I & I Final Report
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# Advanced Overfire Air System For Stoker Type Boilers and Furnaces

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Grantee

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## Narrative

A. Brief Summary of the Original Project Goals

The objective of the proposed project is to design, install and optimize a prototype advanced tangential OFA air system on two mass feed stoker boilers that can burn coal, biomass and a mixture of these fuels. The results will be used to develop a generalized methodology for retrofit designs and optimization of advanced OFA air systems. The advanced OFA system will reduce particulate and NOx emissions and improve overall efficiency by reducing carbon in the ash and excess oxygen. The advanced OFA will also provide capabilities for carrying full load and improved load following and transitional operations.

B. Variance from Project Goals

1. Tangential OFA System

The baseline and advanced OFA simulations indicated that a tangential OFA system would not be feasible without the costly expense for additional fan capacity. The primary reason is the inability of the OFA jets to penetrate and mix with the combustion gases. The simulations showed that penetration and mixing could be improved by reducing the number of OFA jets to increase momentum and for spreader stokers, like Vanderbilt's, by injecting more of the OFA from the coal feed side rather than from the rear of the furnace where most of the coal volatiles are burned.

This discovery led to a three-tiered approach of increasing costs for examining advanced OFA configurations for efficiency improvement. For the Vanderbilt and Cox furnaces efficiency improvement was achieved through Tier 1 configurations that only require reducing the number of existing OFA jets to the extent allowed by the existing fan capacity. The cost for these advanced OFA configurations is about ten (10) percent of the original estimated costs for a tangential OFA system.

2. Dynamic Testing

The dynamic testing approach to optimization of the process controls for maximum efficiency and minimum NOx and CO emissions had to be dropped from the project. The PhD student's research fell behind the DOE project schedule. The student's thesis for optimization of the process controls for NOx and CO emissions from Vanderbilt Unit # 7 is now available from the Vanderbilt Chemical Engineering Department. The technique still appears to be promising approach for optimizing efficiency through process control. Milestone/Task 4 – Dynamic Testing, Model Verification and Evaluation was terminated and the remaining funds transferred to Milestone/Task 3.

3. PCGC-3 Software

The PCGC-3 software licensed from Brigham Young University took almost a year and a half (rather than the four to five months as originally planned) before simulations of the Vanderbilt and Cox furnaces could be performed routinely. The problems can be attributed to inexperience with the software, problems with the PC version of the software that had to be corrected by the software authors and the transfer of the graduate student responsible for the simulations to another thesis topic midway through the grant. It was not until early 2003 that simulations became a relatively routine procedure. As a result, Milestone/Task 3 – PCGC-3 Model Verification and Evaluations required far more resources than originally planned.

C. Discussion of Project Results

1. CFD Workshop

CFD Workshop is a generalized computational fluids dynamic (CFD) computer code that uses numerical modeling to simulate processes. It is based on the comprehensive combustion code, PCGC-3, and models three-dimensional turbulent gas flow, particle motion, heterogeneous and homogeneous chemical reactions and heat transfer. The model was developed by the Advanced Combustion Engineering Research Center (ACERC) under DOE sponsorship and can be licensed from Combustion Resources, LLC, an affiliate of Brigham Young University.

The personal computer version of the CFD Workshop was used in this project. The basic approach was to simulate the baseline operations of Vanderbilt's coal burning unit # 7 and the two identical Cox wood burning units. The input data for the baseline operations are given in Tables 1 and 2. The results of the simulations can be presented in a variety of plots and summary data. The plots which can be viewed during a simulation and after the convergence criteria has been met include raster, surface, 2D (X-Y), filet, trajectory, scatter (3D) and velocity (2D, 3D). In this project filet plots of temperature, oxygen and CO concentration have been the primary results used for comparing alternative OFA configurations with the baseline temperature, oxygen and CO concentrations.

2. VU Unit # 7 Baseline Tests

Baseline tests were conducted on Vanderbilt unit # 7 on October 16, 2002. The objectives of the tests were to determine the effects on steam rate, steam temperature, steam pressure, furnace exit temperature, CO emissions and NOx emissions as the excess oxygen was varied. The excess oxygen was varied by changing the OFA flows, while maintaining the UFA flow constant. The steam rate was a typical high range of 55,000 to 60,000 #/hr. The tests were conducted with the steam rate and UFA and OFA flows in manual control. The emissions were measured using a portable Land instrument located at the economizer outlet. The control panel readings are shown in Table 3. The emissions data are plotted in Figures 1 and 2.

The control panel results show that there is no significant change in steam rate, steam temperature, steam pressure or furnace exit temperature as the excess oxygen was changed from 5.8 to 3.5 percent. This indicates the potential for efficiency improvement by reducing the excess air provided by the OFA system.

Figure 1 shows that the CO emissions increased as the excess oxygen level decreased below about 4 percent. This result indicates that the lower acceptable air flows for the existing OFA system corresponds to about 3.5 to 4.0 excess oxygen. Figure 2 shows that the NOx emissions decrease as the excess oxygen decreases. The trends in Figures 1 and 2 are consistent with previous results by Energy Systems Associates and Berkau Associates

The CO emissions increase below 3.5 to 4.0 percent excess oxygen and establish limits for the reduction in the excess oxygen by the existing OFA system and the potential efficiency gain. The guideline for excess oxygen used by the plant operators for 60,000 lb/hr of steam is 4.9 %. The corresponding CO and NOx emissions are 31 and 195 ppm.

3. VU Unit # 7 Baseline Simulations

A schematic of the Vanderbilt unit # 7 furnace and the upper levels of OFA jets is shown in Figure 3. The furnace grate is about 16.5 ft. by 9.5 ft. There are a total of five (5) upper jets on each end of the furnace, three upper and two lower. The jets are interspersed with spreader or feed wall upper three being about 10 ft. above the grate. The re-injection or rear wall upper three and the feed wall lower two jets are about eight feet above the bed. The lower two jets on the rear wall are about 6.5 feet above the bed. There are also eight lower OFA ports just below the feeders on the front wall to help protect the feeders from hot coals and flames. The eight lower jets on the back wall are just above the bed and help to keep the flames and hot coals from the water walls. The waterwalls are 2” diameter pipes on 3” centers. In Figure 4 are photographs of the OFA jets, reinjection ports and waterwalls on the rear wall of the furnace.

Table 4 is a summary of the primary baseline data gathered for the simulations. It has been assumed based on videos and discussions with the operators, that the spreader distributes the coal on the bed as follows:

- 55% on the back 1/3
- 30% on the middle 1/3
- 15% on the front 1/3

The baseline steam rate is 60,000 lbs/hr of steam. The measured bed residence time at this steam rate is 2.4 hours. The OFA accounts for about 16 percent of the total combustion air. The calculated efficiency based on the ASME short form is 82.6 percent. The difference in the excess oxygen at the furnace and economizer outlets is attributed to the location of the thermocouple and the non-uniformity of the oxygen in the furnace flue gases.

A PCGC-3 schematic of the Vanderbilt University unit # 7 furnace is shown in Figure 5. The schematic shows the entire furnace, OFA system, the coal feeders and three zones of the bed through which the OFA is uniformly distributed. Figure 6 is a baseline simulation showing the oxygen content in a filet plot of the furnace. The plot shows the non-uniformity of the oxygen concentration with the existing OFA system operating at a steam rate of 60,000 lbs/hr. The non-uniformity is attributed primarily to the uniform UFA flow and oxygen being used up in the middle and rear sections of the furnace where most of the coal volatiles are being burned. This non-uniformity of oxygen in the furnace will be one of the principal criterium used for evaluating improvements in alternative OFA configurations.

4. VU # 7 Alternative OFA Simulations

The approach taken to improve the design of the overfire air system was to examine changes in the jet configurations in three tiers of increasing costs. Table 5 is a brief description of the changes in the OFA system and range in costs for each tier. Tier 1 involves relatively simple changes in the existing jet configurations. These can include removal of jets from service or changing the direction of air flow or port size, but using the existing fan and air delivery system. Tier 2 configurations may require furnace penetrations for additional jets, but within the capabilities of the existing fan and delivery system. Tier 3 can be viewed as a complete redesign of the OFA system with additional fan capacity, modifications to the delivery system and new jet penetrations. The costs are expected to increase as illustrated in the table, with labor the major cost in Tier 1 and equipment and labor more equally distributed in Tier 3.

In addition to oxygen and temperature distributions, another factor considered in comparing alternative configurations with the baseline is the creation of fuel rich regions. These have been shown by Pershing (U.S. patent # 4,592,289, June 3,1986) to reduce NOx emissions. Consequently, an improved configuration would exhibit more uniform temperature and oxygen concentrations through the furnace and a uniform fuel rich region above the bed where the volatiles are burning.

A schematic illustrating the nomenclature used for Tier 1 configurations and simulations is shown in Figure 7. The baseline simulations are compared to alternative configurations that use only eighty percent (80 %) of the baseline OFA flow. The purpose is to simulate alternative configurations with improved efficiency potential based on reduced oxygen requirements when compared to the baseline.

The simulations of the baseline configurations with no OFA are shown in Figure 8; with one hundred percent (100 %) OFA, in Figure 9; and with eighty percent (80 %) OFA, in Figure 10. All show a region on the rear side of the furnace from the bed to the entrance of the superheat tubes that is fuel rich and a source of carbon in the flyash. This fuel rich region is reduced in magnitude only partially by adding the full amount of OFA. When the OFA is reduced to eighty percent (80 %), the fuel rich region expands near the superheat region. The simulations of the base case that show the fuel rich region explain why the NOx emissions are lower than the EPA report “AP 42” values used for typical spreader stokers, i.e., 0.25 lb/mmbtu versus 0.65 lb/mmbtu. However, the fuel rich region extending into the superheat tubes also limits the extent to which the OFA can be reduced to improve efficiency.

All of the alternative OFA configurations that reduce the number of jets, balance the OFA between the feed and rear wall jets or bias the OFA to the feed wall jets result in improved mixing and distribution of the oxygen. These configurations also create a fuel rich region for NOx reduction. The simulation in Figure 16 that has three (3) OFA jets on the rear wall and none on the front wall represents the worse of all cases simulated.

The simulation in Figure 12 that has three (3) OFA jets on the feed wall and none on the rear wall is one of the more promising configurations. It shows more uniform oxygen concentration in the upper part of the furnace and a fuel rich region above the bed. The simulation of the configuration, A5, which imparts a tangential rotation of the combustion gases and creates a fuel rich region in the center of the furnace, also appears to be promising. Comparing the results, it is apparent that injecting the OFA on the feed side of the furnace improves penetration and mixing of the OFA with the volatiles that are released and burning primarily over the rear and middle part of the furnace.

5. VU # 7 Testing of Advanced OFA Configurations

The simulation results provide a basis for modifying the existing OFA system to improve efficiency. To test and compare the alternative configurations with the baseline, each of the ten (10) upper OFA jets was modified with a ball valve to allow each jet to be operated fully open or fully closed. These modifications allow all of the Tier 1 configurations to be tested experimentally and assure that the OFA system can be returned to the original configuration and operation. The operation of the eight (8) OFA jets below the feeders and the eight (8) OFA jets located at the re-injection ports was not modified for these tests. However, these sixteen (16) jets would need consideration for any future efforts to further reduce NOx emissions.

The modifications to the feed side jets of unit # 7 are shown in Figures 17 and 18. The total costs for the installation of the ten (10) valves was $20,550 , $2,895 for the valves and $17,655 for the labor. The testing of the baseline and alternative OFA configurations was done May 21-22, 2003. The test plan, including changes made during the testing, is shown in Table 6. Some of the configurations tested on May 21, 2003 were not planned but a result of the flow direction indicated by the valve handle on the upper feed side jets (F1, F2, F3) being opposite to the other valves. Consequently, these jets were closed when they were supposed to be open. See, for example, test B1A compared to test B1.

Each configuration was tested by opening or closing the appropriate valves and allowing the control panel and Land instrument readings to level out. The Land instrument readings were made on the flue gas collected by an EPA Method 26 sample train**.** The Method 26 sample probe (5/8” stainless steel tubing with Teflon lining) was located at the outlet of the economizer and adjusted to the approximate center of the ducting. Generally, it required 15 to 30 minutes for the control panel and Land instrument readings to level out or reach a steady state condition. The control panel, OFA supply manifolds pressures for the feed and rear side of the furnace and the Land instrument readings were collected over a 15 to 30 minute period after steady state was reached. The steam rate and the UFA and OFA flows were operated in manual control. The only intentional changes made were in the OFA flow. However, there were some variations in the steam flow rate due to variability introduced by the plant's cogeneration gas turbines. Each test required 30 minutes to an hour to complete, provided there were no upsets.

The average readings collected during the tests are summarized in Table 7. Steam rate ranged from 62,000 to 64,000 lb/hr. Steam pressures were relatively constant at 650 psi. Steam temperatures ranged from 703 to 740 $^{o}$F, which was considered normal by the operators. The coal rate was calculated from the number of discharges or dumps from the day bunkers over a period of time. The day bunkers hold about 200 # of coal. The coal rate ranged from 5,193 to 8,000 lb/hr for an average of about 7,000 lb/hr. The residence time on the grate was measured at 2.4 hours and the ash thickness was about 5 inches at the ash discharge. The under grate pressure varied from 1.0 to 1.3 inches of water compared to the design value of 0.7 inches of water.

There is a main supply manifold from the OFA fan that delivers air to three manifolds on each end of the furnace; one to the upper three (3) OFA jets, one to the two (2) middle OFA jets and one to the lower eight (8) OFA jets. At the beginning of the tests the dampers on each of the three manifolds front and rear were adjusted to the design values that tended to bias the air flow to the rear of the furnace. It was learned during the tests that the manifold to the upper OFA jets on the feed end was fully open and could not be adjusted. Consequently, all of the dampers were adjusted to fully open. Only the main supply damper was adjusted during the tests.

The flue gas exit temperature from the furnace ranged from 1309 $^{o}$F to 1415 $^{o}$F. The economizer inlet temperature ranged from 593 $^{o}$F to 616 $^{o}$F, while the economizer outlet temperature ranged from 369 $^{o}$F to 382 $^{o}$F. The excess oxygen values recorded by the control panel for the alternative OFA configurations ranged from 1.8 to 3.8 percent, while the Land instrument values ranged from 2.5 to 4.6 percent. The lower the excess flue gas excess oxygen, the closer the agreement between the control panel and the Land instrument readings. The is consistent with the results of the simulations that indicate better mixing and oxygen uniformity with the more promising OFA configurations.

The NOx emissions ranged from 0.22 to 0.37 lb/mmbtu, while the CO emissions ranged from 24 to 489 ppm. For the more promising alternative OFA configurations (A1, A2, A5A, A5B, and ARAD), the excess oxygen ranged from 1.3 to 2.7 percent on the control panel and 2.7 to 3.6 on the Land instrument. The corresponding NOx values were all about 0.25 lb/mmbtu, while CO values ranged from 22 to 47 ppm.

The emissions and efficiency results of the more promising Tier 1 configurations are compared with those for the baseline in Table 8. The data indicate that all of the alternative OFA configurations can be operated at about half of the 6.2 percent excess oxygen of the baseline with acceptable CO emissions. In addition the NOx levels are all about 0.25 lb/mmbtu, compared to 0.315 lb/mmbtu for the baseline or about a twenty (20) percent reduction. Based on the reduction in excess oxygen alone, the efficiency of the ARAD configuration as calculated by the ASME short form is 84.1 percent or 1.5 percent higher than the baseline. Table 9 shows that the simple payback period is 1.56 years. This assumes a 1.5 percent improvement in efficiency and that the costs for modifying VU units # 8 and # 9 will be about half of the costs for unit # 7 or about $10,000 each.

The conclusions that can be drawn from the simulations and testing of VU#7 are summarized in Table 10. The primary conclusion is that the existing OFA system can be modified by a number of alternative configurations to improve the efficiency at an acceptable CO level and reduce NOx emissions.

While fly ash samples were not collected and analyzed for carbon content, visual observation of the fly ash samples that were collected suggested that the carbon content of the fly ash was reduced. This is attributed to the improved mixing of the oxygen with the combustible flue gases. There is also evidence that operation of the lower excess oxygen levels of the Tier 1 configurations increased the furnace temperature and potentially reduced the carbon content of the bed. These results are consistent with previous full scale testing of stokers at the Painesville, Ohio municipal power plant (Gummuluri and Berkau, AWMA 87th Meeting, June 19 –24, 1987).

The experimental results have verified the simulation trends and established the value of numerical modeling as an inexpensive and reliable tool for examining alternative OFA configurations for a variety of combustion related operations.

The improvement in efficiency for the Vanderbilt units by only 1.5% has a simple payback of 1.56 year. This is remarkable considering that the Vanderbilt stokers are relatively modern and have always operated above 80% efficiency. For older less efficiency units, the efficiency improvements are likely to be more substantial and the simple payback period less than one (1) year.

## 6. Vanderbilt University Power Plant Mini-Conference

A mini-conference was held at the Vanderbilt University power plant facilities on June 5, 2003. The sponsors were Vanderbilt Plant Operations and the Department of Energy. The eight (8) facilities and eighteen (18) representatives from these facilities are listed in Table 11. There were two (2) local and one (1) out-of-state industrial facilities (Nissan, Dupont, AGP) represented. The remaining five (5) facilities were university and medical institutes from Kentucky and Tennessee. The University of Louisville had also planned to attend, but cancelled at the last minute due to a conflict.

The agenda for the meeting is shown in Table 12. The primary purpose of the meeting was to report the results of the OFA simulations and testing on VU # 7 and to assess the mini-conference as a marketing tool for soliciting future business. Follow-up calls to the attendees has indicated interest in efficiency improvements and emissions, primarily

NOx, reduction. Similar work to the DOE project is planned at the Nissan facility. The other interested facilities will be visited over the next few months. These include Tennessee Technological University, East Tennessee State University, Eastern Kentucky University, Western Kentucky University and The Medical Center Steam Plant of Louisville, KY. The mini-conference appears to be a useful tool for attracting stoker boiler owners and will also be considered at the Cox facility for wood burning facilities. After a successful project (e.g., Nissan), a mini-conference may also be considered if the owners are agreeable.

7. Cox Baseline Tests

There are two identical boilers at Cox that burn a mix of hardwood sawdust, saw ends and hogged pallet. The units were designed to produce 40,000 lb/hr of steam, but typically operate at 33,000 lb/hr of steam. The furnace is designed to operate as a gasifier with approximately forty (40) percent of the combustion air provided by the underfire air (UFA) and sixty (60) percent by the overfire air (OFA).

The units have an eight (8) by twenty (20) foot sloping grate composed of twenty (20) sections. Each section is composed of twenty-four (24) 4” x 2’ bars. There are moveable sections in the front, middle and rear of the grate that are sequenced to move the fuel down the bed. Figure 19 is a photograph of the grate and Figure 20 is a photograph of a bar or ram. The standard sequence is five (5) extensions (or walks) of the front section rams to one (1) walk of the middle section rams. After four (4) walks of the middle section rams (25 walks of the front section rams), there is one (1) walk of the rear section rams. This sequence is labeled “5/4/1” and there is 118 seconds between walks.

The UFA is introduced into five (5) isolated compartments below the grate. The OFA is introduced at two levels above the center of the grate as shown in Figure 21. There are twenty-two (22) opposing one inch internal diameter (ID) jets on each side of the arched opening to the upper furnace and about seven (7) to eight (8) feet above the grate in the first level. The second level of OFA jets are located about thirty inches above and at right angles to the lower jets. There are fourteen (14) one inch ID jets on each side of the opening to the upper furnace and clustered in three groups of three (3) and one group of five (5). The OFA jets are supplied by a single fan. Figure 22 is a photograph of the manifolds supplying the two levels of OFA jets.

The baseline conditions for the Cox units are shown in Table 2. The nominal heating value of the dry wood mix is 6000 btu/lb. The surface moisture content is typically forty-five (45) percent. The steam rate for the baseline is 33,000 lb/hr and the average excess oxygen content is eight (8) to nine (9) percent. Baseline tests were conducted on Cox unit # 1 on June 4, 19 and 20 in 2002. The average $SO_2$ emissions ranged from 5 to 30 ppm and the NOx emissions ranged from 28 to 77 ppm. Average CO emissions ranged from 380 to 1275 ppm. The carbon content of the bottom ad fly ash was about 9 percent**.** The ASME short form efficiency was about 63 percent.

Table 13 is a summary of the baseline emissions test results. Under standard conditions the UFA damper is in automatic control to maintain stream pressure. The front two UFA compartments correspond to the section of the grate where the raw fuel is fed into the furnace and are closed to help prevent combustion of the fuel in the feed hopper. The sequence for walking the bars was 5/4/1 with 118 seconds between walks.

The primary variables examined during the June 4, 2002 baseline tests were the OFA damper settings and maintaining the middle bars extended (rather than retracting as is normal) to see if air flow through the middle of the bed could be improved. The testing was done on unit # 1 at a steam rate of 28,000 to 30,000 lb/hr. In all of the tests the average CO emissions ranged from 1046 to 1275 ppm and the number of CO spikes above 1000 ppm were about 1 per minute, except for Test # 5. In the latter test at the highest OFA damper setting (50 %) the number of CO spikes above 1000 ppm dropped to 0.4 per minute. Many of the CO spikes exceeded the 2000 ppm upper limit for the portable Land instrument. Analysis of the spikes and the walk cycle indicated that they were related.

Figures 23, 24, 25 and 26 show the variability in the CO and O2 emissions as the OFA damper was increased from 15 percent to 50 percent and the middle ram position extended during the off cycle. The average excess O2 concentration increased from 6.5 percent to over 9 percent with some reduction in CO emissions as shown in Table 13. While the number of CO spikes decreased when the OFA damper was set at 50 percent, the excess oxygen concentration became more erratic. Leaving the middle ram extended appeared to increase the UFA flow through the bed, but did not reduce the oxygen or CO fluxuation or the CO spikes.

The baseline operation at an OFA damper setting of 15 percent provided the lowest excess oxygen operation and the most stable CO and excess oxygen concentrations, while the OFA damper setting at 50 percent reduced the CO spikes from 1.0 to 0.4 per minute. The concern for the high CO readings led to the second series of baseline tests on 6/19/02 and 6/20/03. The primary variables considered were the walk sequence (5/4/1, 10/4/1, 15/2/1), walk frequency (118, 94, and 86 seconds), opening of the front compartments UFA dampers and the OFA damper settings (30 and 5 percent). The testing was conducted on unit # 1 at a steam rate of 28,000 to 30,000 lb/hr.

The variables examined on 6/19/02 were ram cycle (5/4/1 and 10/4/1) and opening the front two dampers on the UFA compartments. In normal operation the front two UFA compartment dampers are closed to reduce the potential of a fire spreading to the feed hopper. Comparing the results in Table 13, the average CO levels ranged from 528 to 615 ppm, while the number of CO spikes above 1000 ppm ranged from 0.3 to 0.4 per minute. The average excess oxygen content ranged from 7.7 to 10.4 percent.

The data suggest that the 5/4/1 cycle and opening the front two UFA compartment dampers may have reduced the number of CO spikes above 1000 ppm. Test 2 (6/19/02) had an average CO concentration of 528 ppm and the number of CO spikes was 0.3/min. The average oxygen content was 7.7 percent. The CO and oxygen content are plotted in

Figure 27. Comparing Test 2 (6/19/02) with Test 1 (6/4/02) results, the average CO emissions have been reduced from 1216 to 528 ppm and the CO spikes from 1 per minute to 0.3 per minute. The average oxygen content increased from 6.5 to 7.7 percent.

Another series of tests were conducted on 6/20/02 and examined cycle (10/2/1 and 15/2/1) at a walking frequency of 86 to 94 seconds and OFA damper setting of 30 percent and 75 percent. The results for Test 1 (6/20/02) in Table 13 suggest that an OFA damper setting of 75 percent, a walk cycle of 10/2/1, a walk frequency of 86 seconds and opening the front two UFA compartments reduced the average CO concentration to 379 ppm. Figure 28 shows the CO and oxygen results for Test 1 (6/20/02). CO spikes were reduced to only one (1) above 1000 ppm during the sampling period. The average oxygen content for the test was 8.5 percent.

Reducing the OFA damper setting to 30 percent in Test 2 (6/20/02) increased both the CO concentration and the number of CO spikes above 1000 ppm. Extending the front rams in Test 4 (6/20/02) did not improve the results over Test 1 (6/20/02) and changing the ram cycle to 15/2/1 increased the average CO concentration and the number of CO spikes over 1000 ppm. Test 5 (6/20/20) was an unsuccessful attempt to duplicate Test 1 (6/20/02). The inability to reproduce the results cannot be explained at this time, but could have been related to the manual operation in Test 4 (6/20/02) and insufficient time for the unit to reach steady state. Figures 28, 29, 30 and 31 show the CO and oxygen results for Tests 1, 2, 4 and 5 (6/20/02).

The conclusions from the baseline testing are that the average CO concentration can be reduced below 500 ppm and the CO spikes above 1000 ppm can be essentially eliminated by adjusting certain critical parameters. These include the walk sequence, walk frequency, opening the front UFA compartments and increasing the OFA air flow. Although not extensively tested, extending the front rams did not seem to improve the air flow through the bed sufficiently to reduce CO formation or CO burnout.

Table 14 is an attempt to correlate the CO spikes with the ram walks. The data indicate that the walks of the front rams are the primary source of the CO spikes. This suggests that the CO spikes are formed primarily in the feed section of the grate and that increasing the UFA flow in this region may mitigate the CO formation. This may not be entirely possible when safety issues associated with fire in the feed hopper are considered. The redesign of the OFA system may be the primary alternative.

## 8. Cox Baseline Simulations

A PCGC-3 schematic of the Cox furnace is shown in Figure 32. The schematic shows the twenty-two (22) opposed one (1”) inch I.D. jets at the arch and the fourteen (14) opposed jets about thirty (30) inches above and at right angles to the arch jets. The baseline conditions are given in Table 2. A filet plot of the CO concentration in the furnace at a steam rate of 33,000 lb/hr is shown in Figure 33. The simulation shows the inability of the OFA jets to penetrate and react with the CO that evolves from the bed.

The average CO content in the flue gas exiting the furnace is 1000 ppm at an excess air content of 6.6 percent.

## 9. Cox Alternative OFA Configurations and Simulations

There were two alternative Tier 1 configurations simulated. These are shown in Figure 34. The approach used in selecting the alternative configurations was to reduce the number of jets on both levels to increase the momentum and mixing with the combustion gases of the OFA air. The target CO concentration in the flue gas was set at less than 100 ppm. Configuration Tier 1-12x10x8x8 has two adjacent jets opposed by two offset adjacent jets in the arch and eight (8) jets, two per set on each side of the upper OFA jets. The results of this simulation are shown in Figure 35 and show that the average CO concentration in the flue gas is reduced from 1,308 to 465 ppm. Although reducing the CO concentration, this configuration did not meet the 100 ppm target.

The number of jets are further reduced in the Tier 1-9x9x4x4 configuration. This configuration has three sets of three arch jets opposed by three sets of three arch jets offset, a total of nine (9) on each side of the arch, and one jet per set, total of four (4), on each side of the upper OFA jets. The results of this simulation shown in Figure 36 show that the average CO concentration is reduced to less than 100 ppm. Based on the experience in reducing jets during the Vanderbilt tests, it was anticipated that the OFA flow would be reduced as the number of jets were reduced. The simulation in Figure 37 shows that the CO concentration remains below 100 ppm even when the excess air is reduced by fifty (50 %) percent. As a result the Tier 1-9x9x4x4 configuration was selected for testing.

## 10. Testing of Alternative OFA Configurations on COx Unit # 1

Baseline tests were conducted on units #1 and #2 on 7/30/03. This was to provide a basis for comparison to subsequent tests of a modified OFA system. Both units have received major improvements. These included rebuilding of all furnace internal refractory, replacing all burned outside wall metal and sealing tramp air. The secondary re-injection air was removed and the UFA maximum damper setting was reduced from 18% to 13%. The five UFA air compartment dampers were adjusted to the following settings starting from the feed end or front of the furnace: #1– closed; #2 – ½ open; #3 – ½ open; #4 – ¼ open; #5 – 1/8 open. The walk cycle was set at 4/3/1 with 72 sec frequency.

The tests were conducted on 7/30/03 at a steam rate of 24,000 to 25,000 #/hr. The UFA air flow was set on automatic to control the steam pressure. Emissions data were collected for both units at identical locations in each boiler’s ducting from the boiler to the multi-clone. Three sets of data were collected for each unit at upper, middle and lower sample ports.

Table 15 summarizes the baseline results from the tests conducted on 7/30/03. The data indicate that unit #2 operates better than unit #1, having lower CO emissions at a lower oxygen content and having no CO spikes above 1000 ppm over a 30 minute period.

Figures 38 and 39 show the variations in flue gas CO and oxygen content for unit #1 and #2. The results from unit #1 on 7/30/01 are comparable to those obtained on Tests #1, #3 and #4 on 6/20/03 (See Table 13 and Figures 28 and 30); although sequence, frequency, OFA damper position and UFA front compartment positions are significantly different.

No explanation for unit #2 operating better than unit #1 can be offered at this time. However, the results show that testing an alternative OFA configuration for unit #1 would be more logical. Table 16 shows the effect of sample location on the flue gas CO and oxygen concentrations. While the data suggest that there may be some differences in the readings; e.g., lower CO at the lower ports, the variability in the data shown in Figures 38 and 39 precludes any definite conclusions.

On 8/6/03 alternative OFA configurations were tested on unit #1 and a baseline test conducted on unit #2. The results are summarized in Table 15. The alternative configurations examined on unit #1 were the basic Tier 1– 9x 9 modification to the lower OFA jets coupled with two configurations of the upper OFA jets, Tier 1– 9 x 9 x 9 x 9 and Tier 1– 9 x 9 x 4 x 4 as illustrated in Figure 34. The steam rate for unit #1 was 23,000 to 24,000 lb/hr. The walk sequence was 4/3/1 and the walk frequency was 58 seconds. The maximum UFA damper setting was set at 16% in Tests #1 through #5 and 13% in Test #6. The front UFA compartment was closed, while the other four compartment doors were particularly opened as shown in Table 15. The OFA damper was varied from 45% to 75% open.

The results of Test #1 (8/6/03) are comparable to those of Test #1 (7/30/03) even though only 9 of the 22 lower OFA jets on each side of the arch were open and the overall oxygen content was 5 percent. This result suggests that the upper OFA jets are the primary ones affecting the CO burnout and controlling the CO spikes. The variations in CO and oxygen concentrations for the baseline Test #1 (7/30/03) and the Tier 1-9x9x14x14 alternative configuration in Test #1 (8/6/03) are shown in Figures 38 and 40.

In Test #2 (8/6/03) the OFA damper opening was increased from 45 to 75%. The result was an increase in the flue gas oxygen and CO content and the number of CO spikes. The variability in CO and oxygen content is shown in Figure 41. In Tests #3 and #4 the number of upper OFA jets was reduced to 9 x 9 and 4 x 4. The result was a major increase in oxygen and CO concentration and CO spikes. The data suggest that CO burnout and control of CO spikes are primarily through the upper OFA jets. The variability in CO and oxygen content of the flue gas in these tests is shown in Figures 42 and 43.

Tests #5 (8/6/03) and #6 (8/6/03) were attempts to re-establish the conditions in Tests #2 (8/6/03) and #1 (8/6/03). While the CO concentration was reduced in Test #5, the oxygen content was 8%. In Test #6 the oxygen content dropped to 5 percent, but the CO increased to 1041 ppm. The variation in CO and oxygen for these tests is shown in Figures 44 and 45. The figures show decreasing variability in CO and oxygen and suggest that the conditions in Test #1 (8/6/03) and Test #2 (8/6/03) might be achieved as the unit approaches steady state.

The results of the tests with Unit #1 on 8/6/03 indicate that the upper OFA jets are the primary sources of oxygen for the CO burnout and control of the CO spikes. Test #1 (8/6/03) with only 9 x 9 lower OFA jets produced a lower average CO and 02 content than the control, Test #1 (7/30/03) with 22 x 22 lower OFA jets (See Figures 38 and 40). The data suggest that the lower OFA jets should be configured to enhance penetration and mixing in the center of the arch.

Tests #1 (8/6/03) and #2 (8/6/03) indicate that there is little additional OFA when the OFA damper is increased from 45 to 75%. This indicates that the available fan pressure limits reducing the total number of OFA ports to increase penetration. Increasing the upper limit on the UFA air damper from 13 to 16 percent has a much greater effect on the oxygen content.

Test #7 (8/6/03) on Unit #2 was done at a steam rate of 19,000 to 20,000 lb/hr compared to 24,000 to 25,000 lb/hr in Test #2 (7/30/03). The results are comparable but Test #7 (8/6/03) has higher oxygen content. The variation in CO and oxygen for Unit #2 is shown in Figure 46 for Test #7 (8/6/03) and in Figure 39 for Test #2 (7/30/03). The operation of Unit #2 is reproducible and better than Unit #1 with respect to average CO content in the flue gas and CO spikes under seemingly identical conditions.

The efficiency of Cox unit # 1 has improved by 2 to 3 percent (63 % to 66 %) since the beginning of the project. This has been a result of major modifications to the furnace (of both units) and the alternative OFA configuration 14x14x9x9. The lower fuel rate in the more recent tests may also have been a factor in the improvement. However, the alternative configuration could not be fully evaluated due to limitations on the fan capacity. Another alternative OFA configuration, allowing more OFA flow and longer term testing, is planned later this year.

Installation costs for the alternative OFA configuration at Cox was $1,367. This included installation of 28 valves and plugging 26 of the 44 lower OFA jets. Materials costs were $743 and labor, $624.

D. Completed Milestone Table

See Attachment A

E. Final Gantt Chart

See Attachment B

F. Updated Energy, Waste and Economic Savings

There have been some significant changes since the beginning of the project in mid-2001. Some of these changes have become trends and are briefly described in Attachment C1.

The most important change has been the increase in the cost of stoker coal. This is a result of the reduction in the number of stoker coal boilers and a reduction in the number of coal companies that supply stoker coal. The increase in stoker coal prices, the decrease in the number of stoker boilers and the increase in the cost of stoker coal are trends that will continue into the future. For purposes of this analysis the price of stoker coal, including ash disposal, has been assumed to increase from $37.5/ton in the base case to $58/ton in the present day case. The number of present day coal fired stokers has been assumed to be eighty (80 %) percent of the base case.

For wood we have assumed that the number of wood/waste stoker fired units has remained constant. However, waste wood supplies for stoker use are changing as markets for the wood waste have developed. This has increased the costs or availability of wood fuels or required supplemental fuels such as coal. This is also a trend that is likely to continue into the future. In this analysis, as in the base case, savings from efficiency improvement have been calculated in terms of reduction in supplemental fuel use in equivalent tons of coal.

Attachment C2 compares the reduction in fuel and emissions and savings for the base case and the present day case for a two percent (2 %) and five percent (5 %) efficiency improvement. This range has been selected based on the results of the project. A two percent improvement is more likely in units that have been maintained and tuned, such as the Vanderbilt and Cox units. A five percent efficiency improvement can be expected with older units.

The results in Attachment C2 suggest that the total savings in fuel costs are likely to range from $67,000,000 to $168,000,000 compared to the base case estimate of $123,000,000. Reduction in stoker coal use can range from 1,000,000 to 1,500,000 tons per year compared to 2,800,000 tons per year in the base case. Total emissions reduction can be expected to range from 3,300,000 to 15,400,000 tons per year compared to 9,300,000 to 17,100,000 tons per year in the base case. Savings from emissions reduction can range from $29,000,000 to $86,000,000 per year compared to $94,000,000 to $107,000,000 per year in the base case.

G. Fuel/Energy Source BTU Conversion

See Attachment D

H. Market Penetration Estimates /Technical Transfer Activities

The number of coal stokers has been decreasing steadily since 1985 (Berkau Associates Study for GRI, 1996) while the number of wood burning stokers appears to have remained relatively constant. The trend with coal-fired facilities has been confirmed in the present study.

The loss of coal units is attributed to a number of factors:  Among these are:

- The reduction in manufacturing facilities in the US,
- The decreased availability of stoker coal equipment.
- Increasing cost of stoker coal
- Environmental requirements for reducing SO2 and NOx emissions
- Difficulty in permitting new coal facilities
- Conversion to natural gas

The wood stoker market on the other hand has stayed relatively constant and is can be expected to remain relatively constant over the next 20 years.  However the market for waste wood is growing and the availability of "free" wood for burning in stokers is likely to decrease over the next 20 years.  This trend in the wood market could be a significant factor affecting the market for improved efficiency in wood-burning stokers.  Also efficient burning of wood and co-firing with coal can be cost effective alternatives to conversion to natural gas.

The assumptions used for coal-fired stokers in Attachment E are that the number of coal units will continue to decrease by 5% each five year period for the next 10 years and then decrease at a rate of 10% each 5 years over the next 10 year period.  Wood burning stokers are projected to remain essentially constant over the next 20 years.

The technology developed in the subject project can improve efficiency generally by 2 to 5% and reduce NOx, CO and smoke emissions for only a relatively small capital investment ($2000 to $20000/stoker).  Developing the design basis for the modifications can cost an additional $25,000 + $35,000/stoker.  The simple payback is expected to be less than one (1) year in most cases.

However, tuning of coal and wood fired stoker boilers can provide short-term efficiency improvement for a relatively minor investment as the work at Cox has demonstrated.  By contrast redesign of the OFA system can provide long term efficiency and emissions reduction improvements.  One of the biggest issues is to convince boiler operators of the long-term benefits of OFA redesign.  The other major issue is that most of the coal fired stoker boiler facilities that attended the Vanderbilt conference are currently examining alternatives to coal, a significant barrier to committing to an improved efficiency project.

Consequently the market penetration estimates in Attachment E are very conservative.  The approach we plan to take is to focus on the attendees to the Vanderbilt conference to assess the potential market for coal-fired facilities.  We plan a similar mini-conference for wood burning facilities to assess the wood burning market.  In addition we will continue to develop a database on operating wood and coal fired stoker facilities in the southeast and the US and identify coal-fired stoker facilities that may be candidates for conversion to wood or to co-firing with wood rather than natural gas.  The results of the assessments will determine the near term focus for our efforts.

I. Cost Sharing

The initial estimates for cost sharing to the project in the proposal included in-kind and cash commitments by Vanderbilt University Plant Operations and Cox Waste to Energy for contributions of up to $250,000 each for “design, fabrication, purchase and installation of an advanced OFA system based on the results of the PCGC-3 simulation model.” The contribution of $250,000 each or a total of $500,000 was derived from preliminary estimates of the costs for an OFA system that was based on tangential or vortex mixing of the flue gases. During simulations of both the Vanderbilt and Cox furnaces and OFA systems, it was learned that tangential or vortex mixing was ineffective without major modifications to the existing OFA system. These included new fan capacity, transfer manifolds and furnace penetrations for the OFA jets and would be classified as Tier 3.

The PCGC simulations of the baseline (existing OFA system) suggested that simple modifications to the existing OFA system could provide the improvements in mixing of the OFA and flue gases necessary for increasing efficiency and reducing emissions. These type modifications simply require valves on the existing manifolds to change the OFA configurations and are classified as Tier 1. The costs for Tier 1 modifications were found to range from $1,400 for Cox to $20,550 for Vanderbilt. The simple payback for the Tier 1 modification is less than two (2) years for Vanderbilt and less than one (1) year for Cox compared to over six (6) years for the Tier 3 tangential configuration. The six (6) year payback period is unacceptable to utilities. It is unlikely that any stoker facilities would apply the higher cost tangential technology.

The research results from the PCGC-3 simulations identified a technology and an approach that is likely to be acceptable to facilities using stoker boilers. The primary benefit to DOE of the lower cost Tier 1 modification is that many facilities are likely to consider and apply the lower cost technology. This will result in significant savings in fuel costs and reduced omissions. An additional benefit that can improve the acceptability of the technology is that the modifications to the stokers are relatively minor and less disruptive, especially when compared to the Tier 3 tangential configuration.

Attachment F shows the actual cost sharing in the project. The total contributions are $60,206. This includes $13,875 in in-kind and $46,331 in cash contribution. The total cost for the Vanderbilt and Cox OFA modification was about $22,000 or less than half of the total cash contribution to the project.

J. Partners and Contractors (Not Applicable)

## Supplemental Information

Attachments



Figures

Tables