FINAL TECHNICAL REPORT
September 1, 1996, through August 31, 1997

Project Title: **COMBUSTION TECHNOLOGY FOR MINIMIZING NO_X EMISSIONS BURNING ILLINOIS COALS**

ICCI Project Number: 96-1/5.1A-2
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ABSTRACT

The objective of this project is to demonstrate the combined application of low-NO_x burner and pulverized coal reburning technologies as a low-cost option to reduce NO_x emissions (possibly as low as 0.15 lb/MM Btu) while firing Illinois coal in dry-bottom pulverized coal steam generators. A successful demonstration may help to maintain or increase Illinois coal use for power generation in the face of economically and environmentally driven competition from both Powder River Basin coal and natural gas.

The project was conducted in the CONSOL 1.5 MM Btu/h combustion pilot plant. Both wall-fired and tangentially-fired burner configurations were investigated firing two commercial high-volatile (36-40% dry volatile matter) Illinois Basin bituminous coals from two CONSOL mines. Pulverized coal was used as both primary and reburn fuels. The impact of the furnace operating variables on NO_x emissions and fly ash loss on ignition (LOI) was assessed.

There were significant differences in NO_x emissions between the two burner configurations and minor differences between the two test coals. Specifically, NO_x emissions were 0.08-0.16 lb/MM Btu lower in the tangentially-fired configuration than in the wall-fired configuration, with larger differences at higher reburn stoichiometries. Pulverized coal reburning reduced NO_x emissions from 0.77 (baseline) to 0.23 lb/MM Btu (70% reduction) in the wall-fired configuration, and from 0.61 (baseline) to 0.15 lb/MM Btu (75% reduction) in the tangentially-fired configuration. There were significant differences in LOI between the two test coals and minor differences between the two burner configurations. Pulverized coal reburning increased LOI from less than 1% (baseline) to 10-13% for the higher heating value coal and 2-4% for the lower heating value coal.

The reburn stoichiometry was the dominant operating variable affecting NO_x emissions and LOI. An optimum reburn stoichiometry of about 0.84 was identified for low NO_x emissions. Changes in the firing rate, the primary stoichiometry and the final stoichiometry produced relatively minor changes in NO_x emissions and LOI.

EXECUTIVE SUMMARY

The objective of this project is to demonstrate the combined application of low-NO_x burner and pulverized coal reburning technologies as a low-cost option to reduce NO_x emissions while firing Illinois coal in dry-bottom pulverized coal steam generators. A successful demonstration of low NO_x emissions (near or below 0.15 lb/MM Btu) may help to maintain or increase Illinois coal use for power generation in the face of economically and environmentally driven competition from both Powder River Basin coal and natural gas.

The project was carried out in the CONSOL 1.5 MM Btu/h combustion pilot plant. A pulverized coal reburn system and an over fire air system were independently designed, constructed, tested and installed. Pulverized coal was used as both primary and reburn fuels.

The CONSOL combustion pilot plant is a multi-burner coal combustion test facility with typical feed rates of 100 lb/h for high heating value bituminous coals. It is demonstrated that the combustion pilot plant provides a realistic simulation of virtually any commercial pulverized coal-fired steam generator furnace. It is the only test facility which provides for pulverized coal-fired furnace testing in multiple firing configurations, i.e., wall-fired or tangentially-fired. The project takes advantage of this feature by investigating the application of pulverized coal reburning to both commonly used pulverized coal firing configurations.

In this study, CONSOL investigated both opposed wall-fired and tangentially-fired burner configurations firing two commercial high-volatile (36-40% dry volatile matter) Illinois Basin bituminous coals from two CONSOL mines: one containing 0.9% sulfur, 1.6% nitrogen and 12,300 Btu/lb heating value, the other, lower in rank, containing 3.2% sulfur, 1.2% nitrogen and 11,000 Btu/lb heating value. CONSOL also investigated the impact of four furnace operating variables on NO_x emissions and fly ash loss on ignition (LOI): firing rate, primary combustion zone stoichiometry, reburn combustion zone stoichiometry and final stoichiometry.

There were significant differences in NO_x emissions between the two burner configurations and minor differences between the two test coals. Specifically, NO_x emissions were 0.08-0.16 lb/MM Btu lower in the tangentially-fired configuration than in the wall-fired configuration, with larger differences at higher reburn stoichiometries. Pulverized coal reburning reduced NO_x emissions from 0.77 (baseline) to 0.23 lb/MM Btu (70% reduction) in the wall-fired configuration, and from 0.61 (baseline) to 0.15 lb/MM Btu (75% reduction) in the tangentially-fired configuration. However, NO_x emissions as low as 0.20 and 0.13 lb/MM Btu were obtained in the two burner configurations, respectively. There were significant differences in LOI between the two test coals and minor differences between the two burner configurations. Pulverized coal reburning increased LOI from less than 1% (baseline) to 10-13% for the higher heating value coal and 2-4% for the lower heating value coal.

The reburn stoichiometry was the dominant operating variable affecting NO_x emissions and LOI. An optimum reburn stoichiometry of about 0.84 was identified for low NO_x emissions. Changes in the firing rate, the primary stoichiometry and the final stoichiometry produced relatively minor changes in NO_x emissions and LOI.

OBJECTIVES

The objective of the pilot-scale combustion test program is to demonstrate the NO_x reduction potential of the combined application of low-NO_x burner and pulverized coal reburning technologies firing two Illinois Basin high-volatile bituminous coals using both wall-fired and tangentially-fired furnace configurations. Optimum settings for operating the combustion system are assessed.

INTRODUCTION AND BACKGROUND

Coal production in the Illinois Basin is adversely affected by the Clean Air Act Amendments of 1990. Additional regulations aimed at reducing NO_x emissions from coal-fired boilers are also under consideration. For example, future EPA regulations may limit NO_x emissions during the summer ozone season to 0.15 lb/MM Btu for a thirty-seven state region in the eastern US (including Illinois). This limit would require fuel switching and/or expensive Selective Catalytic Reduction (SCR) NO_x control systems. This would disadvantage Illinois coal producers and utilities in the deregulated utility market, as utilities would select the least costly fuel to burn. Illinois coals typically produce higher NO_x emission levels compared to both natural gas and subbituminous Powder River Basin coals. A potential alternative for compliance with more stringent NO_x emission limits is NO_x control utilizing less costly (relative to fuel switching and SCR) combustion modification techniques. Combustion modification for NO_x control includes low-NO_x burner retrofit, air staging (over fire air application), reburning, and combinations of these techniques.

Low-NO_x burners reduce NO_x formation (from fuel nitrogen) by utilizing multiple combustion air streams to delay fuel/air mixing. This creates a fuel rich environment in the near burner zone which favors the conversion of fuel nitrogen to N_2 instead of NO_x. Generally, NO_x emission levels between 0.4 and 0.5 lb/MM Btu can be achieved with low-NO_x burners burning high-volatile bituminous coals. More stringent NO_x limits require alternate or additional control measures, such as air staging and reburning.

The reburning process reduces NO_x emissions by introducing a secondary (reburn) fuel downstream of a fuel lean primary combustion zone. This creates a fuel rich reburn combustion zone which destroys a portion of the NO_x produced in the primary zone. Over fire air is added further downstream to complete the combustion. Generally, NO_x reductions exceeding 50% can be achieved with reburning. Pulverized coal as a reburn fuel compares favorably with other fuels, including natural gas. In addition, there are several advantages to using pulverized coal as a reburn fuel in a coal-fired boiler, such as avoiding operational and fuel supply problems typically associated with the use of multiple fuels. The combination of low-NO_x burner and reburning technologies may achieve very low NO_x emission levels, thus providing a low-cost alternative to SCR for NO_x control in coal-fired power plants.

The test program presented here is a pilot-scale study to demonstrate the effectiveness of the combined application of low-NO_x burner and pulverized coal reburning technologies to achieve low NO_x emissions (possibly as low as 0.15 lb/MM Btu) at relatively low capital cost burning Illinois Basin coals. The application to two common pulverized coal-fired steam generator types, wall-fired (single-wall or opposed-wall) and tangentially-fired, is investigated. The project may help to maintain existing Illinois coal markets under more stringent NO_x emission limits for new and existing boilers by demonstrating low-cost NO_x compliance options, while continuing to fire 100% Illinois coal. With deregulation on the horizon, utilities are seeking low-cost options to comply with environmental regulations.

The CONSOL 1.5 MM Btu/h combustion pilot plant facility, shown in Figure 1, is uniquely suited to accomplish the objective of this project. Four individual pulverized coal burners can be configured for either wall or tangential firing. Low-NO_x burners are already demonstrated for both the wall-fired and the tangentially-fired configurations. The two low-NO_x firing configurations in the pilot combustor are depicted in Figure 1. It is already demonstrated that the combustion pilot plant provides a realistic simulation of many commercial pulverized coal-fired steam generator furnaces. It provides a similar thermal (total energy and heat flux) and kinetic (time and temperature) environment to that in a specified, including a so-called "typical", utility boiler furnace. The furnace temperature profile is controlled by simultaneously specifying the firing rate and the heat removal rates over the furnace height through up to seven cooling circuits on the walls. The individual flames in the combustion pilot plant also display thermal similarity to commercial low-NO_x burner flames, demonstrated by temperature profile measurements on the burner axis in both pilot and power plant studies. The pilot plant low-NO_x burners and the associated flames scale by one-twelfth to the commercial burners, i.e., one inch at pilot-scale is equivalent to one foot at full-scale.

Using a simulation of the ABB C-E Low-NO_x Concentric Firing System (LNCFS™) Level 3 (see Figure 1), the combustion pilot plant generated NO_x emission levels below 0.35 lb/MM Btu burning a medium-sulfur Pittsburgh seam coal (high-volatile bituminous). Fly ash loss on ignition (LOI) levels were maintained below 4%. Similar NO_x emission levels were demonstrated at the NYSEG Milliken station with slightly higher fly ash LOI levels. These results demonstrated a good pilot simulation under both conventional and low-NO_x firing conditions.

In short, both low-NO_x burner and reburning technologies are effective combustion modification techniques for NO_x control in coal-fired power plants. A combination of these two techniques may achieve very low NO_x emission levels, thus providing a low-cost alternative to SCR for NO_x control. It is demonstrated that the CONSOL combustion pilot plant can successfully simulate commercial pulverized coal-fired steam generator furnaces, both wall-fired and tangentially-fired, as well as combustion modification techniques for NO_x control (including low-NO_x burners and over fire air application). The combined use of low-NO_x burners and pulverized coal reburning is investigated in this study.

EXPERIMENTAL PROCEDURES

The tests were conducted in the CONSOL 1.5 MM Btu/h pilot-scale combustion test facility. The test program included gas emissions measurements (including O_2 and NO_x) and combustion efficiency measurements (fly ash LOI). The variables are those listed in the following table:

Variable	Levels	Low Level	High Level
Firing Configuration	2	--	--
Coal	2	--	--
Primary Firing Rate, Btu/h-ft^3	2	9,000	12,000
Primary Stoichiometry	2	1.05	1.10
Reburn Stoichiometry	4	0.83	0.98
Final Stoichiometry	4	1.10	1.25

The NO_x reduction potential of pulverized coal reburning is assessed in two furnace firing configurations, opposed wall-fired and tangentially-fired, utilizing low-NO_x burners. The two test coals are representative Illinois Basin coals from two CONSOL mines: Rend Lake, a low-sulfur (0.9%), high-nitrogen (1.6%) and higher heating value (12,300 Btu/lb) product from a deep mine in Jefferson county, and Burning Star 2, a high-sulfur (3.2%), low-nitrogen (1.2%) and lower heating value (11,000 Btu/lb) product from a surface mine in Perry county. Both are high-volatile (36-40% dry volatile matter) bituminous coals, with ASTM group classifications of B and C, respectively. As-received analyses of the two coals prior to grinding are presented in Table 1. The two selected primary (before reburn fuel addition) firing rate levels (9,000 and 12,000 Btu/h-ft^3) cover a practical range for dry-bottom wall-fired and tangentially-fired commercial boilers. The two primary stoichiometry levels (1.05 and 1.10) cover a practical range in the application of reburning. The four reburn stoichiometry levels (between 0.83 and 0.98) also cover a practical range in the application of reburning. Four levels (rather than two) are assigned to the reburn stoichiometry because this operating variable is expected to have a dominant effect on NO_x emissions and LOI, and to provide additional data in assessing optimum settings. The final stoichiometry (overall excess air following over fire air addition) is expected to have a minor effect on the outcome of reburning. For selected tests, the variation in the final stoichiometry between 1.10 and 1.25 is investigated.

Overall, four weeks of combustion tests were conducted as listed in the following table:

Test Week	Firing Configuration	Coal	Test Dates
1	Opposed Wall-Fired	Rend Lake	01/20/97-01/24/97
2	Opposed Wall-Fired	Burning Star	01/27/97-01/31/97
3	Tangentially-Fired	Rend Lake	05/12/97-05/16/97
4	Tangentially-Fired	Burning Star	05/05/97-05/09/97

Each week of testing, corresponding to a specific coal and a specific firing configuration, consisted of 36 tests, as listed in the following table:

The Experimental Test Matrix for Each Test Week

Test	Primary Firing Rate	Stoichiometric Ratio			Repeated
No.	Btu/h-ft^3	Primary	Reburn	Final	Test
	Baseline				
1	12,000	1.15	--	--	*
2	9,000	1.15	--	--	*
	Pulverized Coal Reburning				
3	12,000	1.10	0.98	1.15	*
4	12,000	1.10	0.93	1.15	
5	12,000	1.10	0.88	1.15	*
6	12,000	1.10	0.83	1.15	
7	12,000	1.05	0.98	1.15	*
8	12,000	1.05	0.93	1.15	
9	12,000	1.05	0.88	1.15	*
10	12,000	1.05	0.83	1.15	
11	9,000	1.10	0.98	1.15	*
12	9,000	1.10	0.93	1.15	
13	9,000	1.10	0.88	1.15	*
14	9,000	1.10	0.83	1.15	
15	9,000	1.05	0.98	1.15	*
16	9,000	1.05	0.93	1.15	
17	9,000	1.05	0.88	1.15	*
18	9,000	1.05	0.83	1.15	
19	9,000	1.05	as needed	1.15	
	Variation of SR3				
20	12,000	1.05	0.88	1.10	

21	12,000	1.05	0.88	1.20	
22	12,000	1.05	0.88	1.25	
	Air Staging				
23	12,000	0.98	--	1.15	
24	12,000	0.92	--	1.15	
25	9,000	0.98	--	1.15	
26	9,000	0.92	--	1.15	

The experimental test matrix included statistically designed factorial arrangements with respect to four independent variables: firing rate, primary stoichiometry, reburn stoichiometry and final stoichiometry. The following is a brief discussion of the advantages of using statistical designs in evaluating the effects of the variables of interest.

Statistically designed testing allows evaluation of the effects and the statistical significance of the independent variables on a response (NO_x and LOI in this study) using a small number of tests compared to traditional parametric testing in which one variable is varied at a time. Common statistical designs incorporate factorial arrangements, in which selected levels of a factor (independent variable) are tested in combination with selected levels of other factors. A factorial design allows independent evaluation of the individual effects of the variables of interest and their interactions. The simplest design is a two-level factorial, where each independent variable is assigned two levels: a low value and a high value. A two-level factorial is sufficient to produce a linear correlation describing the effects of the variables including two-variable interactions, but is incapable of accounting for non-linear effects. Estimating non-linear effects requires additional testing in which the factors are assigned intermediate values (in addition to low and high). The number of intermediate levels depends on the desired complexity of the design. Multiple regression is used to identify the statistically significant effects and to derive correlations relating the response to the factors. Non-significance is established if the variation of the response due to a factor is small compared to the sum of squares of the difference between the measured and predicted responses (the value minimized in the regression).

Tests 1-2 in the experimental test matrix (previous table) are baseline tests using only low-NO_x burners with no reburn fuel and no over fire air. The results are used to evaluate the reburning effectiveness (NO_x reduction). Tests 3-22 are pulverized coal reburning tests consisting of two sets: (1) Tests 3-18 constitute a factorial set in which the firing rate and the primary stoichiometry are assigned two levels each and the reburn stoichiometry is assigned four levels; and (2) Tests 9 and 20-22 assess the effect of the final stoichiometry at the same firing rate, primary stoichiometry and reburn stoichiometry. Tests 23-26 are air staging tests (using over fire air). The results are used for qualitative comparison with the reburning results.

The two Illinois Basin coal products selected for testing were acquired in twenty ton lots. For each week of testing, a batch of pulverized coal was prepared on site to a typical pulverized coal fineness grind of 70-75% passing 200 mesh with less than 0.5% retained on 50 mesh using the CONSOL C-E Raymond bowl mill with a capacity of up to two tons per hour. The pulverized coal was stored in silos under an inert atmosphere (N_2 gas purge). Coal samples obtained using an automatic pulverized coal sampler prior to silo storage were analyzed for proximate, ultimate, heating value, major elemental and particle size distribution (wet screen). As-fired (pulverized) coal analyses for the four test weeks are presented in Table 2.

Four weeks of testing were conducted in the CONSOL pilot-scale combustion test facility, each corresponding to one coal and one burner firing configuration. Within each week, 36 individual tests, 90-minutes each, assessed the effects of the variables of interest, as previously discussed. A process control and data acquisition system was used for on-line continuous monitoring and storage of real-time process data. Data collection included continuous emissions measurements of O_2, CO_2, CO, SO_2 and NO_x. A fly ash sample was collected during each test and subsequently analyzed for LOI as a measure of the combustion efficiency. The tests included ten replicates, used to estimate the experimental uncertainty. Statistical methods were used to analyze and interpret the test results, including assessing the optimum settings for low NO_x emissions applying the coal reburn system, and assessing the significance levels of the variables affecting NO_x and LOI.

The experimental set-up for reburn testing includes a pulverized coal reburn (feed and control) system independent of the primary fuel feed system, and an over fire air injection system. The pilot combustor is equipped with several utility ports which can be fitted to inject the reburn fuel and the over fire air at the desired locations.

The pulverized coal reburn system consists of two identical water-cooled injectors, each placed on one opposing side of the combustor. The two injectors introduce opposing jets of equal air flow (300 scfh) into the furnace, one transporting the reburn fuel and the other enhancing the mixing between the reburn fuel and the primary combustion products by opposing jet action. Good mixing in the reburn zone is desirable because it generates a sharper dependence on the reburn stoichiometry and a sharper optimum, reduces the reburn fuel requirement by creating a less fuel rich optimum, and enhances the reburning effectiveness (greater NO_x reduction). Each injector is constructed of a 5/8" stainless steel tube connected to a nozzle designed to produce a flat wide flame in the horizontal plane at the injection location. The injector design is shown in Figure 1. The pulverized coal reburn fuel is injected into the furnace with an expansion angle of 22 degrees, through a nozzle providing a smooth transition from the circular cross-section of the injector tube (0.555" inner diameter) to the 1.2"x0.138" rectangular opening at the exit. The reburn fuel jet outlet velocity is estimated at 75 feet per second. The pulverized coal reburn fuel is introduced using an independently controlled volumetric coal feeder and is transported by an independently controlled air flow. During tests in which no reburn fuel is injected (baseline and air staging tests), the transport air flow is minimized (reduced by a factor of six) but not eliminated, to maintain additional cooling to the injectors which helps to prevent damage due to exposure to the high temperatures in the furnace.

The over fire air system is independent of the coal reburn system. It consists of two identical sub-systems, each consisting of three injectors (one per sampling port), constructed of 1" ceramic tubes. Each sub-system is placed on one opposing side of the combustor in the same horizontal plane. In each sub-system, air is introduced into the three injectors through a common header receiving four independently controlled and monitored air flows.

The pulverized coal reburn system and the over fire air system were installed in the upper furnace of the combustion pilot plant at Levels 3 and 7, respectively (see Figure 1), using the two opposing ports at each level. The reburn fuel and the over fire air injection locations satisfied the recommended minimum residence time requirements in the primary and the reburn zones of 0.3 and 0.4 seconds, respectively. Sufficient residence time is necessary in the primary zone to achieve sufficient primary fuel burnout and to minimize oxygen carryover into the reburn zone which would reduce the reburning effectiveness. Furthermore, sufficient residence time is necessary in the reburn zone for NO_x to decay to lower levels.

RESULTS AND DISCUSSION

A pulverized coal reburn system, independent of the primary fuel feed system, and an over fire air system were designed, constructed, tested and installed in the CONSOL 1.5 MM Btu/h combustion pilot plant for pulverized coal reburn testing. The reburn fuel injectors generated a flat wide flame in the horizontal plane at the injection location. Opposing jets with outlet velocities of 75 feet per second achieved adequate mixing between the reburn fuel and the primary combustion products.

Four weeks of testing were completed in opposed wall-fired and tangentially-fired burner configurations burning two Illinois coals. The test coals are two commercial steam high-volatile bituminous coals from the CONSOL Rend Lake and Burning Star 2 mines, differing mainly in sulfur content, nitrogen content and heating value (Tables 1 and 2). The test data and the results for the four test weeks are presented in Tables 3-12, and in Figures 2-5, as follows:

Firing Configuration	Coal	Test Data Table	Replicated Data Table	Reduced Matrix Table	Reburning Results Figure
Opposed Wall-Fired	Rend Lake	3	7	9	2
Opposed Wall-Fired	Burning Star	4	7	10	3

Tangentially-Fired	Rend Lake	5	8	11	4
Tangentially-Fired	Burning Star	6	8	12	5

Each test week, corresponding to a specific coal and a specific firing configuration, consisted of 36 tests, including ten replicates. The test data (Tables 3-6) included the total firing rate, the reburn fuel amount (% of total), the combustion air distribution among primary, two secondary and over fire air flows, the furnace exit gas temperature, the gas emissions measurements of O_2 (wet and dry) and dry CO_2, CO, NO_x and SO_2, and the fly ash analysis data (carbon and ash contents). With few exceptions, CO concentrations below 30 ppm were measured. Consequently, CO variation was not a concern in this study. The test results assessed the effects of firing rate, primary stoichiometry (prior to reburn fuel addition), reburn stoichiometry (following reburn fuel addition), and final stoichiometry (following over fire air addition) on NO_x emissions and LOI in two firing configurations (opposed wall-fired and tangentially-fired) and for two coals (Rend Lake and Burning Star). The NO_x emissions in lb/MM Btu were calculated from measured flue gas O_2 and NO_x concentrations according to EPA Method 19 (40CFR60, Appendix A). LOI was calculated as the percentage of non-ash in the fly ash. Replicated test results (Tables 7 and 8) were used to estimate the experimental uncertainty, presented as 95% confidence levels (also shown in Tables 7 and 8). The replicated results were averaged and included in the reduced test matrices (Tables 9-12).

Four statistically balanced test sets were extracted from the reduced test matrices of Tables 9-12, with NO_x and LOI as the dependent variables, as follows:

Variable	Test Set A Baseline	Test Set B Reburning Fixed SR3	Test Set C Reburning Variable SR3	Test Set D Air Staging
Firing Configuration	2	2	2	2
Coal	2	2	2	2
Total Firing Rate	2	2	--	2
Primary Stoichiometry	--	2	--	2
Reburn Stoichiometry	--	4	--	--
Final Stoichiometry	--	--	4	--

The above table shows the independent variables for each test set and the number of levels for each variable. The baseline tests used only low-NO_x burners, with no reburn fuel and no over fire air. It should be noted that the low-NO_x burners were not operated at optimum conditions for low NO_x emissions, since the focus was on maintaining stable, non-slagging primary flames. Furthermore, none of the tests utilized over fire air in the burner zone. For tests requiring over fire air addition (reburning and air staging), the air was introduced at Level 7 (see Figure 1).

Analysis of the four test sets (A, B, C and D) showed that in all cases (baseline, reburning and air staging), NO_x emissions strongly depended on the firing configuration, with minor differences between the two test coals, whereas LOI strongly depended on the coal burned, with minor differences between the two firing configurations. Additionally, in all cases, changes in the firing rate produced relatively minor changes in NO_x emissions and LOI. Analyses of the individual test sets are further discussed.

Analysis of the pulverized coal reburning results (Test Set B) showed a minor effect of the firing rate on NO_x emissions and LOI. In some cases (apparent at reburn stoichiometries below 0.9), higher firing rates reduced LOI, attributed to higher temperatures in the furnace. However, the effect was relatively small (compared to the experimental uncertainty) and was assumed to be statistically insignificant. Analysis of the results also showed that the effect of the primary stoichiometry was not statistically significant. This result is contrary to prior experience with reburn testing, showing higher NO_x emissions and lower LOI at higher primary stoichiometries. The findings of this study were attributed to relatively small differences between the primary stoichiometry levels, which were typically 0.02-0.03 instead of the set-point difference of 0.05 (between levels 1.05 and 1.10). The small differences between the primary stoichiometry levels were unanticipated and were attributed to experimental limitations caused by the random order in which the tests were performed. As expected, the reburn stoichiometry was the dominant operating variable affecting both NO_x emissions and LOI. Graphical presentations of the pulverized coal reburning results, showing variations of NO_x emissions and LOI with respect to the reburn stoichiometry for the four test weeks are shown in Figures 2-5. Also shown are the baseline results (Test Set A) at a nominal stoichiometry of 1.15. The graphs show the relatively small effects of the firing rate and the primary stoichiometry on NO_x emissions and LOI.

The pulverized coal reburning results showed relatively minor effects of the firing rate and the primary stoichiometry on NO_x emissions and LOI. Furthermore, the firing configuration and the reburn stoichiometry were the dominant variables affecting NO_x emissions, whereas the coal type and the reburn stoichiometry were the dominant variables affecting LOI. Both the baseline (no reburn) and the reburning results were grouped to show only the effects of the dominant variables, as seen in Figure 6. The baseline NO_x emissions were firing configuration dependent, averaging 0.77 lb/MM Btu (0.70-0.85 range) in the wall-fired configuration, and 0.61 lb/MM Btu (0.52-0.72 range) in the tangentially-fired configuration. The baseline LOI values were coal dependent, averaging 1.0% (0.4-2.3 range) for the Rend Lake coal and 0.5% (0.1-1.1 range) for the Burning Star coal. With reburning, the lowest NO_x emissions were 0.20 lb/MM Btu in the wall-fired configuration and 0.13 lb/MM Btu in the tangentially-fired configuration. An optimum reburn stoichiometry for low NO_x emissions was observed (Figure 6). The optimum values (for reburn stoichiometry, NO_x and LOI) were estimated by extracting the results at reburn stoichiometries between 0.82

and 0.86 (range of the optimum), applying a 25% exclusion criteria for NO_x emissions (high values) and LOI (low and high values), and averaging the results. An optimum reburn stoichiometry of 0.84 was obtained. At the optimum, NO_x emissions were 0.23 lb/MM Btu in the wall-fired configuration and 0.15 lb/MM Btu in the tangentially-fired configuration. NO_x reductions due to pulverized coal reburning were 70% and 75%, respectively. NO_x emissions were 0.08-0.16 lb/MM Btu lower in the tangentially-fired configuration than in the wall-fired configuration. The differences were larger at higher reburn stoichiometries. At the optimum, LOI values were 10-13% for the Rend Lake coal and 2-4% for the Burning Star coal. Both coals are high-volatile bituminous coals, but with different ASTM group classifications. The Burning Star coal (Group C) produced lower LOI than the Rend Lake coal (Group B), attributed mainly to its lower rank and higher reactivity.

Analysis of the pulverized coal reburning results in which the final stoichiometry (overall excess air) was varied (Test Set C), again showed that NO_x emissions depended mainly on the firing configuration, whereas LOI depended mainly on the coal burned. The reburn stoichiometry had values between 0.88 and 0.90, and was not a variable in these tests. Variations in the final stoichiometry between 1.12 and 1.27 produced no statistically significant effects on NO_x emissions and LOI. A graphical presentation of the results is shown in Figure 7.

Analysis of the air staging results (Test Set D) also showed that NO_x emissions depended mainly on the firing configuration, whereas LOI depended mainly on the coal burned. In these tests, the primary stoichiometry was fuel rich and over air was added (same location as with reburn testing) to complete the combustion. As expected, the fuel rich primary stoichiometry was the dominant operating variable affecting NO_x emissions and LOI. The effect of the firing rate was not statistically significant. As with the reburning results, the air staging results were grouped to show only the effects of the dominant variables (firing configuration and primary stoichiometry for NO_x, coal and primary stoichiometry for LOI), as seen in Figure 8. A direct comparison between reburning and air staging is difficult and is not attempted in this study. The air staging results are presented only for qualitative evaluation.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were derived from evaluation of the combined application of low-NO_x burners and pulverized coal reburning in the CONSOL 1.5 MM Btu/h combustion pilot plant using opposed wall-fired and tangentially-fired burner configurations to burn two high-volatile bituminous Illinois coals:

1. Very low NO_x emissions (near or below 0.2 lb/MM Btu) were achieved burning high-volatile bituminous Illinois coals, demonstrating that these coals can compete well with natural gas and subbituminous coals in achieving stringent NO_x limits, and that

pulverized coal reburning can be an attractive low-cost alternative to SCR for NO_x control.

2. Pulverized coal reburning reduced NO_x emissions from 0.77 (baseline) to 0.23 lb/MM Btu (70% reduction) in the wall-fired configuration, and from 0.61 (baseline) to 0.15 lb/MM Btu (75% reduction) in the tangentially-fired configuration. NO_x emissions as low as 0.20 and 0.13 lb/MM Btu were obtained for the two burner configurations, respectively.

3. Pulverized coal reburning increased LOI from less than 1% (baseline) to 10-13% for the Rend Lake coal and 2-4% for the Burning Star coal. Both coals are high-volatile bituminous coals, but with different ASTM group classifications. The Burning Star coal (Group C) produced lower LOI than the Rend Lake coal (Group B), attributed mainly to its lower rank and higher reactivity.

4. The reburn stoichiometry was the dominant operating variable affecting NO_x emissions and LOI, with an optimum for low NO_x emissions at 0.84±0.02.

5. There were significant differences in NO_x emissions between the two burner configurations and minor differences between the two test coals. Specifically, NO_x emissions were 0.08-0.16 lb/MM Btu lower in the tangentially-fired configuration than in the opposed wall-fired configuration. The differences were larger at higher reburn stoichiometries.

6. There were significant differences in LOI between the two test coals, attributed mainly to differences in reactivity, and minor differences between the two burner configurations.

7. Changes in the firing rate, the primary stoichiometry and the final stoichiometry produced relatively minor changes in NO_x emissions and LOI.

The following are recommended to enhance the performance of pulverized coal reburning:

1. Reburning can substantially reduce NO_x emissions, but can also substantially increase LOI. Using finer grind coal, especially as the reburn fuel, is recommended to control the increase in LOI and possibly to further reduce NO_x emissions using the reburn system.

2. In this study, the low-NO_x burners were not operated under optimized conditions for low NO_x emissions. Investigating the possibility of further reducing NO_x emissions by reducing NO_x generation in the primary combustion zone is recommended in future studies.

3. In scaling up the reburn system, it is essential that the reburn fuel injectors achieve adequate mixing in the reburn zone, and that sufficient residence times be allowed in the primary and reburn zones. In this study, the primary and reburn zone residence times exceeded 0.7 and 1.0 seconds, respectively.

DISCLAIMER STATEMENT

Nomenclature

ABB C-E	Asea Brown Boveri Combustion Engineering
ASTM	American Society for Testing and Materials
BS	Burning Star Coal Test
Btu	British Thermal Units
C	Carbon
CFR	US Code of Federal Regulations; 40CFR60 Refers to Part 60 of Title 40
CO	Carbon Monoxide
CO_2	Carbon Dioxide
FEGT	Furnace Exit Gas Temperature (Nose Level)
FR	Firing Rate
ft	Feet
h	Hour
lb	Pounds
LNCFS™	The ABB C-E Low-NO_x Concentric Firing System
LOI	Loss on Ignition
MM	Million
NO_x	Nitrogen Oxides = Nitric Oxide (NO) + Nitrogen Dioxide (NO_2)
O_2	Oxygen
OFA	Over Fire Air
PA	Primary Air Flow in the Burner
ppm	Parts Per Million, Volume
RL	Rend Lake Coal Test
SA	Secondary Air Flow in the Burner
SA_{in}	Secondary Air Through Inner Annulus of Dual Register Burner
SA_{out}	Secondary Air Through Outer Annulus of Dual Register Burner
SCR	Selective Catalytic Reduction (for NO_x Control)
scfh	Standard Cubic Feet of Gas Flow Per Hour
SO_2	Sulfur Dioxide
SR	Stoichiometric Ratio, Actual Air to Theoretical Air Ratio
SR1	Stoichiometric Ratio in the Primary (Main) Burner Zone
SR2	Stoichiometric Ratio After Reburn Fuel Addition
SR3	Stoichiometric Ratio After Final Over Fire Air Addition
T	Tangentially-Fired Test
W	Wall-Fired Test

Table 1. As-Received (Crushed) Coal Analyses.

	REND LAKE COAL	BURNING STAR COAL
Total Moisture, %	11.42	13.11
As Determined Moisture, %	6.77	7.94
HGI (At Det. Moisture)	58	53
Btu/lb, Dry	13663	12465
Proximate, Dry %		
Ash	6.02	10.44
Volatile Matter	36.41	40.35
Fixed Carbon	57.57	49.21
Ultimate, Dry %		
Carbon	78.26	69.81
Hydrogen	5.11	5.13
Nitrogen	1.82	1.34
Chlorine	0.400	0.061
Sulfur, Total	1.01	3.82
Ash	6.02	10.44
Oxygen (Difference)	7.38	9.40
Sulfur Forms, Dry %		
Pyritic Sulfur	0.39	1.26
Sulfate Sulfur	0.0	0.4
Organic Sulfur	0.62	2.16
Reducing Ash Fusion Temperature, °F		
I.D.	2446	1990
H=W	2503	2038
H=W/2	2544	2172
Fluid	2596	2274
Oxidizing Ash Fusion Temperature, °F		
I.D.	2552	2428
H=W	2614	2490
H=W/2	2671	2550
Fluid	2710	2565
Major Ash Elements, % (Ignited at 750 °C)		
SiO2	52.78	46.99
Al2O3	25.76	19.32
TiO2	1.37	0.94
Fe2O3	10.68	22.76
CaO	1.42	2.81
MgO	1.15	0.82
Na2O	2.32	0.48
K2O	2.89	2.01
P2O5	0.30	0.07
SO3	1.08	3.63
Undetermined	0.25	0.17

Table 2. As-Fired (Pulverized) Coal Analyses.

	REND LAKE COAL		BURNING STAR COAL	
	Wall-Fired Tests	Tangentially-Fired Tests	Wall-Fired Tests	Tangentially-Fired Tests
As-Fired Moisture, %	4.71	4.22	4.17	3.84
Btu/lb, Dry	13575	13681	12217	12431
Proximate, Dry %				
Ash	6.18	6.08	10.73	10.17
Volatile Matter	36.41	36.63	39.64	40.45
Fixed Carbon	57.41	57.29	49.63	49.38
Ultimate, Dry %				
Carbon	77.01	77.69	69.23	70.07
Hydrogen	5.22	4.82	4.74	4.45
Nitrogen	1.77	1.86	1.29	1.38
Sulfur	1.13	0.97	3.62	3.57
Ash	6.18	6.08	10.73	10.17
Oxygen (Difference)	8.69	8.58	10.39	10.36
Sieve Size, Weight %				
+48	0.1	0.4	0.1	0.2
48x100	4.5	4.9	3.1	5.9
100x200	21.2	23.3	24.7	20.5
200x325	21.4	19.9	25.0	20.4
- 325	52.8	51.5	47.1	53.0

Table 3. Test Data for Rend Lake Coal in Wall-Fired Configuration.

	Test	FR	Reburn	Combustion Air Split				FEGT	Wet	Dry Flue Gas					SO_2	Fly Ash	
	ID	Btu/	Fuel	PA	SA_{in}	SA_{out}	OFA		O_2	O_2	CO_2	CO	NO_x	SO_2	lb/MM	C	Ash
		$h\text{-}ft^3$	%	%	%	%	%	F	%	%	%	ppm	ppm	ppm	Btu	%	%
W	-RL-01	11982	0.0	23.4	24.1	51.7	0.0	1945	3.35	3.92	14.64	0	469	756	1.52	0.5	99.2
W	-RL-02	11982	0.0	23.7	24.3	37.4	13.8	1926	3.16	3.72	14.76	0	346	766	1.52	4.0	94.6
W	-RL-03	11982	0.0	23.5	24.1	29.6	22.1	1913	3.32	3.86	14.66	0	188	773	1.55	13.9	85.1
W	-RL-04	15100	20.6	17.9	18.3	34.0	26.5	1998	3.73	4.24	14.42	0	167	762	1.56	10.6	88.3
W	-RL-05	14147	15.3	20.5	20.7	40.1	14.8	2043	3.09	3.70	14.78	0	268	787	1.56	3.9	94.1
W	-RL-06	15100	20.6	17.2	17.8	31.9	29.7	2024	4.76	5.19	13.59	0	180	718	1.56	7.5	90.7
W	-RL-07	13548	11.6	21.0	21.3	39.1	14.6	2044	3.21	3.77	14.79	0	306	781	1.56	3.4	95.5
W	-RL-08	15100	20.6	19.8	19.9	37.2	19.4	2107	2.52	3.10	15.47	0	206	816	1.57	7.8	90.9
W	-RL-09	15781	24.1	18.1	18.6	36.6	23.2	2112	3.54	4.06	14.63	0	215	773	1.57	5.0	94.0
W	-RL-10	15100	20.6	18.9	19.2	35.1	23.2	2121	2.99	3.56	15.05	0	198	802	1.58	6.6	91.7
W	-RL-11	14147	15.3	20.1	20.5	40.8	14.8	2069	2.96	3.55	14.92	0	326	776	1.53	4.4	95.0
W	-RL-12	16734	28.4	16.9	17.5	34.5	27.9	2166	3.17	3.71	14.88	0	225	794	1.58	11.5	87.2
W	-RL-13	14910	19.6	19.2	19.7	38.5	18.9	2137	2.96	3.55	15.03	0	305	802	1.58	5.5	93.3
W	-RL-14	15781	24.1	17.9	18.9	36.3	23.4	2171	3.17	3.66	14.92	0	261	797	1.58	8.9	91.3
W	-RL-15	13534	11.5	20.1	20.6	41.2	14.2	2092	3.72	4.24	14.10	0	390	771	1.58	1.0	98.7
W	-RL-16	15999	25.1	17.6	18.1	33.2	27.7	2121	3.12	3.70	14.65	0	216	806	1.60	11.7	89.4
W	-RL-17	14283	16.1	19.9	20.2	37.2	19.0	2106	3.27	3.81	14.49	0	297	807	1.61	4.0	94.8
W	-RL-18	15114	20.7	18.7	19.0	35.4	23.2	2110	3.41	3.98	14.35	0	216	805	1.62	5.8	93.4
W	-RL-19	11982	0.0	23.5	24.0	51.8	0.0	2090	3.21	3.77	14.45	0	501	832	1.66	0.3	99.4
W	-RL-20	9259	0.0	26.7	26.5	45.9	0.0	1941	3.35	3.64	14.84	13	575	795	1.57	0.3	99.8
W	-RL-21	9259	0.0	27.2	26.9	31.1	13.8	1891	3.28	3.61	14.86	13	455	793	1.57	2.3	97.5
W	-RL-22	9259	0.0	26.6	26.3	28.8	17.3	1861	3.39	3.72	14.77	14	331	775	1.54	8.5	91.6
W	-RL-23	11070	16.4	22.8	23.0	34.4	14.6	1935	3.48	3.79	14.85	23	383	757	1.51	7.2	92.1
W	-RL-24	10607	12.7	23.1	22.9	34.5	14.5	1879	3.36	3.66	15.11	9	328	755	1.50	5.3	94.1
W	-RL-25	12377	25.2	20.5	20.3	31.4	23.3	1939	3.44	3.76	15.14	19	202	751	1.50	11.3	88.1
W	-RL-26	11832	21.7	21.1	20.6	30.4	23.3	1937	3.62	3.95	15.00	21	205	736	1.48	9.0	90.9
W	-RL-27	11083	16.5	22.9	22.2	35.0	15.0	1938	3.62	3.92	15.00	15	390	730	1.47	3.3	95.6
W	-RL-28	13112	29.4	19.0	18.9	30.0	27.8	2000	3.20	3.60	15.16	32	143	722	1.43	10.8	86.8
W	-RL-29	11682	20.7	21.5	21.1	33.2	19.5	1968	3.50	3.84	14.95	20	277	712	1.43	4.5	93.7
W	-RL-30	12377	25.2	20.3	20.2	31.4	23.6	1978	3.58	4.05	14.80	28	219	704	1.43	6.0	93.2
W	-RL-31	10607	12.7	23.6	23.5	33.1	14.7	1918	3.77	4.11	14.70	14	365	693	1.41	2.4	96.2
W	-RL-32	12513	26.0	19.3	19.7	28.8	27.7	1951	3.63	3.97	14.91	36	146	701	1.41	8.1	89.9
W	-RL-33	11165	17.1	21.8	21.9	32.4	19.1	1929	3.81	4.13	14.74	19	279	690	1.40	4.0	94.5
W	-RL-34	11832	21.7	20.6	20.7	30.8	23.3	1936	3.83	4.18	14.72	22	205	686	1.40	4.9	93.3
W	-RL-35	9259	0.0	27.3	27.1	44.5	0.0	1917	3.45	3.80	14.93	11	619	688	1.37	0.3	99.4
W	-RL-36	11573	20.0	21.3	21.0	31.3	21.6	1913	3.86	4.19	14.65	18	250	674	1.38	3.9	94.8

Table 4. Test Data for Burning Star Coal in Wall-Fired Configuration.

	Test	FR	Reburn	Combustion Air Split				FEGT	Wet	Dry Flue Gas					SO_2	Fly Ash	
	ID	Btu/	Fuel	PA	SA_{in}	SA_{out}	OFA		O_2	O_2	CO_2	CO	NO_x	SO_2	lb/MM	C	Ash
		h-ft^3	%	%	%	%	%	F	%	%	%	ppm	ppm	ppm	Btu	%	%
W	-BS-01	12323	0.0	23.2	23.1	52.9	0.0	1966	3.22	3.67	14.88	10	530	2785	5.53	0.0	99.9
W	-BS-02	12323	0.0	23.1	23.3	38.9	14.0	1932	3.04	3.50	15.16	11	321	2829	5.57	0.7	99.1
W	-BS-03	12323	0.0	23.2	22.8	30.7	22.6	1936	3.12	3.53	15.17	12	177	2815	5.55	1.9	97.6
W	-BS-04	15466	20.3	17.1	17.5	35.7	26.3	2017	3.55	3.95	14.81	13	175	2812	5.68	1.2	98.1
W	-BS-05	14492	15.0	20.0	19.9	41.5	14.8	2054	3.03	3.47	15.21	12	360	2907	5.71	0.5	99.3
W	-BS-06	15466	20.3	16.3	17.3	33.4	29.8	2027	4.48	4.81	14.11	11	191	2674	5.69	1.0	98.5
W	-BS-07	13888	11.3	20.0	20.8	40.4	14.8	2043	3.13	3.56	15.17	11	360	2882	5.69	0.4	99.5
W	-BS-08	15478	20.4	18.7	19.3	38.4	19.9	2121	2.23	2.65	16.02	15	205	3052	5.73	1.5	98.0
W	-BS-09	16205	24.0	17.2	18.0	37.8	23.6	2142	3.10	3.53	15.29	14	220	2908	5.73	1.2	98.1
W	-BS-10	15478	20.4	17.9	18.8	36.4	23.4	2124	3.16	3.59	15.23	13	208	2894	5.72	0.8	98.7
W	-BS-11	14505	15.0	19.2	20.0	42.0	14.9	2074	3.12	3.55	15.04	12	342	2894	5.71	0.6	99.2
W	-BS-12	17191	28.3	16.1	17.0	35.3	28.3	2189	2.91	3.39	15.28	18	188	2954	5.77	1.8	97.6
W	-BS-13	15293	19.4	18.3	19.1	39.8	19.2	2146	2.88	3.11	15.16	14	237	2955	5.69	1.0	98.5
W	-BS-14	16218	24.0	17.3	18.1	37.5	23.6	2180	2.92	3.59	15.04	17	208	2961	5.86	1.9	97.0
W	-BS-15	13876	11.2	20.1	20.6	40.6	14.6	2068	2.92	3.44	15.02	12	309	2900	5.69	0.6	99.2
W	-BS-16	16452	25.1	17.2	17.5	34.1	27.8	2172	2.84	3.60	15.20	17	175	2936	5.81	1.9	97.3
W	-BS-17	14603	15.6	19.2	19.6	38.4	19.2	2123	2.88	2.95	15.34	14	255	2919	5.57	1.2	98.4
W	-BS-18	15466	20.3	17.9	18.4	36.7	23.4	2161	2.92	3.05	15.14	17	214	2919	5.60	1.8	97.4
W	-BS-19	12323	0.0	23.1	23.2	53.0	0.0	2096	3.07	3.31	15.06	12	498	2901	5.65	0.2	98.6
W	-BS-20	9119	0.0	26.7	26.6	45.8	0.0	1929	3.98	4.23	14.67	10	539	2703	5.55	0.0	99.9
W	-BS-21	9119	0.0	26.9	26.7	31.3	14.1	1835	3.60	3.95	14.47	12	403	2717	5.49	0.4	99.3
W	-BS-22	9119	0.0	26.5	26.4	29.1	17.1	1850	3.73	4.06	14.66	12	325	2730	5.55	0.8	97.6
W	-BS-23	10918	16.5	23.3	23.0	33.7	14.8	1912	3.59	3.92	14.45	14	346	2769	5.58	0.6	98.9
W	-BS-24	10438	12.6	23.7	23.4	32.8	14.9	1900	3.16	3.60	14.64	17	360	2833	5.61	0.8	98.4
W	-BS-25	12151	24.9	20.4	20.4	31.2	23.5	1927	3.46	3.82	14.46	24	194	2817	5.64	2.5	96.5
W	-BS-26	11658	21.8	20.6	20.8	30.8	23.1	1925	3.57	3.93	14.37	23	212	2782	5.61	1.4	97.8
W	-BS-27	10931	16.6	22.4	22.7	34.9	15.0	1914	3.61	3.96	14.33	21	352	2765	5.59	0.5	99.1
W	-BS-28	12939	29.5	19.0	19.1	29.7	28.0	1952	3.41	3.82	14.68	24	165	2831	5.67	3.0	95.9
W	-BS-29	11535	20.9	21.5	21.6	32.8	19.4	1938	3.39	3.81	14.59	23	280	2825	5.66	1.2	98.1
W	-BS-30	12151	24.9	20.1	20.6	30.9	23.8	1967	3.37	3.77	14.66	30	208	2857	5.71	2.1	96.7
W	-BS-31	10438	12.6	23.5	23.4	33.0	14.9	1911	3.65	4.00	14.35	31	403	2787	5.64	0.4	99.4
W	-BS-32	12336	26.1	19.9	20.0	28.3	27.5	1958	3.60	3.95	14.47	45	175	2836	5.73	3.3	94.8
W	-BS-33	10992	17.0	22.3	21.9	31.8	19.2	1914	3.78	4.11	14.22	46	333	2778	5.66	0.9	98.5
W	-BS-34	11658	21.8	21.0	20.7	30.5	23.1	1936	3.58	3.92	14.35	53	228	2823	5.69	2.0	97.1
W	-BS-35	9119	0.0	27.7	27.0	44.4	0.0	1879	3.86	4.17	13.96	58	546	2710	5.54	0.1	99.9
W	-BS-36	11362	19.7	21.6	21.5	30.5	21.6	1897	3.68	4.03	14.14	74	270	2793	5.67	1.7	97.2

Table 5. Test Data for Rend Lake Coal in Tangentially-Fired Configuration.

	Test	FR	Reburn	Combustion Air Split				FEGT	Wet	Dry Flue Gas					SO_2	Fly Ash	
	ID	Btu/	Fuel	PA	SA_{in}	SA_{out}	OFA		O_2	O_2	CO_2	CO	NO_x	SO_2	lb/MM	C	Ash
		h-ft^3	%	%	%	%	%	F	%	%	%	ppm	ppm	ppm	Btu	%	%
T	-RL-01	12138	0.0	24.0	38.2	37.0	0.0	1905	3.40	4.04	14.19	13	458	679	1.36	0.3	99.4
T	-RL-02	12138	0.0	24.5	30.6	29.9	14.2	1878	3.22	4.00	14.21	15	314	677	1.35	2.3	97.0
T	-RL-03	12138	0.0	23.7	27.8	28.8	18.9	1871	3.36	3.97	14.35	16	224	699	1.39	10.5	88.0
T	-RL-04	15117	19.7	17.9	25.9	26.4	26.2	1940	3.85	4.44	14.12	20	140	690	1.42	11.5	87.8
T	-RL-05	14317	15.2	20.8	30.6	29.6	15.1	2005	3.16	3.82	14.57	15	318	700	1.38	4.0	94.9
T	-RL-06	15131	19.8	17.6	24.4	24.9	29.7	1933	4.57	5.15	13.38	16	137	637	1.37	11.6	87.1
T	-RL-07	13586	10.7	21.5	29.6	30.3	14.6	1988	3.28	3.93	14.34	14	295	687	1.37	3.5	95.7
T	-RL-08	15117	19.7	20.0	27.9	28.7	19.6	2028	2.63	3.26	14.97	17	156	716	1.37	8.1	90.4
T	-RL-09	16000	24.1	18.4	27.6	26.8	23.6	2053	3.40	4.04	14.34	17	180	688	1.38	6.2	92.8
T	-RL-10	15117	19.7	19.1	26.7	27.3	23.3	2060	3.12	3.76	14.54	17	159	696	1.37	6.7	92.3
T	-RL-11	14331	15.3	20.7	30.5	29.9	15.0	2018	3.18	3.77	14.45	13	338	686	1.35	3.4	95.8
T	-RL-12	16952	28.4	17.3	26.1	25.0	28.2	2076	3.24	3.89	14.41	16	181	692	1.37	8.5	90.1
T	-RL-13	15117	19.7	19.6	29.4	27.6	19.7	2072	2.98	3.68	14.48	14	261	669	1.31	5.1	93.9
T	-RL-14	16000	24.1	18.7	27.9	25.9	24.0	2095	3.14	3.68	14.45	17	196	658	1.29	7.9	91.2
T	-RL-15	13600	10.8	21.5	29.8	29.8	14.8	2067	3.20	3.72	14.30	14	344	647	1.27	2.2	97.4
T	-RL-16	16069	24.5	17.7	25.2	25.7	28.0	2047	3.18	3.68	14.59	18	155	667	1.31	8.5	89.8
T	-RL-17	14303	15.1	20.0	28.3	28.9	19.0	2048	3.18	3.62	14.62	14	266	703	1.37	5.1	94.2
T	-RL-18	15117	19.7	18.6	26.8	27.7	23.3	2072	3.02	3.46	14.80	15	187	723	1.40	6.6	92.4
T	-RL-19	12138	0.0	23.7	38.1	37.4	0.0	2055	3.46	3.88	14.29	11	549	705	1.40	0.2	99.5
T	-RL-20	9379	0.0	27.9	35.6	35.6	0.0	1909	3.45	3.87	14.05	12	450	651	1.29	0.9	96.0
T	-RL-21	9379	0.0	28.2	28.6	28.4	13.8	1858	3.34	3.73	14.22	14	220	657	1.29	0.9	98.6
T	-RL-22	9379	0.0	27.4	26.3	27.5	17.8	1833	3.57	3.99	14.01	16	161	645	1.29	5.1	93.7
T	-RL-23	11172	16.0	23.8	28.4	27.9	14.9	1902	3.22	3.65	14.43	18	212	686	1.34	3.8	94.8
T	-RL-24	10620	11.7	24.0	27.4	28.9	14.7	1905	3.32	3.77	14.29	15	230	684	1.35	2.7	96.2
T	-RL-25	12510	25.0	21.3	25.7	25.1	23.3	1902	3.27	3.84	14.33	26	94	646	1.28	12.0	84.1
T	-RL-26	11848	20.8	21.6	25.0	25.7	23.1	1904	3.49	4.01	14.17	26	95	636	1.27	10.0	88.2
T	-RL-27	11200	16.3	23.3	28.5	28.3	15.0	1926	3.45	4.01	14.20	19	234	650	1.30	3.1	96.1
T	-RL-28	13310	29.5	19.2	24.2	24.1	28.2	1976	3.09	3.59	14.75	29	90	676	1.32	8.9	89.2
T	-RL-29	11862	20.9	21.9	27.2	26.8	19.4	1962	3.13	3.68	14.60	24	142	661	1.30	7.6	91.4
T	-RL-30	12510	25.0	20.5	25.6	25.1	24.3	1951	3.28	3.89	14.32	17	108	641	1.27	9.4	88.1
T	-RL-31	10620	11.7	24.0	27.5	28.7	14.7	1929	3.29	3.86	14.27	14	237	664	1.32	3.4	95.5
T	-RL-32	12565	25.4	20.0	23.4	24.7	27.6	1944	3.45	4.02	14.28	20	85	667	1.33	11.3	87.0
T	-RL-33	11200	16.3	22.2	26.0	27.8	19.2	1927	3.83	4.42	13.89	15	195	648	1.33	3.1	94.8
T	-RL-34	11862	20.9	20.8	24.7	26.8	23.2	1916	4.10	4.63	13.76	18	143	639	1.33	6.4	92.4
T	-RL-35	9379	0.0	28.6	35.6	34.8	0.0	1895	4.05	4.58	13.64	12	397	633	1.31	0.2	99.4
T	-RL-36	11558	18.9	22.6	25.5	25.5	21.5	1885	3.93	4.50	13.88	17	160	638	1.31	4.5	94.2

Table 6. Test Data for Burning Star Coal in Tangentially-Fired Configuration.

	Test	FR	Reburn	Combustion Air Split				FEGT	Wet	Dry Flue Gas					SO_2	Fly Ash	
	ID	Btu/	Fuel	PA	SA_{in}	SA_{out}	OFA		O_2	O_2	CO_2	CO	NO_x	SO_2	lb/MM	C	Ash
		h-ft^3	%	%	%	%	%	F	%	%	%	ppm	ppm	ppm	Btu	%	%
T	-BS-01	12582	0.0	23.5	38.1	37.7	0.0	1953	3.22	3.73	14.49	11	384	2619	5.14	0.1	99.9
T	-BS-02	12582	0.0	23.5	31.0	30.7	14.0	1914	3.17	3.77	14.48	12	262	2648	5.21	0.3	99.5
T	-BS-03	12582	0.0	23.0	28.1	29.3	18.8	1903	3.25	3.72	14.48	13	179	2658	5.21	1.3	98.3
T	-BS-04	15703	19.9	17.8	25.9	26.5	26.3	1975	3.51	4.08	14.36	14	120	2650	5.31	1.5	97.6
T	-BS-05	14784	14.9	20.4	31.0	29.7	15.0	2030	2.89	3.41	14.91	12	224	2750	5.30	0.6	99.2
T	-BS-06	15690	19.8	17.0	25.0	25.2	29.5	1924	4.32	4.83	13.78	13	115	2477	5.19	2.1	96.9
T	-BS-07	14042	10.4	20.4	30.2	30.7	14.7	1977	2.91	3.42	14.93	12	229	2723	5.25	1.2	98.4
T	-BS-08	15061	16.5	19.1	28.5	29.1	19.7	2015	2.64	3.16	15.21	12	138	2778	5.28	1.6	97.7
T	-BS-09	16533	23.9	17.8	28.0	27.1	23.6	2062	2.95	3.42	15.03	12	148	2757	5.32	1.3	98.0
T	-BS-10	15715	19.9	18.2	27.0	28.0	23.2	2076	2.80	3.28	15.10	10	139	2751	5.26	1.0	98.7
T	-BS-11	14809	15.0	19.4	30.8	31.1	14.8	2066	2.98	3.47	14.78	12	250	2756	5.33	0.4	99.4
T	-BS-12	17565	28.4	16.5	26.2	26.0	28.0	2150	2.85	3.38	14.89	14	133	2765	5.32	0.8	98.9
T	-BS-13	15640	19.5	18.5	29.6	29.0	19.2	2117	2.93	3.46	14.71	14	175	2743	5.30	0.5	99.4
T	-BS-14	16546	24.0	17.5	27.8	27.6	23.6	2153	2.82	3.41	14.78	15	141	2766	5.33	0.6	99.1
T	-BS-15	14017	10.2	20.7	29.8	30.7	14.7	2104	2.93	3.71	14.38	16	223	2659	5.21	0.4	99.2
T	-BS-16	16596	24.2	17.6	25.7	25.4	27.9	2106	3.06	3.66	14.44	18	113	2646	5.17	1.0	98.8
T	-BS-17	14797	15.0	19.8	28.8	28.6	19.0	2068	3.09	3.63	14.58	15	172	2731	5.33	0.9	98.6
T	-BS-18	15703	19.9	18.4	27.5	27.4	23.1	2110	2.83	3.38	14.84	15	128	2769	5.33	0.8	99.0
T	-BS-19	12582	0.0	23.2	38.1	37.9	0.0	2077	3.19	3.70	14.40	13	411	2628	5.15	0.8	98.0
T	-BS-20	9311	0.0	28.3	35.6	35.1	0.0	1872	3.48	4.03	13.91	13	366	2501	5.00	0.1	99.6
T	-BS-21	9311	0.0	28.7	28.5	27.9	13.9	1811	3.49	3.98	13.90	13	247	2524	5.03	0.3	99.4
T	-BS-22	9311	0.0	28.0	25.8	27.1	18.1	1788	3.66	4.13	13.76	14	189	2502	5.03	1.1	98.3
T	-BS-23	11148	16.5	24.4	27.9	27.6	14.9	1858	3.35	3.88	14.05	13	236	2584	5.12	0.6	98.8
T	-BS-24	10556	11.8	24.6	27.4	28.2	14.6	1851	3.37	3.85	14.00	12	247	2553	5.05	0.5	98.8
T	-BS-25	12444	25.2	21.6	25.4	24.9	23.4	1857	3.21	3.66	14.17	14	112	2580	5.04	2.4	96.3
T	-BS-26	11790	21.0	21.7	24.9	25.5	23.1	1874	3.18	3.62	14.14	13	110	2573	5.02	1.7	97.1
T	-BS-27	11148	16.5	24.1	28.0	27.8	14.9	1880	3.28	3.77	13.94	11	245	2536	4.99	0.5	99.1
T	-BS-28	13211	29.5	19.9	23.9	23.6	28.1	1935	3.16	3.64	14.13	14	117	2600	5.08	1.6	97.4
T	-BS-29	11802	21.1	22.5	27.0	26.1	19.5	1913	3.20	3.65	14.02	12	167	2568	5.02	0.9	98.5
T	-BS-30	12419	25.0	21.4	25.4	24.5	23.9	1852	3.35	3.87	14.28	16	101	2533	5.01	2.5	96.4
T	-BS-31	10556	11.8	24.9	27.2	27.9	14.7	1843	3.49	3.98	14.07	13	241	2525	5.03	0.5	99.2
T	-BS-32	12494	25.5	20.6	23.0	24.1	27.7	1890	3.33	3.84	14.29	17	91	2608	5.15	2.0	97.1
T	-BS-33	11148	16.5	23.0	26.0	27.0	18.9	1863	3.34	3.93	14.15	15	155	2583	5.13	0.9	98.5
T	-BS-34	11802	21.1	21.4	24.8	26.1	22.8	1878	3.30	3.85	14.25	16	97	2626	5.19	1.4	97.8
T	-BS-35	9311	0.0	28.6	35.9	34.4	0.0	1843	3.71	4.41	13.55	13	355	2488	5.08	0.0	99.9
T	-BS-36	11525	19.2	22.5	25.5	25.6	21.4	1838	3.54	3.99	14.09	15	124	2609	5.20	1.4	97.8

Table 7. Repeatability Data in Wall-Fired Configuration.

Test ID	Firing Rate Btu/h-ft^3	SR1	SR2	SR3	NO_x lb/MM Btu	LOI %
Rend Lake Coal						
W-RL-01	11982	1.19	1.20	1.20	0.678	0.8
W-RL-19	11982	1.16	1.17	1.17	0.718	0.6
W-RL-05	14147	1.11	0.99	1.16	0.383	5.9
W-RL-11	14147	1.13	1.00	1.18	0.461	5.0
W-RL-09	15781	1.10	0.88	1.14	0.313	6.0
W-RL-14	15781	1.12	0.89	1.16	0.372	8.7
W-RL-07	13548	1.08	1.01	1.18	0.439	4.5
W-RL-15	13534	1.11	1.03	1.20	0.575	1.3
W-RL-10	15100	1.08	0.90	1.17	0.280	8.3
W-RL-18	15114	1.08	0.90	1.17	0.313	6.6
W-RL-20	9259	1.16	1.17	1.17	0.818	0.2
W-RL-35	9259	1.12	1.13	1.13	0.889	0.6
W-RL-24	10607	1.08	1.01	1.18	0.467	6.0
W-RL-27	11083	1.10	0.98	1.15	0.564	4.4
W-RL-25	12377	1.08	0.86	1.12	0.289	11.9
W-RL-30	12377	1.10	0.87	1.14	0.319	6.8
W-RL-23	11070	1.07	0.96	1.12	0.550	7.9
W-RL-31	10607	1.07	0.99	1.16	0.534	3.8
W-RL-26	11832	1.06	0.88	1.15	0.297	9.1
W-RL-34	11832	1.07	0.89	1.17	0.301	6.7
95% Confidence Level					**0.034**	**1.4**
Burning Star Coal						
W-BS-01	12323	1.16	1.17	1.17	0.757	0.0
W-BS-19	12323	1.16	1.16	1.16	0.697	1.4
W-BS-05	14492	1.09	0.97	1.13	0.508	0.7
W-BS-11	14505	1.10	0.98	1.15	0.485	0.8
W-BS-09	16205	1.10	0.88	1.15	0.312	1.9
W-BS-14	16218	1.09	0.87	1.14	0.296	3.0
W-BS-07	13888	1.07	1.00	1.17	0.511	0.5
W-BS-15	13876	1.05	0.98	1.15	0.436	0.8
W-BS-10	15478	1.07	0.89	1.17	0.296	1.3
W-BS-18	15466	1.08	0.90	1.18	0.295	2.6
W-BS-20	9119	1.18	1.19	1.19	0.796	0.1
W-BS-35	9119	1.15	1.16	1.16	0.803	0.2
W-BS-23	10918	1.08	0.96	1.13	0.502	1.1
W-BS-33	10992	1.09	0.96	1.19	0.488	1.5
W-BS-25	12151	1.11	0.89	1.16	0.280	3.5
W-BS-30	12151	1.09	0.87	1.14	0.299	3.3
W-BS-24	10438	1.06	0.99	1.16	0.512	1.6
W-BS-31	10438	1.08	1.00	1.18	0.587	0.6
W-BS-34	11658	1.09	0.91	1.18	0.331	2.9
W-BS-36	11362	1.07	0.91	1.16	0.394	2.8
95% Confidence Level					**0.022**	**0.4**

Table 8. Repeatability Data in Tangentially-Fired Configuration.

Test ID	Firing Rate Btu/h-ft^3	SR1	SR2	SR3	NO_x lb/MM Btu	LOI %
Rend Lake Coal						
T-RL-01	12138	1.11	1.12	1.12	0.660	0.6
T-RL-19	12138	1.15	1.16	1.16	0.783	0.5
T-RL-05	14317	1.08	0.96	1.13	0.452	5.1
T-RL-11	14331	1.09	0.97	1.14	0.479	4.2
T-RL-09	16000	1.08	0.86	1.13	0.259	7.2
T-RL-14	16000	1.07	0.86	1.13	0.276	8.8
T-RL-07	13586	1.06	1.00	1.17	0.422	4.3
T-RL-15	13600	1.05	0.99	1.16	0.486	2.6
T-RL-10	15117	1.06	0.89	1.16	0.225	7.7
T-RL-18	15117	1.06	0.90	1.17	0.260	7.6
T-RL-20	9379	1.15	1.16	1.16	0.642	4.0
T-RL-35	9379	1.13	1.14	1.14	0.591	0.6
T-RL-23	11172	1.10	0.98	1.15	0.298	5.2
T-RL-27	11200	1.12	1.00	1.17	0.336	3.9
T-RL-24	10620	1.09	1.03	1.20	0.326	3.8
T-RL-31	10620	1.08	1.01	1.19	0.338	4.5
T-RL-34	11862	1.09	0.92	1.20	0.213	7.6
T-RL-36	11558	1.04	0.90	1.15	0.237	5.8
T-RL-30	12510	1.08	0.86	1.14	0.154	11.9
T-RL-32	12565	1.08	0.86	1.18	0.122	13.0
95% Confidence Level					**0.026**	**0.8**
Burning Star Coal						
T-BS-01	12582	1.12	1.12	1.12	0.542	0.1
T-BS-19	12582	1.14	1.14	1.14	0.579	2.0
T-BS-05	14784	1.07	0.95	1.12	0.310	0.8
T-BS-11	14809	1.08	0.96	1.13	0.348	0.6
T-BS-09	16533	1.07	0.86	1.12	0.205	2.0
T-BS-14	16546	1.06	0.84	1.11	0.195	0.9
T-BS-07	14042	1.06	0.99	1.16	0.318	1.6
T-BS-15	14017	1.02	0.96	1.13	0.314	0.8
T-BS-10	15715	1.05	0.88	1.15	0.191	1.3
T-BS-18	15703	1.05	0.88	1.15	0.177	1.0
T-BS-20	9311	1.13	1.14	1.14	0.526	0.4
T-BS-35	9311	1.09	1.10	1.10	0.522	0.0
T-BS-23	11148	1.06	0.94	1.11	0.336	1.2
T-BS-27	11148	1.07	0.96	1.12	0.347	0.9
T-BS-24	10556	1.05	0.99	1.16	0.351	1.2
T-BS-31	10556	1.03	0.97	1.14	0.345	0.8
T-BS-34	11802	1.04	0.88	1.13	0.138	2.2
T-BS-36	11525	1.02	0.88	1.12	0.178	2.2
T-BS-30	12419	1.04	0.83	1.09	0.144	3.6
T-BS-32	12494	1.02	0.81	1.12	0.129	2.9
95% Confidence Level					**0.011**	**0.4**

Table 9. Reduced Test Matrix for Rend Lake Coal in Wall-Fired Configuration.

Test ID	Firing Rate Btu/h-ft^3	SR1	SR2	SR3	NO_x lb/MM Btu	LOI %
Baseline						
W-RL-01,19	11982	1.17	1.18	1.18	0.698	0.7
W-RL-20,35	9259	1.14	1.15	1.15	0.854	0.4
Pulverized Coal Reburning Factorial Tests: Firing Rate, SR1, SR2						
W-RL-05,11	14147	1.12	0.99	1.17	0.422	5.5
W-RL-13	14910	1.14	0.96	1.18	0.432	6.7
W-RL-09,14	15781	1.11	0.88	1.15	0.343	7.4
W-RL-12	16734	1.12	0.84	1.17	0.321	12.9
W-RL-07,15	13541	1.10	1.02	1.19	0.507	2.9
W-RL-17	14283	1.09	0.96	1.18	0.427	5.2
W-RL-10,18	15107	1.08	0.90	1.17	0.297	7.4
W-RL-16	15999	1.06	0.83	1.15	0.308	10.6
W-RL-24,27	10845	1.09	0.99	1.16	0.516	5.2
W-RL-29	11682	1.11	0.93	1.16	0.399	6.3
W-RL-25,30	12377	1.09	0.87	1.13	0.304	9.3
W-RL-28	13112	1.11	0.83	1.15	0.203	13.2
W-RL-23,31	10839	1.07	0.97	1.14	0.542	5.8
W-RL-33	11165	1.08	0.95	1.18	0.408	5.5
W-RL-26,34	11832	1.07	0.89	1.16	0.299	7.9
W-RL-32	12513	1.06	0.84	1.16	0.212	10.1
Variation of SR3						
W-RL-04	15100	1.09	0.91	1.24	0.246	11.7
W-RL-06	15100	1.06	0.88	1.26	0.281	9.3
W-RL-08	15100	1.09	0.90	1.12	0.284	9.1
W-RL-10,18	15107	1.08	0.90	1.17	0.297	7.4
Air Staging						
W-RL-02	11982	1.02	1.02	1.19	0.495	5.4
W-RL-03	11982	0.93	0.94	1.21	0.271	14.9
W-RL-21	9259	0.97	0.99	1.14	0.646	2.5
W-RL-22	9259	0.95	0.97	1.17	0.473	8.4

Table 10. Reduced Test Matrix for Burning Star Coal in Wall-Fired Configuration.

Test ID	Firing Rate Btu/h-ft^3	SR1	SR2	SR3	NO_x lb/MM Btu	LOI %
Baseline						
W-BS-01,19	12323	1.16	1.17	1.17	0.727	0.7
W-BS-20,35	9119	1.16	1.18	1.18	0.800	0.1
Pulverized Coal Reburning Factorial Tests: Firing Rate, SR1, SR2						
W-BS-05,11	14499	1.09	0.97	1.14	0.497	0.8
W-BS-13	15293	1.09	0.92	1.14	0.328	1.6
W-BS-09,14	16212	1.10	0.87	1.14	0.304	2.4
W-BS-12	17191	1.08	0.81	1.13	0.264	2.4
W-BS-07,15	13882	1.06	0.99	1.16	0.474	0.6
W-BS-17	14603	1.08	0.96	1.18	0.350	1.7
W-BS-10,18	15472	1.08	0.90	1.17	0.296	2.0
W-BS-16	16452	1.07	0.84	1.17	0.249	2.7
W-BS-27	10931	1.10	0.98	1.15	0.511	0.9
W-BS-29	11535	1.11	0.93	1.15	0.403	1.9
W-BS-25,30	12151	1.10	0.88	1.15	0.290	3.4
W-BS-28	12939	1.10	0.82	1.14	0.238	4.2
W-BS-24,31	10438	1.07	0.99	1.17	0.550	1.1
W-BS-23,33	10955	1.08	0.96	1.16	0.495	1.3
W-BS-34,36	11510	1.08	0.91	1.17	0.363	2.9
W-BS-32	12336	1.08	0.85	1.17	0.254	5.2
Variation of SR3						
W-BS-04	15466	1.06	0.89	1.20	0.254	1.9
W-BS-06	15466	1.07	0.89	1.27	0.292	1.6
W-BS-08	15478	1.07	0.90	1.12	0.277	2.0
W-BS-10,18	15472	1.08	0.90	1.17	0.296	2.0
Air Staging						
W-BS-02	12323	0.98	0.99	1.15	0.454	0.9
W-BS-03	12323	0.88	0.89	1.15	0.251	2.4
W-BS-21	9119	1.00	1.01	1.18	0.585	0.7
W-BS-22	9119	0.98	0.99	1.20	0.475	2.4

Table 11. Reduced Test Matrix for Rend Lake Coal in Tangentially-Fired Configuration.

Test ID	Firing Rate Btu/h-ft^3	SR1	SR2	SR3	NO_x lb/MM Btu	LOI %
Baseline						
T-RL-01,19	12138	1.13	1.14	1.14	0.722	0.6
T-RL-20,35	9379	1.14	1.15	1.15	0.617	2.3
Pulverized Coal Reburning Factorial Tests: Firing Rate, SR1, SR2						
T-RL-05,11	14324	1.08	0.96	1.13	0.466	4.6
T-RL-13	15117	1.08	0.91	1.13	0.368	6.1
T-RL-09,14	16000	1.08	0.86	1.13	0.268	8.0
T-RL-12	16952	1.08	0.81	1.14	0.258	9.9
T-RL-07,15	13593	1.06	0.99	1.16	0.454	3.5
T-RL-17	14303	1.07	0.95	1.17	0.374	5.8
T-RL-10,18	15117	1.06	0.89	1.16	0.243	7.7
T-RL-16	16069	1.05	0.83	1.16	0.219	10.2
T-RL-23,27	11186	1.11	0.99	1.16	0.317	4.6
T-RL-29	11862	1.11	0.93	1.15	0.200	8.6
T-RL-25	12510	1.09	0.87	1.13	0.134	15.9
T-RL-28	13310	1.10	0.83	1.15	0.126	10.8
T-RL-24,31	10620	1.09	1.02	1.20	0.332	4.1
T-RL-33	11200	1.09	0.97	1.20	0.287	5.2
T-RL-34,36	11710	1.07	0.91	1.17	0.225	6.7
T-RL-30,32	12538	1.08	0.86	1.16	0.138	12.4
Variation of SR3						
T-RL-04	15117	1.06	0.89	1.21	0.207	12.2
T-RL-06	15131	1.04	0.88	1.25	0.211	12.9
T-RL-08	15117	1.07	0.90	1.12	0.215	9.6
T-RL-10,18	15117	1.06	0.89	1.16	0.243	7.7
Air Staging						
T-RL-02	12138	0.95	0.96	1.12	0.451	3.0
T-RL-03	12138	0.93	0.94	1.16	0.321	12.0
T-RL-21	9379	0.98	0.99	1.15	0.311	1.4
T-RL-22	9379	0.96	0.98	1.19	0.231	6.3

Table 12. Reduced Test Matrix for Burning Star Coal in Tangentially-Fired Configuration.

Test ID	Firing Rate Btu/h-ft^3	SR1	SR2	SR3	NO_x lb/MM Btu	LOI %
Baseline						
T-BS-01,19	12582	1.13	1.13	1.13	0.561	1.1
T-BS-20,35	9311	1.11	1.12	1.12	0.524	0.2
Pulverized Coal Reburning Factorial Tests: Firing Rate, SR1, SR2						
T-BS-05,11	14797	1.07	0.95	1.12	0.329	0.7
T-BS-13	15640	1.08	0.91	1.12	0.243	0.6
T-BS-09,14	16540	1.07	0.85	1.11	0.200	1.5
T-BS-12	17565	1.08	0.81	1.12	0.184	1.1
T-BS-07,15	14030	1.04	0.98	1.14	0.316	1.2
T-BS-17	14797	1.05	0.94	1.16	0.241	1.5
T-BS-10,18	15709	1.05	0.88	1.15	0.184	1.2
T-BS-16	16596	1.04	0.83	1.15	0.159	1.2
T-BS-23,27	11148	1.07	0.95	1.11	0.342	1.1
T-BS-29	11802	1.06	0.89	1.11	0.235	1.5
T-BS-25	12444	1.06	0.84	1.10	0.157	3.7
T-BS-28	13211	1.06	0.80	1.10	0.164	2.6
T-BS-24,31	10556	1.04	0.98	1.15	0.348	1.0
T-BS-33	11148	1.04	0.93	1.14	0.221	1.5
T-BS-34,36	11664	1.03	0.88	1.13	0.158	2.2
T-BS-30,32	12457	1.03	0.82	1.11	0.137	3.2
Variation of SR3						
T-BS-04	15703	1.05	0.88	1.19	0.173	2.4
T-BS-06	15690	1.05	0.88	1.25	0.173	3.1
T-BS-10,18	15709	1.05	0.88	1.15	0.184	1.2
Air Staging						
T-BS-02	12582	0.95	0.96	1.11	0.371	0.5
T-BS-03	12582	0.91	0.92	1.13	0.253	1.7
T-BS-21	9311	0.96	0.97	1.13	0.354	0.6
T-BS-22	9311	0.94	0.95	1.16	0.273	1.7