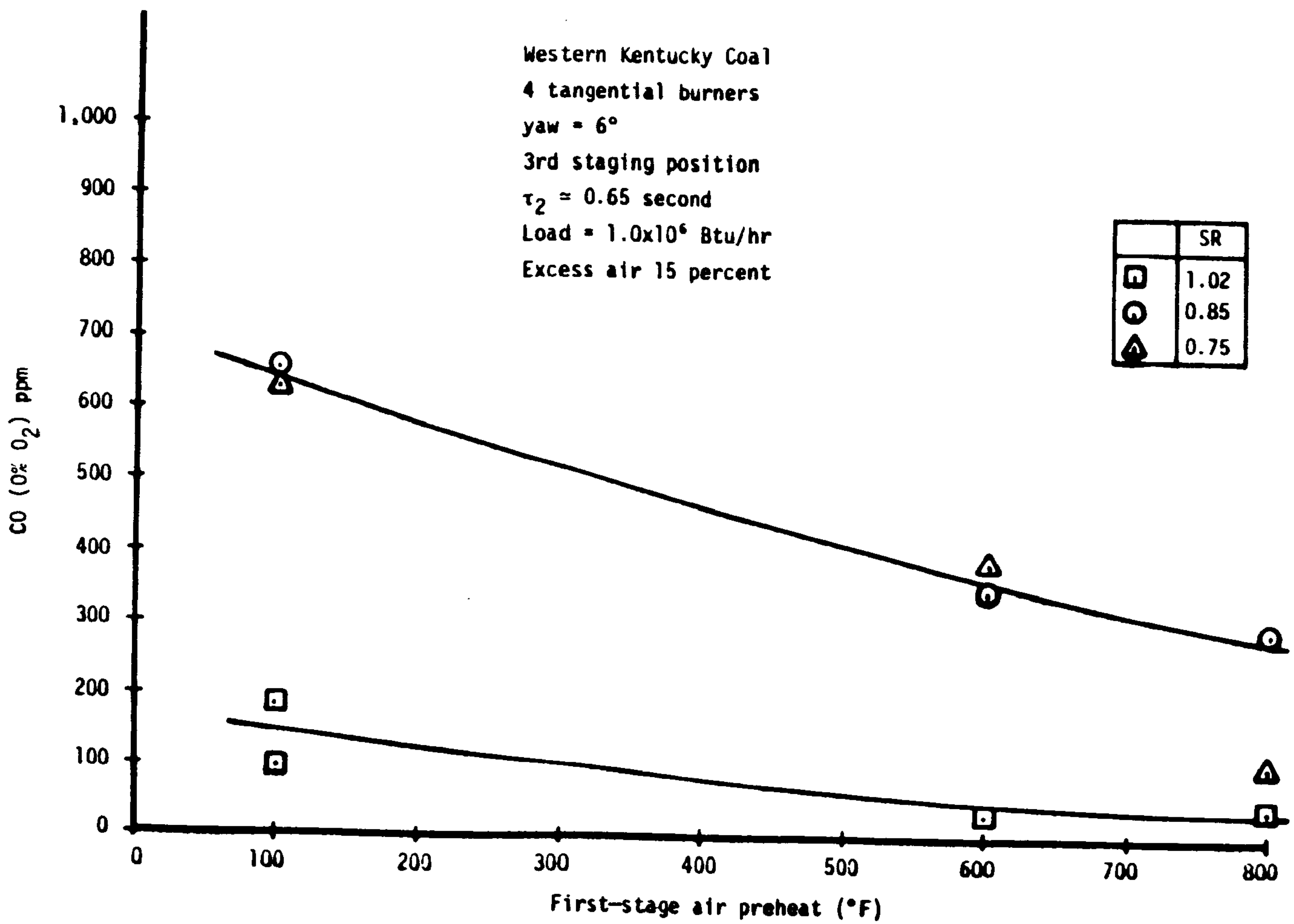
EFFECT OF FIRST-STAGE AIR PREHEAT

FRONT-WALL-FIRED



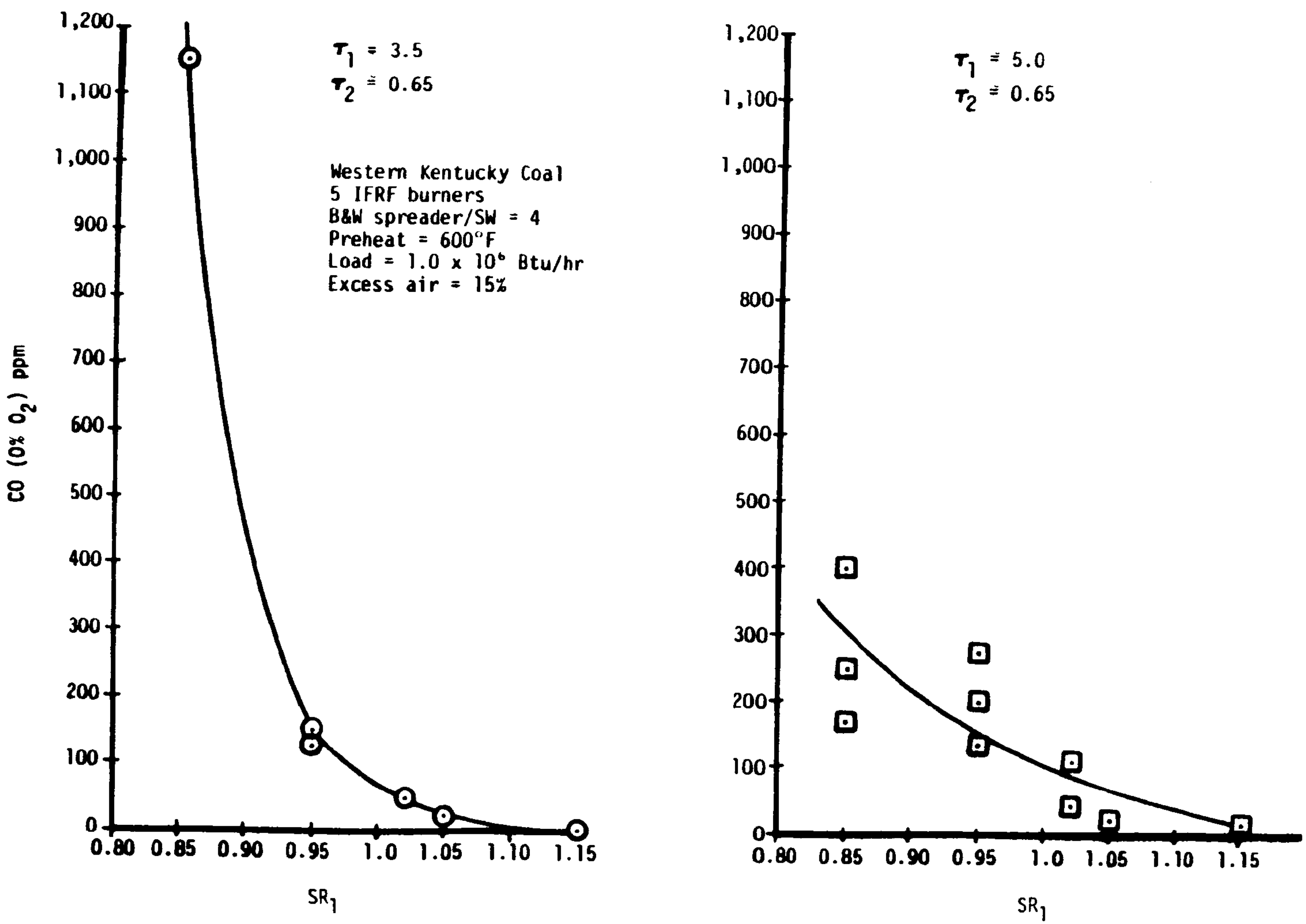
EFFECT OF FIRST-STAGE AIR PREHEAT

TANGENTIALLY-FIRED



EFFECT OF FIRST-STAGE RESIDENCE TIME

FRONT-WALL-FIRED

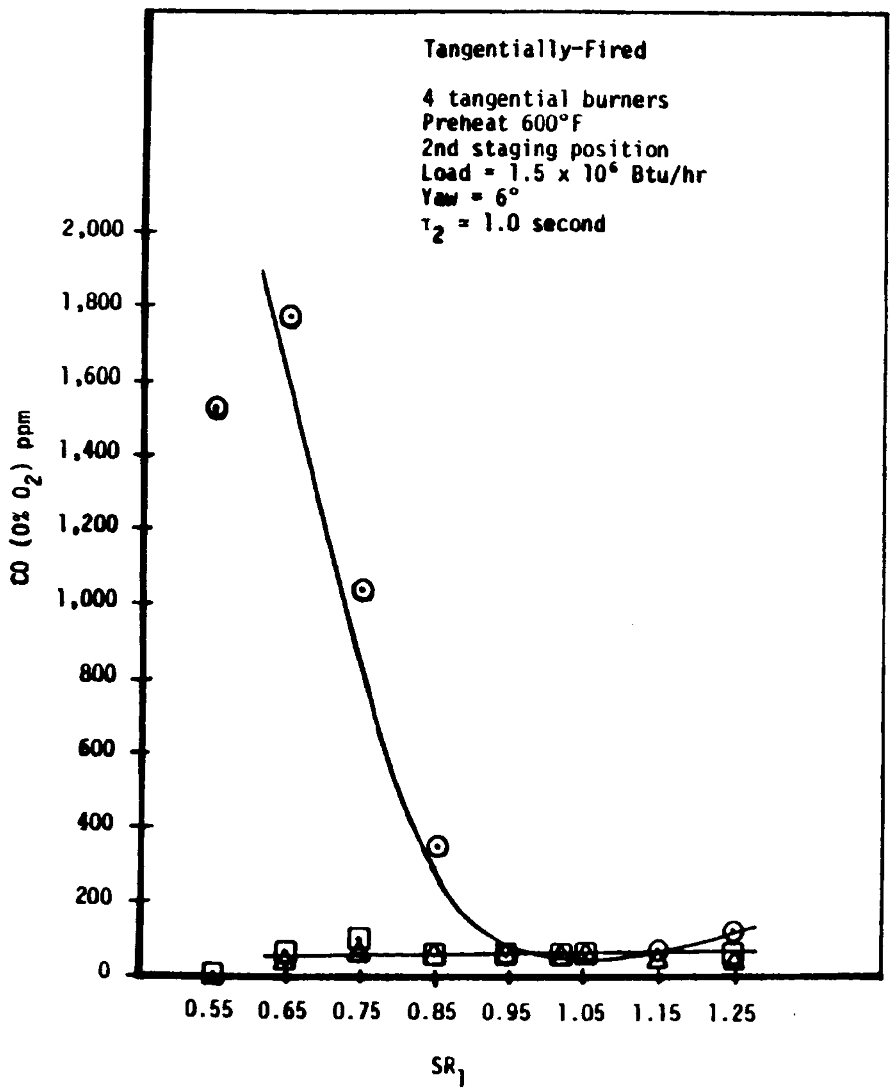


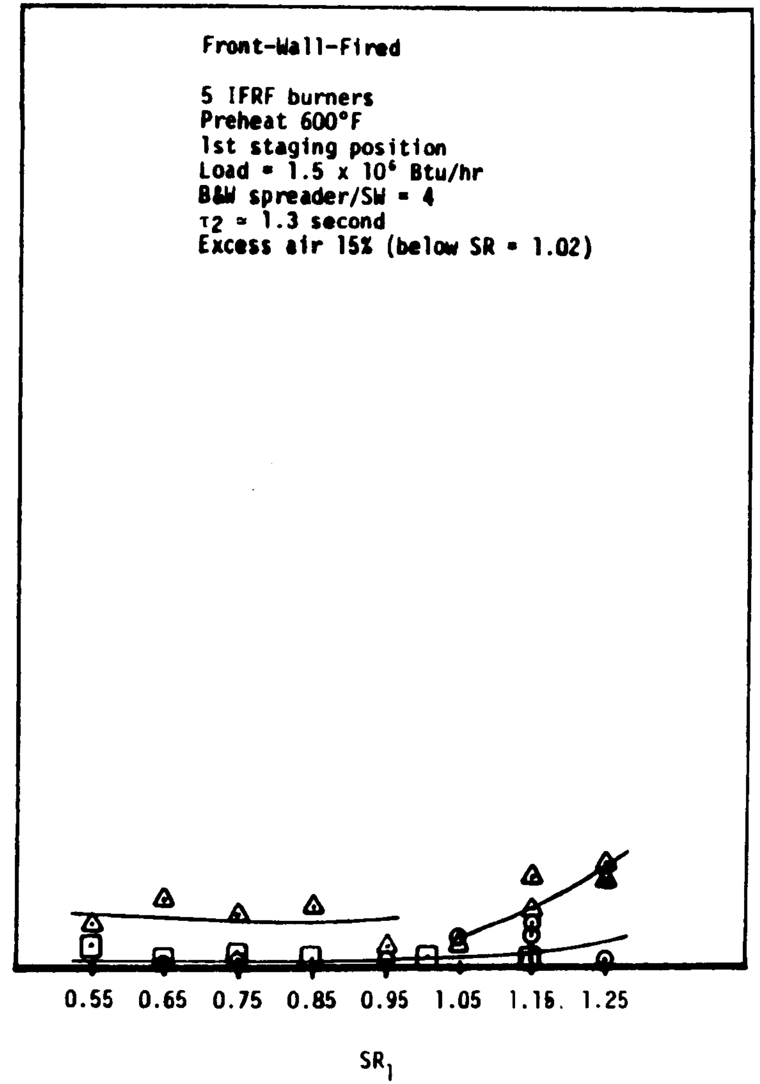
CO CONCLUSIONS

COAL COMPOSITION

- AT 1.5 x 10^6 BTU/HR THE MONTANA COAL PRODUCED GREATER CO AS THE SR DECREASED FOR THE FWF CONFIGURATION
- AT 1.0 x 10^6 BTU/HR NO DIFFERENCE BETWEEN COALS
- FOR THE TANGENTIAL CONFIGURATION THE PITTSBURGH #8 PRODUCED SLIGHTLY HIGHER CO LEVEL OVER ALL SR'S
- FOR THE TANGENTIAL CONFIGURATION THE PITTSBURGH #8 CO LEVELS INCREASED WITH EA AT BASELINE CONDITIONS

EFFECT OF COAL COMPOSITION





A.3-9

CO CONCLUSIONS

MIXING

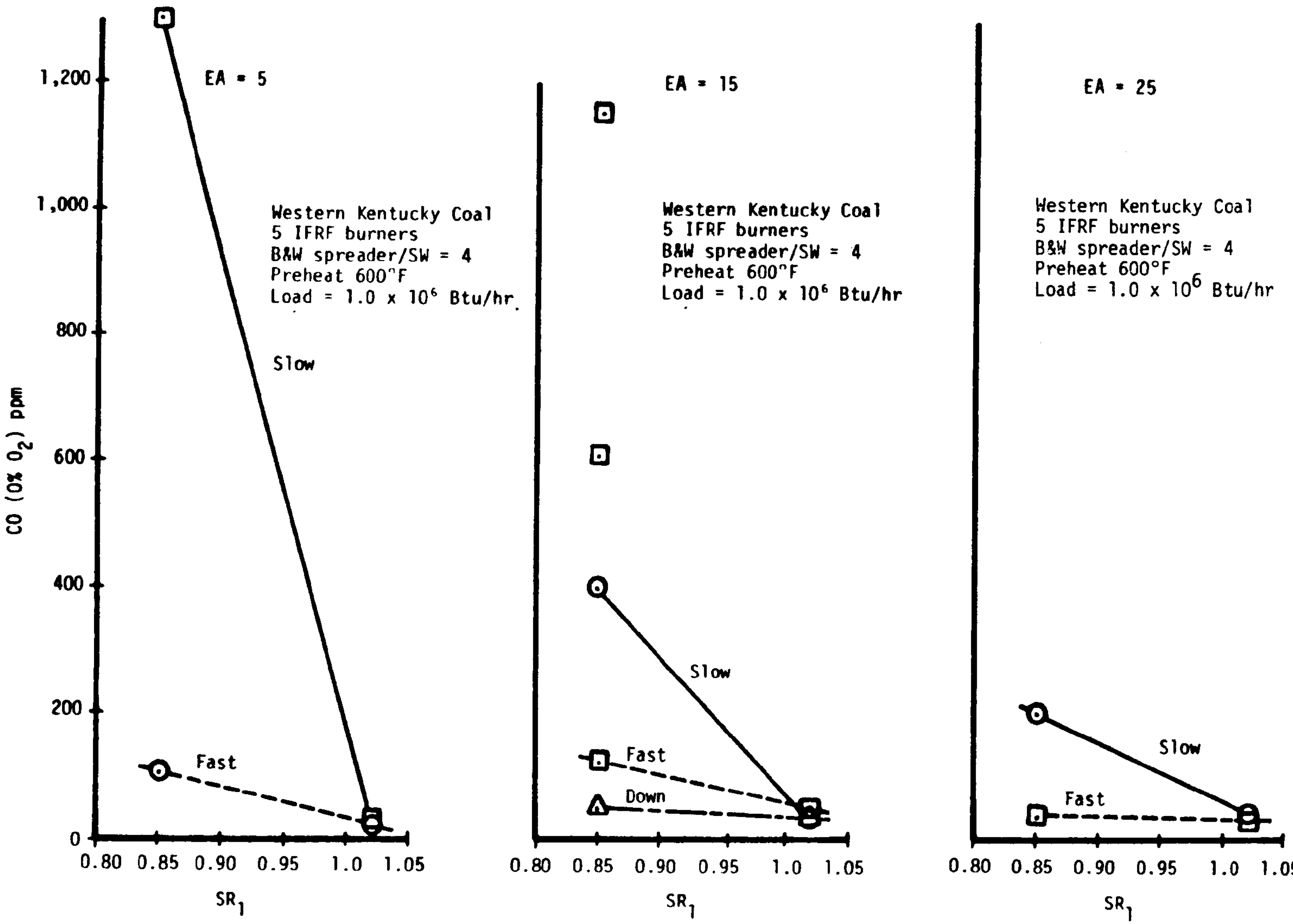
1ST STAGE

- AXIAL INJECTOR PRODUCED GREATER CO LEVELS AT EA = 5%
- TANGENTIALLY FIRED CONFIGURATION ALSO PRODUCED GREATER CO LEVELS AT EA = 5%
- NO DIFFERENCE BETWEEN ANY CONFIGURATION AT EA > 5%

2ND STAGE

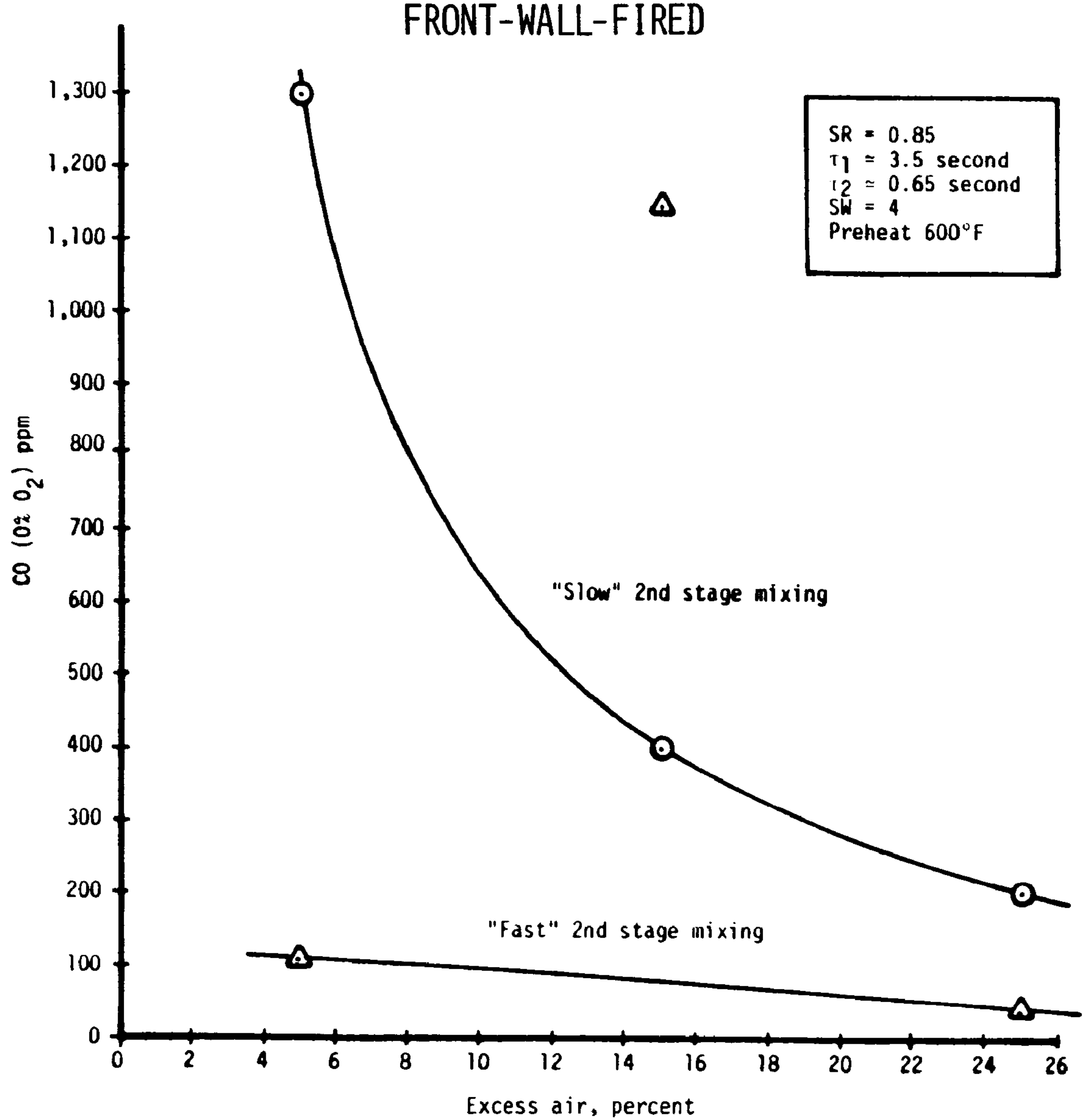
- SLOW MIXING PRODUCED HIGHER CO LEVELS AT $SR_1 = 0.85$
- NO DIFFERENCE WAS SEEN AT SR = 1.02 DUE TO MIXING TECHNIQUE
- THE HIGHER CO LEVELS FOR THE SLOW-MIX CONDITION COULD BE REDUCED BY INCREASING THE EXCESS AIR

EFFECT OF SECOND-STAGE MIXING ON CO

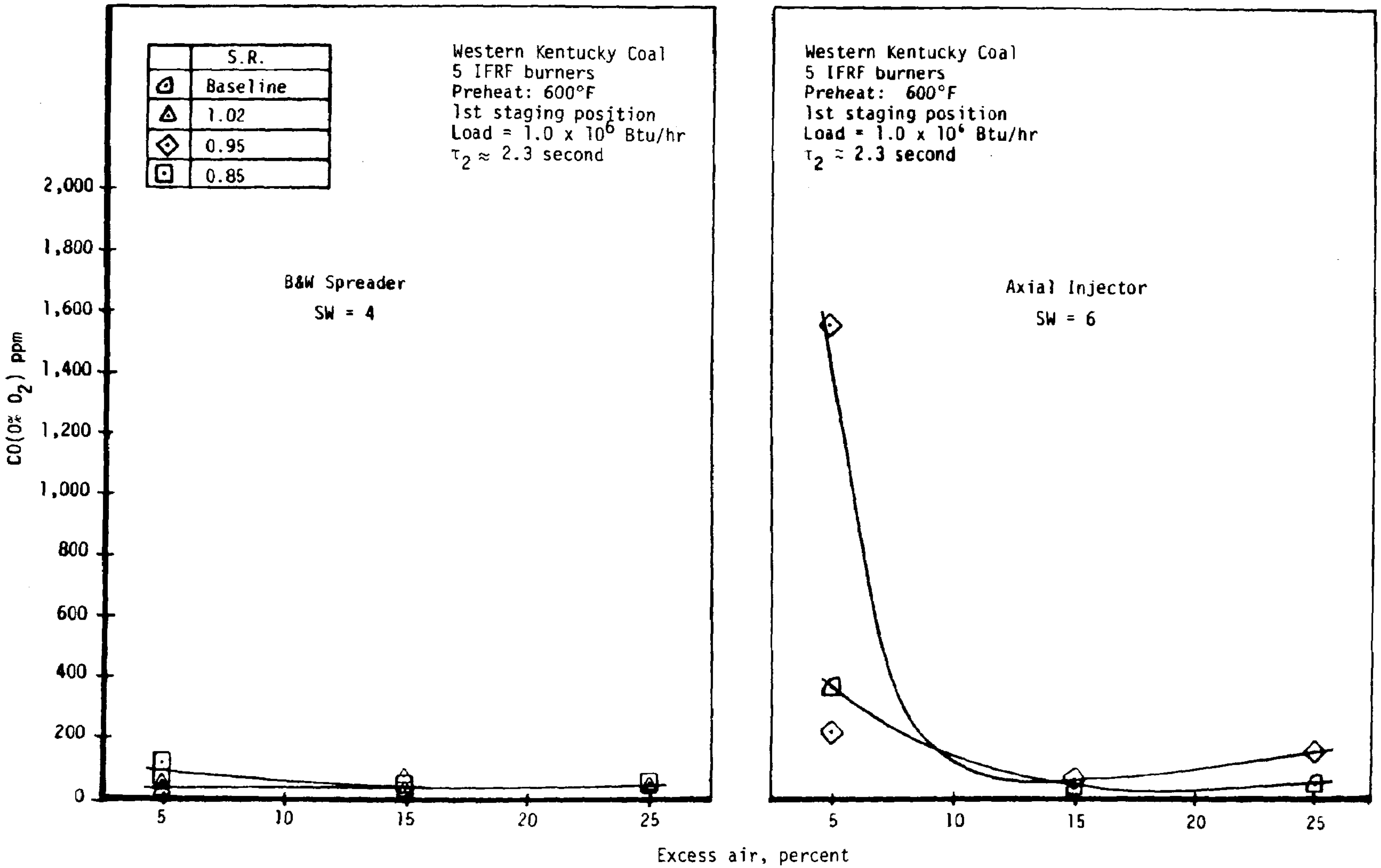


EFFECT OF SECOND-STAGE MIXING

FRONT-WALL-FIRED



EFFECT OF FIRST-STAGE MIXING

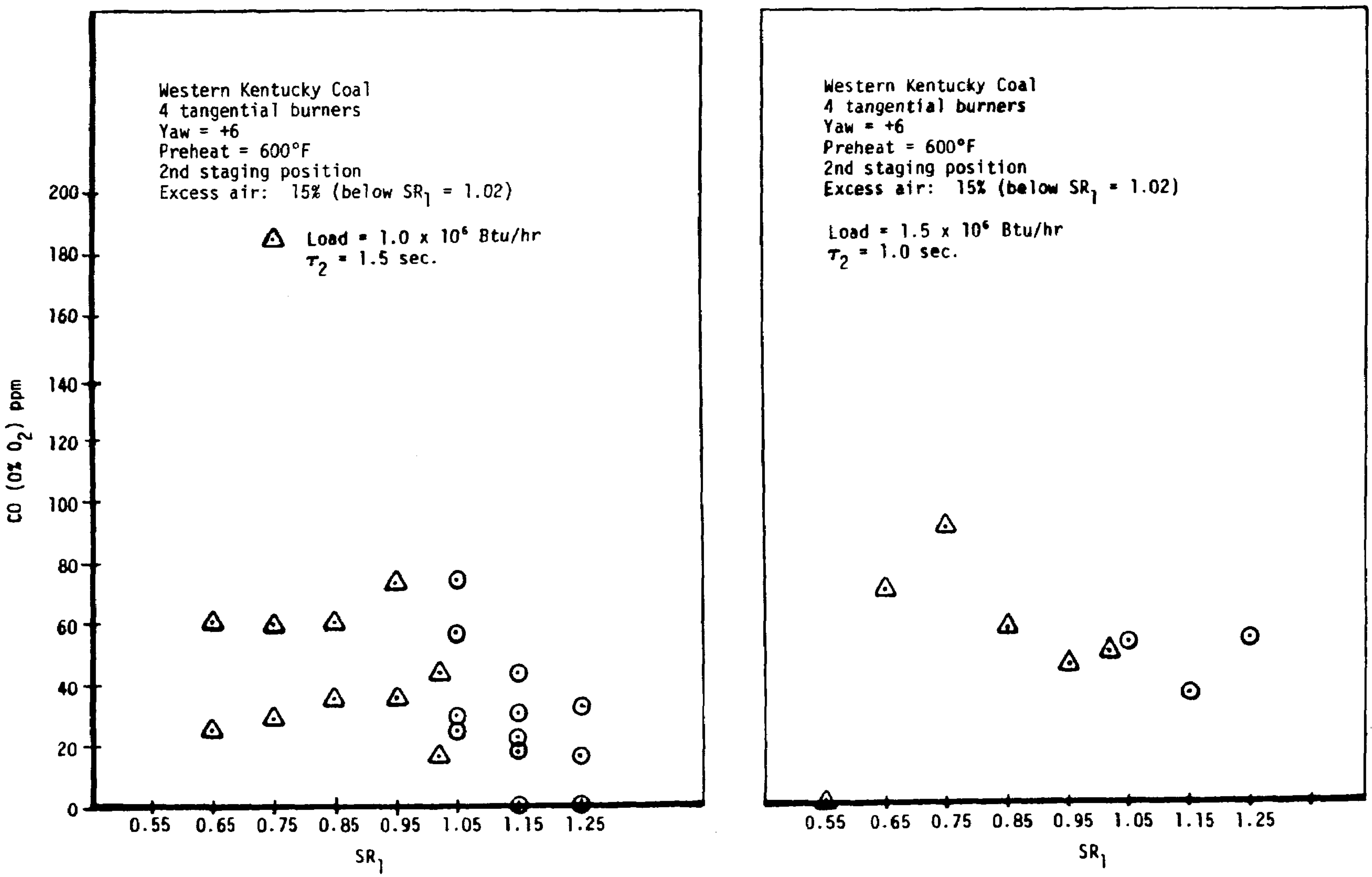


CO CONCLUSIONS

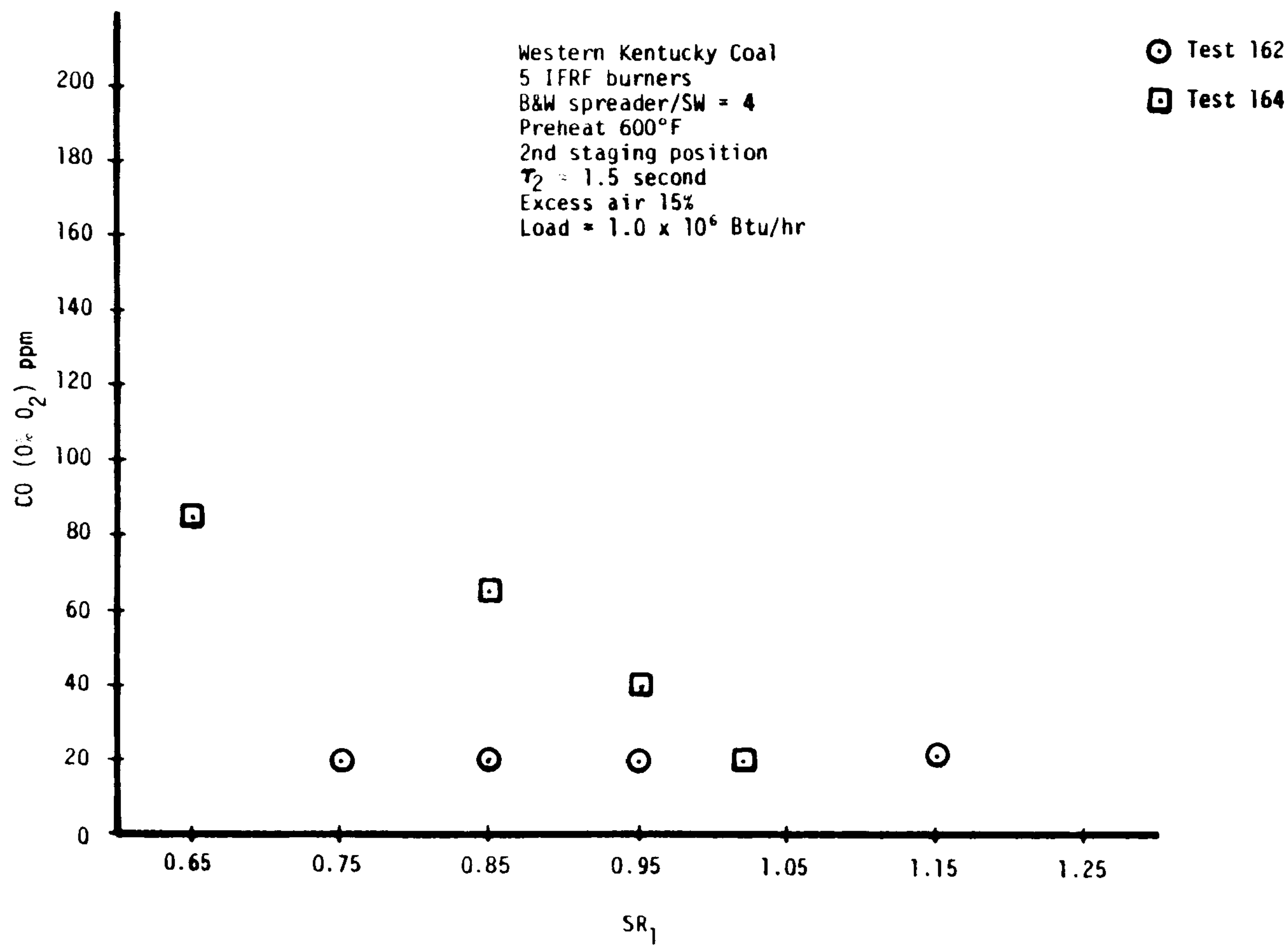
STOICHIOMETRY – 1ST STAGE

- CO INCREASES (SLIGHTLY) AS SR DECREASES FOR $\tau_2 > 1.0$ SEC (EA = 15%)
- CO INCREASES SIGNIFICANTLY AS SR DECREASE FOR $\tau_2 < 1.0$ SEC (EA = 15%)
- CO LESS THAN 100 PPM WERE EASILY ACHEIVED AT ALL SR_1's
- NO SIGNIFICANT DIFFERENCE BETWEEN FWF AND TANGENTIALLY FIRED

EFFECT OF FIRST-STAGE STOICHIOMETRY: TANGENTIALLY-FIRED



EFFECT OF FIRST-STAGE STOICHIOMETRY: WALL FIRED



CO CONCLUSIONS

RESIDENCE TIME (RT)

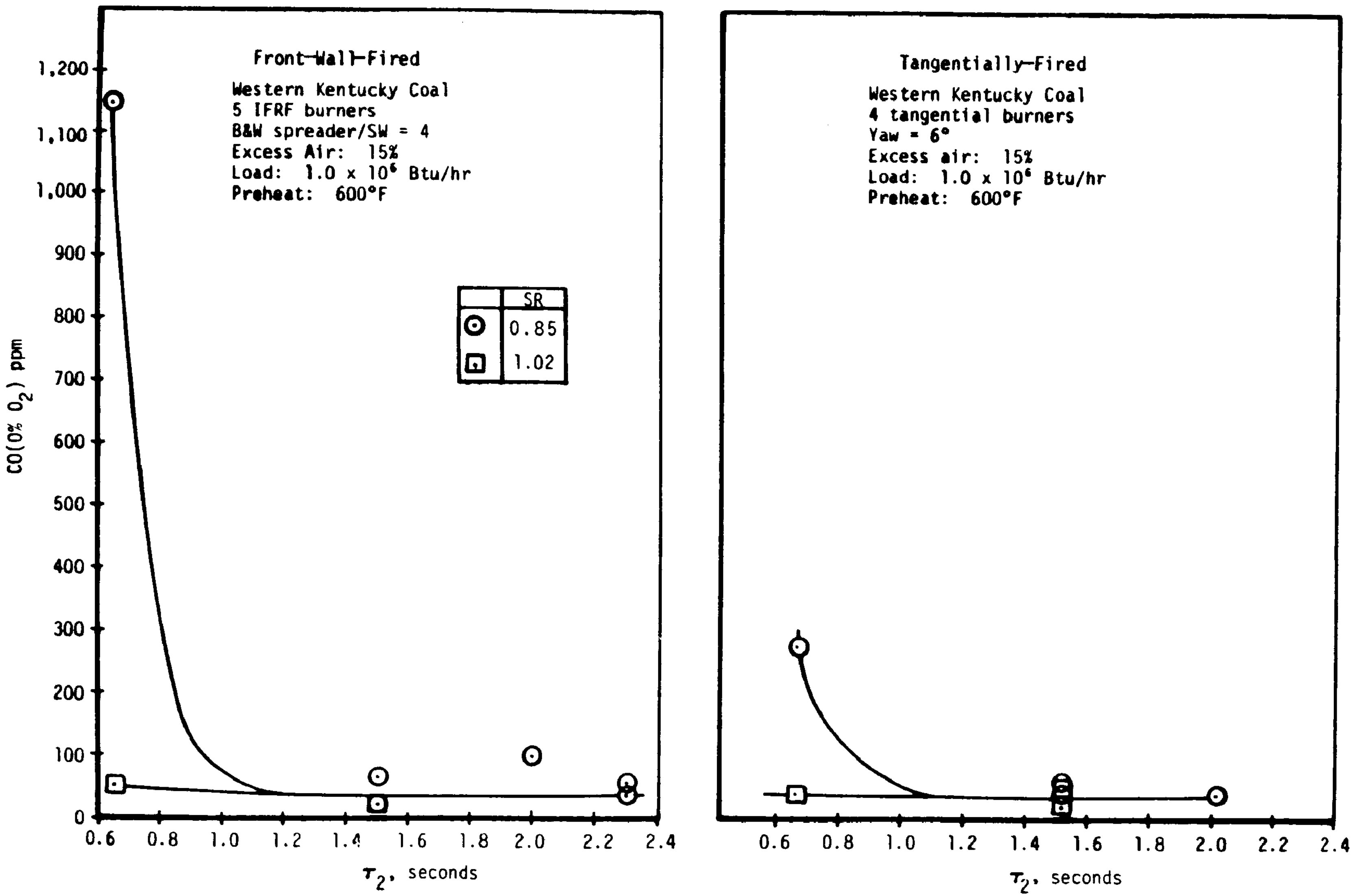
1^{ST} STAGE

- NO MAJOR EFFECT

2^{ND} STAGE

- FOR SR $<$ 0.95 CO LEVELS INCREASED DRAMATICALLY AT $RT_2 < 1.0$ SEC
- FOR SR $>$ 0.95 NO EFFECT ON CO LEVELS AT ANY RT TESTED
- AT RT $>$ 1.0 NO EFFECT ON CO LEVELS
- SIMILAR RESULTS FOR FWF AND T.F.

EFFECT OF SECOND-STAGE RESIDENCE TIME

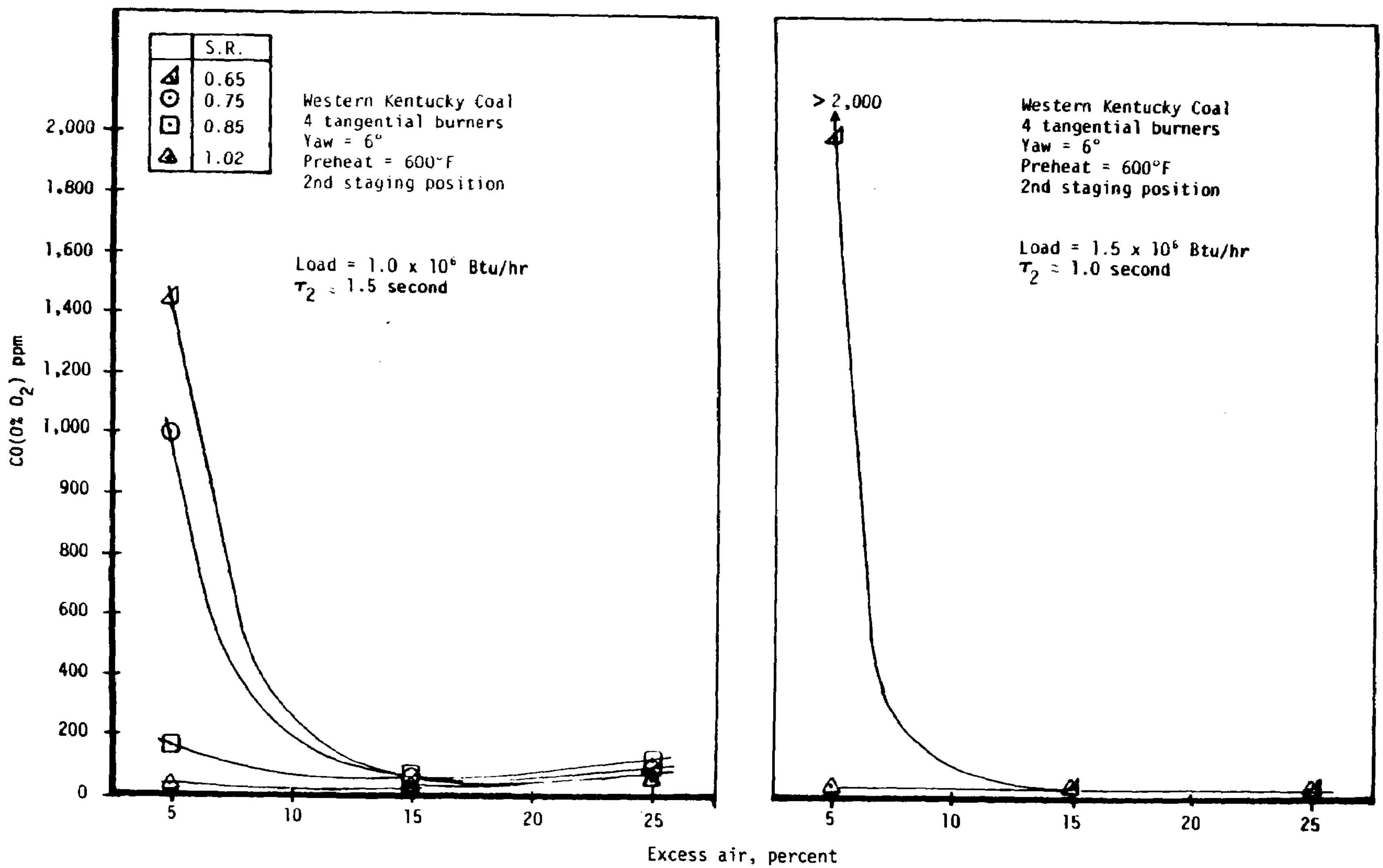


CO CONCLUSIONS

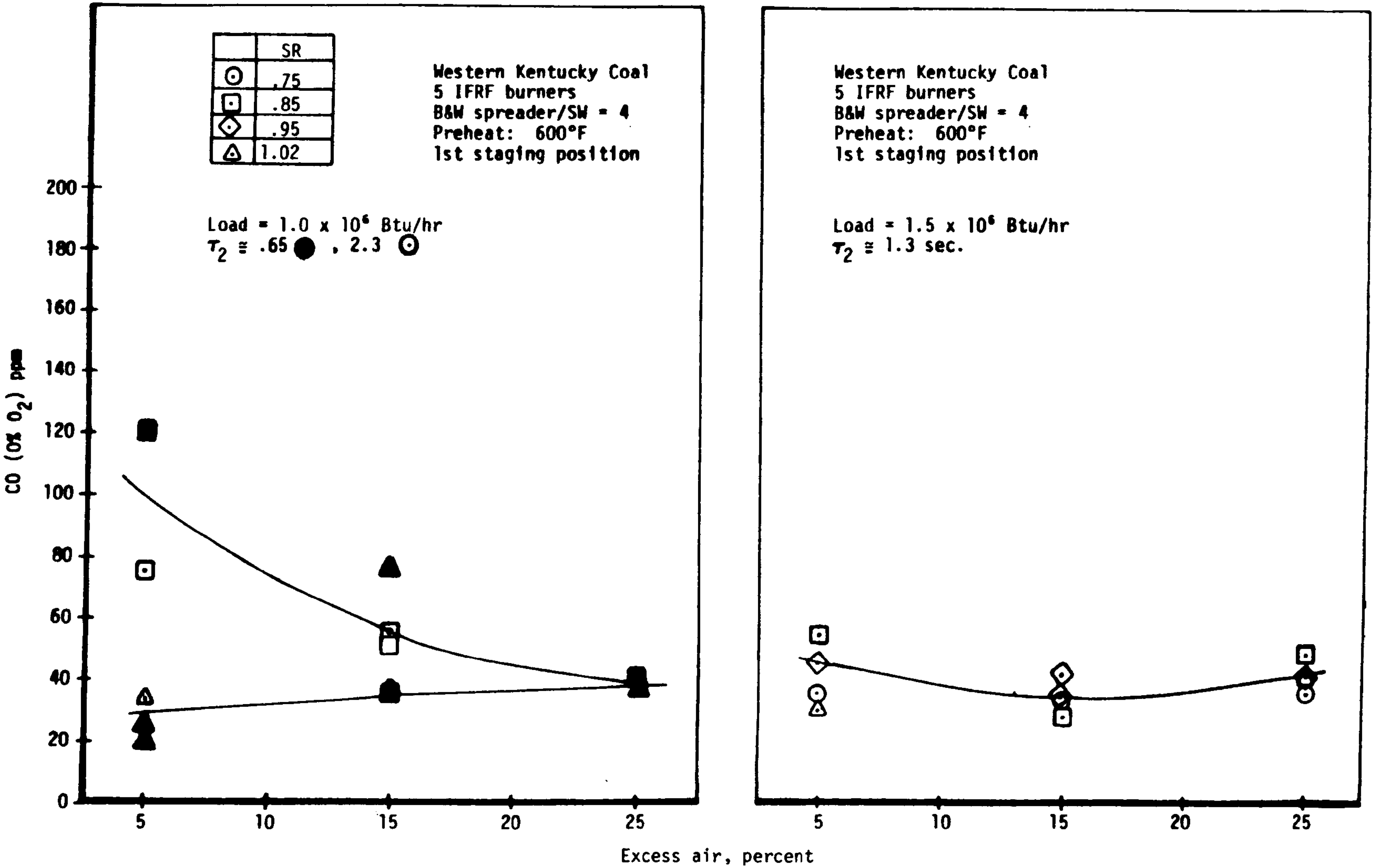
STOICHIOMETRY – 2ND STAGE

- CO DECREASES WITH INCREASING EXCESS AIR
- TANGENTIALLY-FIRED PRODUCES GREATER CO AT EA = 5%
- CO $<$ 100 PPM ACHIEVED AT EA $>$ 5%, $RT_2 > 1$ SEC

EFFECT OF EXCESS AIR: TANGENTIALLY-FIRED



EFFECT OF EXCESS AIR: WALL-FIRED



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16. ABSTRACT The report gives results of an investigation of advanced NOx control techniques on a pilot scale test facility firing pulverized coal. The 440 kW pilot scale test facility can simulate front wall, opposed, or tangentially fired utility and industrial boilers. Baseline and control technology tests were performed on three coal types over a range of parameters. Baseline NO levels closely simulated full scale results in both levels and trends over these parameters. The primary control technology investigated was staging. First- and second-stage parameters investigated include stoichiometry, excess air, temperature, mixing, residence time, and coal composition. The most important first-stage parameters were stoichiometry and residence time. A minimum NO level was achieved at a stoichiometric ratio between 0.75 and 0.85, depending on fuel and furnace configuration. The first-stage residence time was also found to be critical: the longer first-stage residence times gave lower stack NO levels. To obtain NO levels below 150 ppm, first-stage residence times of up to 3 seconds were required. Second-stage parameters were found to be of second-order importance.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Nitrogen Oxides	Stationary Sources	07B
Combustion Control	Staged Combustion	21B
Coal	Tangentially Fired	21D
Boilers	Wall Fired	13A

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