WRI 06-R024

# FINAL REPORT

## EVALUATION OF BIOMASS AND COAL SLURRIES AS FUEL-LEAN REBURN FUELS

**Jointly Sponsored Research Proposal**
**Task 55 Final Report Under DE-FC26-98FT40323**

**November 2006**

**For**
**Breen Energy Solutions**
**Pittsburgh, Pennsylvania**

**And**
**U.S. Department of Energy**
**National Energy Technology Laboratory**
**Morgantown, West Virginia**


**By**
**Western Research Institute**
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## DISCLAIMER

## ABSTRACT

Breen Energy Solutions (BES) and Western Research Institute (WRI) tested biomass and coal slurries and other carbonaceous substances such as fuel oil/water emulsions as $NO_x$ reburn fuel in the combustion test facility (CTF).

The overall goal of the project was to determine the $NO_x$ reduction potential of various biomass and coal reburn fuels, and to identify the optimum conditions for $NO_x$ control. Specific objectives were to inject biomass, biosolids, coal, biomass/coal, and biosolids/coal slurries into the upper furnace of CTF and determine the resulting $NO_x$ reductions and CO emissions, to identify optimum injection rates and injection locations for these reburn fuels, and to install a reaction zone stabilizer device in CTF and determine its effectiveness in reducing CO and further reducing $NO_x$.

Combustion tests achieved 40% to 60% $NO_x$ reductions with 10% to 20% reburn fuel heat input. The project has demonstrated the technical feasibility of in-situ gasification of slurries including pulverized coal and 75% pulverized coal/25% biosolids by weight, and the ability to utilize the gasification products as $NO_x$ reburn fuel.

This work also demonstrated that pulverized coal/water slurries can be successfully gasified and used as reburn fuels, and there is no need for use of micronized coal. Very good burnout of the pulverized coal slurry was demonstrated in this work.

Similarly, the project has demonstrated the technical feasibility of in-situ gasification of oil/water emulsion and the ability to utilize the associated gasification products as $NO_x$ reburn fuel.

## TABLE OF CONTENTS

# LIST OF FIGURES AND TABLES

## EXECUTIVE SUMMARY

Breen Energy Solutions (BES) and Western Research Institute (WRI) tested biomass and coal slurries and other carbonaceous substances such as fuel oil/water emulsions as $NO_x$ reburn fuel in the combustion test facility (CTF).

Reburn refers to the technique where a carbonaceous species is injected into the upper furnace of a coal-fired boiler to reduce $NO_x$. In this process, hydrocarbons from the reburn fuel reduce $NO_x$ by converting NO to $N_2$ and inert species. In conventional reburn applications, additional air is added downstream of the reburn fuel injection point to burn out any unreacted fuel, CO, and hydrocarbons. In fuel-lean reburn configurations, the injection rate of the reburn fuel is sufficiently low that the overall furnace remains fuel-lean, and the excess oxygen in the flue gas (typically 3-4%) burns out any unreacted fuel. However, the reburn fuel is injected in such a way that fuel-rich pockets are formed. These fuel-rich pockets are individual reburn zones where $NO_x$ is reduced during initial mixing with the flue gas; subsequently, the reburn fuel is consumed by excess oxygen as the fuel-rich pockets complete mixing with the flue gas.

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# INTRODUCTION

Reburn refers to the technique where a carbonaceous species (natural gas, coal, biomass etc.), is injected into the upper furnace of a coal-fired boiler to reduce $NO_x$. In this process, hydrocarbons from the reburn fuel reduce $NO_x$ by converting NO to $N_2$ and inert species. In conventional reburn applications, additional air is added downstream of the reburn fuel injection point to burn out any unreacted fuel, CO, and hydrocarbons. In fuel-lean reburn configurations, the injection rate of the reburn fuel is sufficiently low that the overall furnace remains fuel-lean, and the excess oxygen in the flue gas (typically 3-4%) burns out any unreacted fuel. However, the reburn fuel is injected in such a way that fuel-rich pockets are formed. These fuel-rich pockets are individual reburn zones where $NO_x$ is reduced during initial mixing with the flue gas; subsequently, the reburn fuel is consumed by excess oxygen as the fuel-rich pockets complete mixing with the flue gas.

Breen Energy Solutions (BES) has extensive experience in designing and implementing fuel-lean reburn systems for $NO_x$ control in coal-fired utility boilers. The original reburn systems utilized natural gas as the reburn fuel. However, the current high prices of natural gas have made this technique uneconomical. BES is investigating the use of low-cost, renewable fuels such as biomass and bio-solids as reburn fuels. In these applications, the biomass is injected as a slurry. The water in the slurry rapidly vaporizes when it enters the furnace, and the steam reacts with the biomass under gasification conditions (in-situ gasification) to produce gaseous reducing species (CO, $H_2$, $CH_i$, HCN, etc.) that convert $NO_x$ to $N_2$.

For the in-situ gasification and reburn process, a carbonaceous fuel is mixed with water to form slurry. The slurry is injected as a stream or spray, and the liquid quickly penetrates the flue gas and vaporizes from the intense radiative heat field. As the water vapor and solid fuel particles rise as a plume in the upper furnace, the carbon and water vapor gasify, and the gasification products react in this plume under reburn conditions to reduce $NO_x$. The gaseous products then mix with the flue gas to complete combustion of the CO and $H_2$. The process is shown schematically in Figure 1.

The slurry is prepared with at least the stoichiometric amount of water required for the carbon/water gasification reaction to go to completion. The minimum water content of the slurry is the stoichiometric requirement because it is desired to gasify the fuel with minimal increases in unburned carbon content in the flyash. In this example, the quantity of water required for completion of the carbon-water reaction is 50% (all percentages by weight in this example).

Coal (at 67% carbon or 0.67 lb C/lb coal): $H_2O(v)$ + C → CO + $H_2$
18 lb/mole 12 lb/mole

*1 mole $H_2O$ per mole C = 1*18/12 = 1.5 lb water/lb C * (0.67 lb C/lb coal) = 1 lb water/lb coal*

The gasification and re-burn reaction paths are schematically shown in Figure 2.

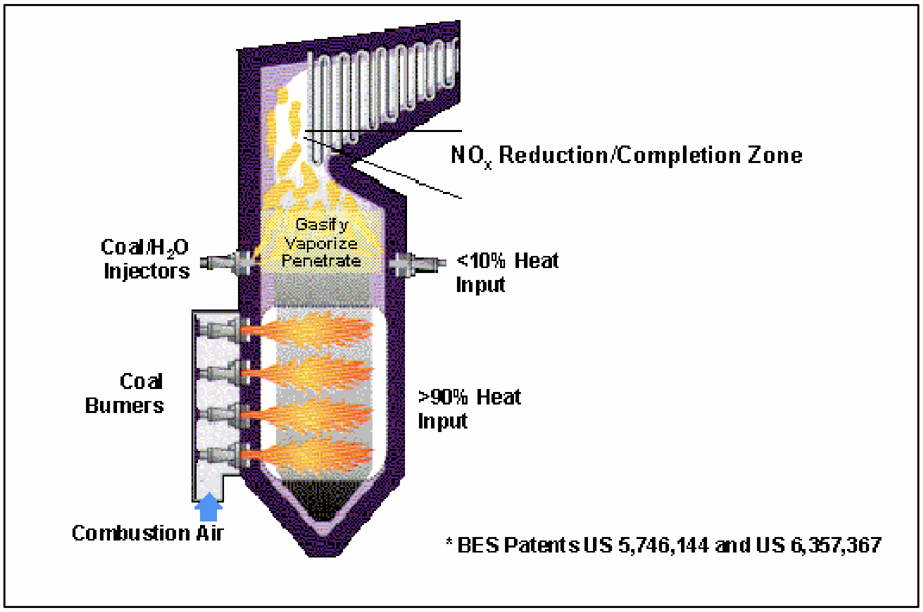


**Figure 1 Coal/Water Slurry Reburn Process Schematic**

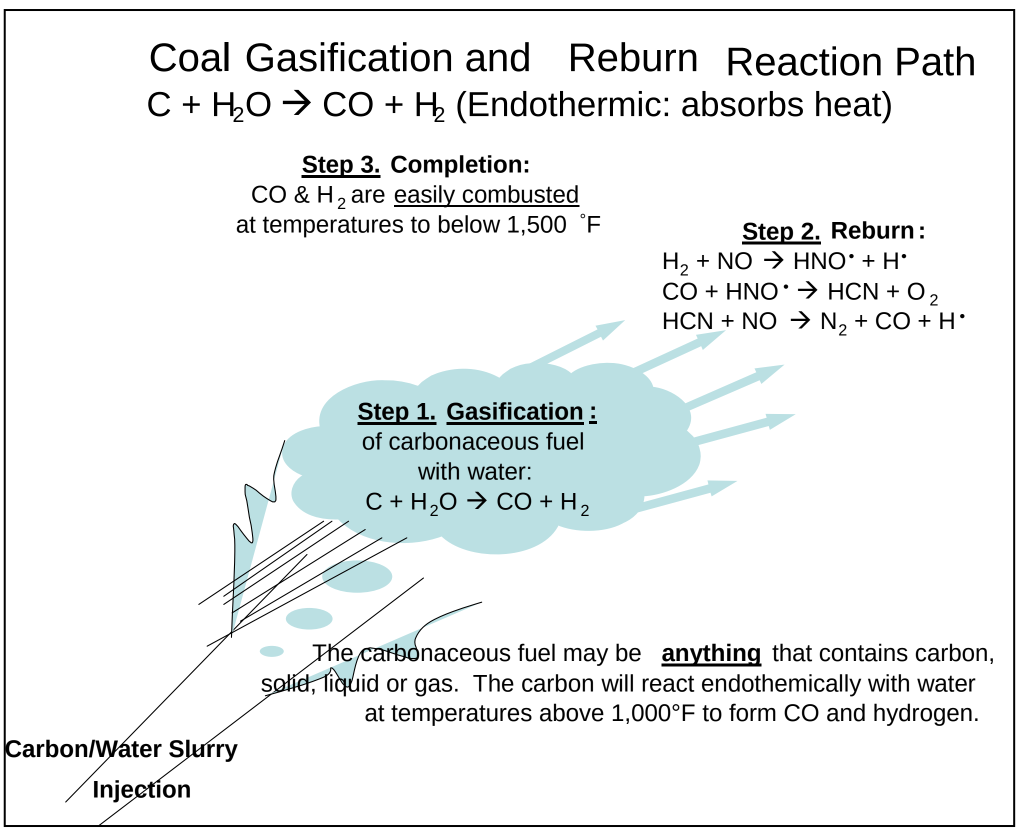


**Figure 2. Coal Gasification and Reburn Reaction Path**

Bench-scale combustion tests performed at Iowa State University have indicated that this slurry infection indeed has the potential to significantly lower $NO_x$. However, the biggest $NO_x$ reductions occurred in cases where CO levels were excessively high. To counteract the high CO levels and make such slurry-based reburn technically feasible, BES is also developing a reaction zone stabilizer (RZS) device that serves to mix and burn out un-reacted CO and further reduce $NO_x$.

Under the auspices of the DOE JSR Program, BES and WRI collaborated to use the Combustion Test Facility (CTF) to test various biomass, biosolids, and coal reburn fuels, and to test and optimize their reaction zone stabilizer (RZS). This report describes the results of the tests.

## PROJECT OBJECTIVES

The goal of the project was to determine the $NO_x$ reduction potential of various biomass and coal reburn fuels, and to identify the optimum conditions for $NO_x$ control. Specific objectives included:

- Inject biomass, biosolids, coal, biomass/coal, and biosolids/coal slurries into the upper furnace of CTF and determine the resulting $NO_x$ reductions and CO emissions,
- Identify optimum injection rates and injection locations for these reburn fuels, and
- Install a reaction zone stabilizer device in CTF and determine its effectiveness in reducing CO and further reducing $NO_x$.

## COMBUSTION TEST FACILITY

The WRI's coal combustion test facility is a nominal 250,000 Btu/hr balanced-draft system designed to replicate a pulverized coal-fired utility boiler. A photograph and a schematic of the CTF are shown in Figures 3 and 4, respectively. In its present configuration, the unit has been set up to simulate a tangential-fired boiler, but may be easily adapted to wall-fired or other configurations. The fuel feed system consists of screw-based feeders and pneumatic transport to four burners inserted in the corners of a refractory-lined firebox. The burners can be angled to attain different tangential flow characteristics in the firebox. The unit is equipped with appropriately sized heat-recovery surfaces such that the time/temperature profile of a utility boiler can be replicated. These surfaces comprise water-cooled panels that simulate the waterwall, an air-cooled super heater, pre-heater, and two economizers. CTF includes provisions for preheating the combustion air to mimic a utility air pre-heater. The system also includes over-fire air injection ports for combustion staging. The unit is equipped with two baghouses for continuous fly ash removal.

Continuous monitoring and recording of process parameters and gas concentrations (i.e., $CO_2$, $SO_2$, $NO_x$, CO, $O_2$, and Hg) are accomplished through data acquisition system. The data are logged every ten seconds interval through a PC-based data acquisition system. Similarly, all process parameters are logged on a separate PC-based data acquisition system.

**Figure 3. The Combustion Test Facility at Western Research Institute**

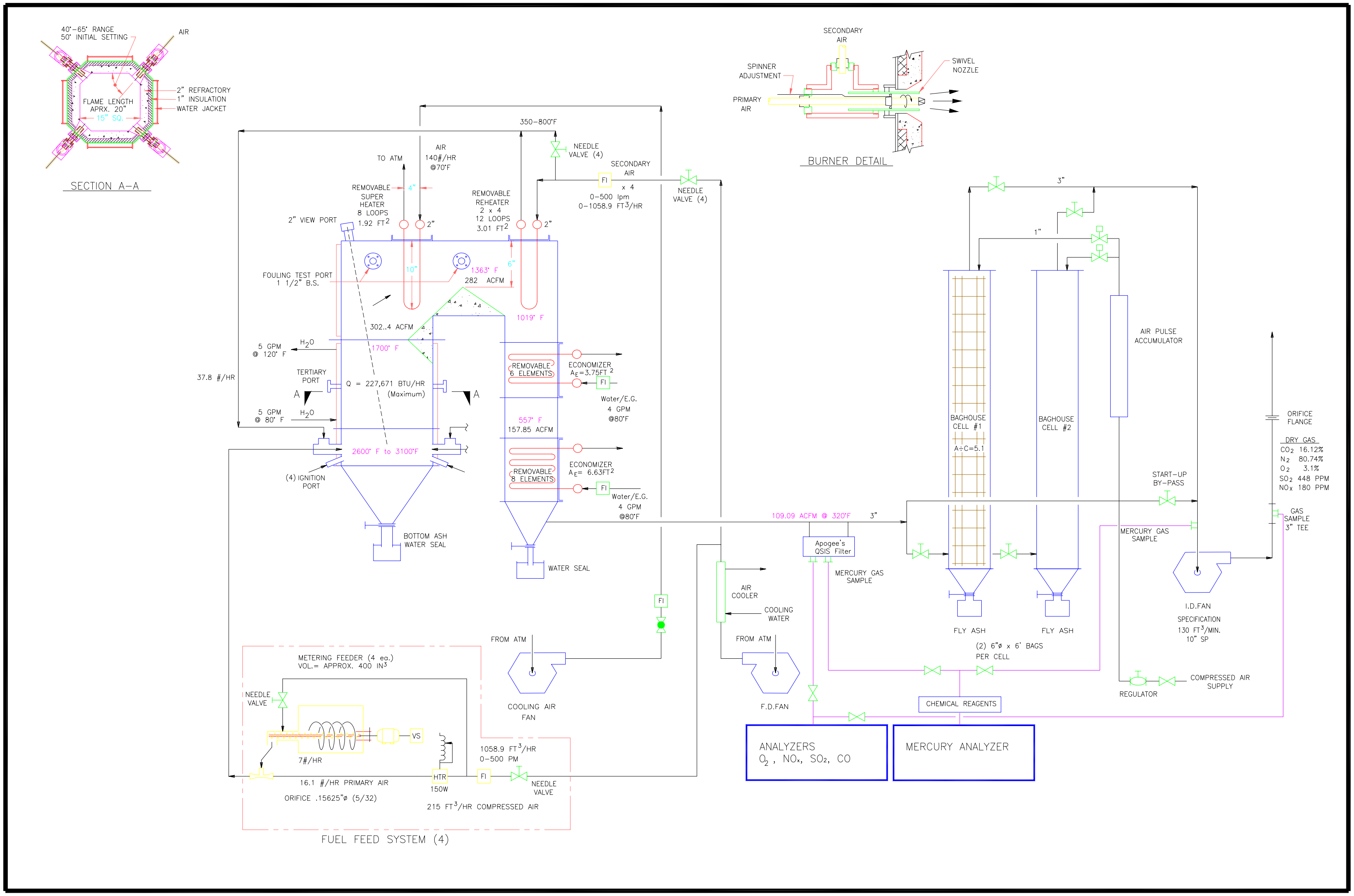

**Figure 4. A Schematic of the CTF**

## TESTING, RESULTS & DISCUSSION

The work was concluded in two separate test campaigns. A description of the two campaigns is given below. Associated results and conclusions are also described in each campaign.

**Test Campaign 1: Evaluation of In-Situ Gasification Of Coal/Biomass and Coal Slurries for Utilization As Fuel-Lean Reburn Fuels.**

Objective of this series of tests was to demonstrate the technical feasibility of in-situ gasification of slurries including pulverized coal and biosolids. The biosolid used in the study was limed sewage sludge from a municipal wastewater treatment plant.

The CTF was adapted to accommodate slurry fuel injection for reburn configurations. A single injection port was installed approximately one-half of the distance between the over-fire air ports and the boiler nose. A stinger constructed of quarter-inch stainless steel tubing was installed in the reburn injection port through the port cap. The reburn fuel injection temperature was estimated at 2200°F. A schematic reflecting the injection location is shown in Figure 5.

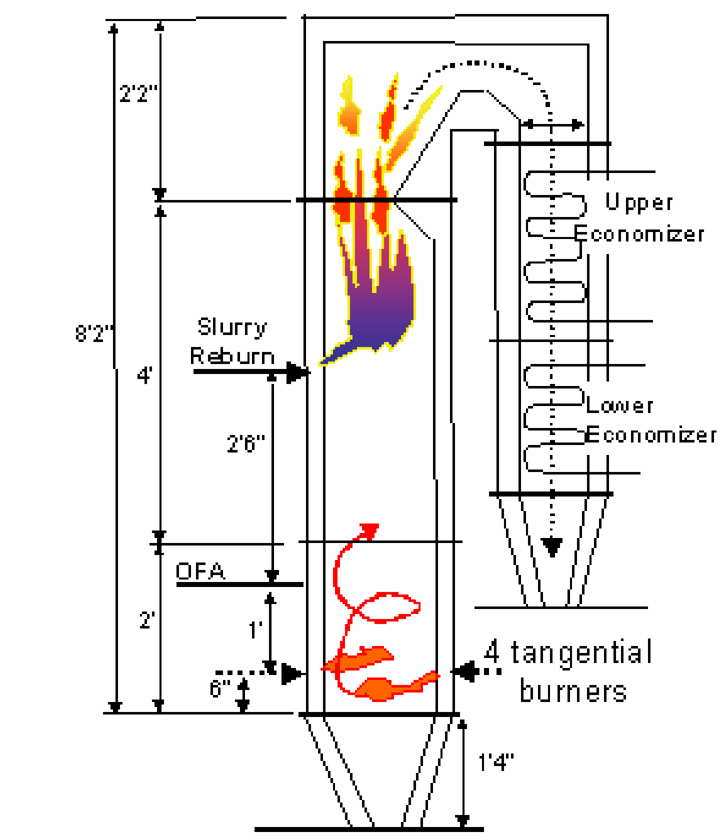


**Figure 5. Reburn Fuel Injection Location**

The fuels that were successfully prepared into slurries were bituminous coal, subbituminous coal and biosolids in the form of limed, treated sewage sludge. Slurry was prepared containing 80% water and 20% solids; in this case, the solids were 75% bituminous coal and 25% biosolids. Another, slurry was prepared with 60% water and 40% solids in the form of subbituminous coal.

The slurry was injected in a fuel lean reburn configuration above subituminous coal combustion in the burner zone. Reburn rates of approximately 10% and 20% slurry fuel heat input were compared to baseline operation.

Figure 6 shows the data for the $NO_x$ and CO emissions as a function of excess oxygen for the tests conducted with bituminous coal/biosolids slurry injection above a subbituminous coal flame. The data displayed show that baseline $NO_x$ and CO levels were 530±30 ppm and 60±20 ppm, respectively. With slurry injection at a rate of 10% thermal input, there appears to be a 40% reduction in the $NO_x$ emissions while there is a concomitant increase in CO levels. Ash analyses showed an increase in LOI from 0.76% to 0.92%. With 20% slurry injection rate, observed $NO_x$ reduction was about 60%. The CO and LOI observed were >850 ppm and 34%, respectively.

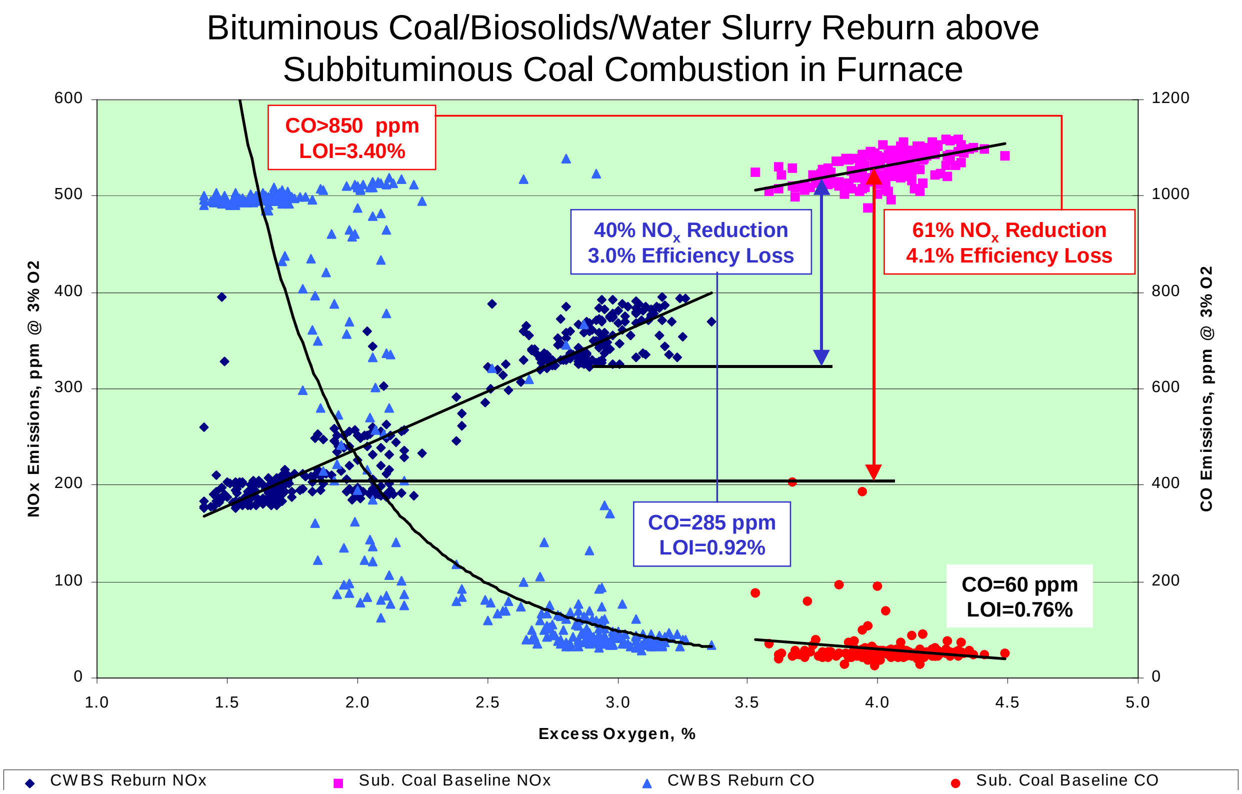


**Figure 6. Coal/Water/Biosolids Slurry Reburn Results**

Even though 60% $NO_x$ reduction was achieved, the thermal input required is too high and is accompanied by unacceptably high CO and LOI levels. Another negative impact of this slurry injection stemmed from high water required for biosolid-based slurry. Boiler efficiency losses of 3-4% are estimated by the heat loss method.

The next series of tests during this campaign used slurry prepared with 60% water and 40% solids in the form of subituminous coal. The subituminous coal slurry was injected in a fuel lean reburn configuration above bituminous coal combustion in the burner zone. A reburn rate of 10% slurry fuel heat input was compared to baseline operation. The higher reburn rate was attempted, but CO emissions were not controllable and no data were collected. Results of the tests with this coal slurry are shown in Figure 7.

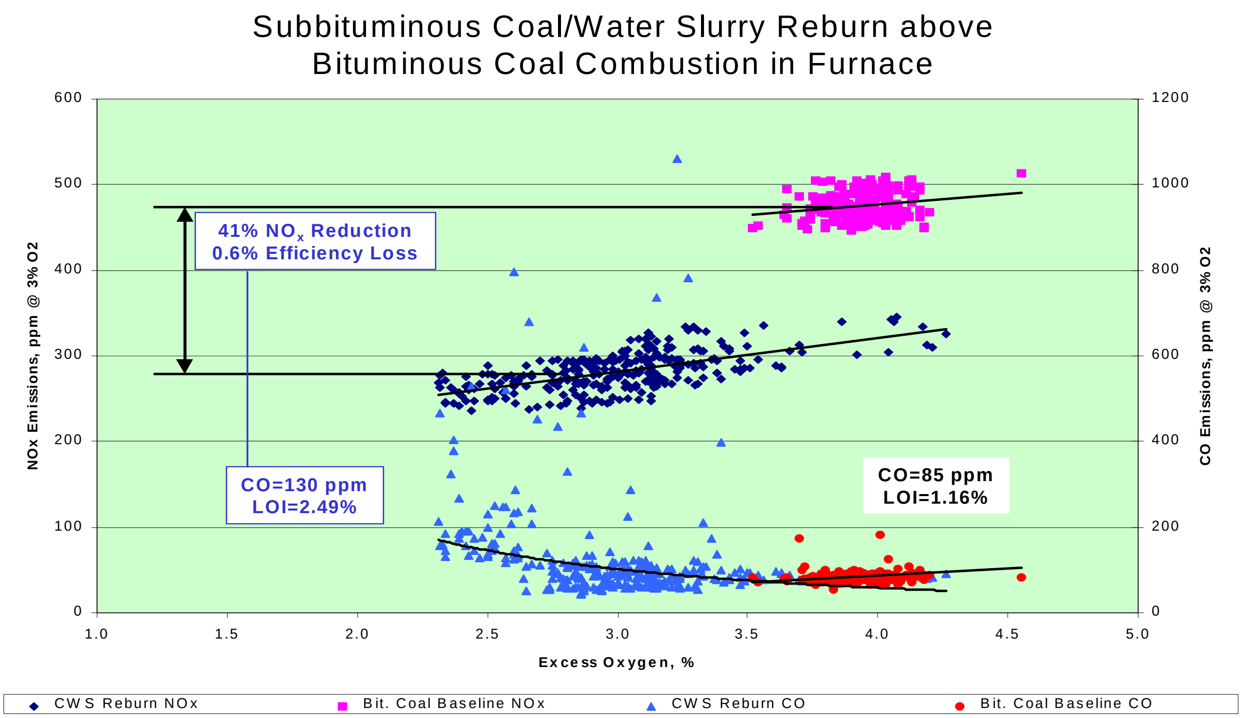


**Figure 7. Coal/Water Slurry Reburn Results**

The $NO_x$ reductions demonstrated for these tests were over 40% with only 10% reburn fuel input. This reduction was achieved with only a 50 ppm increase in CO levels, and the ash analyses indicated that the LOI levels increased by just over one percentage point. Because the water content in this slurry was lower, boiler efficiency losses were limited to just over one-half a percentage point.

Table 1 summarizes the data from Test Campaign 1.

**Table 1 Summary of Slurry Reburn Test Data from Campaign 1**

| Slurry | Reburn Heat Input | $NO_x$ | CO | LOI |
|---|---|---|---|---|
| None (baseline) | 0% | 510 ppm | 60 ppm | 0.8% |
| Bituminous Coal/biosolids/water | 10% | 320 ppm | 285 ppm | 0.9% |
| Bituminous Coal/biosolids/water | 20% | 220 ppm | > 850 ppm | 3.4% |
| None (baseline) | 0% | 480 ppm | 85 ppm | 1.2% |
| Subituminous Coal/water | 10% | 280 ppm | 130 ppm | 2.5% |
| Bituminous coal 12,299 Btu/lb | Sewage sludge 4,200 Btu/lb | Subituminous coal 10,445 Btu/lb | | |

In summary, Campaign 1 testing clearly established that in-situ gasification of slurries is indeed possible and can be used to control $NO_x$ emissions from coal-fired boilers. Very good burnout of the pulverized coal slurry indicates that micronized coal may not be needed for such applications.

**Test Campaign 2. <u>Evaluation of In-Situ Gasification of Fuel Oil/Water Emulsion For Utilization As Fuel-Lean Reburn Fuels</u>**

Objective of this series of tests was to demonstrate the technical feasibility of using oil/water emulsions to reduce $NO_x$ emissions from coal-fired boilers.

The emulsions that were successfully prepared were a mixture of # 6 fuel oil/diesel oil and water. The emulsion contained 43.3% by weight fuel oil/diesel oil and the balance water.

The fuel oil/water slurry was injected in a fuel lean reburn configuration above a bituminous coal flame in the burner zone. Reburn rates of approximately 5.5% and 10% emulsion fuel heat input were used. $NO_x$ and CO emissions data from these are compiled in Figures 8 and 9 in a manner described earlier for the solids-based slurries.

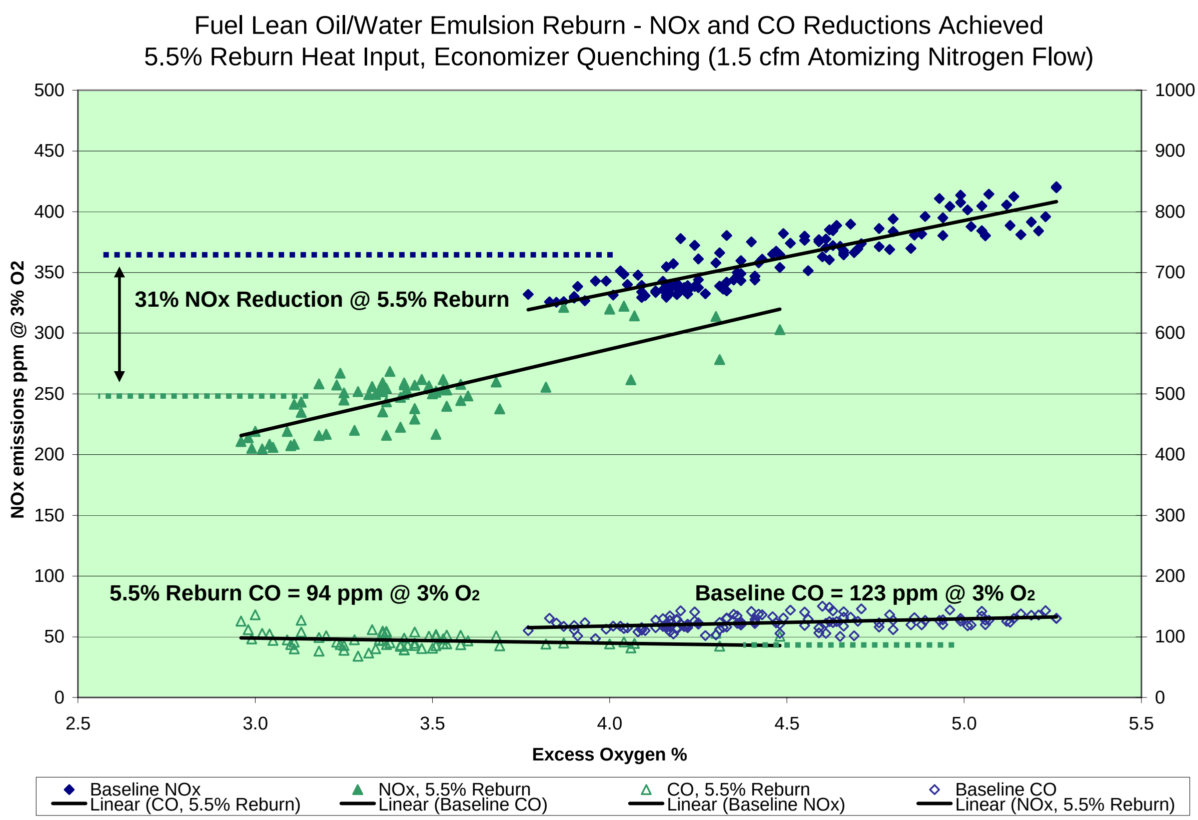


**Figure 8. Fuel Oil/Water Emulsion Reburn Results at 5.5% Reburn Fuel Heat Input**

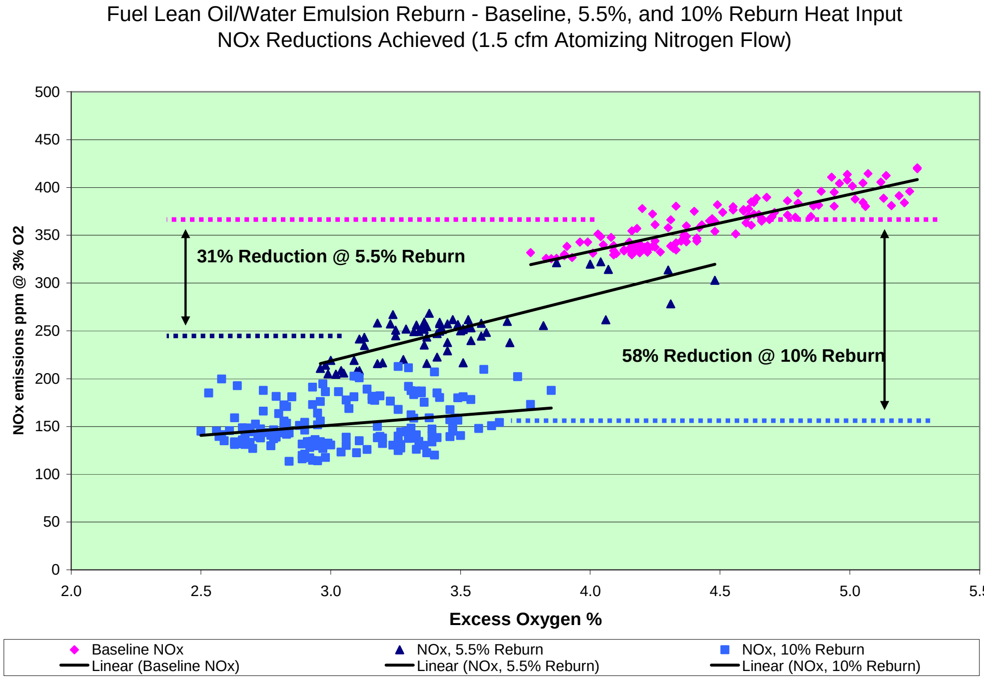


**Figure 9. Fuel Oil/Water Emulsion Reburn Results at 10% Reburn Fuel Heat Input**

From the data displayed in these figures, it is evident that the $NO_x$ reductions achieved were over 31% and 58% with 5.5 and 10% reburn fuel input. The $NO_x$ reductions for the 5.5% reburn fuel input were achieved with less CO levels than in those observed in the base case, possibly a reflection of the inherent data scatter in such data. At 10% reburn fuel firing rate, an increase in CO level was observed. If warranted, this increase in CO level with high reburn rate can be minimized by enhanced mixing in the regions above the gasification pockets through the use of reaction zone stabilizer device or an equivalent mixing device.

In summary, the results of the tests employing oil/water slurry reburn in Table 2 confirmed that the reburn concept also works with oil/water mixtures.

**Table 2. Summary of Emulsion Reburn Test Results**

| Emulsion | Reburn Heat Input | $NO_x$ | CO |
|---|---|---|---|
| None (baseline) | 0% | 361 ppm | 123 ppm |
| Fuel Lean Oil/Water | 5.5% | 248 ppm | 94 ppm |
| Fuel Lean Oil/Water | 10% | 152 ppm | 705 ppm |
| Bituminous coal 12,325 Btu/lb | Fuel Lean Oil 17,500 Btu/lb | | |

## REACTION ZONE STABILIZER

Reviewing the results from the two test campaigns, the highest $NO_x$ reductions were achieved when CO emissions were also high. This led BES to develop a flue gas counter mixing device that acts to mix pockets of low $O_2$/low $NO_x$/high CO with pockets of high $O_2$/high $NO_x$/low CO within the bulk flue gas to consume the CO and further reduce $NO_x$. The device is placed in the flue gas at the lowest temperature where sufficient kinetics exists for reburn to complete. The high CO reacts to thermally initiate the reburn process, and as the flue gas is mixed, the CO is consumed as and a further reduction in $NO_x$ occurs. Any CO that reacts with $O_2$ reacts at a sufficiently low temperature and further $NO_x$ production is prevented.

The flue gas temperature history and concepts underlying this chemistry for this process are schematically presented in Figure 10 below.

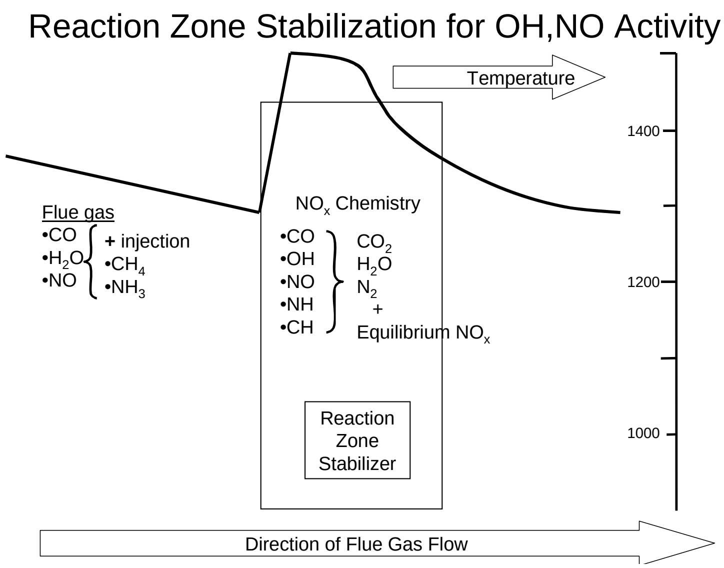


**Figure 10. A Schematic Representation of Reaction Zone Stabilizer Chemistry**

Components of the reaction zone stabilizer were received at WRI from BES, but BES decided not to proceed with further testing with this device due to the low carbon monoxide emitted with reasonable $NO_x$ reductions at low reburn heat input.

## SUMMARY AND CONCLUSIONS

Breen Energy Solutions (BES) and Western Research Institute (WRI) tested biomass and coal slurries and other carbonaceous substances (natural gas, coal, biomass etc.) as $NO_x$ reburn fuel in the combustion test facility (CTF).

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