AMMONIA-FREE NO_x CONTROL SYSTEM

QUARTERLY TECHNICAL PROGRESS REPORT NO. 41865R4 JULY 1 THROUGH SEPTEMBER 30, 2004

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Abstract

Research is being conducted under United States Department of Energy (DOE) Contract DE-FC26-03NT41865 to develop a new technology to achieve very low levels of NO_x emissions from pulverized coal fired boiler systems by employing a novel system level integration between the PC combustion process and the catalytic NO_x reduction with CO present in the combustion flue gas. The combustor design and operating conditions will be optimized to achieve atypical flue gas conditions. This approach will not only suppress NO_x generation during combustion but also further reduce NO_x over a downstream catalytic reactor that does not require addition of an external reductant, such as ammonia.

This report describes the work performed during the July 1 to September 30, 2004 time period.

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1.0 EXECUTIVE SUMMARY

1.1 Project Overview

State-of-the-art NOx control technology for pulverized coal (PC) steam plants involves a combination of low NOx combustion and selective catalytic reduction (SCR) technologies. Development of these systems has approached a plateau and further improvements will likely be incremental. To advance NOx control technology to the next level, new concepts must be considered.

The objective of this project is to evaluate the viability of a novel integration between the PC combustion process and flue gas NOx reduction. The concept exploits the relationship between CO and NOx both in the combustion and flue gas NOx destruction processes to achieve very low levels of NOx from the boiler system without adding any external reductant, such as ammonia, typically used for SCR processes.

The project starts with a review and evaluation of existing NOx reduction and CO oxidation catalysts, including those catalyst formulations successfully used in the automotive applications, for their use in PC power plants. This knowledge, combined with prior catalyst research experience for power plant applications allows the project team to identify and test catalyst formulations robust enough for the oxidizing flue gas environment in power plants, and capable of achieving competitive NOx reduction performance and economic targets.

A detailed PC combustion study, applying computational fluid dynamics simulation program to perform boiler and burner design modeling, complements the catalyst development effort by investigating ways to optimize the combustion process for the lowest NOx formation while generating sufficient levels of CO needed by the downstream catalytic NOx reduction process. Furnace configuration, air staging, and burner design will be evaluated in this process.

The study will then focus on the comparative evaluation of a conceptual, 400 MWe, coal-fired PC boiler system, utilizing this novel NOx control concept. For this evaluation, the concept plant will be compared to a traditional PC boiler configured with current low NOx combustion technology and an ammonia-based SCR system. The comparison will involve conceptual level design of the furnace and catalyst reduction system to obtain equipment pricing, operational costs, performance data as well as qualitative reliability information.

1.2 Progress During the Quarter

The project work during this quarter included Task 2 - Catalyst Testing and Task 3 - Furnace Optimization. The goal of Task 2 was to screen and characterize candidate catalyst samples conceived and selected through in-depth literature study and development work by the project team. Task 3 was focused on finding the means to obtain the required CO/NOx ratios for post combustion NOx reduction and to optimize overall furnace performance.

1.2.1 Catalyst Development

A short list of candidate catalysts was identified for Task 2 testing. The first group of test catalyst samples (activated carbon-based, multi-metal oxide catalysts) were prepared by aqueous incipient impregnation method and tested on the bench scale catalyst test rig at Lehigh University.

Tests with various combinations of Fe, Cu, Ce, and K on activated carbon support were carried out under a wide range of conditions simulating real life coal-fired power plant flue gas. In total, more than 10 catalysts have been prepared and tested. To ensure repeatable results, multiple tests were done for most of these catalysts, with each test usually lasting a day. The test results are discussed in the following sections.

Very promising data were obtained during testing with a dry simulated flue gas mixture described in the last quarterly report with Fe/Cu/Activated Carbon (AC) catalysts, and in this quarterly report these catalysts, as well as a Fe/Cu/Ce/AC catalyst and a Fe/Cu/K/AC catalyst, have been tested in the presence of moisture and SO₂. Most of the catalysts exhibited high catalytic reactivity with NO conversion reaching 80-90% (outlet NO concentration 25-50ppmv) at relatively low temperatures, and with little or no N₂O formation. Some catalysts also achieved CO reductions as high as 85-95% in a wide range of operation temperatures, especially at low temperatures. Data analyses also revealed that the performance of the NO - Catalyst - CO system was determined by four main competing reaction pathways, as follows:

1. Direct reduction of NO by CO, either added in the test gas mixture or generated *in situ* from the carbon support,
2. Destruction/oxidation of excess CO,
3. Partial combustion/gasification of the supporting activated carbon, and
4. Direct reaction of NO with the carbon support.

Depending upon the catalyst components present, the presence of 8% moisture in the gas stream promoted, slightly inhibited, or had no effect on the NO and CO conversions, but it tended to increase the oxygen consumption for a few hours following moisture addition. The presence of 200 ppm SO₂ over the, Fe/Cu/Ce/AC, and Fe/Cu/K/AC catalysts led to gradual deactivation of the catalysts toward NO reduction (on the order of a few hours), but the activity then tended to stabilize at some 50-70% of the original activity in the absence of SO₂. In contrast, the Cu-free Fe/AC catalyst exhibited an initial rapid deactivation toward NO reduction. The catalysts after testing in SO₂ - containing gas were cooled down with nitrogen purge and retested in dry, SO₂-free gas mixture to probe regeneration of these catalysts. For Fe/Cu/Ce/AC, and Fe/Cu/K/AC catalysts, the activity for NO reduction was restored to original levels before SO₂ exposure. For Fe/Cu/AC catalysts, the original activity was achieved by increasing the reaction temperature by about 25 °C.

In the presence of SO₂, the Fe/Cu/AC and K/Fe/Cu/AC catalysts also exhibited gradually declining activity for oxidation and removal of CO from the gas stream, in contrast with the Fe/Cu/Ce/AC catalyst that exhibited no inhibition of CO conversion to CO₂ in the presence of SO₂. The Cu-containing catalysts promoted the nearly complete conversion of SO₂, while the Cu-free Fe/AC catalyst showed a rapidly declining SO₂ removal rate from the gas stream.

As of the end of this quarter, Task 2 – Catalyst Testing and Evaluation - is still ongoing. We will continue the Task 2 work in the fourth quarter of 2004 to have selected catalysts tested and more data available and analyzed to support Task 3 - Furnace Optimization and Task 4 - System Conceptual design.

1.2.2 Furnace Optimization

The objective of this task is to achieve minimum NOx emissions and adequate CO to NOx ratios at the inlet to catalytic reactor for NOx reduction with CO. The furnace optimization study is based on a 400 MWe commercial boiler designed and delivered recently by Foster Wheeler. This reference unit represents the state-of-the-art subcritical pressure, natural circulation PC boiler firing a high volatile bituminous coal (Illinois #6).

A 3-D CFD simulation of the furnace was performed using the computer program, FW-FIRE. The outlet conditions of the FW-FIRE model were then applied as the inlet conditions to a 2-D Fluent model of the heat recovery area (HRA) to predict CO and NOx at the HRA outlet. Since the FW-FIRE model does not include the finishing superheater and finishing reheater (located between the furnace outlet and the HRA inlet), the outlet temperature distribution from these banks was calculated using the Foster Wheeler program, HEATEX.

The furnace optimization work during this quarter indicates that adequate CO/NOx ratios can be obtained by modifying furnace operation conditions, without any physical changes to the burner and boiler equipment. By reducing the overall excess air level or by increasing the over fire air portion of the total combustion air, CO concentration in the flue gas can be increased, and NO reduced. CFD simulation suggests that CO/NOx ratio of about 1.5 is achievable by either excess air or over fire air adjustments. The effects by these adjustments on boiler efficiency, unburned carbon in flyash, and furnace exit gas temperature are relatively small and within the range seen in normal power plant operations.

Higher CO/NOx ratios may be achieved by combining lower boiler excess air with higher OFA flow, and by taking some burner(s) out of service. These cases will be further evaluated.

2.0 CATALYST DEVELOPMENT

2.1 Test Rig

A fixed bed reactor at Lehigh University was the main experimental tool employed in this study. The catalyst testing system featured a vertical down flow quartz tube reactor (10.5 mm ID x 13 mm OD). Temperature in the reactor was monitored by an axial thermocouple located in the catalyst bed usually positioned 2.5 to 4.5 cm below the top of the catalyst bed. Heating was accomplished with a vertical split-tube furnace surrounding the reactor. The gas stream inlet and outlet 316 stainless steel sections were wrapped with heating tapes and insulation and heating was controlled by two Variacs. Temperatures of the inlet and outlet lines were monitored by six thermocouples and maintained above 100°C.

A process flow diagram of the NO reduction test rig was shown in the previous quarterly report. Approximately 20 ml of weighed catalyst sample was placed in the reactor and supported by a quartz wool plug. Based on literature survey, the CO-NO reaction under study is not catalyzed by the quartz reactor tube at temperatures below 1000°C. Individual gas flow meters were used to regulate flow rates from gas cylinders containing NO/N₂, CO/N₂, O₂, CO₂, N₂, and SO₂/N₂ to simulate flue gas from coal-fired power plants. A cylinder pump was used to inject desired amount of distilled water through a vaporizing pipe section into the heated inlet gas line to the reactor. The outlet test gas goes through a chiller before entering the gas analyzers. A bypass valve can be used to connect the inlet gas stream directly to the analyzers to check and confirm the inlet concentrations of NO and other gases. A bubble flow meter was used to calibrate the rotameters for individual gas streams.

Analysis of the NO, N₂O, and SO₂ concentrations in the gas stream were achieved with a Siemens Ultramat 6 non-dispersive infrared (NDIR) analyzer, while O₂ was analyzed by a Siemens Oxymat 6 Paramagnetic analyzer. CO was determined by a Testo 325-3 digital CO analyzer. Monitoring of these gases in the reactor inlet and outlet streams was carried out to determine if these components of the gas mixture were being generated or consumed. Moisture CO₂, and N₂ concentrations were calculated based on their flow rates into the reactor.

2.2 Catalyst Preparation

The 12-20 Mesh size activated carbon (AC) was purchased from Aldrich and was designated as Darco Activated Carbon obtained from American Norit Co. It was derived from lignite. Due to its relatively low cost, lignite-based activated carbon has been widely used in the waste to energy industry for trace pollutant removal, and is currently being demonstrated to capture mercury for coal fired utility plants. The BET surface area of an “as received” sample was determined (6-point analysis) by nitrogen adsorption at -196°C using a Micromeritics Gemini 2360 V1.03 instrument. Before analysis, the sample was purged with flowing N₂ while heating from 60°C to 200°C over a period of 55 min. The sample was then maintained at 200°C for 2 hr and cooled to ambient temperature. During this thermal treatment, the sample exhibited a 1.5 wt% loss of weight. The determined surface area of the activated carbon was 525 m²/g. After loading of the catalytic components the surface area for catalyst Type B became 468 m²/g, which is very close to that of the as received AC.

The catalysts were prepared by an impregnation method. Reagent grade chemicals of metal nitrates from Fisher Scientific (ACS Certified) or Strem Chemicals were dissolved in distilled water and heated to 60°C. To the solution was added AC while maintaining constant stirring. The solution was then evaporated over a period of a few hours, and when the solid was dry to the touch, it was placed in a plastic bottle. The open plastic bottle was placed in an N₂-filled glove bag containing a beaker of Drierite desiccant.

Activation of catalysts was carried out by decomposition of metal salts. The impregnated multi-metal nitrate salts were decomposed by heating under established flow rates of the simulated gas mixture containing approximately 3.0% O₂, 14% CO₂, 520 ppm CO, and balance N₂. The gas hourly space velocity (GHSV) used for the decomposition treatment was about 855 hr⁻¹. The inlet and exit lines as well as the furnace were then heated. Usually, the catalyst was slowly heated to about 270°C over a period of 3-5 hr and maintained at this temperature for 0.5-3 hr until the level of emitted NO achieved low levels.

During this treatment, a large amount of NO was released from the catalyst, as a result of nitrate salt decomposition, which peaked in the temperature range of 100-200°C and then decreased with further increase of temperature and time of equilibration. CO, O₂, and N₂O were also measured during decomposition/activation at increased temperatures. After the decomposition treatment, the furnace controller was turned off and only the flow of N₂ was maintained overnight as the furnace cooled to ambient temperature.

2.3 Catalyst Test Procedure

For NO reduction activity determination, the flow rates of the gas mixture components were reestablished and the flow rates were measured/confirmed by means of a bubble meter. The reactor was then heated and the NO/N₂ flow was turned on. The temperature of the catalyst bed was then sequentially changed to obtain a conversion-temperature profile both in steady state and in transient conditions. To screen the performance of different catalysts, a constant GHSV of 1050 hr⁻¹ at ambient temperature and pressure and the inlet gas composition was used. The established dry reactant gas mixture consisted of the following for most of the tests:

NO	CO	O ₂	CO ₂	N ₂
260 ppm	520 ppm	3.0 %	14.0%	83%.

This gas mixture gives a CO/NO molar ratio of 2.0, with enough excess reductant for the NO reduction reaction. To study the catalyst reactivity for NO reduction without the interference of poisoning or inhibition, most of the initial catalyst evaluation tests were carried in the absence of SO₂ and moisture. Further testing during this quarter of work included addition of moisture and SO₂ to the reactant gas stream to determine inhibition and poisoning effects.

Catalytic reactivity is expressed by conversions, where the calculated conversions are multiplied by 100 to obtain % Conversion, i.e.

$$\text{NOx Conversion} = 1 - (\text{NOx})_{\text{out}} / (\text{NOx})_{\text{in}}$$

$$\begin{array}{ll} \text{N}_2\text{O} & \text{Conversion} = (\text{N}_2\text{O})_{\text{out}} / (\text{NOx})_{\text{in}} \\ \text{CO} & \text{Conversion} = 1 - (\text{CO})_{\text{out}} / (\text{CO})_{\text{in}} \\ \text{O}_2 & \text{Conversion} = 1 - (\text{O}_2)_{\text{out}} / (\text{O}_2)_{\text{in}} \\ \text{SO}_2 & \text{Conversion} = 1 - (\text{SO}_2)_{\text{out}} / (\text{SO}_2)_{\text{in}} \end{array}$$

It was assumed that there was no significant difference between gas inlet and outlet in its molar flow rates, considering that about 97% of the dry feed gas is N_2 or CO_2 , which are not expected to participate in any of the reactions under study here. The NO reduction levels were determined following attainment of steady state. As a post-combustion NO control process, a low NO level of 260 ppm was used in this test, assuming some form of low NOx combustion technology is already being used.

The temperature of the catalyst bed was changed and the NO conversion was determined as it approached to a steady state at each set point. The set point temperatures were selected to achieve the maximum NO reduction for each catalyst. The NOx conversion as a function of temperature and time were recorded. The other gases, such as O_2 , CO, SO_2 , and N_2O were also recorded. They are used to analyze catalytic selectivity, NOx reduction pathways, and possible side reactions, especially the relations among NOx reduction, CO depletion, and O_2 consumption. The reactivity profile of NOx reduction vs. temperature can then be plotted to compare the performance from different catalysts.

After a test, the test sample was cooled down and preserved in an N_2 environment for subsequent characterization. Most of the tested catalysts were subjected to repeat test(s) under identical conditions as used for the first day test. The multi-day tests ensure data/procedure repeatability and provide clues to any deactivation over time on stream.

Tests on various combinations of Fe, Cu, Ce, and K on the AC support have been conducted. To date, 11 catalysts have been prepared and evaluated. In addition Fe/Cu/alumina catalysts have been prepared, and the testing results obtained with this catalyst will be reported in the next quarterly report.

Table 1 describes the various catalyst samples tested. The amount of each metal impregnated on the AC support is expressed as the percentage of a reference total metal loading. The test runs in this report are reported as a combination of letters and numbers, such as A-1, B-2, where the letter indicates the catalyst type tested and the number indicates the order of the test run, for example, 1 for first run (e.g. Day 1).

Table 1. Catalyst Samples Tested*

Catalyst Name	Test Date	Catalyst Formula	GHSV, l/hr
A	4/07	As-received AC	1050
B	4/09	10% Fe/10% Cu	1050
C	4/21	40% Fe/10% Cu	1050
D	4/30	10% Fe/30% Cu	1050
E	5/21	40% Fe/0% Cu	1050
F	5/26	7% Fe/7% Cu	840
G	5/29	40% Fe/10% Cu	1050
H	6/09	40% Fe/30% Cu	1050
I	6/22	Aqueous-treated AC	1050
J	6/29	40% Fe/30% Cu/20% Ce	1050
K	7/22	10% Fe/10% Cu/20% K	1050
L (duplicate of E)	8/13	40% Fe/0% Cu	1050
M (duplicate of H)	9/02	40% Fe/30% Cu	1050

* Percentage in catalyst formula refers to a reference total loading.

2.4 Test Results

2.4.1 Overview of Catalyst Tests

To screen the performance of different catalysts under dry conditions, a constant GHSV of 1050 hr⁻¹ measured at ambient temperature and pressure was used. The established reactant gas mixture consisted of the following:

NO	CO	O ₂	CO ₂	N ₂
260 ppm	520 ppm	3.0 %	14.0%	83.0%.

For experiments with moisture added to the gas stream, water was injected and vaporized to give the following reactant gas mixture with an overall GHSV of 1140 hr⁻¹:

NO	CO	O ₂	H ₂ O	CO ₂	N ₂
240 ppm	480 ppm	2.8 %	8.0%	12.9%	76.3%.

When the reactant stream contained SO₂, a 5727 ppm SO₂/N₂ mixture was utilized and its flow rate was compensated by decreasing the N₂ flow rate accordingly to maintain the overall GHSV at 1140 hr⁻¹. The resultant reactant gas mixture consisted of:

NO	CO	SO ₂	O ₂	H ₂ O	CO ₂	N ₂
240 ppm	480 ppm	200 ppm	2.8 %	8.0%	12.9%	76.3%.

2.4.2 Reproducibility of Catalyst Testing

The reproducibility of catalyst testing was established by utilizing a fresh 20 ml portion (Test 2 - Catalyst M) of the 40% Fe/30% Cu/AC catalyst that had been tested previously (Test 1 -Catalyst H). The as-prepared catalyst had been stored under a N₂ environment, and the testing of the two samples was three months apart. Comparisons of the activities and selectivity observed during the tests with the dry reactant gas mixture are shown in Figure 1. It is clear that the testing procedure demonstrated reproducible behavior of the catalyst.

Figure 1 Conversion of NO, CO, and O₂ and N₂ Product Selectivity Over the 40% Fe/30% Cu AC Catalyst

2.4.3 Effects of Moisture and SO₂ Over the Fe/Cu/AC and Fe/Cu/Ce/AC Catalysts

The catalyst testing during this quarter was particularly centered on studying the effects of moisture injection and simultaneous addition of moisture and SO₂ on the activity and selectivity of the more active catalysts prepared here. It was shown in the previous quarterly report that both **Catalyst H** and **Catalyst J** (see Table 1) were active catalysts for NO reduction in the presence of dry simulated flue gas. With the 40% Fe/30% Cu/AC catalyst (Catalyst H), the index temperature (T₅₀) for achieving 50% NO reduction was 240°C, while with the 40% Fe/30% Cu/20% Ce/AC catalyst (Catalyst J) T₅₀ was lowered further to 210-220°C. At the same time, the O₂ consumption “light-off” temperature was reduced 15-20°C by the presence of Ce. With both catalysts, approximately 90% depletion of CO was observed at all temperatures studied. Both catalysts exhibited >20% NO reduction <200°C, where little O₂ consumption was observed.

To study possible inhibition/poisoning effects of moisture and SO₂ over these two catalysts, the additives were injected into the reactant gas stream after establishing the steady-state activity in the dry, SO₂-free gas mixture. Upon addition of 8% moisture to the gas stream, the concentrations of the other components decreased accordingly to the following:

NO	CO	O ₂	H ₂ O	CO ₂	N ₂
240 ppm	480 ppm	2.8 %	8.0%	12.9%	76.3%,

and the overall GHSV was 1140 hr⁻¹. The usual observation upon injection of moisture was initially (1) desorption of a quantity of NO, (2) desorption of a smaller quantity of CO, and (3) enhanced consumption of O₂. This was typically followed by a return to the approximately the same levels as the original NO and CO conversions and a much slower decrease in the O₂ consumption with time on-stream. An example for **Catalyst M** (duplicate of H) test is shown in Figure 2.

Figure 2 NO, CO, O₂, and SO₂ Conversion Over the 40% Fe/30% Cu/AC Catalyst at Approximate 257°C (M-3)

Also shown in Figure 2 is the effect upon subsequent addition of 200 ppm SO₂ to the reactant gas stream, where the flow rate of the SO₂/N₂ was compensated by proportionately decreasing the flow rate of the N₂ stream. It is evident from Figure 2 that the presence of SO₂ over the catalyst led to a gradual decrease both the NO and CO conversions. At the same time, there was little effect on the O₂ consumption other than an initial discontinuity. About 7.5 hr after addition of the SO₂ to the gas stream, it appeared that the NO and O₂ conversion levels had reached steady-states, while the CO conversion rate was still declining. Increasing the reaction temperature 8°C led to a significant enhancement in the NO reduction level, a smaller improvement in the CO conversion, and no significant effect on the O₂ consumption. During the addition of SO₂ to the gas stream, all of the SO₂ was removed from the reactants.

Similar testing with **Catalyst J** containing Ce was carried out. After reaching steady-state at 239°C, the injection of moisture was begun. As shown in Figure 3, initial exposure of the 40% Fe/30% Cu/20% Ce/AC catalyst to H₂O vapor led to transient desorption of quantities of NO and CO, as well as to enhanced consumption of O₂. Addition of SO₂ to the gas stream led to gradual decline in the observed NO reduction activity, but with this catalyst there was no accompanying decline in the CO removal rate observed with time on-stream. Indeed, the catalyst temperature decreased a few degrees and about 98% CO conversion was maintained. Upon termination of the injection of both moisture and SO₂, the NO removal rate stabilized at about 50%.

While moisture and SO₂ were being fed into the gas stream, the consumption of O₂ gradually declined and stabilized at 10% O₂ removal from the reactant gas. Removal of both moisture and SO₂ from the inlet gas resulted in a further lowering of the O₂ consumption to a steady-state level of about 6%. Once again, all of the SO₂ in the inlet gas stream was converted upon passing over the catalyst.

After purging the catalyst with N₂ as it cooled and at ambient temperature overnight, the catalyst was retested under dry conditions. The observed conversions and N₂O selectivity are shown in Table 2 as Day 5 Test results. Between the entries for the Day 5 tests, the catalyst had been tested at higher temperatures, including at 254° where the NO, CO, and O₂ conversions were 83%, 87%, and 13%, respectively. Therefore, high conversions were attained after the Day 4 testing with moisture and SO₂ and after purging with N₂ overnight.

Figure 3 Conversions of NO, CO, O₂, and SO₂ Over the 40% Fe/30% Cu/20% Ce/AC Catalyst at 239°C

Table 2. Conversions and N₂O Selectivity over the 40% Fe/30% Cu/20% Ce/AC Catalyst J at 239 ± 1°C. Dry Gas Reactant Mixtures consisted of 260 ppm NO, 520 ppm CO and O₂, CO₂, N₂. Wet Gas Mixtures Compositions were 240 ppm NO, 480 ppm CO, 8% H₂O_(gas), (with or without 200 ppm SO₂), and O₂, CO₂, N₂.

Test	%NO Conv.	%N ₂ O Sel.	%CO Conv.	%O ₂ Conv.	%SO ₂ Conv.
Day 3 Test - Dry	82	6.2	89	9.8	---
Day 3 Test - with 8% Moisture After 2 hr	74	1.7	89	14.4	---
Day 4 Test - Dry	79	3.9	88	9.7	---
Day 4 Test - with 8% Moisture After 1 hr	71	1.6	88	15.4	---
Day 4 Test - with 8% Moisture + 200 ppm SO ₂ After 4 hr*	51	3.7	98	9.2	≈100
Day 4 Test - 2.25 hr After Terminating Moisture and SO ₂	51	1.6	88	6.5	---
Day 5 Test - Dry: After 4 hr	64	5.1	88	2.3	---
Day 5 Test - Dry: After Higher Temp. Treatment and then 2 hr at 240°C	59	5.6	89	1.4	---

*Temperature had decreased to 236°C.

2.4.4 Activity of the Cu-Free 40% Fe/AC Catalyst in the Presence of Moisture and SO₂

As shown in the previous quarterly report, the temperature index T₅₀ for NO reduction observed for the Fe/Cu/AC catalysts is strongly dependent on the presence or absence of Cu and its content in the catalysts. For example, for Cu loadings of 0, 10, and 30% in a 40% Fe/AC catalyst, T₅₀ declines from 320°C to 270°C to 240°C, respectively. It was shown for the 40% Fe/30% Cu/AC catalyst (Figure 2) that injection of moisture into the inlet gas mixture produced only transient decline in NO and CO conversion, while addition of 200 ppm SO₂ to the reactant produced a gradual decline in conversion of both of these.

The catalytic behavior of a fresh portion of the Cu-free 40% Fe/AC catalyst (**Catalyst L**, duplicate of E) was utilized to probe the effect of moisture and SO₂ on this single component supported catalyst. The activity of this catalyst was first determined in the dry reactant gas mixture, and it was verified that the temperature “light-off” curve was reproducible and that T₅₀

was also reproduced. Upon testing for Days 2 and 3, the NO conversion at about 320°C tended to at a higher level relative to that observed for Day 1.

Upon injection of moisture, the NO conversion immediately increased, as shown in Figure 4. This contrasts with the behavior of the 40% Fe/30% Cu/AC catalyst (Figure 2), where the measured NO conversion decreased, apparently due to transient desorption of NO from the catalyst. At the same time that the NO conversion increased over the Cu-free catalyst, the consumption of O₂ dramatically increased. As shown in Figure 4, the conversions were maintained at high levels until the addition of SO₂ was initiated. As the SO₂ began passing over the catalyst, the conversion of O₂ sharply dropped, approaching the consumption level observed with the dry reactant gas mixture. At the same time, the NO conversion level more gradually declined to approximately half of the activity shown in the wet reactant gas mixture.

For both NO and O₂, the conversion levels reached steady-state values, with the catalyst not exhibiting further deactivation. Termination of SO₂ injection did little to change the observed removal rates of NO and O₂, but termination of the moisture addition tended to decrease the conversion levels of both of these reactants.

Figure 4 NO, O₂, and SO₂ Conversion Over the Cu-free 40% Fe/AC Catalyst in the Presence of Moisture and SO₂ at 321°C

It is interesting that addition of SO₂ to the reactant mixture did not lead to complete conversion of this “poison” until after the gas flow was interrupted for about 2 min to measure and verify the

inlet gas composition. This momentary stoppage of the gas flow apparently altered the catalyst in some way so that conversion of the SO₂ was promoted. However, the conversion of SO₂ gradually declined with time. This behavior was not observed with the copper-containing catalysts such as the 40% Fe/30% Cu/AC catalyst.

It is noted that in all of the tests with this Cu-free catalyst, relatively large amounts of CO were generated, corresponding to the significant conversion of O₂. This is apparently due to partial oxidation of the carbon support by the O₂ in the presence of the Fe catalyst component at the high reaction temperatures required by the absence of Cu in the catalyst. The O₂ consumption was much higher than the stoichiometric amount required for CO generation, indicating the dominant combustion product was CO₂. This again verifies that Fe is a good catalyst for carbon gasification and combustion, but it does not have a sufficient catalytic function for the CO oxidation reaction.

2.4.5 Effect of Potassium

It is shown that Fe and Cu are very effective catalyst components for NO reduction by carbon or by CO. Ce and K had been reported to enhance catalytic redox processes. Cerium is widely used in automobile three-way catalysts as an oxygen transferring agent due to its redox behavior. We have shown here (Figure 3) that Ce also maintains the CO oxidation reaction to delete CO in the presence of SO₂. Potassium is a basic component that can function as a combustion catalyst. A 40% Fe/30% Cu/20% K/AC catalyst was prepared using KNO₃ as the impregnation reagent.

This K-doped catalyst (**Catalyst K**) exhibited a high catalytic activity for NO reduction and CO oxidation at low reaction temperature, similar to the Fe/Cu/Ce/AC catalyst. Steady-state conversions seemed to take longer to achieve, but the initial NO conversion upon start-up in the 170-205°C temperature range was >30%. The index temperature T₅₀ observed upon multiple-day testing was in the 205-220°C range. At the same time, the CO and O₂ conversions were 88-91% and 2-5%, respectively. Little N₂O was formed, and the selectivity to N₂ tended to stabilize at about 98% with time-on-stream.

An experiment in which moisture was added to the reactant gas stream at 235°C is shown in Figure 5. The behavior of this K-containing catalyst very much resembles that of the K-free 40% Fe/30% Cu/AC catalysts, e.g. see Figure 2. As usual, there was a small exotherm as the initial moisture passed over the catalyst. In addition there was a large desorption of NO, a smaller desorption or lower conversion of CO, and a promotion of O₂ consumption. The NO reduction reaction recovered and the NO conversion in the presence of moisture was higher than the initial conversion under dry conditions. Interruption of the gas flow through the reactor for about 2 min led to subsequent improvement of the NO and CO conversion levels but had no effect of the O₂ consumption. Termination of the moisture addition led to slight decreases in the NO and CO removal rates and a somewhat larger decrease in O₂ consumption. However, the NO reduction level remained higher than the initial activity observed upon start-up under dry conditions.

During a subsequent day of testing at about 232°C, moisture was again injected, followed by the addition of SO₂. The observations for this test are shown in Figure 6. The effects of moisture in

the gas stream were the same as observed in Figure 5. Upon addition of SO₂, very little change in the conversions was initially observed. At the same time, most (but not all) of the SO₂ was converted. A discontinuity in the conversion curves was caused by interruption of the gas flow through the reactor, which led to transient higher conversions of all reactants. With continued time-on-stream, the NO conversion gradually declined, while CO conversion and O₂ consumption showed smaller decreases. Upon termination of the SO₂ addition, the conversions of all reactants stabilized, with CO conversion tending to increase slightly. Removal of moisture from the gas stream led to slightly lower conversions of NO and O₂, while the CO conversion continued to increase with time. Increasing the catalyst temperature to 241°C caused a significant increase in the NO conversion from 54% to 69% and smaller increases in the CO and O₂ conversions.

Figure 5 NO, CO, and O₂ Conversions Over the 40% Fe/30% Cu/20% K/AC Catalyst Before, During, and After Moisture Injection at 235°C

Figure 6 Conversions of NO, CO, O₂, and SO₂ Over the 40% Fe/30% Cu/20% K/AC Catalyst at 232°C

2.5 Discussion

The incorporation of Ce (Catalyst J) and K (Catalyst K) into the 40% Fe/30% Cu/AC catalyst (Catalyst H) increased the activity of the catalyst by shifting the NO “light-off” curves to lower temperature (lower T_{50}), as shown in Figure 7. At the same time, there was little change in the CO conversion and O₂ consumption under these dry conditions.

Compared with other catalysts, Catalysts H, J, and K (all containing 40% Fe/30% Cu/AC) exhibit high NO reduction activity while minimizing the level of O₂ consumption, as shown in Figure 8. In this figure, Catalyst G contained a reduced level of 10% Cu, while Catalyst I was the unpromoted aqueous-treated AC. Catalyst F contained lower quantities of both Fe and Cu. The data shown for Catalysts E and L (E) are the two tests of the Cu-free 40% Fe/AC, and it is clear that without the presence of Cu in the catalyst, the iron oxide component promotes the consumption of O₂ by greatly enhancing the catalytic combustion of the carbon support.

Figure 7 Comparisons of K- and Ce-Containing Catalysts

Figure 8 Conversion of O₂ vs NO under Dry Conditions

Comparisons of the same catalysts in terms of CO Conversion/Generation vs NO Conversion are shown in Figure 9. The catalysts that contained high levels of Cu all exhibited high conversions of CO to CO₂. It is noted that Catalysts H, J, and K contained 30% Cu in addition to the 40% Fe, while Catalyst G contained 10% Cu. Catalysts E and L are the Cu-free catalyst tests, where large quantities of CO were generated and the quantity increased as the reaction temperature was increased. This behavior is clearly shown in Figure 10. Therefore, to inhibit the combustion of the activated carbon support, the active NO reduction catalysts should contain a quantity of Cu that approaches that of the Fe component.

Figure 9 Comparisons of CO vs NO Conversions

As noted earlier in the report, the inhibition of the NO reduction reaction over Catalysts J, K and M (all containing 40%Fe and 30% Cu) with SO₂ in the inlet gas stream was more gradual than catalysts without copper (e.g. Catalyst L or E). This is more clearly shown by replotting the NO conversion data in Figures 2, 3, 4, and 6 in terms of ppm NO remaining in the outlet stream, as indicated in Figure 11. This figure also shows that the deactivation rates for the catalysts J, K and M were similar. In all cases, the NO reduction activity stabilized upon removal of SO₂ from the simulated flue gas stream.

Figure 12, using same data as Figures 2, 3 and 5, shows that effect of 200 ppm SO₂ on CO conversion for catalysts J, K and M (all containing 40%Fe and 30% Cu). During the SO₂ exposure, the Ce-containing catalyst J maintained very high CO conversion, while the CO activity for catalyst M were reduced by the presence of SO₂.

Figure 10 Conversion / Generation of CO vs Temperature

Figure 11 Effect of SO₂ Exposure on NO Conversion

Figure 12 Effect of SO₂ Exposure on CO Conversion

As discussed in section 2.4, the catalyst samples, after SO₂ exposure and cooling in nitrogen purge, were re-tested in dry, SO₂-free gas environment. In Figure 13, test data for catalyst M (Fe/Cu/AC) after SO₂ exposure (M-4, open circles) are plotted along with those before SO₂ exposure for the same catalyst. Catalyst M achieved over 80% NO conversion even after SO₂ exposure. By increasing the reaction temperature about 25 °C, the NO conversion profile for M-4 was restored to a similar pattern as the earlier tests.

Figure 13 Restoration of NO Activity After SO₂ Exposure for Catalyst M (H)

As shown in Figure 14, catalyst J (Fe/Cu/Ce/AC) exhibited complete recovery of NO activity. The after SO₂ exposure test data (J-5, open circles) fell right on the original NO conversion profile before the exposure. High NO conversion (>80%) was achieved at a low reaction temperature. Similarly, test data of catalyst K (Fe/Cu/K/AC) after SO₂ exposure also shown complete restoration of original NO activity at low temperatures.

Figure 14 Restoration of NO Activity After SO₂ Exposure for Catalyst J

3.0 FURNACE OPTIMIZATION

3.1 Introduction

The objective of this task is to investigate a means of producing an adequate ratio of CO/NO_x upstream of the catalyst reactor. A 3-D CFD simulation of the furnace was performed using the computer program, FW-FIRE. The outlet conditions of the FW-FIRE model were then applied as the inlet conditions to a 2-D Fluent model of the heat recovery area (HRA) to predict CO and NO_x at the HRA outlet. Since the FW-FIRE model does not include the finishing superheater and finishing reheater (located between the furnace outlet and the HRA inlet), the outlet temperature distribution from these banks was calculated using the Foster Wheeler program, HEATEX.

3.2 Computer Program Description

FW-FIRE (Fossil fuel, Water-walled Furnace Integrated Reaction and Emission Simulation) simulates furnace combustion, heat transfer and pollutant formation based on fundamental principles of mass, momentum, and energy conservation. The FW-FIRE computer program incorporates the latest state-of-art coal combustion/gasification, pollutant formation, and physical analysis techniques based on extensive empirical research. The FW-FIRE code performs general three dimensional multiphase gas combustion steady state analysis of reactive fluid flows. The program is fully capable of analyzing gas-fired, oil-fired, and coal-fired boilers although FW-FIRE was initially tailored for pulverized coal combustion and gasification.

HEATEX is a Foster Wheeler general-purpose program for thermal/hydraulic analysis of tube banks. The program performs heat transfer calculations on a local basis by dividing the tube bundle into a number of small heat transfer elements.

Fluent is a general purpose commercial CFD software, which can be used for simulation, visualization, and analysis of fluid flow, heat and mass transfer, and chemical reactions.

3.3 Furnace Model

3.3.1 Model Geometry

An FW-FIRE model was made of a current 400 MWe pulverized coal furnace. The model simulates the furnace, in height from the bottom of the hopper to the roof, in depth from the front wall to the rear wall, and in width from the left sidewall to the right side wall. The furnace has a total of 24 opposed wall-fired burners (3 vertical x 4 horizontal x 2 walls) and 10 over fire air ports. The radiant heat transfer surface consists of 2.75" OD waterwalls and five 2.0" OD partial divisional wall panels. Water is circulated in the furnace by natural circulation. Fine meshes are used to model the burners and over-fire air (OFA) ports. The model contains 528,840 (117x113x40) nodes and is shown in Figure 15.

3.3.2 Boundary Conditions

The input data required by FW-FIRE include fuel analysis, coal particle size distribution (mass percentage for each size bin), waterwall fluid temperatures, and the velocities, flow rates and temperatures of primary and secondary gas streams. The waterwalls of the furnace are assumed to be gray and diffusive. The wall temperature at each location is calculated based on the fluid temperature and the heat flux at the wall cell. Coal kinetic parameters were applied for Illinois #6 coal.

Parametric runs were conducted to determine the effects of outlet oxygen concentration and over-fire air (OFA) flow rate on outlet NO_x and CO.

3.3.3 Baseline Case

The baseline (design) case for this unit is 3% O₂ at boiler outlet and 30% OFA. The corresponding boundary conditions were applied to the computational model and FW-FIRE was run until steady state conditions were achieved.

The modeling results for the baseline case are summarized in Table 3. The coal burnout shown in the table is the percentage of dry ash-free based coal burned. The loss on ignition (LOI) represents the percentage of unburned carbon in the ash. The furnace exit gas temperature (FEGT) shown in the table is the average temperature of flue gas before the finishing superheater (vertical plane above the nose. Figure 16 presents a plot of gas temperature in a vertical plane through the second burner column and at the furnace outlet (before the finishing superheater). The mole fraction of O₂ through the second burner column, at the OFA elevation, and at the furnace outlet is presented in Figure 17. CO mole fraction and Flue gas velocity at the second burner column and at the furnace outlet is presented in Figures 18 and 19. Figure 20 is a plot of the NO_x concentration in a vertical plane through the second burner column and at the furnace outlet.

Figure 15 Computational Model of Furnace (with right side wall removed)

Table 3 Summary of Furnace Baseline Case Simulation

Burnout	%	99.66
LOI	%	2.61
CO furnace	ppmvw	1537
NO _x	ppmvw	227
FEGT	F	2100

Figure 16 Furnace Gas Temperature

Figure 17 Furnace O₂ Mole Fraction

Figure 18 Furnace CO Concentration

Figure 19 Furnace Gas Velocity

Figure 20 Furnace NO_x Concentration

3.4 HRA Model

Since the conditions at the furnace outlet tend to be uniform in the width direction, to simplify the analysis a two-dimensional (height versus depth) model of the HRA and finishing superheaters were utilized

3.4.1 Finishing Superheater and Reheater

An HEATEX model was made of the finishing superheater and finishing reheater tube bundles. Inlet temperature and flow distribution were obtained from the FW-FIRE furnace model outlet conditions. Figure 21 presents the corresponding furnace outlet (finishing superheater inlet) and HRA inlet (finishing reheater outlet) flue gas temperature profiles.

3.4.2 Fluent Model

A two dimensional fluent model was made of the HRA. Figure 22 shows the geometry of the HRA. The HRA model simulates the heat transfer, hydraulic resistance, and turbulence of the primary reheater, primary superheater, upper economizer, and lower economizer. The model includes approximately 21,000 cells.

Heat transfer to the tube banks is simulated by distributed heat sinks. Tube bank hydraulic resistance is simulated by a combination of individual tube modeling and distributed resistance. The magnitude of the heat sinks and distributed resistances are calculated to match the predictions of the Foster Wheeler Boiler Performance Computer Program.

Species transport was modeled using the finite rate/eddy dissipation model. CO reaction rate kinetics were obtained from Reference 1 as follows:

$$\frac{d[\text{CO}]}{dt} = A[\text{CO}]^{1.0}[\text{H}_2\text{O}]^{0.5}[\text{O}_2]^{0.25} e^{-\left(\frac{E}{RT}\right)}$$

$$A = 2.61 \text{ E}+12 \text{ kg-mol/m}^3$$

$$E = 45,566 \text{ Kcal/kg-mol}$$

Reaction of NOx with O₂ was neglected (due to low gas temperature). The reaction of CO with O₂ is very sensitive to temperature as shown in Figure 23, which shows the fraction of the CO remaining for given residence time at a constant gas temperature for fully mixed gas flow. Note that in the HRA the residence time is approximately 4 seconds with a gas inlet temperature of 1550°F and a gas outlet temperature of 725°F. In the Fluent model the eddy dissipation model is applied to simulate the turbulence-chemistry interaction, which limits the reaction rate and reduces the maximum CO reductions shown in Figure 23.

Figure 21 Flue Gas Temperature Vs. Height at Furnace Outlet and HRA Inlet, Baseline Case

Figure 22 400 MWe Boiler Design

Figure 23 Ratio of CO/CO_{inlet} Vs. Residence Time and Temperature

Figure 24 – CO Concentration at HRA Inlet Vs. Height

3.4.3 Boundary Conditions

Properties (velocity, CO, NO_x, and O₂) at the furnace outlet plane of the FW-FIRE furnace model were averaged in the width direction to produce a profile versus height at the HRA inlet. Gas temperature versus height was obtained from the HEATEX temperature distribution at the finishing reheater outlet. Figure 24 presents the HRA inlet CO concentration for several cases.

3.4.4 Baseline Simulation Results

The boiler analyzed is designed for an outlet O₂ of 3% and an OFA flow rate of 30% (OFA/Total combustion air). Figure 26 presents the temperature distribution in the HRA. As shown in Figure 23 most of the CO reduction takes place above 1100°F. Consequently significant CO reduction takes place only upstream of the primary reheater and primary superheater and in the upper section of the primary reheater. This is shown Figure 27, which shows the CO concentration. Average CO concentration at the HRA inlet is 1600 ppm and at the HRA outlet is 150 ppm. Figure 28 presents the NO_x distribution in the HRA. Average NO_x concentration in the HRA is 225 (average NO_x concentration is constant through the model since no NO_x reduction mechanism is included). The ratio of CO/NO_x is presented in Figure 29, which shows the CO/NO_x ratio at the HRA outlet ranges from approximately 0.4 to 0.85 with an average value of 0.66. When the outlet OFA is raised to 40%. Figure 30 presents the ratio of CO/NO_x, which at the HRA outlet ranges from approximately 0.4 to 2.7 with an average value of 1.46. Since, these ranges of CO/NO_x may not be acceptable to catalyst performance, a mixing device such as a static mixer may be required between the economizer outlet and the catalyst inlet. Static mixers are routinely used currently for mixing upstream of SCR reactors.

3.4.5 Parametric Cases Simulation Results

A series of runs were made to determine the HRA outlet CO and NO_x as a function of outlet O₂ and over-fire air flow. Figure 31 presents the concentration CO and NO_x concentrations and CO/NO_x ratio at the HRA outlet as a function of boiler outlet O₂ for an OFA flow of 20%. The CO/NO_x ratio ranges from 0.45 at 3% O₂ to 1.55 at 1% O₂. Figure 32 presents the concentration CO and NO_x concentrations and CO/NO_x ratio at the HRA outlet as a function of OFA flow for an outlet O₂ of 3%. The CO/NO_x ratio ranges from 0.21 at 0% OFA to 1.46 at 40% OFA. Increasing OFA flow and/or decreasing boiler outlet O₂ can have a negative effect on fuel burnout. Figures 33 and 34 present the fuel burnout versus outlet O₂ and OFA flow. Fuel burnout is reduced from 99.74% to 99.45% by reducing outlet O₂ from 3% to 0% and reduced from 99.90% to 99.65% by increasing OFA from 0% to 40%. It is judged that this magnitude in fuel burnout reduction is relatively small. Changes in O₂ and OFA can also influence furnace exit gas temperature, which is important for performance, fouling, and metal temperatures. For the ranges of outlet O₂ and OFA flow studied, the maximum change in FEGT is less than 50°F, which is judged to be a relatively small effect.

Contours of Velocity Magnitude (m/s) 18, 2004
FLUENT 6.1 (2d, segregated, spe6, ske)

Figure 25 Flue Gas Velocity Distribution in HRA, Baseline Case

Contours of Static Temperature (f) Oct 13, 2004
 FLUENT 6.1 (2d, segregated, spe6, ske)

Figure 26 Flue Gas Temperature Distribution in HRA, Baseline Case

Figure 27 - CO Distribution in HRA, Baseline Case

Contours of nox_ppm
FLUENT 6.1 (2d, segregated, spe6, ske)

Oct 13, 2004

Figure 28 - NOx Distribution in HRA, Baseline Case

Contours of co/nox
FLUENT 6.1 (2d, segregated, spe6, ske)
Oct 13, 2004

Figure 29 – CO/NOx Distribution in HRA, Baseline Case

Contours of co/nox Oct 13, 2004
FLUENT 6.1 (2d, segregated, spe6, ske)

Figure 30 – CO/NOx Distribution in HRA, 40% OFA, 3% O2

Figure 31 HRA Outlet CO and NO_x Concentration Versus Outlet O₂

Figure 32 – HRA Outlet CO and NO_x Concentration Versus OFA Flow

Figure 33 – Fuel Burnout Versus Outlet O₂

Figure 34 – Fuel Burnout Versus OFA Flow

3.4.6 Future Additional Cases

To achieve higher CO/NO_x ratios, additional cases may be investigated including combining lower boiler O₂ with higher OFA flow and taking some burner(s) out of service.

4.0 CONCLUSION

4.1 Catalyst Development

Although precious metal catalysts have been successfully applied in the automobile industry to convert NO with CO and hydrocarbons as reductants. Those catalysts require a reducing environment as typically found in the gasoline engine exhaust, and therefore are not suitable for power plant flue gas applications, where oxidizing conditions must be maintained for safety and efficiency considerations. The base metal catalysts, prepared and tested in this study, exhibited very promising NO_x conversion under simulated power plant flue gas conditions, including 3% oxygen. This is a crucial step towards a practical, ammonia-free, catalytic NO_x reduction system for combustion power plants.

The experimental work of the current quarter demonstrates further that deposited metals in mono-, bi-, or ternary metal-oxide forms on the activated carbon support lead to higher NO conversion at lower operation temperature ranges, thus avoiding excessive consumption of support AC and CO generation. .

The catalysts studied this quarter in the presence of moisture and SO₂ were Catalysts J, K, and M (H), as well as the Cu-free Fe/AC Catalyst L (E) (see Table 1). Comparisons of the experimental results for the group of Fe/Cu/AC, Fe/Cu/Ce/AC, and Fe/Cu/K/AC catalysts lead to the following observations:

- NO reduction in the range of 80-90% (outlet NO only 25-50 ppmv) was achieved in multiple repeat test runs with operating temperature ranging from 240-350°C with the multi-component catalysts.
- All of the AC supported catalysts showed very good N₂ selectivity upon NO reduction, with little N₂O formation.
- The Fe-only catalyst requires higher reaction temperatures to achieve NO reduction, and at these temperatures it generates large quantities of CO by combustion of the carbon support.
- Addition of Cu to the catalysts promotes the NO reduction reaction at significantly lower temperatures and also promotes the oxidation and removal of CO.
- The presence of Cu in the catalysts directs the CO depletion reaction. High CO conversions were observed for all temperatures studied in this research, even extending down to 170°C. At low temperatures, the NO reduction by CO probably involved a surface reaction between Cu and the adsorbed CO.
- The presence of Cu in the catalysts also slowed the deactivation process induced by the presence of SO₂ in the reactant gas stream.
- The presence of Cu in the catalysts promoted the total or nearly total conversion of SO₂ over the catalysts.
- It appears that the Ce and K promoters enhanced the reactivity toward NO reduction more on the low temperature side, thereby greatly suppresses the CO generation. However, in the presence of moisture and SO₂, the main effect of these two promoters was to maintain the high level of CO oxidation and removal from the gas stream without significant deactivation.

- Removal of SO₂ from the gas stream terminated the deactivation process and the activity for NO reduction was stabilized.
- After exposure to SO₂, the NO reduction activity could be increased with or without continued presence of moisture and SO₂ by increasing the reaction temperature.
- After the SO₂ exposure, cooling with N₂ purge and reheating for new test, the NO conversion activity of Fe/Cu/AC, Fe/Cu/Ce/AC, and Fe/Cu/K/AC catalysts were restored to original levels in dry, SO₂-free gas. For Fe/Cu/AC only catalyst, a 25 °C higher reaction temperature was needed to regain the activity. However, Ce and K promoted catalysts restore their original NO activity without the need for higher temperatures.

In summary, the AC supported base metal catalysts have shown very promising NO_x conversion and selectivity in the oxidizing environment with CO as reductant. The same base metals have been impregnated into and on an alumina substrate, and the results of testing for NO reduction by CO over this more durable, non-oxidizable catalyst will be reported in the next quarterly report.

4.2 Furnace Optimization

The furnace optimization work during this quarter indicates that adequate CO/NO_x ratios can be obtained by modifying furnace operation conditions, without any physical changes to the burner and boiler equipment. By reducing the overall excess air level or by increasing the over fire air portion of total combustion air, CO concentration in the flue gas can be increased, and NO reduced. CFD simulation suggests that CO/NO_x ratio of about 1.5 is achievable by either excess air or over fire air adjustments. The effects by these adjustments on boiler efficiency, unburned carbon in flyash, and furnace exit gas temperature are relatively small and within the range seen in normal power plant operations.

Higher CO/NO_x ratios may be achieved by combining lower boiler excess air with higher OFA flow, and by taking some burner(s) out of service. These cases will be further evaluated.

5.0 REFERENCES

1. Adams, Brandley R., Cremer, Marc A., and Wang, Dave H., “Modeling Non-Equilibrium CO Oxidation in Combustion Systems”, International Mechanical Engineering Congress and Exposition, November 5-10, 2000.