# INVESTIGATION OF FIRST- AND SECOND-STAGE VARIABLES ON CONTROL OF $NO_x$ EMISSIONS USING STAGED COMBUSTION IN A PULVERIZED COAL WALL-FIRED FURNACE

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**Recent tests on an EPA 1- to 1.5 × $10^6$ Btu/hr pilot-scale pulverized coal furnace show that $NO_x$ emissions of 100 ppm to 150 ppm (zero percent $O_2$) are achievable with the use of two-stage combustion. Comparable $NO_x$ emission levels were obtained with three different coal types fired in either the single-wall or tangential configuration. On the basis of these tests, the combustion conditions leading to *minimum* $NO_x$ appear to be (1) operation of the primary flame zone at 75% to 95% of stoichiometric air, (2) complete separation of stage air from the first stage, (3) first-stage mean residence time of 3 sec. to 5 sec., (4) high first-stage volumetric heat release rate and/or high first-stage combustion air preheat. Additionally, the minimum $NO_x$ condition was achieved using the same burners as were used in uncontrolled operation to simulate full-scale equipment.**

**Tests to date have explored the effects of first- and second-stage combustion conditions on $NO_x$ production with three types of coal fired in a 5-burner single-wall configuration and a 4-burner tangential configuration. First-stage conditions varied, including stoichiometry, residence time to injection of stage air, volumetric heat release rate, combustion air preheat, and fuel/air mixing (swirl, injector design). Second-stage variables were residence time to the convective section, stage air preheat, and stage air injector design. Initially, the furnace was operated in the baseline, uncontrolled condition to compare emissions to full-scale equipment. Good simulation of both the level of $NO_x$ emissions and the variation of emissions with excess air was demonstrated for both the wall-fired and the tangentially-fired configurations.**

**The first-stage stoichiometry was the most significant variable in $NO_x$ reduction. Emissions of 100 ppm to 150 ppm (zero percent $O_2$) were achieved at a first-stage stoichiometric ratio of 0.8. This corresponds to about an 85% reduction for the wall-fired configuration and an 80% reduction for the tangential configuration. Below 0.8, the $NO_x$ levels were higher, presumably due to increased second-stage NO formation. At the 0.8 minimum $NO_x$ condition, the emissions were relatively insensitive to first-stage mixing; that is, similar emissions were achieved for both the wall-fired and tangentially fired configurations using several different burner settings and/or injector designs. Operation at a stoichiometric ratio of 0.9 or higher, however, showed a strong effect of first-stage mixing. Here, the lowest $NO_x$ was seen for tangential firing and for wall firing with the use of a slow-mix axial injector. These results suggest that combined burner modification and staged combustion will yield the best $NO_x$ reduction if operation below a stoichiometric ratio of 0.9 is precluded by operational constraints. In general, increasing the first-stage**

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**residence time decreased $NO_x$ emissions. Also, for a fixed residence time, increasing the volumetric heat release rate or the combustion air preheat decreased $NO_x$ at the low stoichiometric ratios.**

**The only second-stage variable significantly affecting the minimum $NO_x$ emission was the stage air injector design. Here, it was found that leakage of stage air back into the first stage increased $NO_x$ over the levels attained with complete separation. These results suggest that the dramatic $NO_x$ reduction achieved with the facility are in large part due to the isolation of the stage air from the first stage. The second-stage residence time had little effect on $NO_x$, but did affect CO emissions. Operation at a residence time of 1.0 sec. or larger and rapid mixing of stage air with the combustion products generally yielded CO emissions of 100 ppm or lower.**

## INTRODUCTION

Utility and industrial boilers are the two largest stationary emitters of $NO_x$. Together they comprised about 65% of nationwide stationary $NO_x$ emissions for the year 1974 (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 to attain and maintain the National Ambient Air Quality Standard for $NO_2$ (100 mg/m$^3$). 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 250 MM Btu/hr (2). The standard for bituminous coal units (0.7 lb. $NO_2/10^6$ Btu, ~580 ppm at zero percent $O_2$) is being revised to 0.6 lb. $NO_2/10^6$ Btu, ~500 ppm, to reflect advances in control technology (3). The same standard has been recommended for lignite-fired units (4). Standards for new industrial boilers are in preparation by EPA's Office of Air Quality Planning and Standards. Additionally, emission standards for new or existing utility and large scale boilers have been set as part of State Implementation Plans to maintain air quality in $NO_2$-critical regions (5).

Despite this concerted regulatory activity, a number of air quality planning studies (6,7, 8,9) 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 have also concluded that, where possible, the additional technology should focus on application to advanced design of new equipment. In response to the need for additional technology, the EPA is developing and demonstrating advanced controls for utility and industrial boilers and other sources (10,11). The near-term emphasis is on use of major hardware modifications for new or existing sources. The far-term emphasis is on major redesign of new sources. The parts per million 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 (10,11):

|  | 1980 goal | 1985 goal |
|---|---|---|
| Utility | 230 | 115 |
| Industrial | 175 | 115 |

The R&D program discussed in this paper is a component in the effort to generate advanced $NO_x$ controls for utility and industrial boilers firing conventional and alternate fuels (12). To date, the testing has concentrated on utility boiler configurations. The overall goal of these tests is to identify low-$NO_x$ operating conditions for the staged combustion of pulverized coal. The results of the program are intended to support both the near-term and far-term efforts mentioned above. To support the near-term application of major hardware

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modifications on units of conventional design, the test facility was designed with a fairly realistic modeling of the geometry and aerodynamics of large multi-burner boilers. This modeling will aid 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 the combustion process modifications important in $NO_x$ control. This flexibility offers the capability of identifying combined low-$NO_x$ process modifications which are beyond the range of field units of conventional design but which may relate to advanced design.

The combustion process modifications investigated in the current test program are as follows:

- Baseline (uncontrolled) burner aerodynamics and wall cooling
- Primary flame zone stoichiometry
- First-stage mixing
- Method of stage air injection
- First-stage residence time
- Second-stage residence time
- First-stage heat release rate and combustion air preheat

## Baseline Conditions

Combustion-generated $NO_x$ is due either to thermal fixation of molecular nitrogen in the combustion air (thermal $NO_x$) or to oxidation of chemically bound nitrogen in the fuel (fuel $NO_x$). Thermal $NO_x$ may account for only around 20% of total $NO_x$ in combustion of high-nitrogen fuels at normal levels of excess air (13,14,15). Thermal $NO_x$ formation is controlled by local fuel/air mixing rates as well as by the local and bulk temperatures. Fuel $NO_x$ emissions with coal at normal levels of excess air result from conversion of only about 20% to 40% of the bound nitrogen (15,16) with the remainder of fuel N presumably reduced to $N_2$. The rate of conversion of fuel N to $NO_x$ at the baseline is controlled by local fuel/air mixing. Temperature appears to have little direct effect on fuel N conversion (13,15,17) although temperature may affect fuel $NO_x$ indirectly by modifying the mixing. Since $NO_x$ emissions from coal combustion are highly sensitive to the combustion conditions, the relevance to practical equipment of the low-$NO_x$ conditions identified in the facility is reinforced by establishing that the pilot-scale baseline emissions simulate results of field tests on full-scale equipment.

The first objectives of the present test series were, therefore, to establish a baseline operation representative of full-scale equipment. This was partially accomplished by the facility design, which includes a volumetric heat release rate and residence time to the convective section the same as full-scale equipment. Additionally, wall-fired and tangential burners were basically scaled-down versions of utility-sized burners. The baseline series of tests consisted of varying the burner settings and the degree of wall cooling to identify the conditions which best represented baseline emission levels and trends with excess air as well as corresponding to conventional utility practice for fuel/air velocities, primary stoichiometry, air preheat, and so on.

## Stoichiometry

Control of $NO_x$ by staged fuel combustion has been widely tested since its initial development in the late 1950s (18). Operation with a near- or substoichiometric first stage effectively suppresses both thermal and fuel $NO_x$ formation. Most tests at near-stoichiometric conditions show a continuing decrease in $NO_x$ emissions as first-stage stoichiometry is reduced. The degree of $NO_x$ control achieved by increasingly fuel-rich stoichiometry may be limited, however, by both practical and theoretical considerations. First, from a practical standpoint there is concern that operations of conventional design boilers at a first-stage stoichiometric ratio (SR) below about 0.95 may yield unacceptable rates of waterwall corrosion. One objective of the present program was therefore to identify low-$NO_x$ conditions for SR $\gtrsim$ 0.95 for potential application to conventional design boilers. Lower SR may be acceptable for new unit redesign, however, 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. Numerous studies have shown that reduced first-stage SR reduces the conversion of fuel N to NO. However, part of the fuel N remains in an intermediary form, primarily HCN, which largely oxidizes to NO in the second stage (19,20,21). Additionally, under fuel-rich conditions, hydrocarbon combustion, even in the absence of fuel N, yields bound intermediaries from molecular nitrogen (20,22, 23).

Sarofim has shown that the equilibrium concentration of these bound nitrogen intermediaries in fuel-rich combustion reaches a minimum at an SR dependent on temperature and fuel and increases as the SR is further reduced (23). Although the equilibrium concentration is low (<100 ppm) at normal coal combustion temperatures, the oxidation of these 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 (21,24). Pershing and Wendt (24) have estimated that 100 ppm 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 limit the effectiveness of staged combustion for $NO_x$ control. In view of these concerns, part of the test program was directed at identifying if a minimum $NO_x$ condition exists at low SR and, if so, how the minimum is affected by first- and second-stage combustion conditions. The combustion conditions which may affect the minimum $NO_x$ conditions are discussed further below.

## Mixing

The $NO_x$ emissions from unstaged combustion and from staged combustion at near-stoichiometric and above are dominated by burner mixing (13,14,25,26). Detailed study of $NO_x$ control by burner modification is beyond the scope of this program and is covered elsewhere (27). 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 (26,28). Thus the study of low-$NO_x$ conditions for application to conventional designs considered both the front-wall-fired and corner-fired configuration with conventional burner designs. Additionally, front-wall tests were run with a delayed mix axial injection to bracket effects of high and low rate of mixing with staging. Second, fundamental considerations indicate that burner mixing may be less significant at the low SR potentially achievable with major redesign. As noted above, it is suspected that $NO_x$ emissions at low SR are limited by the chemistry of bound N intermediaries and by the oxidation of char N. From available data and calculations, it is conceivable that under fuel-rich conditions, these limits are controlled more by the overall kinetic and equilibrium condition (bulk temperature, residence time, fuel composition, stoichiometry) than by the macroscopic mixing. Thus the tests to identify the minimum achievable $NO_x$ condition for these facilities considered evaluation of burner mixing.

## 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 on $NO_x$ of first-stage stoichiometry, residence time, and local fuel/air mixing. Limited results have shown that directing stage air away from the primary flame zone has a substantial effect on $NO_x$ reduction (28,29). These results have motivated the design of the present facility to allow for nearly total separation of the stage air from the first stage. To illustrate the effect of the stage separation, tests were run with biased burner firing using the same primary 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.

## First-Stage Residence Time

Conventional applications of staged combustion inject the staged air directly over the primary flow with a resulting first-stage residence time of less than 1 sec. 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 (20,28, 29,30,32). This is consistent with fundamentals since increased residence at fuel-rich conditions should promote the reducing reactions involving bound nitrogen intermediaries and should also promote the driving off of the char-bound nitrogen prior to oxidation in the second stage. At very rich conditions, however, there could conceivably be compensating effects due to increased formation of bound nitrogen from molecular nitrogen. To explore these effects, the facility design and test plan provided for variations of first-stage residence time independent of load, stoichiometry, and second-stage residence time.

### Second-Stage Residence Time

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 (28,29,30,31,32). One objective of the present program associated with the identification of the best combined low-$NO_x$ operating conditions is the identification of the second-stage residence time required for CO and carbon burnout. This requirement impacts the feasibility of the present results for application to both conventional designs and advanced redesigns. The test plan thus provided for variation of second-stage residence time independent of the first-stage conditions. This test series also evaluated the effect of total excess air on second-stage requirements since minimal excess air is preferred for maximum efficiency, provided CO and carbon burnout is achieved.

### Load and Preheat

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 (3). Under fuel-rich conditions, however, opposite effects may prevail. The work of Sarofim et al. (16,21,23) 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 super equilibrium concentrations of bound N intermediaries in the first stage and thus reduce the conversion to NO in the second stage. Second, high first-stage temperature can reduce the amount of nitrogen carried into the second stage in the char. The present test program includes variation of heat release rate (independent of residence time) and preheat to explore the consequences of the above mechanisms under fuel-rich conditions.

In summary of the above discussion, the objectives of the test program discussed in this paper are to

- verify that baseline $NO_x$ emissions and trends with excess air are representative of full scale equipment
- identify the best combination of low-$NO_x$ combustion conditions for
  - application to conventional designs (SR $\geq$0.95)
  - application to major redesign (SR <0.95)
- identify second-stage residence time requirements to achieve CO and carbon burnout at the low-$NO_x$ conditions.

## DESCRIPTION OF EQUIPMENT

The experimental facility shown in Figure 1 was designed to simulate the aerodynamics of either a front-wall-fired or a tangentially fired boiler. The basic firebox is a 39-in. refractory-lined cube which exits to a refractory-lined heat exchange section. The firebox is lined with 13 in. of 3200°F dense castable refractory backed up by 2 in. of block insulation. Movable heat exchange drawers allow the variation of the combustion gas quench rate, the furnace residence time, or the combustion volume. The primary emphasis in the design of the hardware was to be able to explore staged combustion for $NO_x$ control. Staging ports are provided in each of the heat exchange sections allowing a variety of first- and second-stage residence times to be explored. The furnace exhibits the typical heat release per unit volume of coal-fired furnaces at about 1.0 x $10^6$ Btu/hr to 1.5 x $10^6$ Btu/hr. This firing rate is distributed between 5 burners for the front-wall-fired configuration and 4 corner burners for the tangential configuration. Numerous observation ports are provided in the firebox for flame observation. Combustion air is provided by a 9-lb./sq. in. centrifugal compressor. Preheat temperatures up to 800°F are achieved with an electrical heater. Each burner has individual air flow control valves and measurement orifices. Prepulverized, bagged coal (70% through 200 mesh) is delivered to the burners from a fluidized bed feed system. Again individual control of fuel flow and primary air (transport air) to each burner is possible. The furnace was operated under positive pressure at all times.

### Burners — IFRF

One of the Aerotherm/IFRF burners used in the front-wall-fired configuration is shown in Figure 2. This is an adjustable swirl-block-type burner patterned after one developed at the IFRF (International Flame Research Foundation). The burner allows external variations of secondary air swirl and axial adjustment of the center fuel tube. These burners were fitted with a 30-degree water-cooled quarl with L/D ratio of 0.4. This burner also has the capability of interchangeable quarls and alternate throat sleeves to vary the air velocity.

Two fuel injector types were utilized with the burner. The B&W-type spreader is illustrated in Figure 3. This is patterned after the design used in many commercial burners producing a short, well-mixed bulbous flame. The second type is the open end of the fuel tube, or a single round hole producing a long, slowly mixed axial flame. The corner-fired burner design is illustrated in Figure 4. The corner burners are patterned after the Combustion Engineering burners in the Barry Station of the Alabama Power Company. The relative distribution of the combustion air between the three ports and the exit velocities was kept close to the full-scale design. Natural gas is introduced through the upper and lower fuel nozzles for light-off purposes. Coal was introduced through the center inner port, and annular air, representing 20% of the secondary air, surrounds this coal jet. The air and fuel jets were fabricated in a circular configuration to allow for sleeving to change the air velocity or local mixing. All of the tests in this series were made with no swirl applied to either the air or the fuel streams. The burners also have the capability of ±10° yaw and ±30° tilt. Normal firing was at +6° yaw and 0° tilt.

### Analytical System

The sampling and analysis system allowed for continuous monitoring of NO, CO, $CO_2$, $O_2$, and U/HC using the instruments listed in Table 1. A schematic of the sampling system is shown in Figure 5. The flue gas was withdrawn from the stack through a 3/8 in. I.D. stainless steel probe. Comparisons were made with a water-cooled stainless steel and Teflon-coated probe. No difference in the measured NO was noted even with CO and unburned carbon present. It should be noted, however, that the flue gas had cooled to below 600°F at the point of sampling and there was always at least 0.5% $O_2$ present in the sample.

TABLE 1. ANALYTICAL POLLUTANT EQUIPMENT

NO — Intertech Model 32C Chemiluminescence analyzer

$O_2$ — Intertech Model Mangnos 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

Sample conditioning prior to the instruments consisted of a heated stack filter to take out the bulk of the fly ash, a heated Teflon sample line (250°) to a series of heated paper filters, a 3-pass refrigerant dryer (water condenser), additional cold filters, and stainless sampling pumps.

Particulate samples were taken downstream of the gaseous sampling port but upstream of the baghouse by an Aerotherm-EPA Method 5 train. Analysis of combustibles was then made on the material collected in the cyclones and a percent carbon loss calculated.

### Second-Stage Air System

A number of cold flow studies using $TiO_2$ smoke were made to assess second-stage mixing techniques. It was found that the four 1-in.-diameter opposed-jet ports in the heat exchange section produced very rapid mixing with a minimum of backmixing into the first stage. The various stage air locations referred to in the following text are shown in Figure 6.

## EXPERIMENTAL RESULTS

The results of the staging test program are presented in the following order of test variables:

- stoichiometry
- mixing
- coal composition
- load
- residence time
- temperature

For each of these test variables, both the first- and second-stage effects are discussed for both the front-wall-fired and the tangential configurations. Several definitions need to be emphasized before discussing the data. These are:

| | |
|---|---|
| Primary air | — air used to convey the coal to the burner, expressed as a percent of total at 15% excess air |
| Secondary air | — air introduced through the burners into the first stage exclusive of the primary air |
| First-stage air | — secondary + primary air |
| Stage air | — air introduced into the second stage |
| Total air | — primary + secondary + stage |
| Stoichiometric air | — $\frac{\text{first-stage air}}{\text{stoichiometric air}} = SR$ |
| Residence time | — mean volumetric residence time of the mass flow using a measured temperature to calculate an average density |

Stoichiometry

Baseline NO emissions were determined for the 5 front-wall-fired IFRF burners using the B&W-type coal spreader and for the 4 tangentially fired burners. The results are compared in Figure 7 with the pilot-scale tests of Armento (33), McCann et al. (29), and Pershing and Wendt (24) and with the full-scale tests of Crawford et al. (26) and Selker (28). Both the front-wall-fired and the tangential emissions data compare quite well in overall level and trend with the respective field data. The tangential plot also shows the baseline data for the axial injector in the 5 front wall burners. Although the axial emissions fall slightly below the results with the tangential burner, they are within the range of tangential field data.

The baseline tests discussed above were taken with refractory walls with only natural conductive losses. A number of tests were performed to determine if additional wall cooling would be necessary. However, the baseline emissions for the front-wall-fired data did not change more than about 7% with 300,000 Btu/hr of additional cooling. This adds further evidence (24) to the role of fuel nitrogen as the predominant source of $NO_x$ in coal front-wall-fired burners and the relative insensitivity of fuel $NO_x$ formation to temperature.

Staging tests were performed with the stage air introduced into a number of positions in the heat exchange tower while the first-stage stoichiometric ratio was varied. The NO vs. the first-stage stoichiometric ratio (SR) is shown for both the front-wall-fired and tangential configuration in Figure 8 for the second staging position shown in Figure 6. The effects of the staging position, i.e., first-stage residence time, will be discussed later. As seen from the curve, NO is a strong function of the first-stage stoichiometric ratio. For the front-wall-fired configuration, a 52% reduction in NO was achieved at a stoichiometric first stage and at an overall excess air of 15%. A minimum NO level of 160 ppm was achieved (82% reduction) at an SR of 0.80 to 0.85.

For the tangential case, a 31% reduction was achieved at a stoichiometric first stage and a minimum of 125 ppm (71% reduction) at an SR of 0.85. Further reduction in SR showed a corresponding rise in NO for both configurations at this staging position. The reduction in NO is no doubt attributable to the decreased availability of oxygen in the first stage. The increase below a stoichiometric ratio of 0.85 is probably due to generation of second-stage NO by the mechanisms discussed in the Introduction. At this point, however, other mechanisms, such as an increase in NO coming from the first stage, cannot be ruled out.

The speculation is that, above an SR of about 0.85, most if not all NO is generated in the first stage. Below an SR of 0.85, NO very likely decreases in the first stage with decreasing SR. Armento (33) suggests that first-stage NO decreases to zero at a first-stage equivalence ratio of about 0.65. Figure 8 then suggests that an increasing amount of second-stage NO is somewhat temperature dependent; that is, it was observed that as additional heat was input into the second stage, the NO increased as this section of the firebox came to a new equilibrium.

The difference in the minimum achieved between the two firing configurations is believed to be attributable to bulk residence time effects as opposed to localized burner mixing. This will be further discussed in the sections on mixing and residence time. Tests were also conducted to determine the effect of second-stage stoichiometry on the overall NO levels. Figure 9 shows several typical curves of NO vs. overall excess air at various stoichiometric ratios. As seen here, the overall NO does not seem to be a strong function of excess air under staged conditions. Similar results were obtained for the front-wall-fired configuration, for other loads, coals, and staging positions. The only significant effect is noted at SR = 0.65 between 15% and 5% excess air. At this SR, the NO decreased by 50 ppm at the lower excess air level. Excess air had a significant effect on CO and carbon loss if the second-stage residence time was less than 1 sec. In this case, 20% to 25% 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 sec., the CO was always under 100 ppm and carbon loss was less than 0.5% of fuel input on a Btu basis.

In summary, NO levels as low as 125 ppm can be achieved with the first-stage stoichiometry not less than SR = 0.80 and an overall excess air of at least 15% to achieve CO and carbon burnout. No significant effect of excess air was seen on NO emissions for most first-stage stoichiometries.

### Mixing

A number of first- and second-stage mixing techniques have been investigated to determine their influence in staged combustion. Increasing secondary air swirl slightly increased NO at all first-stage stoichiometric ratios. Increased primary air also increased NO at most stoichiometries but with the effect less sensitive at low SRs. The most predominant effects of first-stage mixing can be seen by comparing the results of the spreader nozzle to the results of the axial nozzle in the front-wall-fired configuration and to the tangential data. First, the differences under baseline conditions can be seen by comparing the spreader data to the tangential and axial data shown in Figure 7. Both the axial and tangential configurations produce long axial flames representing delayed mixing conditions. A rather dramatic effect is seen under baseline conditions with the slow-mixed flames producing only about 55% of the NO of the well-mixed spreader flames.

A comparison of mixing under staged conditions is seen in Figure 10 for the front-wall-fired spreader and axial configurations at 1.0- and 1.5 x $10^6$ Btu/hr load. The influence of first-stage mixing can be seen even under staged conditions where decreased mixing in the first stage produced lower NO for a given stoichiometric ratio, at an SR of 0.85 or greater. This result is attributable to the axial flames' having a greater percentage of fuel-rich regions in the flame zone. This comparison is made at the first staging position where data for the axial and spreader mixing conditions were taken. The front-wall-fired staging data under these conditions reached an asymptote of about 200 ppm to 250 ppm NO. No minimum was observed. This asymptotic effect, not seen in Figure 8 for the second staging position, is believed to be attributable to backmixing of staged air into the first stage for the front-wall-fired configuration.

Similarly, the higher load condition where more rapid mixing occurs also produced higher NO than the 1.0 x $10^6$ Btu/hr condition over the entire stoichiometric ratio range. However, both temperature and mixing contribute to this increased NO. Again, it should be noted that the role of first-stage mixing decreases as the stoichiometric ratio decreases. It appears that below an SR = 0.75 (0.85 for 1.0 x $10^6$ Btu/hr) mixing ceases to have any influence.

Mixing in the second stage was also investigated and the results are shown in Figure 11. Three mixing types were explored — fast, slow, and down mixing (backmixing). The fast mixing condition uses the normal four 1-in.-diameter ports in which the opposing jets meet at the center of the duct under all conditions. The slow mixing case utilized eight 2-in.-diameter ports located in two vacant heat exchanger drawer windows as close to the first staging position as possible. This arrangement resulted in much lower jet velocities. Cold flow smoke studies showed that, if the staged air was introduced from one side only, the jets would impinge on the opposite wall and backmix considerably into the first stage. Therefore, this technique was used to purposely achieve backmixing.

Figure 11 shows that, at a stoichiometric ratio of 0.85, there was virtually no effect of the three second-stage mixing conditions. However, at an equivalence 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 into the first stage. It can be seen that a similar result was obtained for the purposely backmixed condition. It should also be noted that NO is more sensitive to slight changes in the first-stage stoichiometric ratio at an

SR = 1.02. 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. This effect can also be seen from the biased-fired data point also shown in Figure 11. This case represents the extreme in backmixing where the lower three burners were operated at an SR = 0.85, with the excess air delivered through the upper burners. 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 ppm to 500 ppm CO and 1% to 2% carbon loss).

In summary, then, the effect of first-stage mixing decreases as the first-stage stoichiometry is reduced. There is little difference between the spreader and axial injectors at low first-stage stoichiometries.

Second-stage mixing had virtually no effect on NO except as it influenced backmixing into the first stage. Rapid mixing is desirable, however, for CO and carbon burnout. It is felt that the lower values of NO obtained in these tests at any given first-stage equivalence as compared to Armento (<u>33</u>) or McCann et al. (<u>29</u>) are due to the second-stage air injection technique; that is, in those experiments, the injection technique very likely resulted in considerable mixing into the first stage and/or shorter first-stage residence time. Thus, in order to obtain the lowest possible NO for any given first-stage equivalence ratio, it is imperative that a high degree of stage separation be achieved.

<u>Coal Composition</u>

Three different coals were tested to determine the effect, if any, of coal composition on NO emissions for baseline and staged conditions. Table 2 lists the principal properties and nitrogen content and the rationale behind selection of each of these coals. Although the ultimate analyses are quite similar (except for the Montana coal with a water content of 21%), the chemical and physical properties affecting combustion are significantly different. For example, the Pittsburgh coal is a caking coal; many of the particles melt upon heating and a fused carbonaceous residue and ash form cenospheres during combustion. As a result, more difficulty was experienced with ash built up on the fuel nozzle when burning the Pittsburgh coal.

TABLE 2. PULVERIZED COAL COMPOSITIONS

| | Pitts.[a] #8 | West.[b] Ky. | Montana-Powder[c] 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:

a. 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

b. 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

c. Current local importance; future national significance

Typical Western subbituminous in abundant supply

In spite of these differences, the baseline NO emissions for the three coals are not radically different as seen in Figure 12. Emissions with the Montana coal tend to be slightly higher for both the front-wall-fired spreader and the tangential configurations.

The effect of coal composition on NO under staged conditions is shown in Figure 13 for the front-wall-fired and tangential configurations. 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 condition the NO emissions with the Pittsburgh coal did not increase with decreasing equivalence ratio to the same extent as did those from the Western Kentucky coal. The NO from the Montana coal reaches a lower minimum and does not exhibit as much second-stage NO as the Pittsburgh coal below an 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 front-wall-fired configuration at 1.0 x $10^6$ Btu/hr shows a trend similar to the tangential data. However, for the front-wall-fired configuration the NO levels of the Western Kentucky and the Pittsburgh No. 8 coals differed at stoichiometric ratios of 1.0 to 0.85. On the other hand, at a firing rate of 1.5 x $10^6$ Btu/hr, no appreciable difference was observed between the NO levels of these two coals. It is possible that the difference in the 1.0 x $10^6$ 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 No. 8 firing. The trend of the NO data for the Montana coal was consistent for all configurations and firing rates; that is, for the Montana coal the NO levels were higher at baseline conditions and SRs greater than 0.80 to 0.85 but NO achieved a lower minimum at an SR <0.85.

It appears then that the combustion of Western Kentucky and Pittsburgh No. 8 coals yields quite similar results. The Montana coal acts differently under both baseline and staged conditions.

### Load

The effect of load on NO emissions for front wall and tangential firing is shown in Figure 14 for baseline conditions. The trend with excess air is similar but the higher load yields a 25% increase for front wall firing and a 40% increase for tangential firing. This increase is attributable to both aerodynamic effects and temperature. The high-load firing produced more intense, sharply defined flames for both tangential and wall firing.

The differences in load under staged conditions are seen in Figure 15. High-load firing yielded lower $NO_x$ below SR = 0.75. As discussed in the Introduction, NO formation is believed in this region to become kinetically controlled so that one of two mechanisms is occurring:

- Either the higher temperature associated with the higher load accelerates a reduction reaction with the bound N intermediaries, and/or
- The char-bound nitrogen is driven out by the higher temperature and goes either to $N_2$ or to an intermediary that eventually goes to $N_2$ in the fuel-rich first stage.

There was further evidence for these mechanisms whem residence and temperature were varied as discussed below.

### Residence Time

Tests were conducted at three stage air injection positions (see Figure 6 for locations) and two loads, 1.0- and 1.5 x $10^6$ Btu/hr. The 1.5 x $10^6$ Btu/hr load could not be used with the maximum staging position due to insufficient heat exchange surface following the stage air injection.

The variation of NO with residence time is shown in Figures 16 and 17 at various first-stage stoichiometric ratios for the front-wall- and tangentially fired configurations, respectively. The data implies several things:

- At SR $\leq$ 0.95 the NO decreases with increasing residence time.
- At a low stoichiometric ratio (0.85), an increase in combustion intensity may be traded for longer residence times (this will be further substantiated in the sections on temperature).
- NO levels below those shown in the current experiments may be achievable at longer residence times, particularly at high load, than are feasible with the current configuration.
- The lower NO exhibited by tangential firing at low stoichiometry may be due to a longer bulk residence time compared to wall firing. If the tangential data at SR = 0.85 were shifted by an increase in residence time of

0.9 sec. the tangential and front-wall-fired data would coincide. The rationale behind this is that the burner is located physically lower in the firebox and the tangential rotation may result in an effective longer residence time. (The residence times here are volumetric residence times determined by the mass flow rate and flue gas density calculated at an average temperature of 2200°F assuming a well-stirred reaction over the furnace volume.)

If mixing does not influence the NO to any great extent at an equivalence ratio of 0.85 and if the first stage acts as a well-stirred reactor, then only sufficient residence time must be provided for NO decay. This further implies that a kinetically controlled regime has been reached. Additional NO reductions can be achieved by increasing residence time and temperature prior to the addition of stage air.

The effect of second-stage residence time was explored by keeping the stage air location constant and moving the heat exchange surface. Figure 18 shows the effect of second-stage residence time as a function of equivalence ratio and second-stage mixing technique. As can be seen, no effect was observed, indicating either that for these equivalence ratios no second-stage NO is being formed or that it is formed very rapidly.

### Temperature

The effect of first-stage temperature was investigated by varying the secondary air preheat from ambient to 800°F. Figure 19 shows that at baseline condition there is an about 150 ppm to 160 ppm difference between high preheat and no preheat for both the tangential and front-wall-fired configurations. This no doubt represents a good portion of the thermal NO. As the first-stage equivalence ratio is decreased, the difference between the two curves decreases until crossover is achieved at about an SR = 0.92. Both the front-wall- and tangentially fired data show a lower NO level below an equivalence ratio of 0.9 for the higher temperature condition. However, care must be exercised in concluding that below this equivalence ratio the overall NO is lower for higher first-stage temperature. It is believed that below an equivalence ratio of 0.9 there is an increasing amount of second-stage NO being formed which is temperature dependent. Figure 20 shows an example of this temperature dependence. Therefore, the total NO is a combination of the NO coming from the first stage and that generated in the second stage. If the second-stage temperature is sufficiently high then it may offset the decrease coming from the first stage. An example of this is seen in Figure 21 for a similar test at the second staging position. In this case, the overall NO is lower over the whole equivalence ratio range.

## DISCUSSION AND PRACTICAL IMPLICATIONS

A summary of the major findings of this work is presented in Table 3. The results are categorized into moderate staging and a low-stoichiometric first stage. An indication is given for each test parameter as to whether it has a major, moderate, or minor effect on NO and the preferred value or direction for that parameter.

The question may be asked, How might this information be used to design a new boiler or retrofit an existing one? First, let's consider new design, where we have the freedom to make extensive modifications (excluding cost factors at this point).

First, it appears that, if materials could be found to survive in a reducing, sulfur-laden, high-temperature atmosphere (coal gasification studies indicate this is feasible), a first-stage stoichiometric ratio of 0.75 to 0.85 should be selected. It should not matter too much how coal and air are mixed in the first stage. However, either high preheat (>600°F) or high combustion intensity should be selected (say, greater than 20,000 Btu/hr-cu.ft.). The first stage should last for as long as is practically possible but probably for at least 3.5 sec. Just prior to addition of the stage air, sufficient heat should be extracted to lower the temperature to 1700°F. Stage air should then be added and mixed thoroughly with the fuel-rich flue gas. However, extra care must be taken to ensure that backmixing does not occur into the early parts of the first stage. Sufficient second-stage residence time and temperature must be allowed for carbon and CO burnout, probably at least 1 to 2 sec. at 1700°F to 1800°F. Thus NO levels of around 100 ppm should be able to be reached with this design.

If a low equivalence ratio cannot be tolerated, then the rules will change slightly. If a first-stage equivalence ratio of 0.95 to 1.0 is selected, the first-stage mixing becomes important. It is desirable in this case to have a long axial or tangential flame. Also, under these conditions, low preheat or combustion intensity is desirable, as seen in Figure 19 for the tangential flame. Long residence time is still desirable but not as important. Stage separation is important, however, to prevent backmixing. Rapid backmixing and residence time of around 1 sec. are necessary in the second stage for adequate CO and carbon burnout.

In summary, then, considerable data have been presented outlining the effects of first- and second-stage parameters on NO emissions for both front-wall-fired and tangential configurations. And it has been shown how these data may be applied to the practical design of a new boiler or to the retrofit of existing hardware.

However, additional data are needed on the effects of shorter residence times at constant firing rates and of higher heat release rates at constant residence times. It would also be beneficial to determine the concentrations of NO and intermediary compounds at various residence times in the first stage in order to verify the suspected mechanism of NO formation and reduction in staged combustion. Additional testing is planned along these lines using a horizontal extension firebox connected to the same experimental facility. This new capability will allow us to explore several areas of interest:

- NO vs. residence time in the first stage prior to stage addition,
- Intermediary compounds ($NH_3$, HCN) in the first stage as a function of residence time prior to stage air addition,
- Overall NO over a broader range of residence times following stage air addition.

The results from these tests should reveal a clearer picture of the first- and second-stage NO distribution.

In addition to the above, the survivability of materials under the reducing conditions in the first stage over a long period of time needs investigation to ensure that this staging concept is a viable technology.

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TABLE 3. SUMMARY OF MAJOR FINDINGS

| Test Parameter | Baseline and Moderate Staging (SR ≃ 0.95) | Low Stoichiometry (SR ≃ 0.8) |
|---|---|---|
| Excess air | Moderate effect; increases $NO_x$ | Minor effect on $NO_x$; reduces CO and carbon |
| Burner mixing | Major effect; delayed mix burners preferred with staging | Minor effect |
| Stage separation | Major effect; low backmix preferred | Major effect; low backmix preferred |
| First-stage residence time | Minor effect at low load; major effect at high load | Moderate effect at low load; major effect at high load |
| Heat release rate | Moderate effect; increases $NO_x$ by increased temperature, increased mixing | Moderate effect; decreases $NO_x$ at fixed residence time |
| Combustion air preheat | Moderate effect; increases $NO_x$ by increased combustion temperature | Moderate effect; decreases $NO_x$ |
| Second-stage residence time | Minor effect on $NO_x$; CO and carbon burnout achieved | Minor effect on $NO_x$; CO and carbon burnout achieved |

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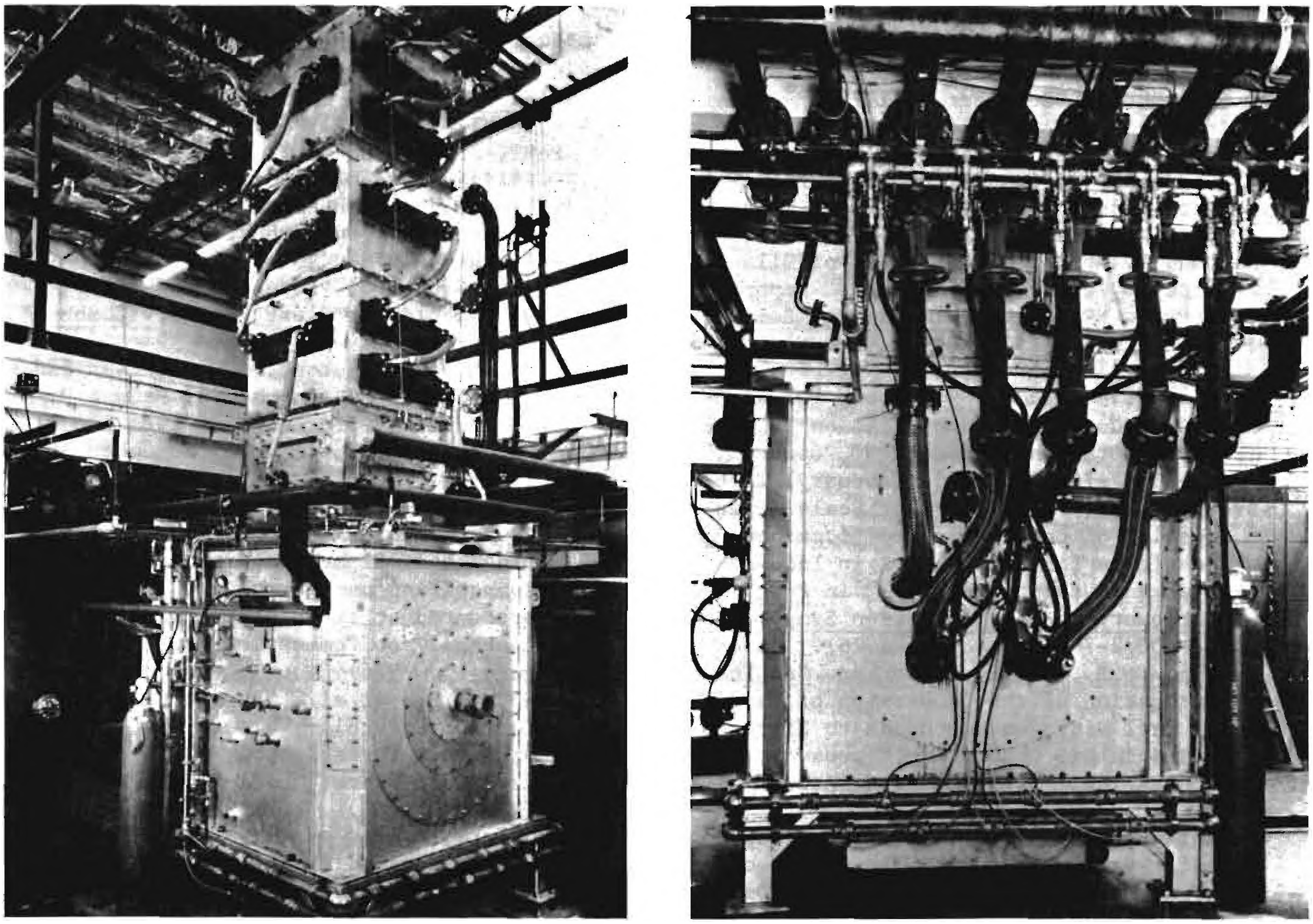

Fig. 1. Coal/oil/gas combustor.

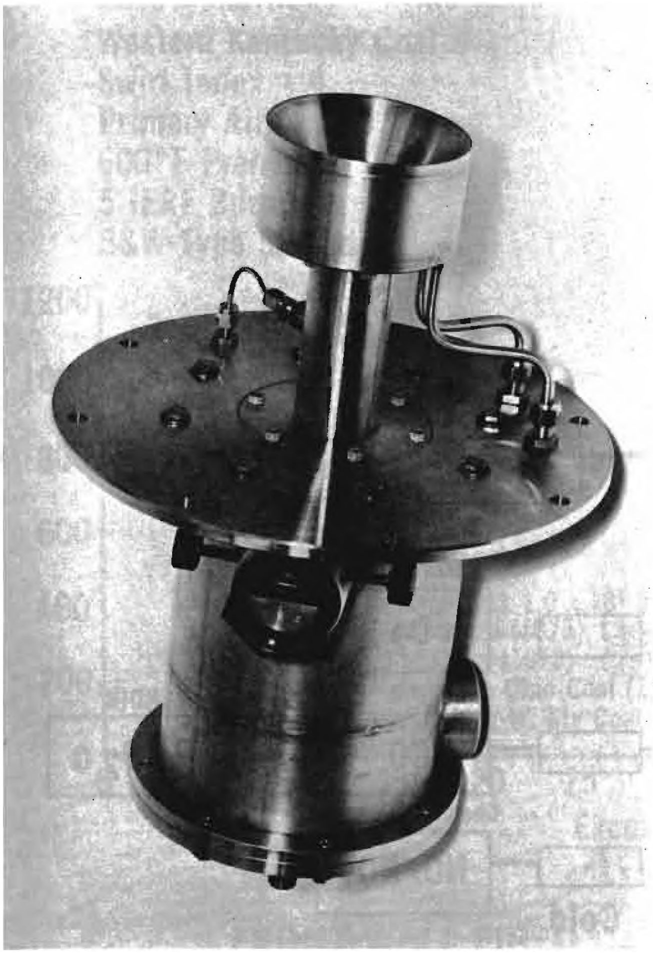

Fig. 2. Acurex/IFRF burner.

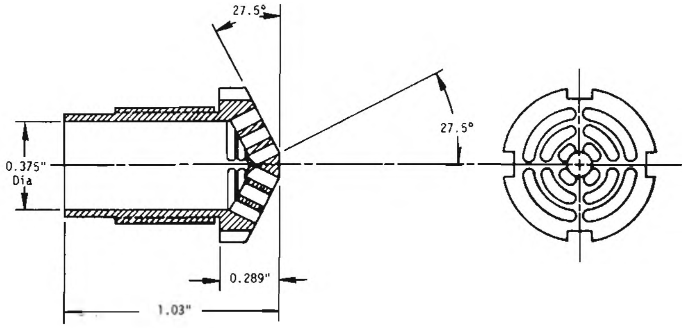

Fig. 3. B&W-type coal spreader.

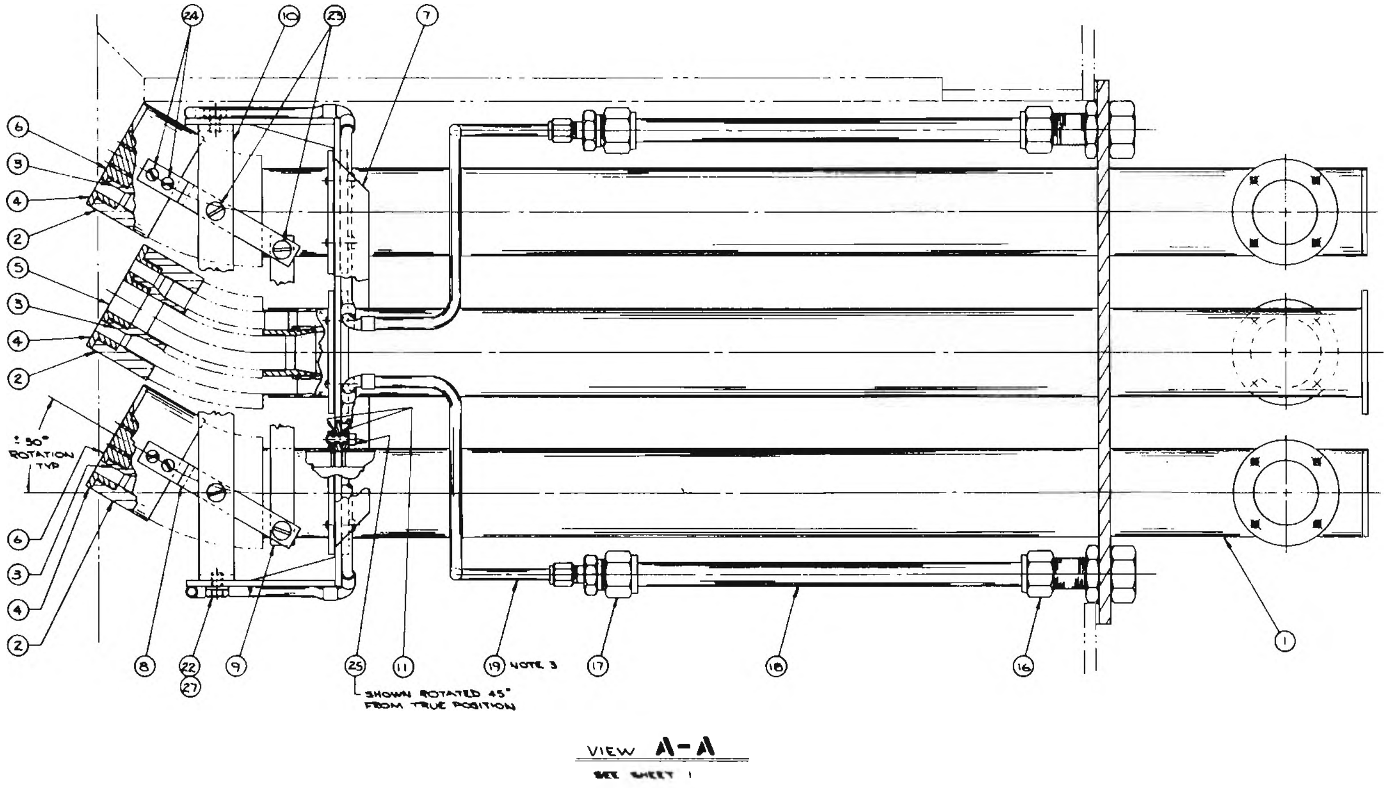

Fig. 4. Corner-fired burner.

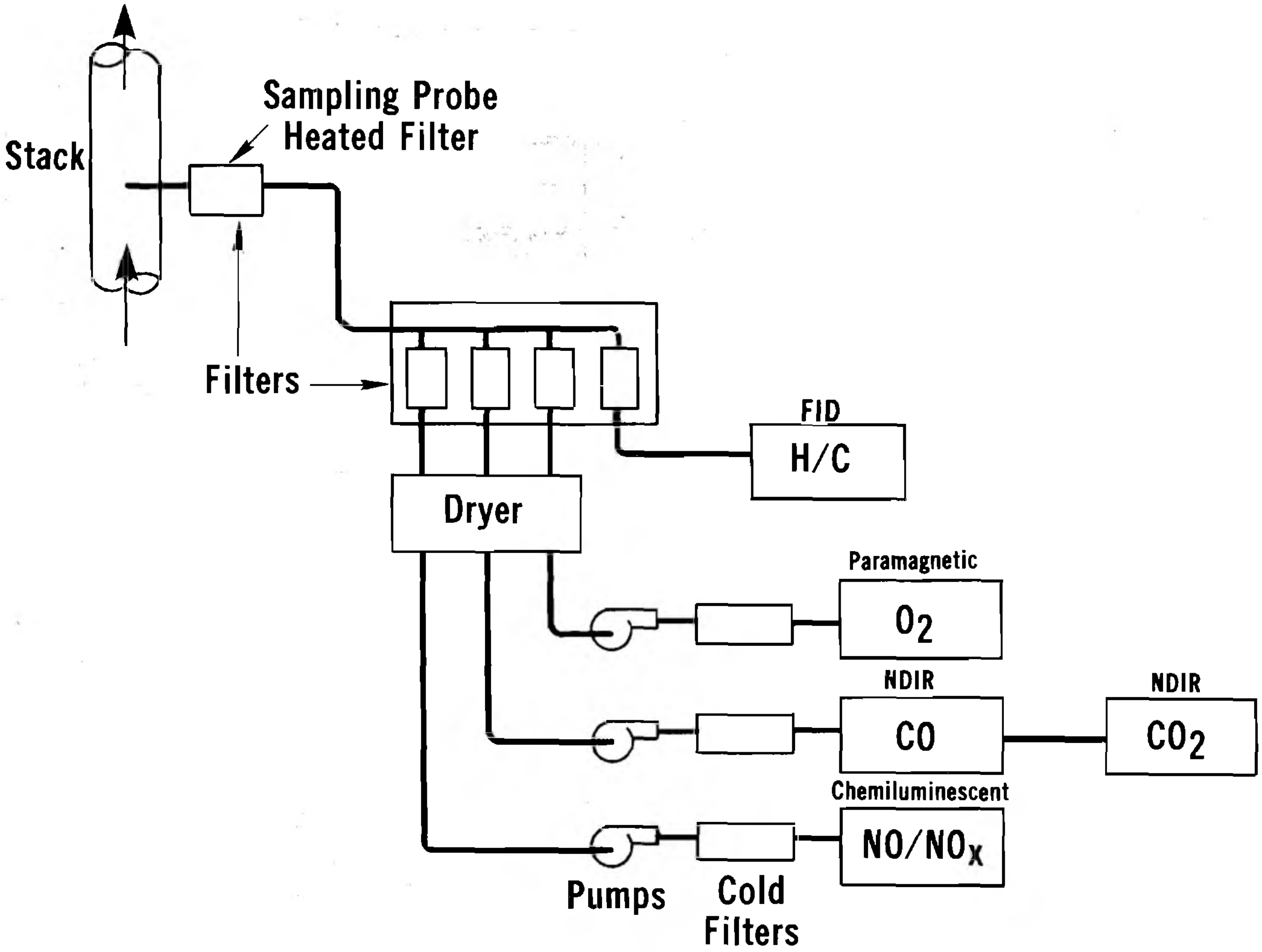

Fig. 5. Sampling system.

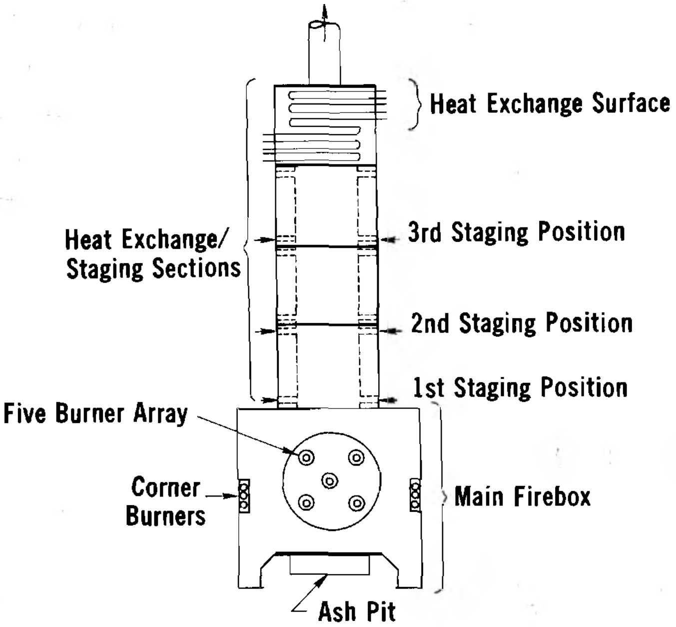

Fig. 6. Staging air locations.

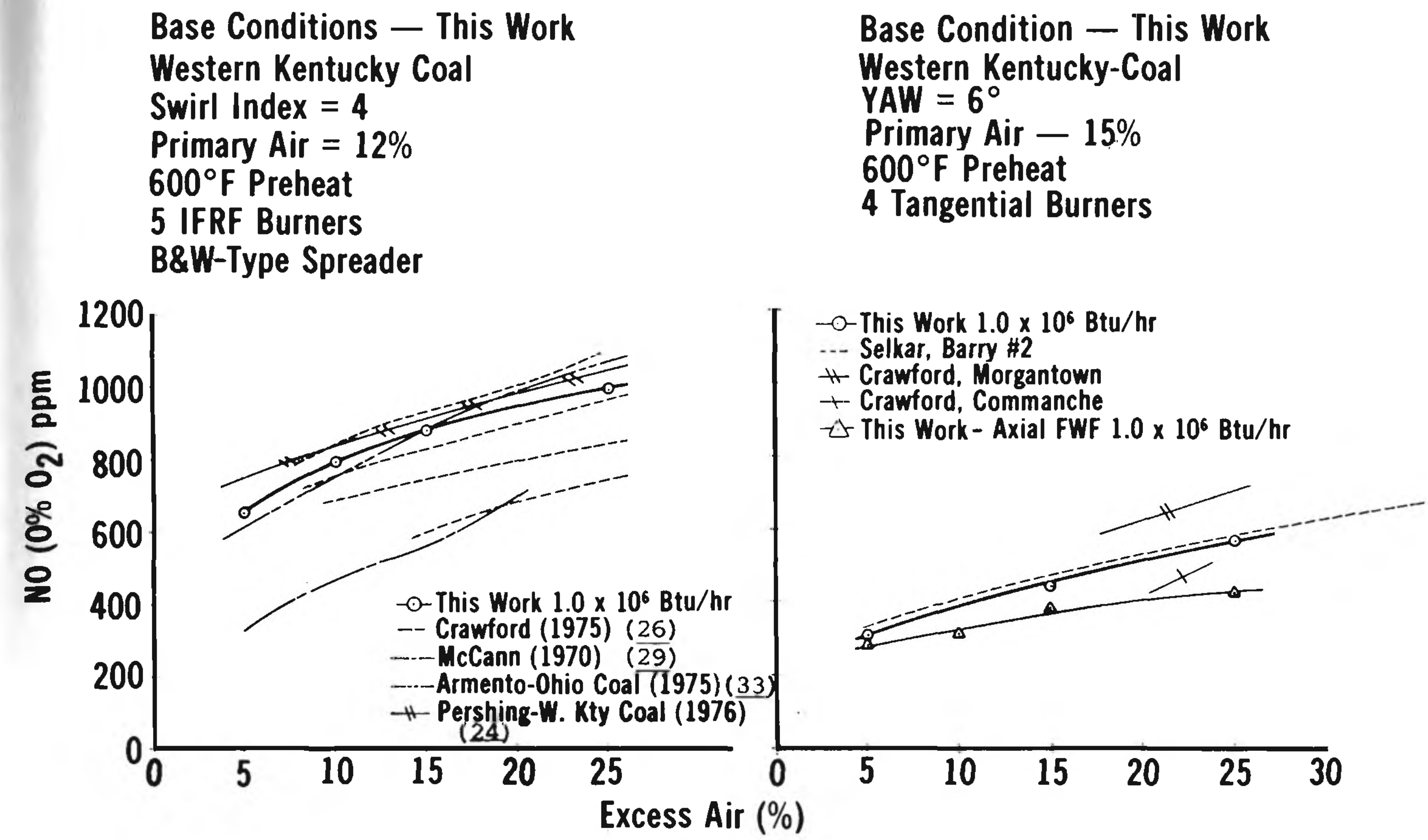

Fig. 7. Baseline NO.

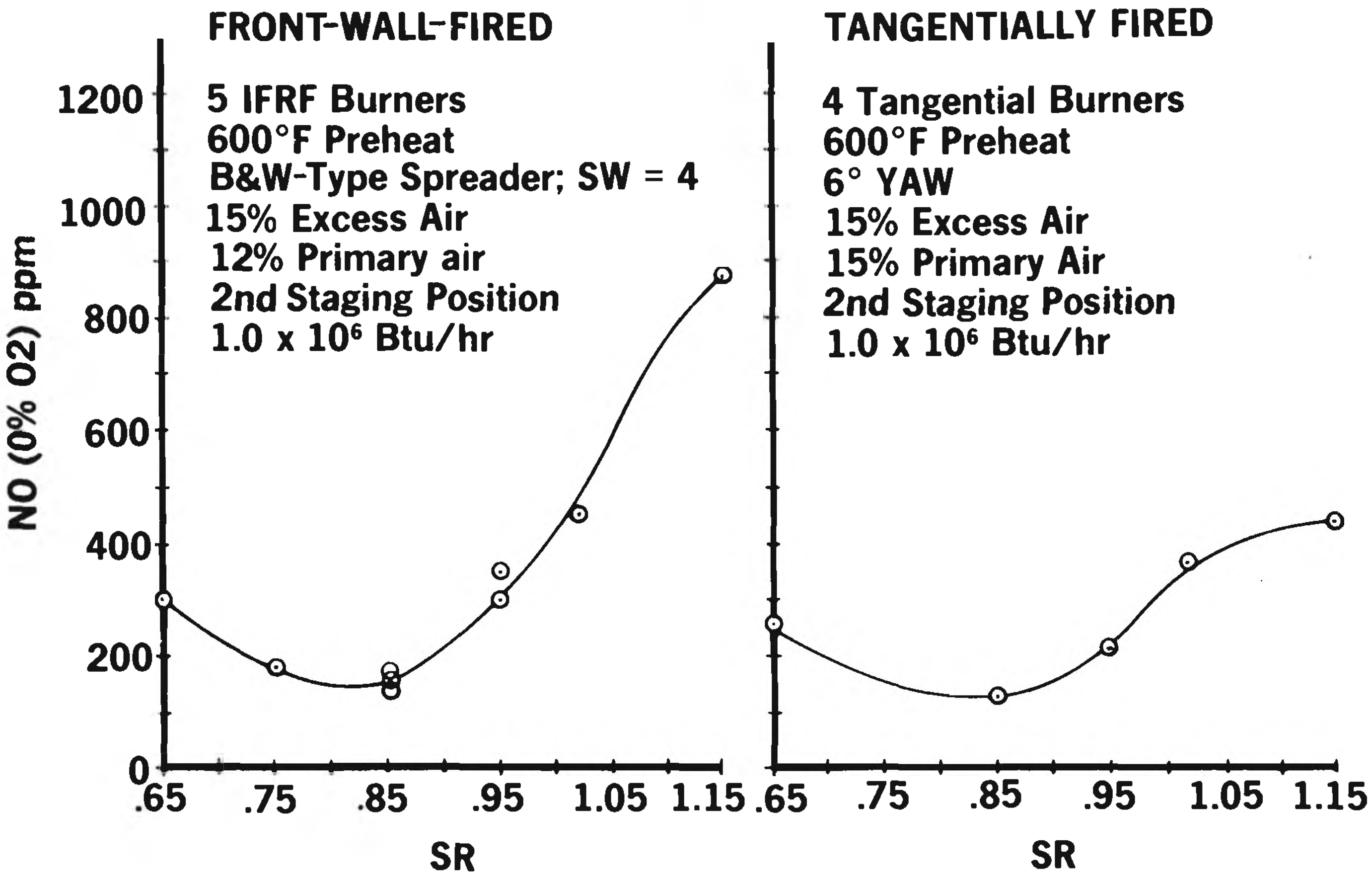

Fig. 8. Effect of stoichiometry—first stage.

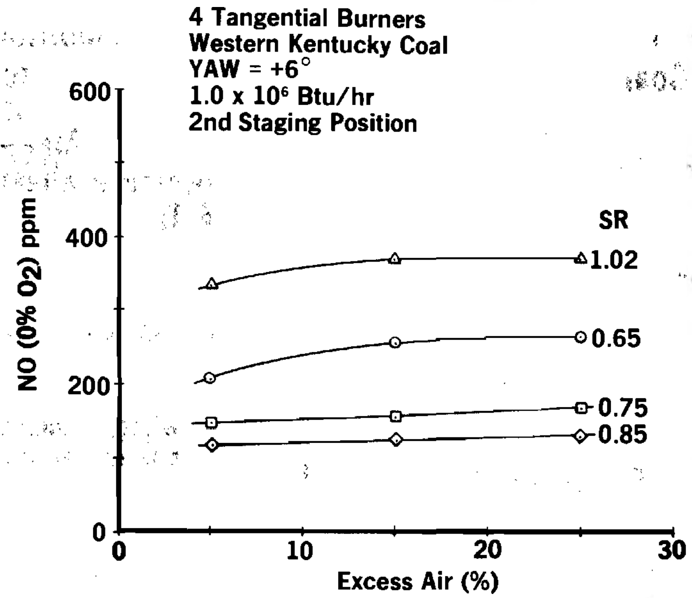

Fig. 9. Effect of stoichiometry—second stage.

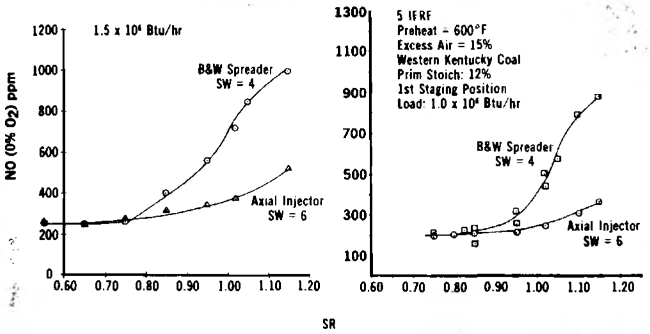

Fig. 10. Effect of mixing—first stage.

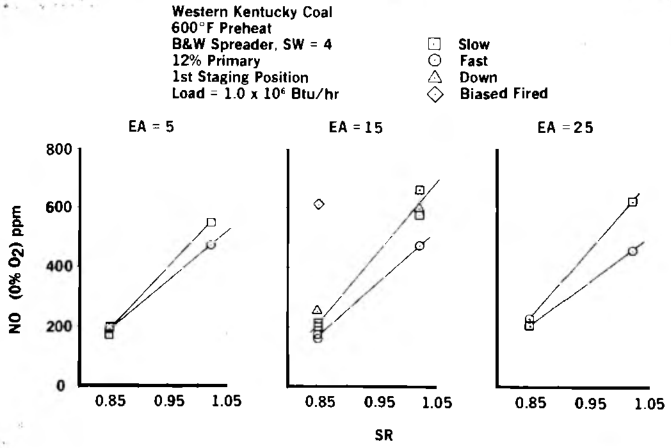

Fig. 11. Effect of second-stage mixing.

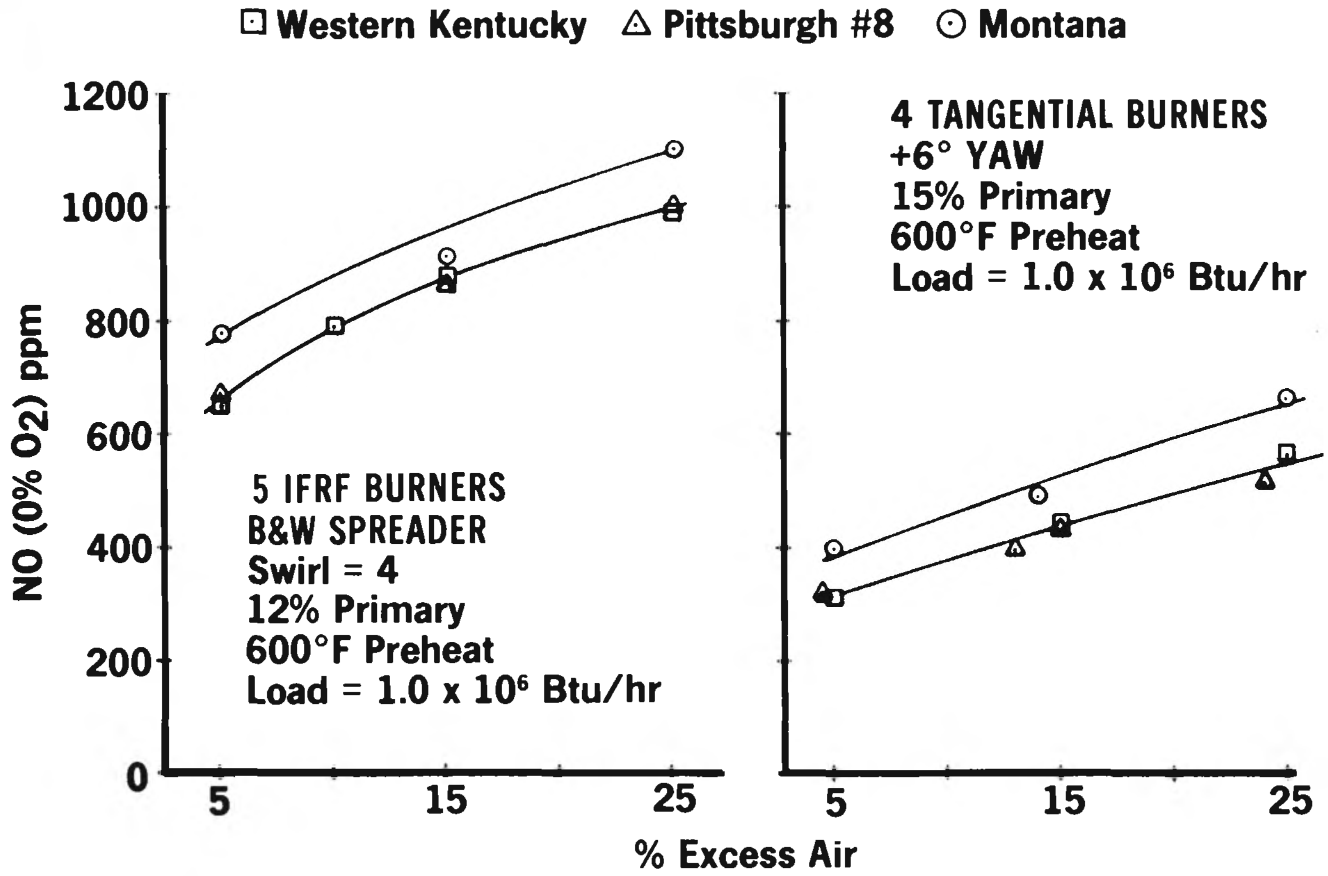

Fig. 12. Effect of coal composition—baseline.

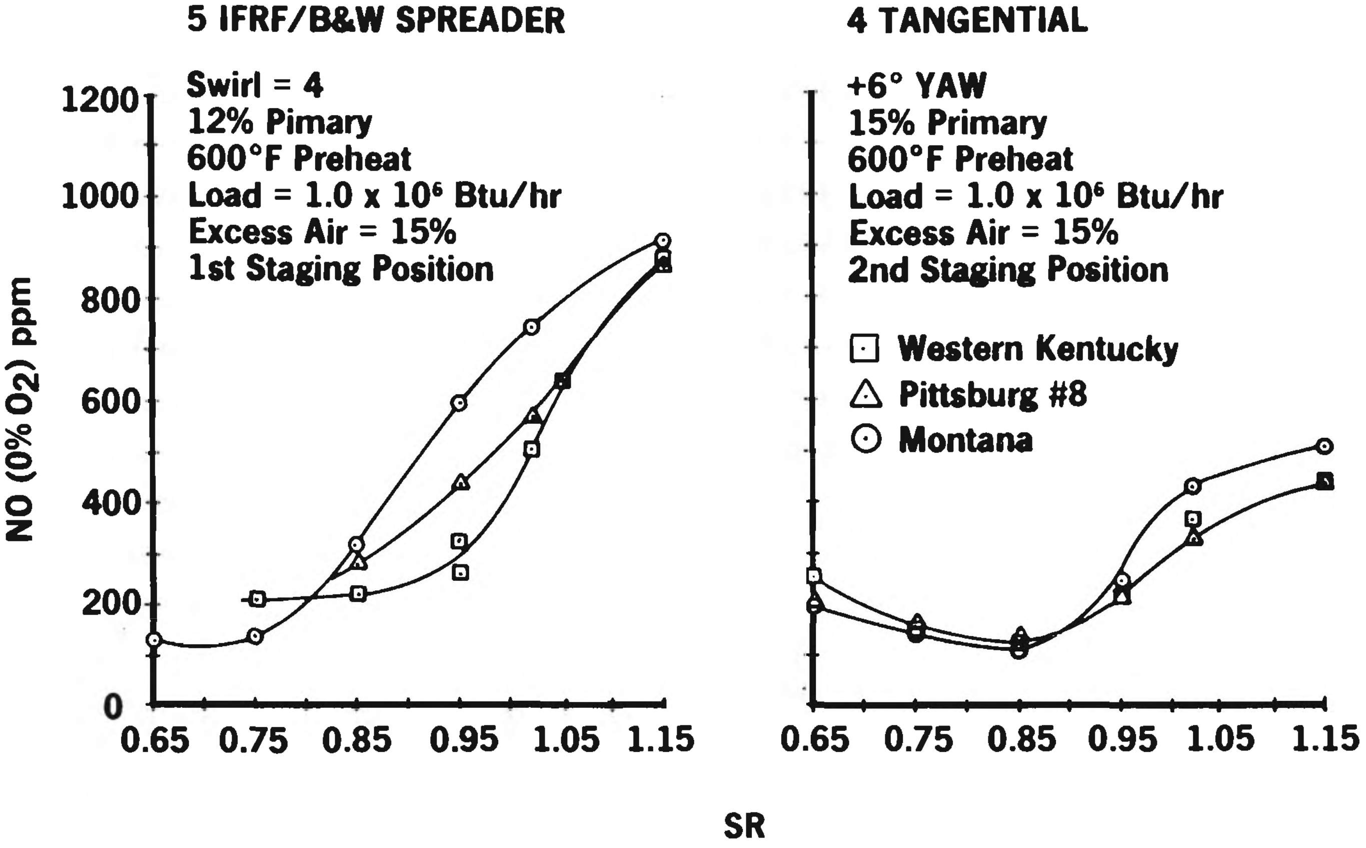

Fig. 13. Effect of coal composition—staged

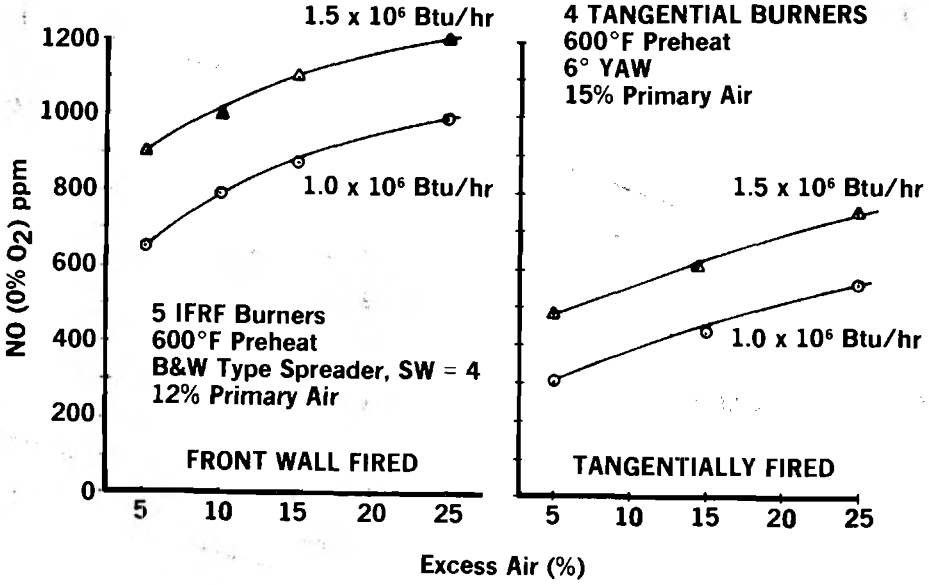

Fig. 14. Effect of load—baseline.

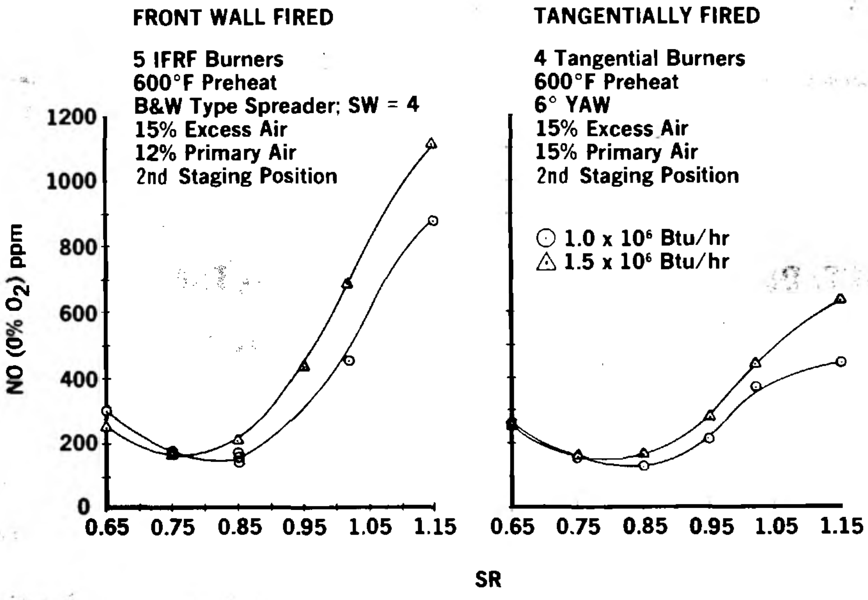

Fig. 15. Effect of load—staged.

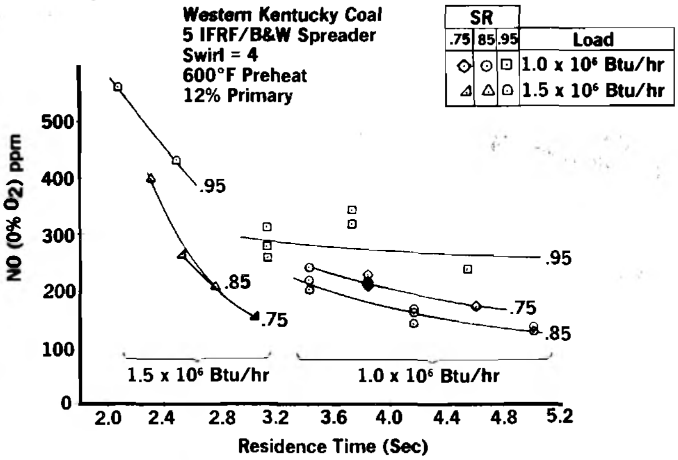

Fig. 16. Effect of residence time—front-wall-fired.

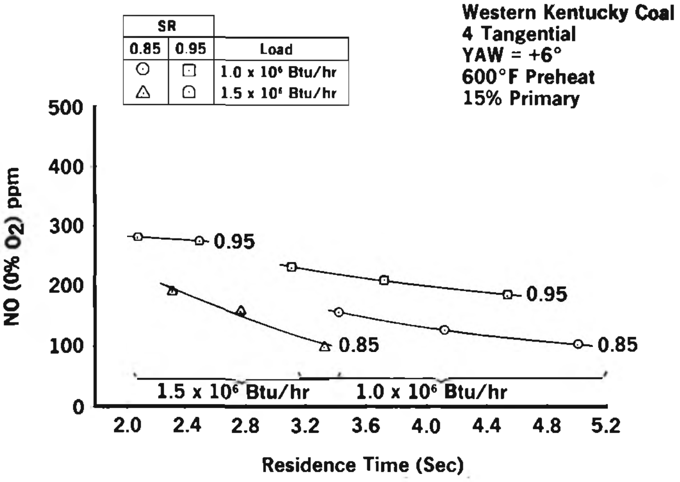

Fig. 17. Effect of residence time—tangentially fired.

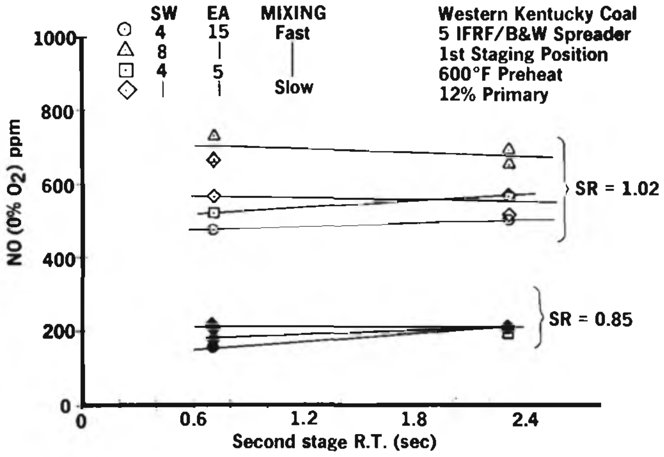

Fig. 18. Effect of second-stage residence time.

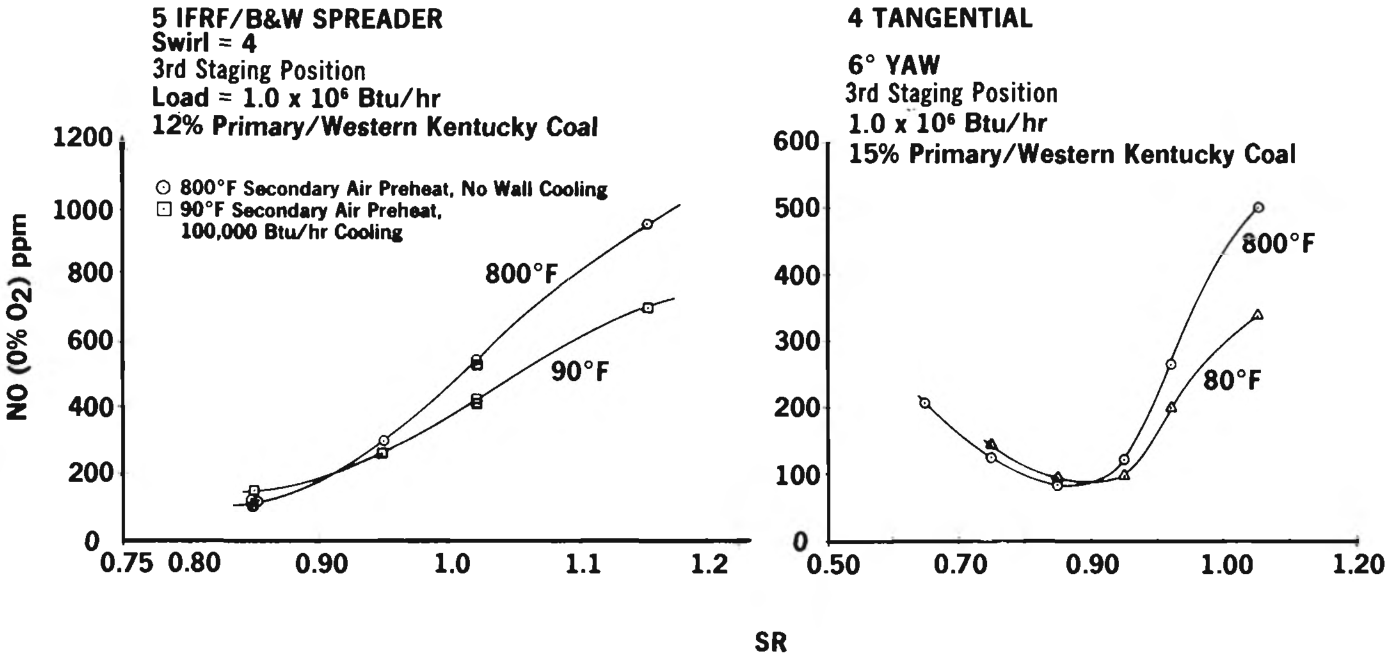

Fig. 19. Effect of temperature.

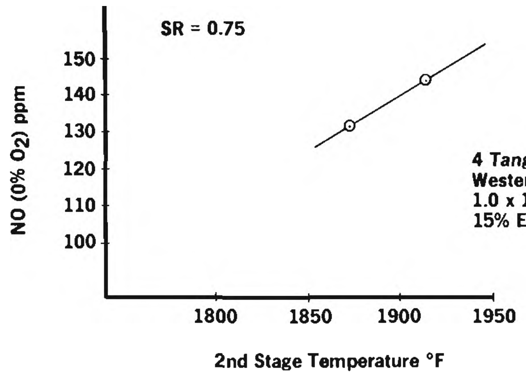

Fig. 20. Effect of second-stage temperature.

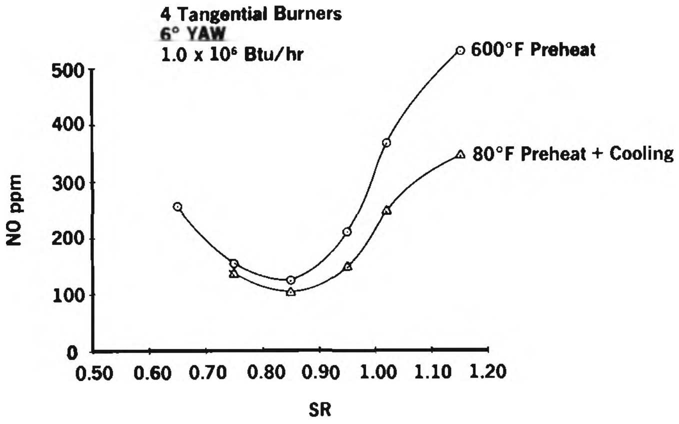

Fig. 21. Effect of temperature—second staging position.