

# **Coal Particle Flow Patterns for O<sub>2</sub> Enriched, Low NO<sub>x</sub> Burners**

Year End Report for Period Ending 9/30/02

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The year-end report summarizes the results of the series of experiments conducted to evaluate the effects of oxygen partial pressure on coal combustion. Specifically, the effects of oxygen partial pressure in the transport air stream on flame stability, flame standoff distance and overall  $\text{NO}_x$  emissions were examined.

### *Hypotheses*

Increasing the partial pressure of oxygen ( $\text{Po}_2$ ) greatly impacts combustion. Not only does it increase the adiabatic flame temperature and resulting peak flame temperatures, it increases combustion intensity, increases flammability limits, and reduces ignition temperature. All these factors enhance combustion (Baukal, 1998). Increasing the oxygen concentration from 21 to 30% increases the adiabatic flame temperature from approximately  $2200^\circ\text{C}$  to  $2500^\circ\text{C}$ . And while the adiabatic flame temperature may not be reached in real furnaces, the increase in peak flame temperature is appreciable. Higher combustion temperatures lead to faster coal devolatilization and ignition. Increasing the  $\text{Po}_2$  of the combustion air has drawbacks however. The higher combustion intensity and temperature can promote Thermal NO formation, especially at temperatures greater than  $1800^\circ\text{K}$ . Fuel NO may also increase as volatilization of nitrogen species occurs under oxidizing conditions due to the increased oxygen levels.

In contrast, oxygen enrichment of the coal transport fluid should favor volatile nitrogen reduction to  $\text{N}_2$  because of the limited quantity of transport fluid oxygen (5 to 15% of the total oxygen requirements). In this scenario, increasing transport air  $\text{Po}_2$

should increase the local combustion intensity. This will increase coal particle temperatures and volatilization rates. However the volatiles will rapidly consume the transport fluid oxygen resulting in a fuel rich combustion zone where volatile nitrogen in the coal jet core will be reduced to form N<sub>2</sub>.

It is expected that increasing transport fluid oxygen partial pressure will enhance combustion stability to form slow mixing Type 0 diffusion flames. While increasing the P<sub>O<sub>2</sub></sub> might not produce attached flames, it might reduce the flame standoff distance; thereby reducing mixing between the fuel jet and combustion air which should also reduce overall NO emissions.

### *Methodology*

At the burner operating conditions, the oxygen partial pressure is synonymous with oxygen mole fraction and is defined as:

$$P_{O_2} = y_{O_2} * P_{sys} \quad (1)$$

where P<sub>sys</sub> is the furnace pressure. During the experiments, the furnace pressure was maintained at nearly neutral pressure, +/- 0.1"WC, thus atmospheric pressure was used as the system pressure.

The partial pressure of oxygen of the transport air stream can be increased by adding pure oxygen or reduced by diluting with nitrogen. It is important to realize that the total moles of oxygen in the transport stream does not change, only the mole fraction. The resultant oxygen mole fraction in the transport air stream,  $y_{O_2,TA}$ , can be calculated as a function of percent enrichment,  $\xi$ :

$$y_{O_2,TA} = \frac{1}{1 + 3.76(1 - \xi)} \quad (2)$$

Equation 2 is based on the assumption that pure oxygen is blended with air to produce the enriched transport fluid. Note that when the transport fluid is diluted with nitrogen,  $\xi$  is a negative number and physically represents percent oxygen depletion. Transport air oxygen concentrations calculated from Equation 2 is plotted against oxygen enrichment in Figure 1. As seen in the figure, the transport air oxygen concentration gradually decreases with oxygen depletion (negative  $\xi$ ), but begins to rapidly increase as the percent oxygen enrichment exceeds 40%. In our study, values of  $\xi$  ranged from -105% to 36%, producing transport air oxygen concentrations of 13% to 29%.

Equation 2 is valid when using room air (21% oxygen) as the standard about which enrichment or depletion occurs. The equation must be modified when using bottled air where the oxygen concentration may not be 21%. The bottled air used in these experiments was made from pure nitrogen and oxygen to comply with bottled breathing air specifications (19 to 23% oxygen content, US Airweld). The modified equation for determining the mole fraction of oxygen in the transport air stream is:

$$y_{O_2,TA} = \frac{1}{1 + \frac{(1 - y_{O_2,b})}{y_{O_2,b}}(1 - \xi)} \quad (3)$$

where  $y_{O_2,b}$  is the oxygen mole fraction in the bottled compressed air.

A major focus of the research was to conduct a *systematic* investigation of the effect of transport air oxygen partial pressure on coal combustion. Four transport air

stream oxygen concentrations were initially targeted: 13%, 17%, 21% and 24%. These concentrations correspond to oxygen enrichment values of -100%, -30%, 0% and +15%, respectively. A value for  $\xi$  of -100% corresponds to doubling the amount of nitrogen present in the transport air stream.

Given the desired oxygen concentrations, an experimental test matrix was developed. The matrix is presented in Table 1. The experiments were conducted at a constant firing rate of 2 kg/hr, 725K (450°C) air preheat temperature, and overall stoichiometric ratio of 1.2. Experimental variables evaluated during the study in addition to oxygen concentration were primary jet velocity and initial wall temperature. During the experimental runs, a single variable was varied (i.e. oxygen partial pressure or wall temperature) while keeping the other variables constant. Note that the stoichiometric ratio and the split between the primary (transport) air and secondary (combustion) air was varied slightly to maintain constant velocities for the various scenarios. The velocities of the primary jets did not differ by more than 3% and the annular velocities differed by less than 4%.

### *Procedure*

The experiments conducted during the partial pressure parametric investigation were very similar in nature. The 2M furnace walls were preheated to the initial set point temperature, operating flow rates and air preheat temperatures were set, and the furnace was lit. After the natural gas used for initial flame stabilization was turned off, flame

stability was evaluated by observing the location of the flame front. Emissions concentrations were monitored with the DAQ. Specific emissions that were measured included carbon dioxide, carbon monoxide, oxygen and nitrogen oxides as NO. When running experiments, the DAQ system logged temperature, emissions and flow data every 30 seconds. 60 second rolling average concentration and temperature data were manually recorded every 3 to 5 minutes for the duration of a run. Stable attached flames were considered to have flame fronts approximately  $\frac{1}{4}$  to  $\frac{1}{2}$ " below the nozzle. Flame standoff distances from the burner to the flame front were measured with of a yardstick mounted beside the flow visualization window. A stable combustion experiment lasted approximately 15 to 20 minutes. In the event of flame blowout, the automatic flame safety system stops furnace operations. Experiments resumed after the furnace was purged of combustible gases.

### *Data Reduction*

Due to the extreme variability in operating conditions, reporting raw pollutant emissions data can be extremely misleading. For example, is a combustor with NO<sub>x</sub> emissions of 200 ppm measured at 7% oxygen emitting more than one with emissions of 250 ppm measured at 3% oxygen (yes). To overcome this variability, emissions data are reported on a basis proportional to the total mass or mole emission rate of NO per unit of fuel burned. Common reporting methods include equivalent NO concentration at 3% excess air or stoichiometric (0% excess air). Emissions are also reported on a "per million BTU's" basis. These methods eliminate concentration reductions due to dilution.

The latter method allows for emissions rate comparison between different fuel types and/or combustion methodologies.

When converting emissions data to a specific oxygen content (i.e. 0% or 3%) for combustion processes utilizing air (without oxygen enrichment/depletion), the pollutant concentration at the desired oxygen basis can be found from:

$$[\text{pollutant}]_{\text{desired O}_2} = [\text{pollutant}]_{\text{measured O}_2} \frac{0.21 - y_{\text{O}_2 \text{ desired}}}{0.21 - y_{\text{O}_2 \text{ measured}}} \quad (4)$$

For example, the equivalent CO concentration for a gas sample containing 300 ppm CO and 6% oxygen would be 360 ppm when adjusted to 3% oxygen. The derivation of Equation 4 is based on assuming complete combustion (0% CO and 0% unburned carbon) and any measured oxygen is from air inleakage. Emissions data obtained from the oxygen partial pressure experiments cannot be adjusted to an equivalent basis by Equation 4 due to the diluent effects of inert nitrogen on the actual pollutant concentration measurements. In the partial pressure experiments, pollutant concentrations would be artificially increased for oxygen-enriched cases due to the reduced amount of nitrogen injected into the system with the combustion air. Equation 4 also does not take incomplete combustion into consideration.

A molar oxygen and carbon balance was derived to calculate equivalent pollutant concentrations for the oxygen partial pressure experiments. The molar carbon and oxygen balance calculates the actual dry moles of exhaust gases,  $M_d$ , exiting the furnace given fuel and air feed rates, and measured concentrations of oxygen, carbon dioxide and

carbon monoxide in the exhaust. Once  $M_d$  is determined, the equivalent  $\text{NO}_x$  concentration at stoichiometric conditions,  $y_{\text{NO},\text{SR}}$ , can be found from:

$$y_{\text{NO},\text{SR}} = y_{\text{NO},m} * \frac{M_d}{\psi_{\text{air},\text{SR}}} \quad (5)$$

Where  $\psi_{\text{air},\text{SR}}$  represents the moles of dry combustion products under stoichiometric conditions.  $\psi_{\text{air},\text{SR}}$  equals 634.98 moles/hr (1.3999 lb-moles/hr) when burning 2 kg/hr Utah coal with air at a overall stoichiometry of 1.0. The variable  $y_{\text{NO},m}$  refers to the measured exhaust NO concentration in parts per million. Equation 5 is similar to the general balance:

$$y_{\text{NO},\text{actual}} \bullet \text{Vol}_{\text{actual}} = y_{\text{NO},\text{stoich}} \bullet \text{Vol}_{\text{stoich}} \quad (6)$$

where Vol represents the volumetric flow rate of the dry exhaust gas and stoich represents theoretical values assuming air is used as the oxidant at a SR of 1.0.

As shown in Equation 5, the equivalent  $\text{NO}_x$  emissions concentration at stoichiometric conditions,  $\text{NO}_{x,\text{SR}}$ , depends on the measured  $\text{NO}_x$  concentration and  $M_d$ , which is a function not only of the measured CO,  $\text{CO}_2$  and  $\text{O}_2$  emissions concentrations, but also of the feed coal, combustion air and transport air flow rates and composition. A total of eight measurements are needed to determine the equivalent  $\text{NO}_x$  concentration, each with a degree of uncertainty. A propagation of error analysis was performed to quantify the relative uncertainty of the equivalent  $\text{NO}_x$  concentration calculated from Equation 5. Uncertainty in  $\text{NO}_{x,\text{SR}}$  ranged from 10 to 20%. The uncertainty increased with increasing  $\text{NO}_{x,\text{SR}}$ . Variability in the oxygen measurements (+/- 0.1%) typically



resulted in a 10 to 15 ppm difference in  $\text{NO}_{x,\text{SR}}$  accounting for 30 to 40% of the total uncertainty. The uncertainty in the carbon dioxide measurements ( $\pm 0.13\%$ ) accounted for 40 to 50% of the total uncertainty. Thus,  $\text{NO}_{x,\text{SR}}$  values are extremely susceptible to errors in  $\text{CO}_2$  measurements.

### *Experimental Results*

The parametric study evaluated the effects of partial pressure of oxygen in the transport air stream on flame stability and  $\text{NO}_x$  emissions. The study included both visual observations of flame detachment and emissions analyses. A stable attached coal flame is presented in Figure 2. Figure 3 presents a stable detached coal flame. The flame front shown in Figure 3a is approximately 15 inches below the burner nozzle. The coal jet upstream of the flame front is shown in Figure 3b.

### Wall Temperature Effects

The exhaust  $\text{NO}_x$  concentration data from the initial trials, adjusted to stoichiometric air conditions are plotted against average wall temperature in Figures 4 through 6 for the 17%, 21% and 24% transport air oxygen cases, respectively. The error bars represent uncertainty in  $\text{NO}_{x,\text{SR}}$ . These data are for attached flame conditions. The 12% transport air oxygen case did not produce a stable attached flame. During the initial trials, the furnace temperature slowly increased due to the heat of combustion. This temperature increase was most noticeable for a wall set point temperatures of 1020K (750°C).  $\text{NO}_x$  emissions also increased during the experiments. It was hypothesized that

the increase in  $\text{NO}_x$  was due to the increased wall temperatures, thus concentration data gathered during individual runs are plotted as a function of wall temperature. Note that data from multiple experiments are presented.  $\text{NO}_{x,\text{SR}}$  increases linearly with wall temperature for each partial pressure case at temperatures up to approximately 1220 K (950°C).

The open symbols in Figures 4 through 6 represent data obtained for a combustion air to transport air velocity ratio ( $\Theta$ ) of 3. The closed symbols are for  $\Theta = 1.5$  emissions data. The velocity ratio is a measure of the mixing intensity between the central and annular jets.

No stable detached flames were observed at wall set point temperatures of 1020K (750°C). Attached flames that detached during a run became unstable and blew out at these low temperatures. Higher furnace wall temperatures 1170K (900°C) supported stable detached flames. Figure 7 presents  $\text{NO}_{x,\text{SR}}$  as a function of wall temperature for both attached and detached flames. The detached flame data are denoted by open symbols and by a “D” in the legend. The data presented in Figure 7 for detached flames show a marked increase in overall  $\text{NO}_x$  emissions as compared with the attached flames. The  $\text{NO}_x$  emissions for the 17% oxygen detached flames are up to 33% higher than attached flames operating at the same conditions. This increase in  $\text{NO}_x$  emissions can be attributed to the increased mixing between the combustion air and the fuel prior to ignition. Under these conditions, fuel-nitrogen compounds volatilize under oxygen-rich conditions thereby promoting  $\text{NO}_x$  formation via Fuel  $\text{NO}_x$  mechanisms. Thermal

(Zeldovich) and Prompt (Fenimore)  $\text{NO}_x$  reaction pathways are not considered to be major contributors of  $\text{NO}_x$  due to their long formation timescales at temperatures encountered in the pulverized coal furnace (Smart, 1992, Wendt, 1987).

### Oxygen Partial Pressure Effects

Increasing the partial pressure of oxygen in the transport air enhances combustion. This is shown by comparing Figures 4 through 6. As mentioned above, the 12% oxygen stream did not produce a stable attached flame. At 17% oxygen (Figure 4), stable attached flames were obtained at either 1020K or 1170K (750 or 900°C) wall temperature set points only for a velocity ratio equal to 3. Increasing the transport air to 21% oxygen produced stable attached flames at the higher wall temperature set point for the lower velocity ratio ( $\Theta = 1.5$ ) scenarios. Further increasing the oxygen concentration to 24% produced stable attached flames for both velocity ratios at both wall temperature settings. These results are similar to the results of Spinti et al. (1997), which showed that reducing the primary oxygen concentration has a destabilizing effect on flame stability for co-fired combustion systems.

The attached flame data for all three oxygen partial pressure scenarios (17, 21 and 24%) are combined in Figure 8. The data in Figure 8 include both multiple experiments as well as temperature dependent data from individual experiments. The data in Figure 8 indicate that the concentration of oxygen in the transport air stream has little effect on the overall  $\text{NO}_x$  emissions for attached flames. These findings are in agreement with Spinti

et al. who found that reducing the primary oxygen from 21% to 13% had a minimal effect on NO production. However as noted above, increasing partial pressure of oxygen enhances combustion through increased flame stability.

The partial pressure of oxygen in the transport air stream also has little effect on NO<sub>x</sub> emissions for the detached flames observed during the initial trials as shown in Figure 7. This was expected, as the flame fronts for the detached flames were 14 to 16” from the burner. This is well beyond the 7.5 to 8 duct diameters required for complete mixing of concentric jets (Thring & Newby, 1952, Becker et al., 1963). And, because the transport air makes up such a small fraction of the total combustion air (5 to 13.5%), the resulting impact of oxygen enrichment of the transport air stream is minimal. For example, the average oxygen concentration of the combined transport and combustion air streams ranges from 20.4% to 21.3% for the 12% and 24% transport air oxygen scenarios, respectively.

However, oxygen partial pressure does affect flame detachment. Therefore oxygen enrichment can reduce overall NO<sub>x</sub> emissions. Comparing emissions for the attached 24% oxygen flame at 1216K with the detached 12% flame at 1217K, one sees a 45% reduction in NO<sub>x,SR</sub> (207 vs. 317 ppm). Comparing emissions for an attached 21% oxygen case with those from a detached 17% oxygen case, each at approximately 1250K also shows a 45% reduction. These reductions are not through modifications in NO reaction pathways, but by enhancement of the overall combustion chemistry. The enriched oxygen cases exhibited better flame stability, which promotes combustion. This reduces the total amount of oxygen available for NO<sub>x</sub> formation, thereby reducing overall

pollutant emissions. Flame attachment also prevents air-fuel premixing causing the fuel nitrogen species to volatilize under fuel-rich conditions, which favors reduction to  $N_2$  over oxidation to NO.

Pershing (1976) observed similar dramatic reductions in  $NO_x$  when operating in attached (flame mode) vs. detached (reactor mode) conditions. When firing a high volatile bituminous coal, he observed 54% reductions in NO emissions for attached vs. detached flames.

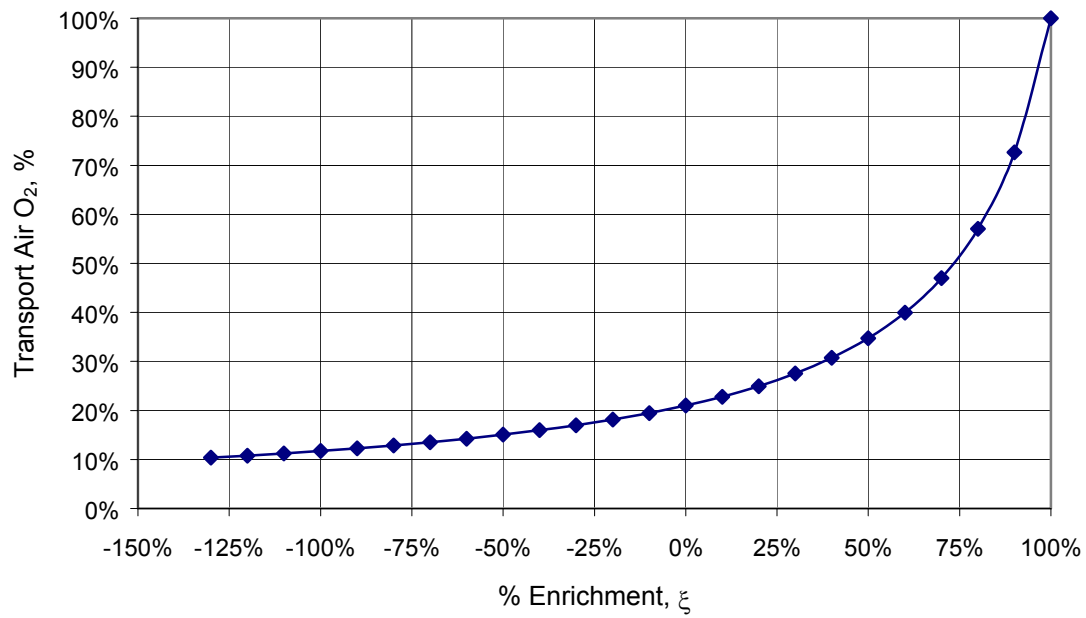
### *Summary*

A series of experiments were conducted to determine the effect of oxygen partial pressure in the transport air on flame stability and resultant  $NO_x$  emissions. In summary, the oxygen partial pressure experiments revealed that

- Increasing oxygen partial pressure in the transport air stream produced stable attached flames that were otherwise detached, reducing  $NO_x$  emissions due to formation of fuel-rich central core which favors reduction of fuel nitrogen to  $N_2$ . Flame attachment also prevents premixing of fuel and air.
- The degree of oxygen enrichment necessary to produce attached flames decreased with increasing wall temperature.
- Increasing oxygen partial pressure in the transport air stream had little effect on emissions for always-attached and always-detached flames. The lack of an effect for always-detached flames is attributed to the extensive pre-mixing that

occurs prior to ignition and the limited impact oxygen enrichment of the small transport air stream has on the oxygen concentration of the premixed transport and combustion air streams.

- Reducing the oxygen partial pressure through nitrogen dilution destabilizes flames leading to flame detachment or blowout. These destabilizing effects increase with decreasing furnace temperature. These results are consistent with published literature.
- The temperature dependence of  $\text{NO}_{x,i}$  for detached flames is approximately 3 times greater than for attached flames.



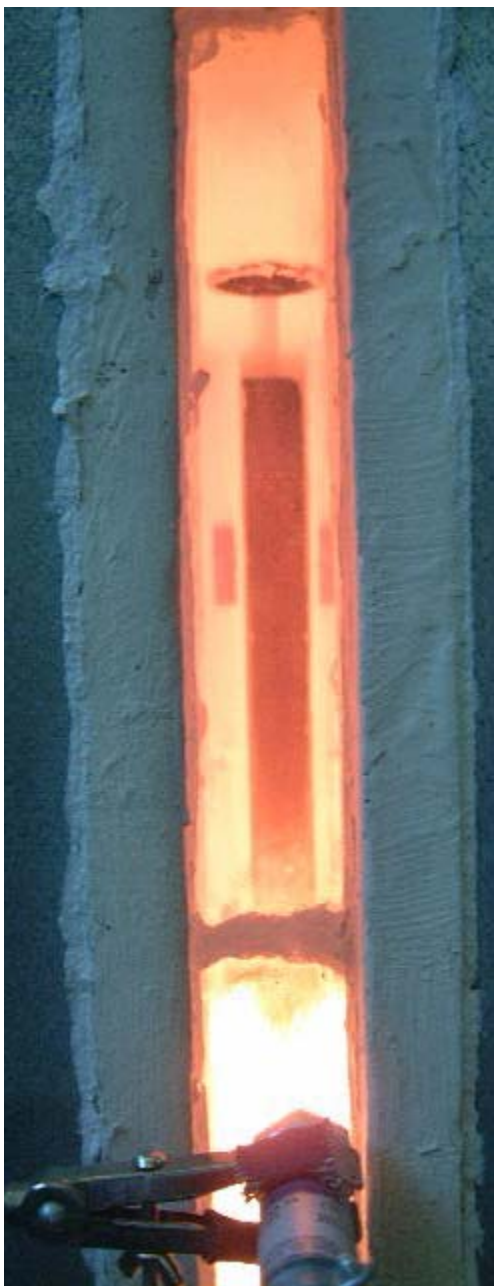
**Figure 1. Effect of Oxygen Enrichment on Transport Air Oxygen**



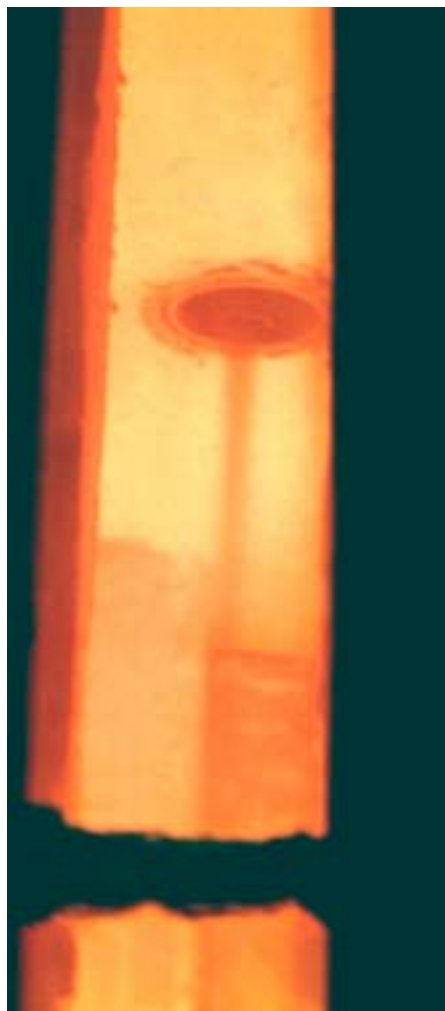
**Figure 2. Stable Attached Coal Flame**

17% Transport Air Oxygen, 900°C Walls



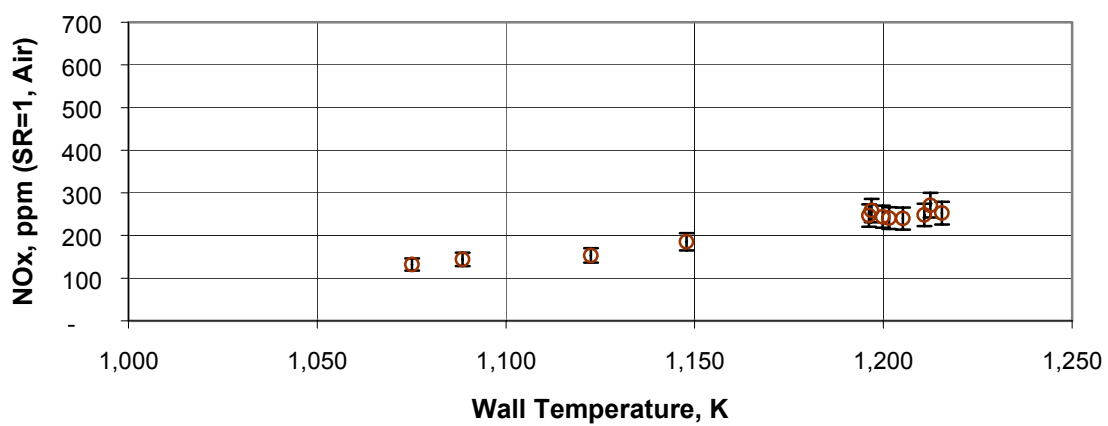


4-3a. Detached Flame,  
Stabilized 15" below burner



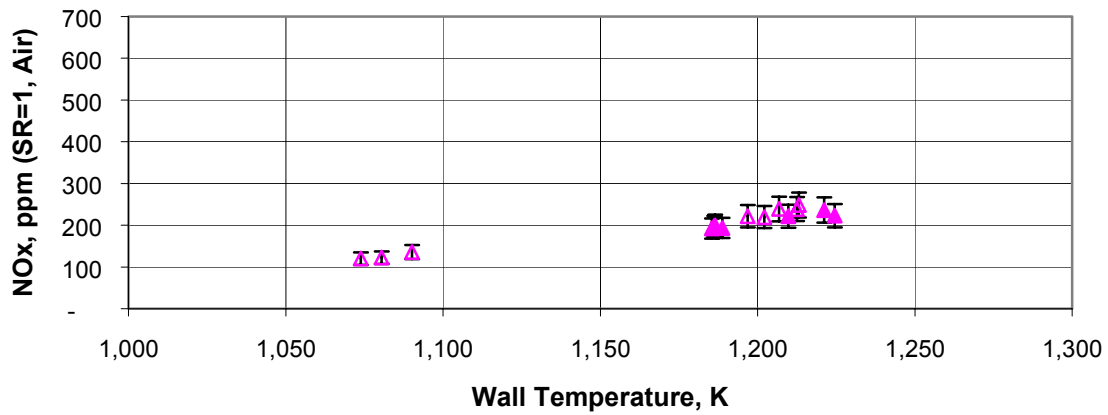
4-3b. Coal Stream of Detached  
Flame.

**Figure 3. Stable Detached Flame**



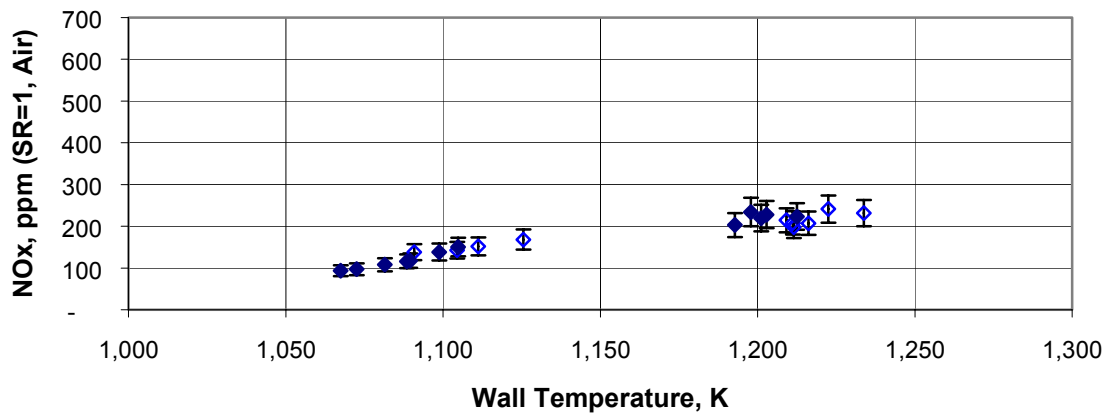
**Figure 4. NO<sub>x,SR</sub> vs. Temperature- 17% Transport Air O<sub>2</sub>-Attached Flames**

Open symbols are at  $\Theta = 3$ .



**Figure 5.  $\text{NO}_{x,\text{SR}}$  vs. Temperature- 21% Transport Air  $\text{O}_2$ -Attached Flames**

Open symbols are at  $\Theta = 3$ , Close symbols are at  $\Theta = 1.5$



**Figure 6.  $\text{NO}_{x,\text{SR}}$  vs. Temperature- 24% Transport Air  $\text{O}_2$ -Attached Flames**

Open symbols are at  $\Theta = 3$ , Close symbols are at  $\Theta = 1.5$

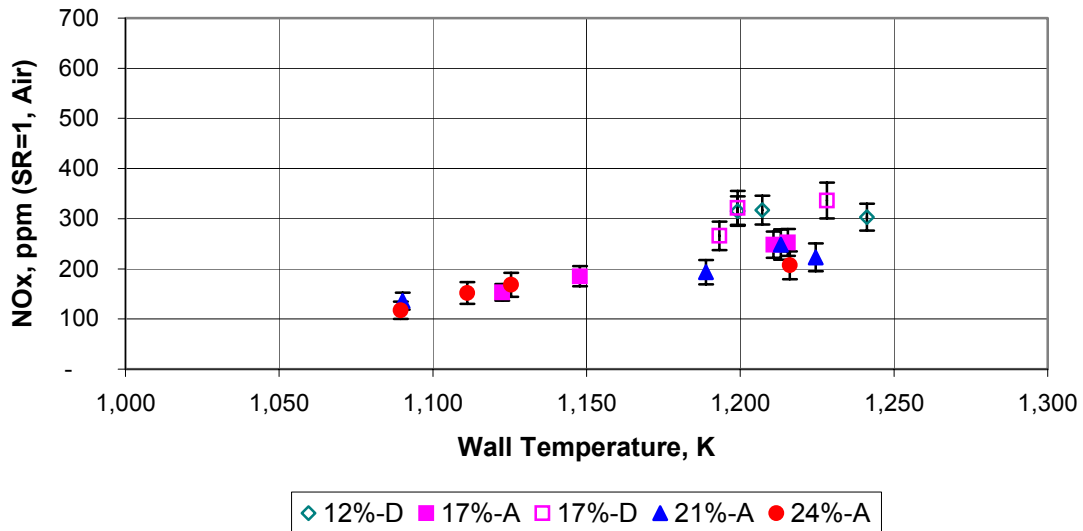


Figure 7. NO<sub>x,SR</sub> vs. Temperature-Attached and Detached Flames

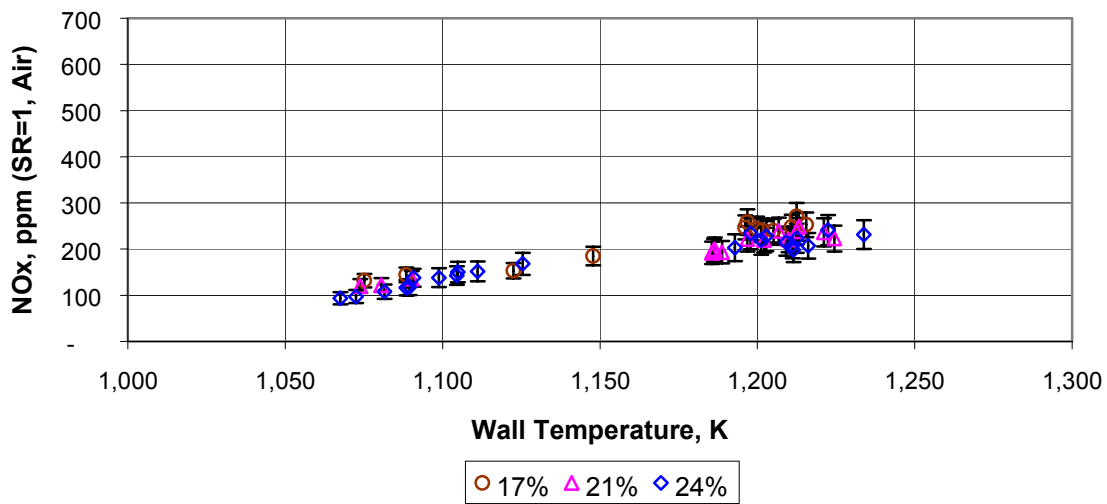


Figure 8. Combined NO<sub>x,SR</sub> vs. Temperature-Attached Flames

**Table 1. Partial Pressure Experimental Matrix**

run	SR	$\xi$	Split	Ta %O <sub>2</sub>	V <sub>c</sub>	V <sub>t</sub>	Wall T	O <sub>2</sub> pp	Notes
1	1.2	0%	10	21.0%	31.8	19.4	750	147	Unstable blew out at 5 minutes
2	1.2	15%	11.5	23.8%	31.2	19.6	750	167	Stable attached
3	1.2	-30%	8.1	17.0%	32.5	19.4	750	120	Unstable w/o gas
4	1.17	-100%	5.7	11.7%	32.5	19.3	750	82	Unstable w/o gas
5	1.2	0%	10	21.0%	31.8	19.4	900	147	Unstable w/o gas
6	1.2	15%	1.5	23.8%	31.2	19.6	900	167	Detached after a few minutes
7	1.2	-30%	8.1	17.0%	32.5	19.4	900	120	Immediately detached
8	1.17	-100%	5.7	11.7%	32.5	19.3	900	82	Immediately detached
9	1.2	0%	10	21.0%	31.8	11.6	750	147	Attached
10	1.2	15%	11.5	23.8%	31.2	11.8	750	167	Attached
11	1.2	-30%	8.7	17.0%	32.5	11.6	750	120	Attached
12	1.17	-100%	5.7	11.7%	32.5	11.6	750	82	Did not run
13	1.2	0%	10	21.0%	31.8	11.6	900	147	Attached
14	1.2	15%	11.5	23.8%	31.2	11.8	900	167	Attached
15	1.2	-30%	8.1	17.0%	32.5	11.6	900	120	Attached
16	1.17	-100%	5.7	11.7%	32.5	11.6	900	82	Immediately detached

Notes: All runs were firing 2Kg/Hr Utah coal with 450°C air preheat with room air for transport air and enriched with pure oxygen.

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