Phase 2 Co-firing Testing of Wood Chips at Alabama Power's Plant Gadsden

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Executive Summary

In October – November, 2007, field tests of co-firing chipped pine trees with coal were conducted by Southern Company, the US Forest Service, and a number of other forestry interests. These tests were successful, and showed that up to 15% by weight wood could be co-fired at Alabama Power's Plant Gadsden Unit 2.

However, a number of questions arose from the test results, and a new and more limited scope series of tests was conducted to determine: a. sources and remedies for unit operating instabilities, b. effect of varying moisture on operations and emissions, and c. effect of co-firing on carbon monoxide emissions. Three types of wood were tested in phase 2. These included high moisture pine left over from the first test phase, moderate moisture green hardwood from Jasper Lumber, and very dry hardwood from a flooring manufacturer. GreenFuels, LLC. was partner with Southern Company in these follow-on tests, procuring and processing the woods to specified top size, and delivering the wood to the plant.

The tests showed that operating instabilities incurred in phase 1 resulted when new digital controls were installed to replace an aging pneumatic control system. With minor adjustments to the controls' response settings, the operating instabilities were removed.

Wood for these tests was much drier than in phase 1, and resulted in many less mill problems. Unlike phase 1, mill under bowl pressures and mill temperatures with co-firing were acceptable, and required no unit load derate. Mill amps increased with co-firing, and were found to be directly related to the percentage of dry wood in the fuel mix. The coal in phase 2 was softer than the synfuel of phase 1, and as a result, the unit was able to achieve full load at 15% wood loading without exceeding mill amp limits.

Only partial results could be determined for boiler efficiency. Slagging occurred in these tests that was related to the phase 2 coal. However, buildup of material on the boiler surfaces over time made it difficult to interpret and compare temperature and dry gas loss measurements. Further, some problem with the ash samples resulted in inconsistent carbon-in-ash measurements, which have not yet been resolved. Moisture losses were increased with the driest wood, because dust suppression water sprays were required.

CO emissions in phase 2 were similar to those in phase 1, with CO beginning to increase as the combustion oxygen was decreased. For both co-firing and coal alone tests, the CO increase began at about the same furnace O2, with the co-firing CO generally increasing faster than with coal alone. However, the breakpoint at which CO increases is typically lower than normal unit operation and should not present a problem with CO increase.

NOx was unexpectedly lower in these tests with co-firing than with coal alone. The reason is not understood. It may relate to the high level of very fine material in the phase 2 wood, or perhaps to the lower volatile level of the phase 2 coal.

Introduction

Alabama Power and Southern Company are participating with a consortium of forestry interests to investigate the potential for co-firing wood chips with coal in pulverized coal electric generating stations. A report entitled "Co-Milling Green Wood Chips at Alabama Power Company's Plant Gadsden Unit 2" detailed tests conducted in Fall 2007 on whole tree and de-limbed pine trees that were ground up, mixed with coal, and burned in the Gadsden power plant. The tests were successful, and the results encouraging. However, several questions arose in the tests concerning unit operation and performance.

The most important question involved unit operating stability. When wood was introduced into the unit in the Fall 2007 tests, the unit was difficult to control. Coal feeder rates and steam pressures swung so widely that the unit was sometimes put in manual control in order to conduct testing. Later analysis suggested that the problem lay in new controls that had been installed immediately before testing. A further testing phase was desired to confirm this diagnosis.

There was also interest in gathering further carbon monoxide data. Only limited CO data were taken during the Fall tests, and further tests could help to better understand the effect of wood addition.

And finally, the wood tested in the fall was in general of very high moisture content (>60%). This was much higher than when the trees were first harvested, and was due to unavoidable testing delay and prolonged outdoor storage between harvest and testing. Further testing was desired to establish the influence of moisture changes on operations, particularly pulverizer performance.

GreenFuels, LLC, of Jasper Alabama offered to manufacture and provide two types of wood fuel for these additional tests. One type was obtained from the Jasper Lumber Company and consisted of mostly hardwood logs of about 35% moisture content. The other type was very dry (<7% moisture) hickory flooring obtained from a manufacturer in Tennessee. Both types of wood were ground up in a tubgrinder to two sizes, approximately 3/8" minus and ¾" minus. Wood supplies were delivered to the plant in coordinated as-needed basis to keep the wood out of the rain and preserve the low moisture levels. GreenFuels provided approximately 1000 tons of fuel for co-firing.

In addition, a small pile of the original phase 1 pine wood remained, sufficient for one day of testing.

Phase 2 tests were conducted in April and May of 2008 at Alabama Power's Plant Gadsden. This plant, located in Etowah County, Alabama, consists of two nominally 60MW tangentially fired coal units. The tests, conducted on Unit 2, included 24 boiler performance tests, 11 carbon monoxide tests, and a pulverizer test.

This report describes the conduct and results of these tests.

Objectives

These tests had the following objectives:

1. Determine the cause of operating instabilities in the Fall 2007 testing
2. Determine the effect of varying fuel moisture on plant operations and emissions.
3. Determine the effect of wood co-firing on carbon monoxide emissions.

Wood

Three types of wood were co-fired in these tests. The wood types and their properties are shown in Table 1 below:

Table 1: Test wood properties

	Test pine Fall/07	Phase 1 pine 4/08	Green Jasper Lumber 4/08	Dry Flooring 4/08
Moisture	58.64	61.98	30.74	7.81
Bulk Density (lb/ft3)	19.5	22.9	15.0	22.9
HHV (AR)	3,536	3,003	5,708	7,192
Ash (% AR)	0.43	0.17	0.94	0.535
C	23.13	19.51	34.43	46.04
H	1.92	2.19	4.00	5.37
N	0.47	0.03	0.085	0.075
S	0.02	0.01	0.015	0.01
Volatiles	31.81	30.04	55.53	74.09
HHV(Btu MAF)	8,640	7,935	8,363	7,846

The phase 1 pine in these tests was production chips that were left over from the phase 1 tests of Fall 2007. The fuel and density properties of the stored wood were reasonably consistent with the November test wood. However, they seem to reflect a loss of about 10% of the fuel energy with storage. Full analyses for the wood samples are presented in Appendix 1.

The wood was processed by GreenFuels, LLC in a tubgrinder, to meet the size limitations specified by the plant. Meeting the top size requirements with this type of grinder was difficult, and resulted in a lot of very fine material being generated as well. Screens of the samples are also presented in Appendix 1

Coal

Coal for the current tests is quite a bit different than that used in the Phase 1 Fall 2007 tests. In 2007, Gadsden was receiving synfuel, a processed coal that included fines and an asphalt binder. The synfuel quality was fairly consistent from day to day.

Production of synfuel ended in December 2007, and Plant Gadsden has since received coal from another provider. There is considerable variation from day to day in sulfur, ash, and heating value content. This variation is one variable to be considered when attempting to evaluate these test results. Averaged coal properties for Phases 1 and 2 as well as for a coal sample taken the day following Phase 2 are shown in the Table 2 below:

Table 2: Averaged coal properties

	Phase 1 Coal only	Phase 2 Coal only	Post Phase 2 Coal
Moist (%)	6.28	4.36	6.81
Btu	12033	12016	12329
HGI	48-54	-	55
Ash (%)	12.53	16.03	12.28
C (%)	66.79	67.16	68.71
H (%)	4.44	4.20	4.28
N (%)	1.39	1.37	1.4
S (%)	1.62	2.20	2.52
Vol. (%)	28.94	25.66	25.88
Btu MAF	14920	15093	15238

Instrumentation and Test plan

Plant instrumentation was used for nearly all measurements in these tests. The unit Operator's Information System (OIS) is the plant automatic data recording system, and it recorded boiler operating and emissions parameters for each test. Some mill parameters which were not on the computer were recorded manually in the control room. The scope of this project was limited and only full load tests were conducted.

Plant O2 was critical for properly comparing test results. However, a series of failures and replacements of the O2 instruments made the boiler O2 measurements unreliable for these tests. Phase 1 measurements of economizer outlet O2 had been made by SCS with a flue gas extractive grid and gas analyzer system, and these O2 measurements were the basis for comparing results in the Phase 1 report. For full load, OIS measurements of unit air flow and steam flow correlated very well with those SCS measurements in Phase 1, as seen in Figure 1. Therefore because boiler O2 instrumentation proved unreliable, and because the phase 2 tests were full load tests, the unit air and steam measurements were used to calculate economizer O2 for data analysis in the Phase 2 tests. These values will

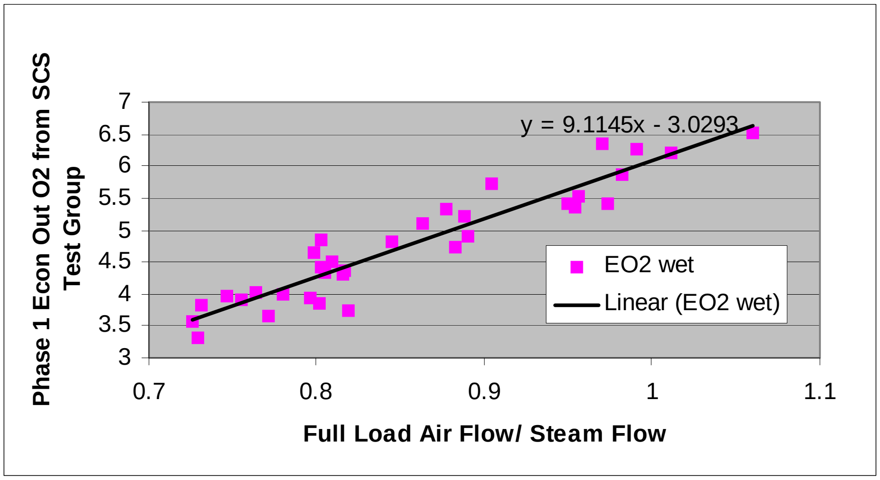

Fig. 1 Correlating full load air and steam flows to predict O2

include duct leakages between the furnace and the air heater inlet, and will be somewhat higher than combustion O2 in the furnace. However, they will be directly comparable with phase 1 measurements.

A portable CO analyzer was loaned to the project by Southern Company Engineering test group, and was installed to monitor CO at a single point in the gas duct. These measurements were taken to seek a trend in the CO, the "knee" in the curve at which CO increased rapidly with decreasing combustion air.

Fly ash samples were taken from the ash hoppers of each precipitator, and bottom ash samples were taken manually from the furnace bottom in each test. Mixed fuel samples were taken from the fuel line between the feeders and the pulverizer.

In the Fall tests, the co-firing mixture was made by metering wood through a separate reclaim onto the coal belt and coal. However, the phase 2 wood would not flow through the reclaim because its bulk density was much lower than that of the November wood. Therefore, co-firing blends were estimated by volume with bulldozers. The bulk density of each wood was measured, and compared with that of coal. Wood and coal were pushed into piles, each of relative volume to make the desired mixture. These piles were then blended on the pile by bulldozer and the mix pushed into the coal reclaim.

Attempts were made to verify the actual percentage of wood in the fuel mix. Fuel analysis results are presented in Appendix 2. Typically, coal and wood Btu have been compared with the HHV of the blend to calculate the percentage of wood. However, the wide variations in coal quality experienced here made such calculations highly unreliable. As a result, samples of wood-coal blend were submitted for radiocarbon analysis. Coal, as an ancient fossil fuel, will have no carbon 14, while the trees will have quite modern amounts of the isotope. It is hoped that carbon 14 can be used as a tracer for calculating percentage of wood. Radiometric test results are not yet available.

Tests

Nearly all the tests were one of two types. For performance tests, the unit was brought to steady operating conditions and test O_2. The ash hoppers were cleaned, and recording of emissions and boiler temperatures and other data was done. Approximately 20 to 30 minutes of steady data were taken, and then ash samples were collected.

The other test type was a CO test. The unit was brought to steady conditions with O_2 at a level higher than normal O_2. Unit data and CO readings from the portable instrument were taken for about 5 minutes, at which time the unit O_2 was decreased by about 0.5% and the test repeated. This procedure was continued until CO increased to about 1000 PPM.

Test #18 was solely a pulverizer test. A particular mix of wood and coal had been introduced into the bunkers, but then problems with the unit meant that that particular blend could not be tested at full load. Instead, in this test, the pulverizers were biased so that a curve of mill amps with fuel flow rate could be determined.

Table 4: Test Results Summary

Test #	Wood Chip	Fuel Feeder Rate	Wood	Est. Wood	Test Type	Steam Flow (Klb/hr)	NOx (lb/MMBtu)	Opacity	AH Gas In Temp (F)	AH Gas Out Temp (F)	Econ out Calc O2	Mill amps total	Amb Air Temp (F)	Dry Gas Loss (%)	Fuel Moisture Loss (%)	Hydrogen Loss (%)	Combust. Loss (%)	Boiler Eff. (%)	Fuel HHV AR (Btu/lb)
	Type		Wt %	Energy %							(% dry)								
1	None	52.61	0	0	P	560.5232	0.47	1.54	379	635	3.27	238	82.1	7	0.42	3.7	3.3	85.04	12,096
2	None	51.65	0	0	P	557.3193	0.57	0.8	383	644	3.87	237	92.7	7.22	0.43	3.73	2.87	85.21	12,016
3	None		0		CO														
4	None	51.33	10	3	P	554.3423	0.77	1.55	388	673	5.16	234	98.9	7.63	0.45	3.69	2.14	85.53	11,936
5	Phase 1	57.45	10	3	P	559.2801	0.62	2.11	375	640	4.16	248	88.8	7.21	0.74	3.69	2.02	85.8	11,823
6	Phase 1		10		CO														
7	Phase 1	59.12	10	3	P	562.195	0.66	0.8	359	642	4.79	260	101.4	6.69	1	3.67	2.45	85.66	11,137
8	Phase 1		10		CO														
9	Phase 1	59.7	10	3	P	554.1005	0.57	0.74	358	633	4.45	260	102.7	6.44	0.95	3.6	2.99	85.49	11,089
10	Green C	67.21	10	4	P	565.8556	0.62	1.9	373	652	4.57	289	92.1	7.2	0.8	3.82	2.49	85.14	11,332
11	Green C		10		CO														
12	Green C	66.75	10	4	P	561.4561	0.5	1.03	372	640	3.85	290	93.7	6.83	0.79	3.78	2.18	85.89	11,338
13	Green C	66.11	10	4	P	560.1962	0.73	1.62	379	669	5.22	289	94.1	7.61	0.79	3.88	3.02	84.15	11,203
14	Green C	65.11	15	6.2	P	570.3858	0.58	1.98	381	668	4.32	272	83.9	7.57	0.88	3.84	1.89	85.27	11,543
15	Green C		15		CO														
16	Green C	71.27	15	6.2	P	569.2082	0.5	1.04	367	647	4.21	291	90.5	6.93	1.04	3.91	2.53	85.05	11,042
17	Green C	69.28	15	6.2	P	564.365	0.64	1.86	369	660	5.1	286	92.6	7.24	1.08	3.82	2.89	84.42	11,154
18	Green C		15		CO														
19	Dry C	60.88	10	6.2	P	546.5651	0.58	0.64	374	643	4.14	324	91.7	7	0.56	3.91	3.05	84.94	11,289
20	Dry C		10		CO														
21	Dry C	60.09	10	6.2	P	542.5794	0.54	0.12	378	633	3.92	326	101.2	6.8	0.62	3.88	4.15	84.02	10,897
22	Dry C	59.53	10	6.2	P	548.2539	0.71	0.64	381	654	4.91	329	104.4	7.24	0.54	3.88	2.6	85.19	11,458
23	Green F	62.6	10	4	P	556.3949	0.74	2.83	388	676	4.7	298	95.9	7.6	0.61	3.88	2.07	85.28	11,718
24	Green F		10		CO														
25	Green F	61.47	10	4	P	529.3262	0.59	1.83	387	637	3.91	287	105.6	7.03	0.67	3.91	3.13	84.73	11,407
26	Green F	62.23	10	4	P	534.0294	0.85	3.36	392	675	6.07	290	108.5	7.91	0.61	3.78	1.76	85.38	11,969
27	Green F	64.24	15	6.2	P	561.3832	0.73	2.98	384	664	4.89	291	98	7.45	0.56	3.85	2.14	85.44	11,974
28	Green F		15		CO														
29	Green F	69.39	15	6.2	P	558.6433	0.73	2.54	381	655	5.09	298	103.2	7.3	0.75	3.79	2.56	85.05	11,602
30	Green F		10		CO														
31a	Green F	73.68	15	6.2	P	604.8135	0.62	2.84	382	655	4.53	305	103.4						
31b	Green F	74.46	15		P	616.9925	0.65	2.94	380	662	4.79	308	101						
32	Dry F	62.12	10	6.2	P	563.8365	0.74	2.75	377	658	5.15	308	97.8	7.16	0.67	3.8	2.18	85.65	11,895
33	Dry F		10		CO														
34	Dry F	65.03	15	9.6	P	560.032	0.76	2.68	381	664	5.46	320	106.2	7.41	0.77	3.84	2.28	85.16	11,602
35	Dry F		15		CO														12,096
36	Dry F	71.38	15	9.6	P	622.67	0.7	3.98	376	668	5.43	334	108.7						12,016

Discussion

Bunker and Feeders

The Gadsden 2 coal flow is metered with Stamet volumetric feeders. In co-firing wood, as the wood percentage is increased, both the fuel bulk density and the energy per pound of the fuel mix are reduced. As a result, the feeders and bunkers must accommodate a larger volume of fuel to meet load. This effect can be seen in feeder data normalized for steam flow and for feeder rate flow for coal alone, as shown in Figure 2 below

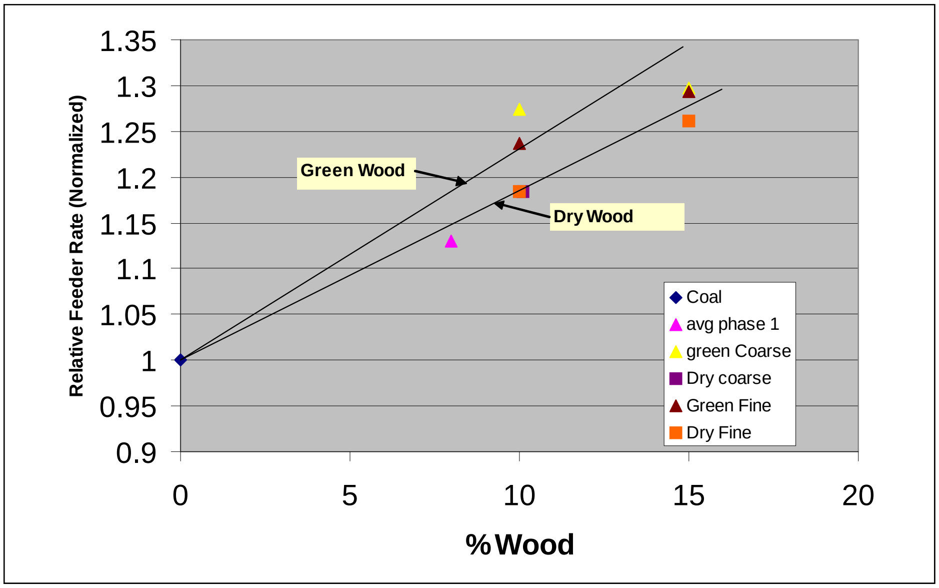

Fig 2. Effect of % wood on feeder rate

The results show that at 15% wood content, the green wood required about 35% more feeder and bunker volume than coal for the same unit load and run time. Because the dry wood was both denser and had higher energy content per pound, the fuel had a higher energy volumetric density than the green wood. At 15% wood content, the dry wood required about 28% more feeder and bunker capacity than coal alone.

These results are very consistent with those obtained in the phase 1 tests with pine, in which roughly 30% additional bunker and feeder capacity were required for 15% wood.

In the bunkers, no particular issues were observed with the wood bridging or hanging on the walls. Unlike the phase 1 tests, there were no needles or leaves present in the co-fired wood in these tests. However, dust was a problem with the dry 7% moisture wood, and to a much less degree with the green wood. Because of the way the wood was processed in a tub grinder hammermill, the product contained a high percentage of fines, especially compared with the phase 1 wood. In phase 1, the trees were processed with a Precision Husky machine that produced far fewer fines.

With the phase 2 green wood, heavy dust was observed in a case where 100% green wood fell onto a moving conveyor. However, once the green wood was mixed with coal, dust was no longer a problem. With premixing the green wood on the coal pile, the dust issue was removed.

The phase 2 dry wood, however, produced prodigious amounts of dust even after being mixed with coal (Figure 3). Dust was observed boiling out of the windows of the transfer belts, and obscured visibility on the tripper room floor. However, the dust was easily suppressed with existing water sprays along the coal belt. There was no way of monitoring the spray flow, but based on estimates while watching the sprays and on later fuel analyses, it is believed that about 30 to 60 gpm water were used to suppress dust. This is discussed in more detail below in the section on boiler efficiency moisture losses.

Fig 3: Dusty Tripper Floor

Mill – Amps

The pulverizer amps increased with increased wood percentage, as seen below in Figure 4. This figure shows mill amps normalized with unit steam flow (total amps per thousand pounds steam rate). These normalized mill amp values are plotted with the percentage of dry wood material in the co-firing fuel mix, and form a fairly linear relationship. It should be the wood fibers themselves that require mill energy to be ground up, while any moisture in the wood fuel would have little effect on mill amps. This is consistent with this curve.

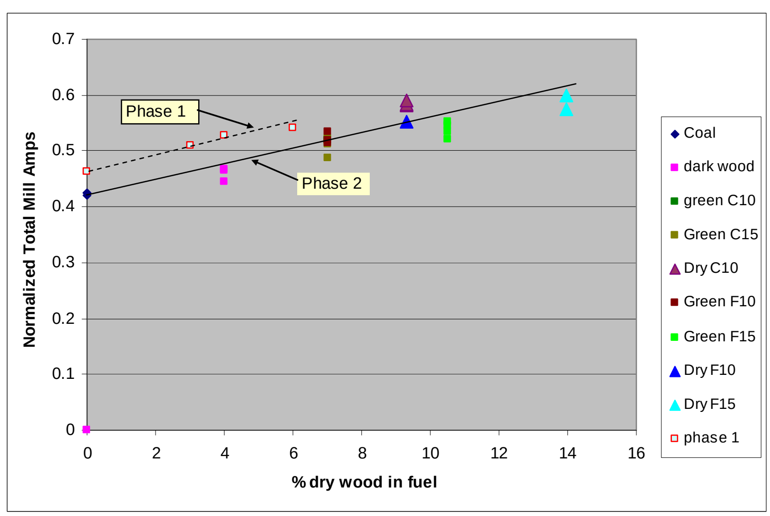

Fig 4 – Mill amps versus % dry wood co-fired (C = Coarse, F = fine)

Also included in the figure are the data from moist pine chips in phase 1. The phase 1 curve is parallel to the phase 2 curve, but offset a little lower. The offset of the phase 2 curve is believed due to the change in coal hardness from phase 1 synfuel to phase 2 coal. The phase 2 coal (HGI = 48-54) was tested by ICT to be somewhat softer than the phase 1 synfuel (HGI = 55), reducing the power requirement of the mill This reduction in baseline coal amps in phase 2 probably accounts for lack of derate in most phase 2 tests, described below.

Mill Roller Displacements

Mill roller displacement was measured with a ruler at an arbitrary mark on the roller arm external to the mill. These readings gave a relative measure of any material accumulating between the roller and the mill bowl. In previous co-firing tests, a layer of wood was seen to develop inside the bowl, lifting the roller against the springs, and increasing mill amps. Similar results were obtained in Phase 2, as shown in Figure 5. In this figure the relative amount of roller lift is plotted with dry wood fiber in the fuel. Wood which remains in the mill for very long may should lose much of its moisture, and the resulting curve looks good.

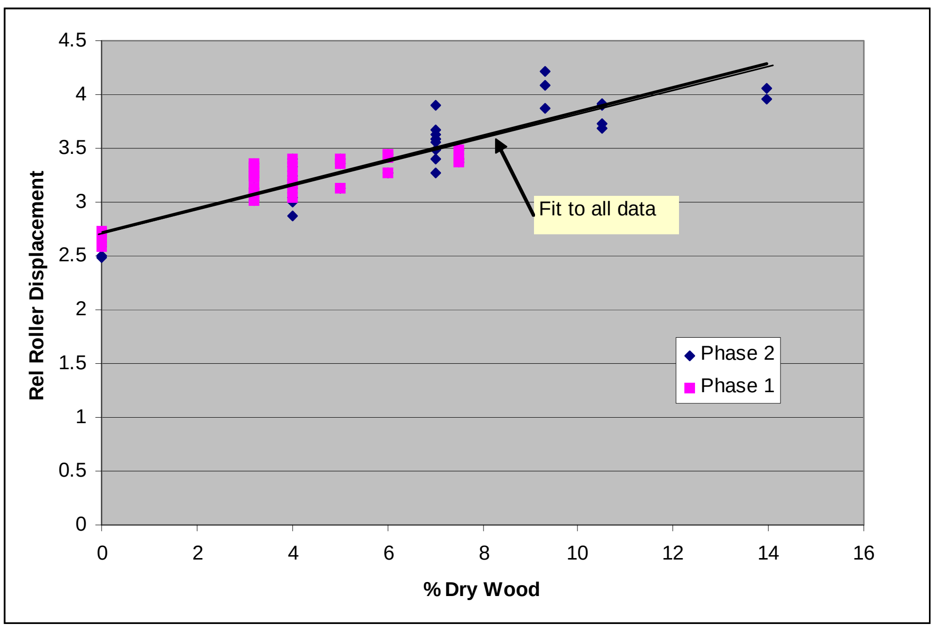

Fig 5. Averaged relative mill roller displacement with % dry wood fiber in fuel

Roller displacement data were similarly measured with a ruler in Phase 1, but were not reported in the first report because more continuous electronic measurements at a different location on the arm were available, The manual phase 1 data with pine wood, also shown in the plot, align very well with the phase 2 hardwood data.

Mill Internal Temperatures

Little or no problems were experienced with mill internal temperature in these co-firing tests (Figure 6). Mill temperature must be maintained sufficiently high to evaporate

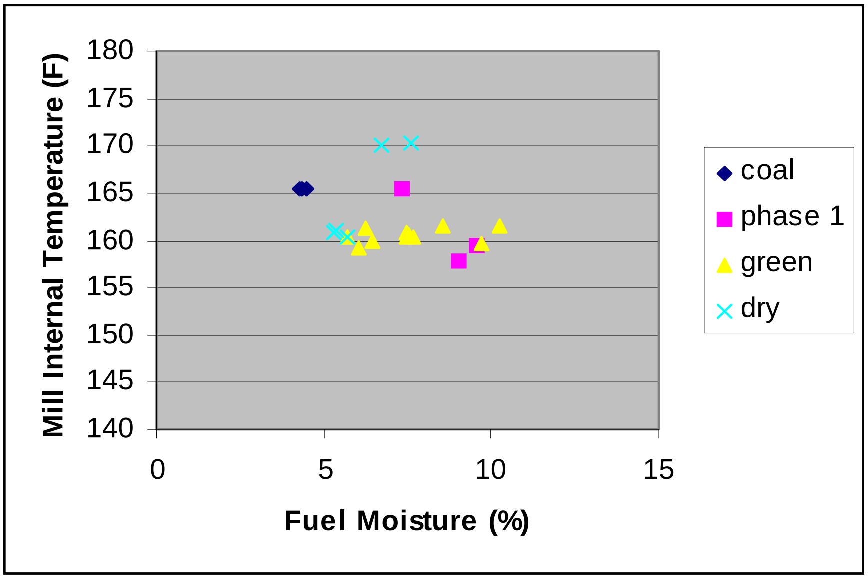

Fig. 6: Average mill temperature related to fuel moisture

the moisture in the fuel. Too much fuel moisture for the mill hot air supply to handle is signaled by a drop in mill temperature. Coal with too high a moisture content does not grind properly and accumulates in the mill. Mill temperature was a major cause of unit derate in the first phase of the Fall 2007 co-firing testing.

At Plant Gadsden Unit 2, the operators strive for a mill temperature of about 165°F, and a mill temperature between 150 and 170 is considered acceptable. In all the phase 2 co-firing tests, the mill temperatures were within these limits, and no load limitations were required due to mill temperature. The coal moisture of phase 2 (4.3%) was much lower than the moisture of the phase 1 synfuel (6.7%), and the phase 2 wood moistures (35% and 7%) were lower than the wood moisture of phase 1 (50%-67%). As a result, the moisture levels of all the phase 2 blended fuels were below 10%. In phase 1, unit derate began at a fuel moisture of about 12%.

Mill Underbowl Pressure

It is important that negative underbowl pressure be maintained in the mill. This is to prevent coal dust from blowing out of the mill into the plant and to prevent contamination of the mill gearbox bearings.

In phase 1, it was sometimes difficult to maintain both load and mill underbowl pressure, and the relatively high pressures were in part responsible for some of the derate experienced in phase 1. In those tests, the underbowl pressures were directly linked to the moisture content of the fuel entering the mill. In particular, the increased pressures

appeared to be tied to the high moisture content of the wood being co-fired. The lack of sufficient hot air to dry the fuel at higher capacity resulted in higher pressures.
In Phase 2, mill underbowl pressure was again seen to increase, but this time resulted in no problems or derate. This is due to the drier nature of the wood in the phase 2 tests. A plot for all the phase 1 and 2 tests of mill underbowl pressure with overall fuel moisture is shown in Figure 7. The data follow essentially a single curve, regardless of the type of wood and percentage of co-firing. Overall fuel moisture content is the main factor in determining mill capacity while maintaining adequate underbowl pressure.

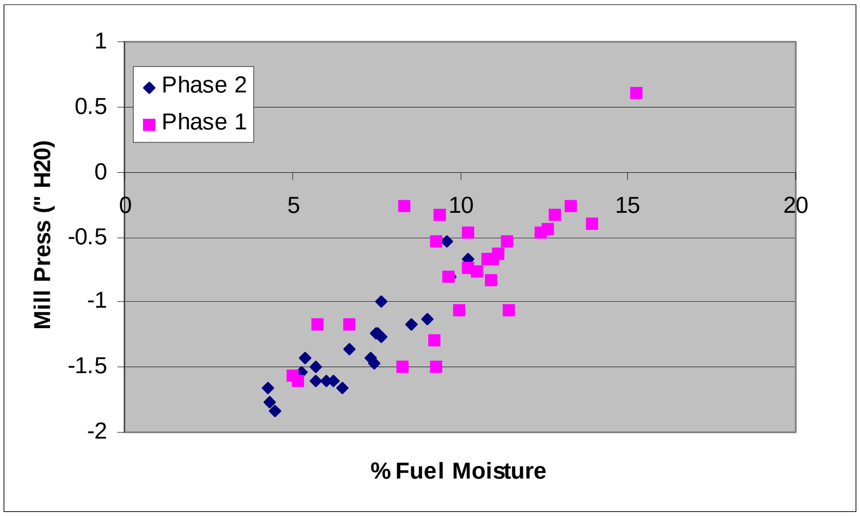

Fig 7. Phases 1 and 2 Mill Underbowl Pressure versus Fuel Moisture Content

Maximum Unit Load

No unit derates occurred due to co-firing wood. However, during two days of testing there was a problem of high rejects with mill 6 which was observed both with coal alone and with co-firing. Mill 6 fuel rate was cut back to reduce rejects, and as a result for those tests, load was reduced. The problem has been intermittent and as of this writing has not been resolved.

For the phase 2 tests, full load was defined as 550,000 lb/hr steam flow, approximately 90% of the unit 2 maximum load. However, two of the phase 2 tests were conducted to seek maximum load possible with the wood, and to find out what unit parameter would limit load. Maximum load was achieved with 15% green fine wood (618,000 lb/hr) and 15% dry fine wood (622,000 lb/hr). In both tests, mill amps were very close to rated nameplate.

Unit Control and Stability
The most important goal of the phase 2 tests was to determine why significant unit control and stability issues were encountered during co-firing in phase 1. From the first phase 1 co-firing test run at 10% wood chips, there was difficulty in getting the unit to settle out in automatic operation. Main steam pressure and mill feeders tended to swing widely, and took up to an hour or more to steady out at a test condition. Even at constant load, the steam pressure swung more than desired. If a mill was taken out or cut back abruptly due to amps or mill temperature, this caused the unit main steam pressure to swing broadly. Many of the early tests included finding how to restore stability.

Such problems were very much a surprise, as no such problems had occurred during earlier tests co-firing green wood sawdust at Plant Gadsden Units 1 and 2 in 2004. However, it was eventually determined that finer tuning was required on newly installed automatic controls. The Unit 2 overall boiler control system had been installed just prior to the 2008 testing, upgrading from a manual controller using pneumatic / hydraulic controllers to a digital controller using programmable logic controllers (PLC) and automatic digital valve positioners.

These upgrades provided for much quicker response times to changes in the boiler outputs, and the controls sensitivity played a major factor in producing a less stable boiler control. To address this, gain was turned down on the boiler master response to main steam and on the mill hot air damper response to mill temperature.

The figures below illustrate the effect of the controls adjustments on the instability. Before modification (Figure 8), feeders and steam pressure have broad cycles at 10% wood, and moderate cycles with coal alone. Later, phase 2 tests were conducted in April 2008 following the controls modifications with both green and dry wood, and the results (Figure 9) show great reductions in feeder and steam pressure oscillations. (All figures are plotted to the same scales.)

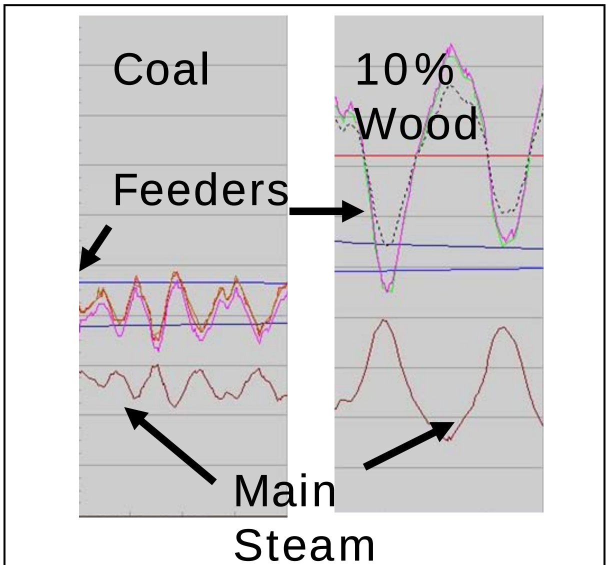

Figure 8: Fuel feeders and main steam pressure before controls modifications – October, 2007

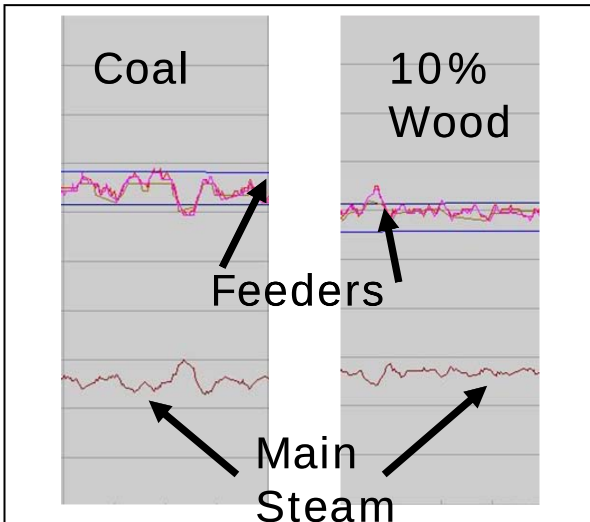

Figure 9: Fuel feeders and main steam pressure after controls modifications – April, 2008

The stability problems that occurred in these tests turned out to be relatively easy to fix. However, the experience points out that the density and heating values of the wood are very different from those for coal. Consideration should be given to the unit automatic control systems when contemplating biomass co-firing.

Flue Gas Temperature

Flue gas temperatures at the economizer outlet are shown plotted with flue gas O2 in Figure 10. As expected the gas temperatures increase with increasing combustion air flow in the furnace. Nearly all the temperatures associated with co-firing are lower than the temperatures associated with coal alone. The high moisture pine fuel from phase 1 had the lowest economizer exit temperatures, in line with those measured during the earlier phase 1 tests. However, the flue gas temperatures with the other phase 2 woods were unexpected, with the moderate moisture green wood having temperatures close to that of coal, and the very dry wood having some of the lowest flue gas temperatures.

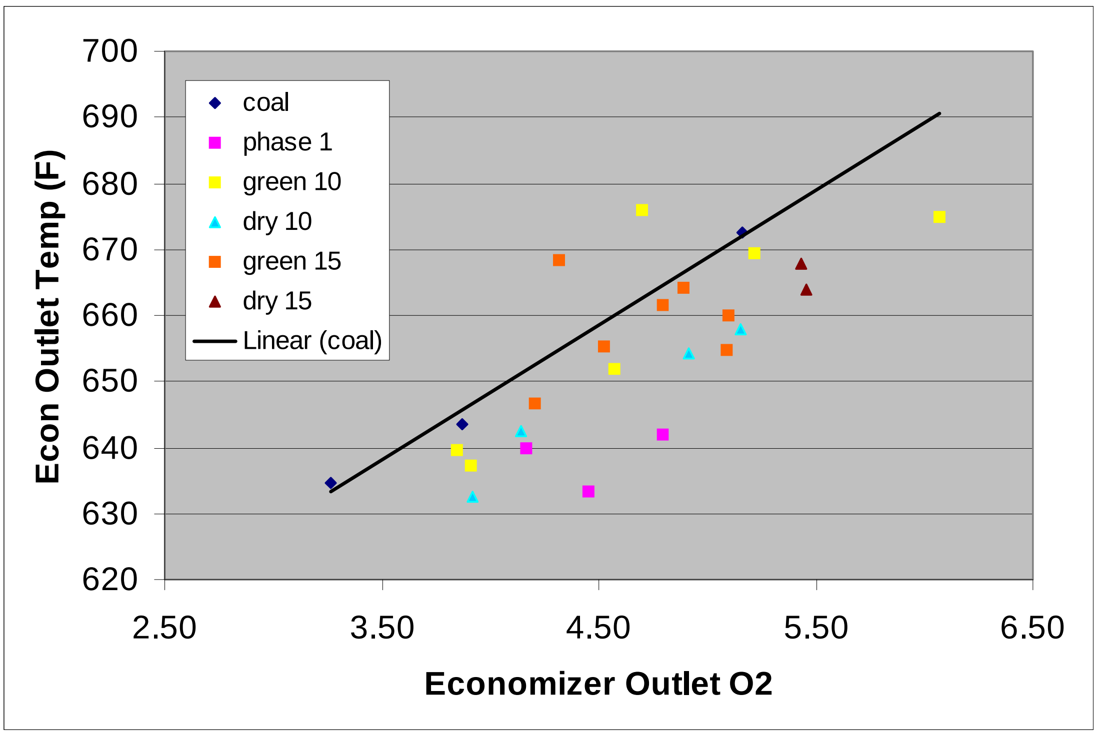

Fig 10: Economizer Outlet temp versus O2

The reason for this is probably how the unit walls were slagging up during the course of the test, and how each operator responded to this with the burner tilts. The burners at the corners of the furnace can be pointed upward or downward to put the fireball at different elevations in the furnace. The higher the fireball is in the furnace, the less heat is absorbed into the furnace walls. The superheater is located in the backpass, downstream of the furnace and consists of convective panels of tubes.

If slag builds in the boiler superheater, heat absorption decreases, and the steam temperature falls. In order to raise steam temperature in the superheater, the burner tilts are raised.

Difficult slagging occurred during the phase 2 tests. The phase 2 coal was far different from the synfuel used in the phase 1 tests. Even before the outage, the type coal used in phase 2 had been prone to slag. The phase 2 tests were started immediately following an outage, so the backpass was clean for the earliest tests. However, as the tests progressed, slagging repeatedly occurred, to such a degree, that testing had to be stopped at times to clean the tubes. Despite these cleanings, a layer of slag gradually accumulated and the operators used the burner tilts to compensate. This is shown clearly in Figure 11, below, which shows a plot of the average burner tilts plotted with test number. As the tests went on, the burner elevations were gradually increased. This is believed to be the major factor in explaining the gas temperatures, and also scatter of dry gas loss results described below.

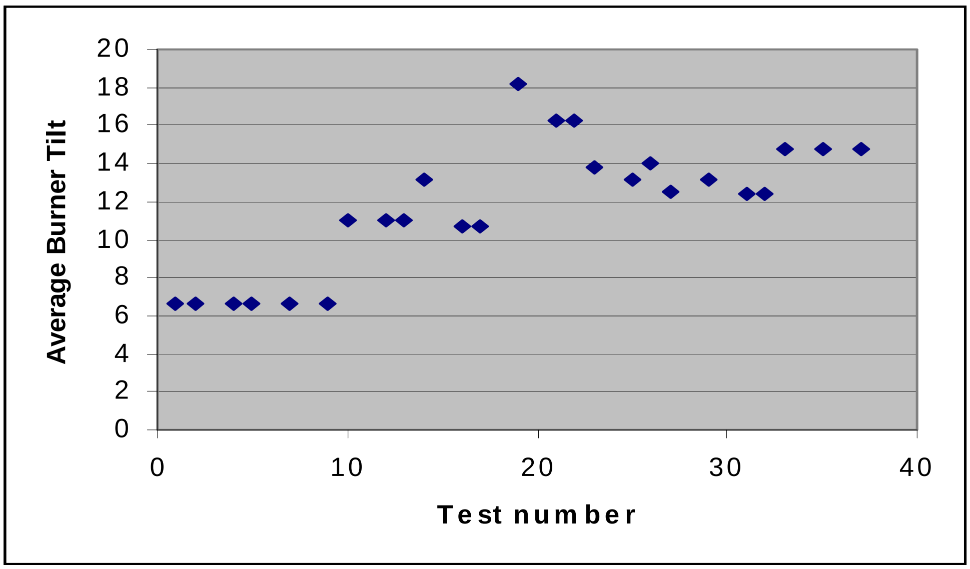

Fig 11. Increase of average burner tilt with time during phase 2 tests

Efficiency
Results of boiler efficiency calculations are summarized with the other test results in Table 1 above. The efficiency results were calculated in accordance with the heat loss method, in which individual losses of energy from the boiler are determined. Boiler efficiency is calculated by subtracting the sum of the losses from 100%. It is generally recognized that this method gives a more accurate determination than an input - output method, in which relatively small errors in fuel or steam flow rate can result in large efficiency errors. It also allows better understanding of boiler efficiency changes.
The sections below discuss in more detail the individual losses and their impact on the resulting efficiency.

Substantial difficulties in these tests call the efficiency measurements into question. The unit experienced slagging and wall build-up during the course of the phase 2 tests. This was caused by a change in fuel from synfuel in phase 1 to a slagging coal in phase 2. Further, there was considerable variability in the coal during the course of the test, with swings in moisture, ash, and sulfur from day to day. And unburned carbon results were scattered, in part due to sampling from ESP hoppers, and in part because of difficulties the lab had in obtaining consistent results from these samples.

Efficiency - Dry Gas Losses
Dry gas losses represent the sensible heat of the dry flue gas that exits the stack. Figure 12 shows a plot of dry gas loss results for these tests. Dry gas losses with wood co-firing were in general lower than that for coal alone. In Phase 1, the flue gas temperature appeared to be directly related to the fuel moisture content and the % wood in the mix. In these tests, the Phase 1 dark wood had the lowest dry gas loss and also the highest

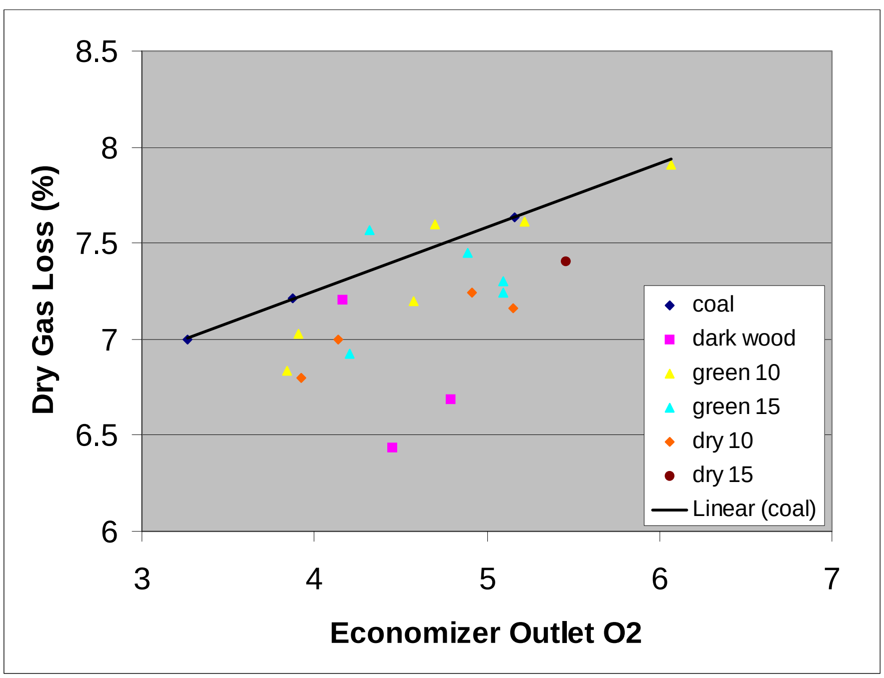

Fig 12. Dry Gas Losses versus Economizer O2 (%)

moisture content. Nearly all the wood co-firing tests had lower dry gas losses, being on average about 0.3 to 0.4 percentage points lower than coal alone. However, there did not appear to be any consistent pattern with dry gas loss and type or percentage of co-fired wood.

This scatter of results is believed to be related to slagging issues described in the section on flue gas temperatures above. Coal used in these tests had a history of serious slagging. The unit started with clean walls, but as the test went on, the buildup required increasing the burner tilts, and raising both the fireball and the furnace exit temperature. Because the dry gas loss is directly related to furnace exit temperature, this slagging would have had a direct effect on the dry gas losses in these tests.

Efficiency - Unburned Combustible Losses

There were a lot of difficulties in determining the unburned combustible losses in phase 2. Fly ash samples were taken from precipitator (ESP) hoppers. The unit is served with two different ESP's that work in series, and the proportion of fly ash collected by each is unknown. However, samples were collected from both ESP's, and it was hoped that the carbon content of an average of the two fly ash samples would indicate at least a relative measure of the effect of co-firing on unburned carbon.

Another and perhaps more important effect was that the bottom ash samples proved difficult to analyze. Results of ash analysis are presented in Appendices 3 and 4. Typically, the bottom and fly ash samples are tested for both loss on ignition (LOI) and carbon content. Carbon is considered the more accurate measure, but there should be a reasonable correlation of carbon with LOI. There was some factor that resulted in a very poor correlation for bottom ash. The carbon measure was taken to best represent the bottom ash. Bottom ash contributes only about 20% of the unburned carbon loss, but the measurement uncertainty makes understanding the effects of co-firing difficult.

Given these caveats, the results of the ash analyses are given below

Bottom Ash Combustible

The unburned carbon content of the bottom ash results (based on Carbon analysis) are shown in Figure 13. For coal only, the bottom ash carbon was very low for O2 above about 4%. At the lowest O2 (3.3%), however, the coal only bottom ash increased rather abruptly to about 8%

With co-firing, the unburned carbon in bottom ash was somewhat higher, with about half the points below 1 percent, and all but one less than 5%. There did not appear to be any correlation of the results with either wood type or percentage of wood.

Because the bottom ash represents only about 20% of the ash collected, the impact uncertainty of its carbon content is reduced. Given the scatter in the data, a typical bottom ash carbon value might be 2.5%. For a typical test, 2.5% additional carbon in the bottom ash due to co-firing decreases the overall boiler efficiency by 0.09 percentage points. This additional lost energy is equivalent to between about 1.7% to and 2.5% of the input wood.

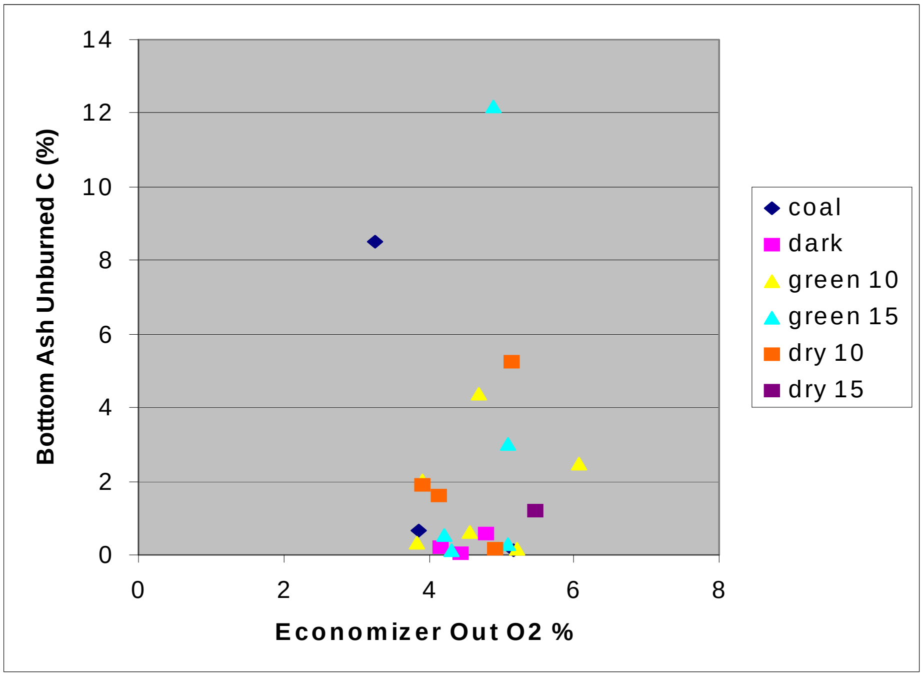

Fig 13: Bottom Ash Unburned Carbon versus O2 (Carbon

Fly Ash Combustible

Fig 14 shows the phase 2 fly ash carbon content, plotted with economizer exit O2. As expected, the unburned combustible content decreases with increasing combustion air. There is considerable scatter in the data, the co-firing data basically making a cloud centered roughly about the coal-only curve. There does not appear to be any correlation with type or percentage wood co-fired.

The cause for the scatter is not known. There was no discernable trend with burner tilts, and some of the scatter is within the same test days. Similar scattered results are seen with both LOI and carbon measurements, two entirely different measurements, so the source does not appear to lie in lab work problems.

A possible cause of the scatter is the sampling of the ESP hoppers. Ash from the hoppers is typically not used to evaluate unburned combustibles for boiler tests, especially for short term individual tests such as these. Instead, ash samples are taken with a high volume ash probe, as was done in phase 1. However, boiler efficiency was outside the original goals of the project and extractive analyzers and high volume ash samples were not used. However, in an effort to gain the most information from these tests, hopper samples were taken. The hoppers were pulled clean for each test, but the possibility of contamination between tests remains real.

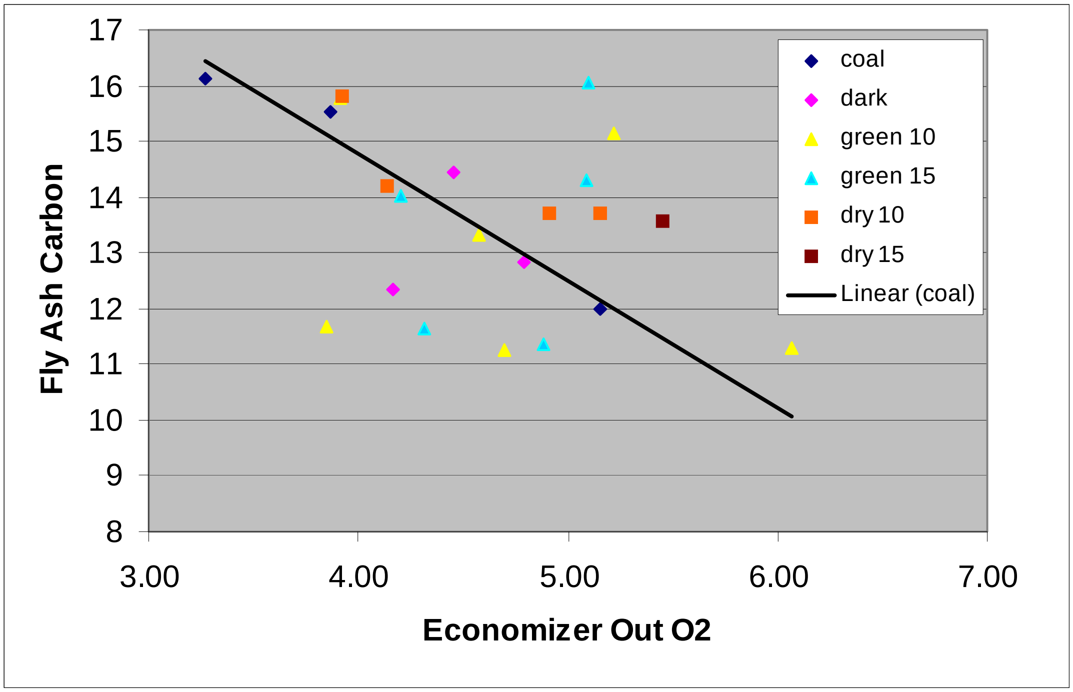

Fig 14. Fly ash carbon content versus Economizer O2

Total Unburned Combustible Loss

The results of the bottom and fly ash combustible measurements were combined to calculate the overall unburned combustible losses, shown in Figure 15. The figure shows the percentage of the original fuel energy that is lost as unburned carbon in ash. The results are all based on the laboratory measurements of carbon, and as expected decrease with increasing amounts of combustion air. The plot closely parallels the fly ash results, with similar scatter. Again there does not seem to be a pattern in the results related in any way to wood type, grind or percentage

As discussed above, the problem may lie with fly ash sampling problems. In the figure, in addition to the black coal only curve, a colored line has been fitted to the data from tests co-firing wood. It is interesting that a curve through the co-firing points passes very closely to the coal only curve.

Based on the strange patterns or lack of patterns in the combustible loss results, the overall accuracy of the results is very much in question. Given that the co-firing results on average are close to coal alone, and because little difference was seen between coal alone and co-firing in phase 1, then it is believed likely that unburned combustible losses here are also probably not much different than with coal alone. However, further tests with these woods will be required to confirm this conclusion.

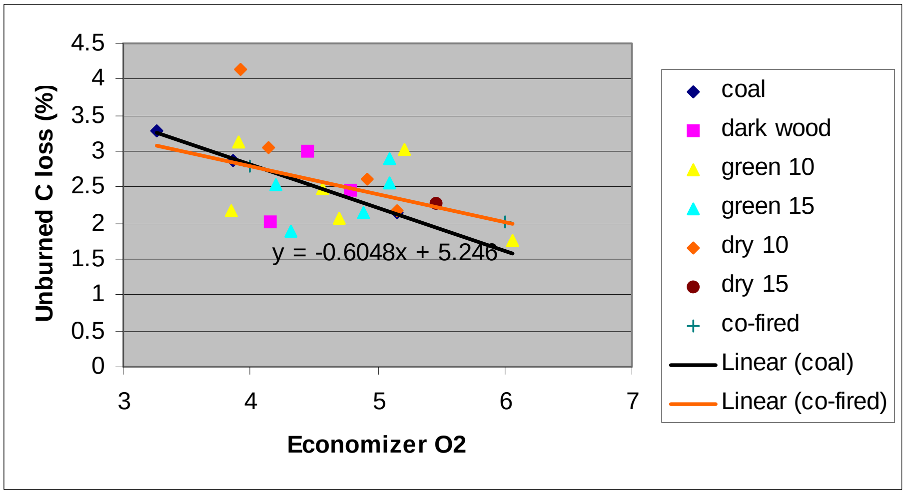

Fig 15. Boiler Losses due to Overall Unburned Combustible show considerable scatter and may not be reliable

Moisture Loss

When co-firing wood, especially green wood, moisture can be expected to be one of the major additional losses associated with co-firing. The results of the moisture efficiency losses plotted with per cent wood are shown below in Figure 16.

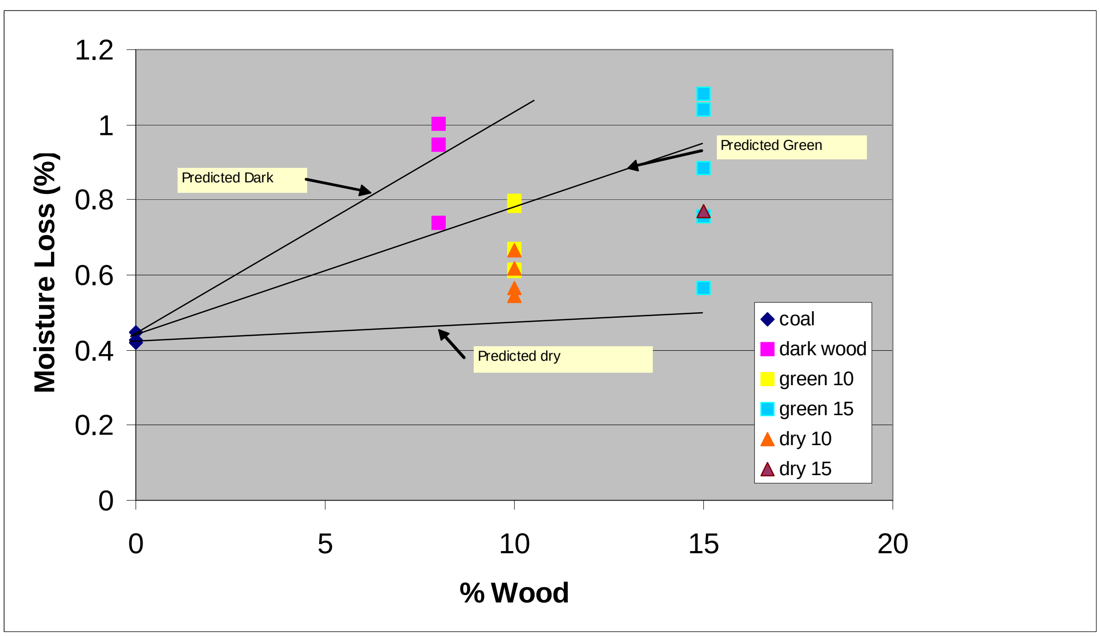

Fig 16. Phase 2 moisture losses plotted with per cent wood.

The lines plotted on the curve represent calculated estimates of moisture losses for each wood, given “typical” wood and coal analyses. There is scatter in the plots due in part to variability in the coal moisture, and also to questions of blend accuracy. However, the test points support the predicted values, with the exception of the dry wood.

The dry wood, with moisture content (7%) only slightly higher than that of the coal (4.5%), should have had little impact on moisture loss overall. Instead, the moisture loss with dry wood is approaching the lower measurements of moisture loss of the green wood. The reason for this is believed to be the water sprays, which were required to cope with dusting No measurement of spray water was available, but visual observation (which was difficult to gauge) suggested about 4 to 6 garden hoses’ flow (about 28 to 42 gpm). The moisture content and moisture loss with the dry wood co-firing blend suggests that about 28 to 52 gpm were used to suppress dust, very comparable values. Therefore, it seems likely that dust suppression sprays are responsible for the higher-than-expected moisture losses with the dry wood. It is estimated the sprays increased the average dry wood moisture from about 7% up to 17% to 22%.

For the green wood, the co-firing moisture losses were higher than coal alone by about 0.36 and 0.55 percentage points for 10% and 15% wood respectively. For the dry wood moistened with the dust suppression water, the measured moisture losses compared with coal were on average roughly half those of green wood. The green wood requires about 8% of its energy to offset the additional moisture loss. Because of its higher energy content and lower moisture loss, the dry wood requires roughly 3% of the dry wood energy input to offset additional moisture loss, including dust suppression.

Overall Boiler Efficiency

Given the amount of scatter and unexplained results in the individual measured losses, there was skepticism regarding the meaning of the overall boiler efficiency. The boiler efficiency for the phase 2 tests as calculated from the individual losses is shown in Figure 17. The efficiency plot reflects the scattered nature of its components.

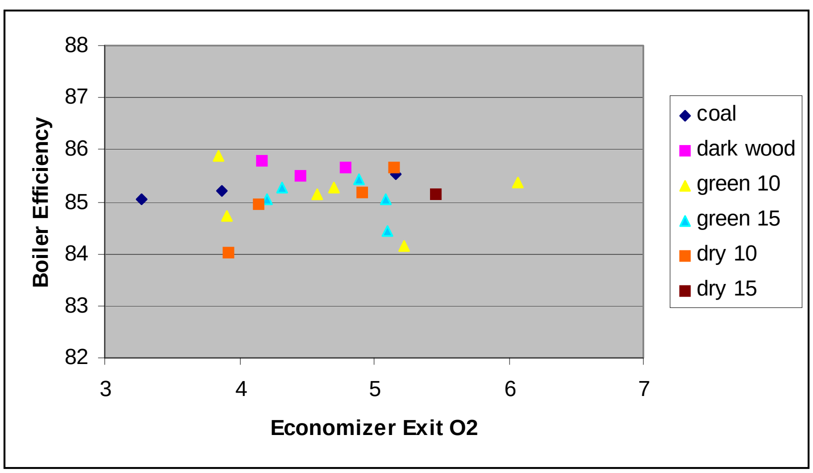

Fig 17. Very scattered Phase 2 boiler efficiency results may not be reliable

There were a number of factors in these tests to produce the scattered efficiency result. Coal properties changed during the testing, and increased slag accumulation during the test phase changed boiler temperature and flame patterns. Ash carbon measurement sampling and measurement problems, together with addition of unknown amounts of dust suppression spray water added further to the uncertainties of these results. Therefore, the results shown in Fig 17 above should not be taken too seriously, as they are probably not always comparing apples.

What is known from these tests is that moisture losses will be higher with wood co-firing while dry gas losses will probably offset some of this loss. Unburned combustibles are a greater uncertainty, but these results suggest that there is not too much difference. This is consistent with the results of other co-firing tests. It is likely that overall the penalty for co-firing wood will be roughly 5% or less of the wood energy. However, final resolution will require further testing.

EMISSIONS

Emissions – NOX

NOx emissions with green wood and dry wood are shown plotted with economizer outlet O2 in Figures 18 and 19, respectively. The black line is a curve fit for NOx emissions with coal alone.

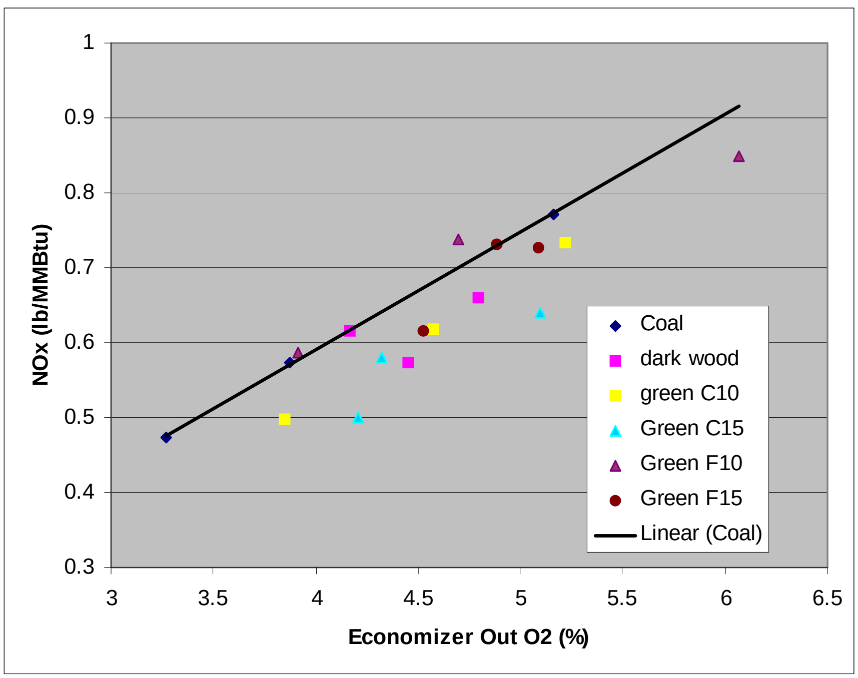

Fig 18: NOx co-firing green woods

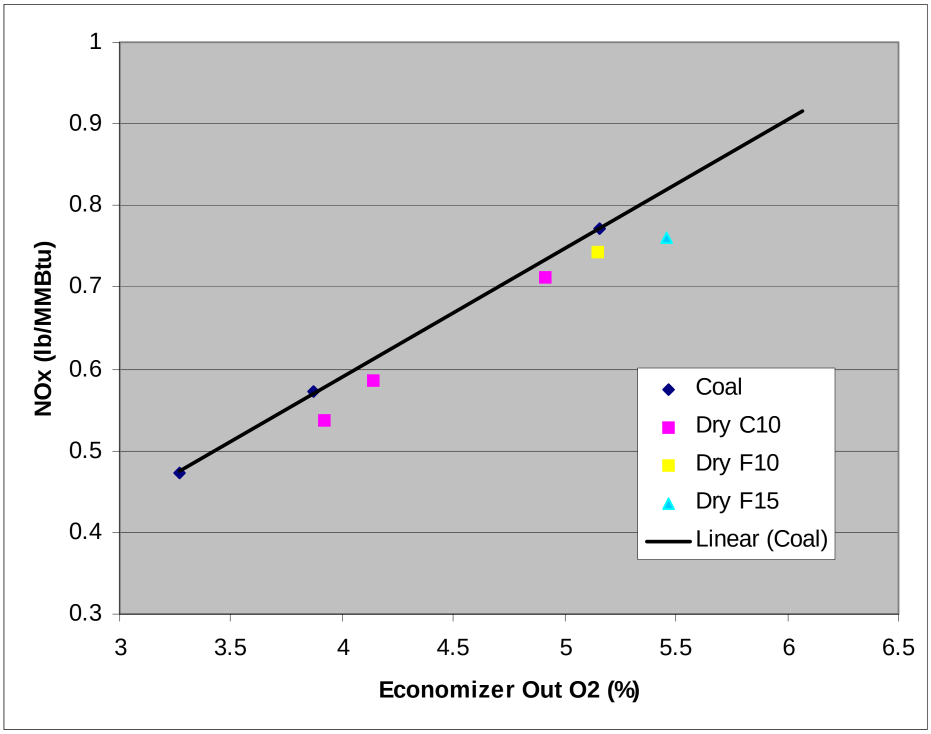

Fig 19 NOx co-firing dry wood

With green wood, nearly all the NOx levels were less with co-firing than with coal alone. The co-firing NOx levels averaged about 8% less than with coal alone. A similar result was seen with dry wood in phase 2, where NOx averaged about 5% less than coal alone. These results were unexpected. Small full load reductions had been observed in earlier tests, and in phase 1 at full load, the small NOx reduction averaged less than about 1%.

Because the results seemed unusual, and because variations had been seen in coal quality and boiler slagging during the test series, further examination was made of the data. Because of the limited nature of this test phase, there were only three baseline coal tests, and these were run consecutively at the start of the series. Therefore, OIS data were gathered for NOx at dates both before and after the co-firing tests. Periods of operation were sought in which the unit was at fairly steady load for some time at steam flows between 540 and 580 klb/hr. The quality of the data did not match the steady nature of the tests, but it was hoped it would be suitable to validate the test results. If coal alone NOx results were different both before and after the tests, then the phase 2 coal or test conditions might be questioned. If there were a trend of wide variation in NOx, then variation in coal might be blamed.

The results are shown in Figure 20 below. All of the wood co-firing points are plotted with colored points, and phase 2 coal is again the black line. The heavy black points are the data taken from before and after phase 2, and it can be seen they fall fairly close to the phase 2 coal alone line. This supports the idea that NOx was actually reduced during these tests by the addition of wood for co-firing.

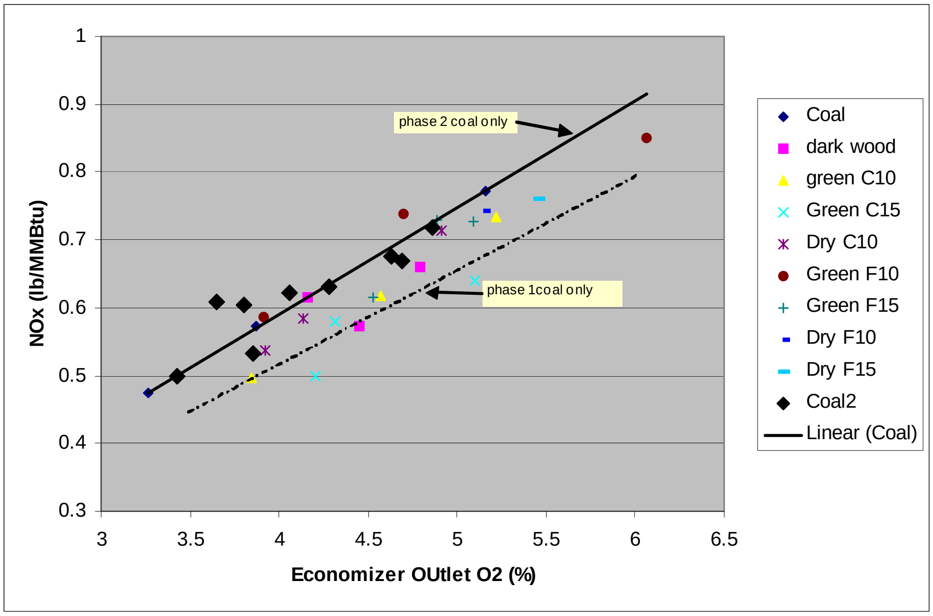

Fig 20   Coal-only NOx before and after the tests were close to test coal-only results

There were at least two differences in the fuel that may account for why NOx was more reduced by co-firing in phase 2 than in phase 1. For one, the coals were different, and had different levels of NOx production in coal only operation. The synfuel used in phase 1 actually had NOx coal only characteristics similar to the co-fire results, about 5% lower than the phase 2 coal. The reason for this is believed to be that the synfuel had higher volatile content than the phase 2 coal. As seen in Table 2 above, fuel volatiles for synfuel (28.94 %) were higher than for phase 2 coal (25.66 %). When adjustments were made for moisture and HHV, the synfuel volatile content was about 12% higher than the phase 2 coal volatiles. However, volatiles of the pine used in Phase 1 (90 lb/MMBtu) were also higher than the hardwood volatiles of phase 2 (80 lb/MMBtu), so overall it is difficult to see how adding the wood would be especially different from one case to the other.

Another factor may be wood grind size. The original grind size of the wood was finer in phase 2 than in phase 1, because of the different natures of the grinding processes. The phase 1 pine was cut into pieces which met top size specifications but such that there was not a high percentage of fines. However, the hardwood of phase 2 was ground in a hammermill, and while the top sizes met test specifications, there was a tremendous amount of fine dust resulting. It is possible that the fineness of the wood dust in phase 2 changed the staging of combustion in the furnace, and affected NOx production.

Carbon Monoxide

Because of some uncertainties of the CO measurements in phase 1, efforts were made in phase 2 to address in more detail the effect of reduced excess air on CO production. In particular, in comparison with coal, at what furnace O2 level did CO with co-firing begin to increase, and at what rate of increase. Because of the more limited scope of these tests, CO was measured with a portable analyzer, installed to monitor CO at a single point. Unfortunately, it was not practical to measure in the stack at this time, so a representative point from the phase 1 grid was chosen for testing at the economizer outlet.

Special tests were run to measure CO, with overall economizer outlet O2 gradually reduced, and the probe CO recorded. Figures 21 and 22 show probe CO plotted with boiler overall economizer out O2 for green and dry wood, respectively. It was thought that the CO meter point reading should give at least an indication of changes in CO in the furnace as a whole. The data plots indicate that at O2 above about 4.1%, CO with co-firing and with coal alone are unaffected and about the same, all below 50 ppm. Below about 4.1 %, CO appears to increase for co-firing at a rate higher than for coal alone. This is particularly true for the green wood. This was similar to the full load break point at 4.1% O2 that was later found with the green wood of phase 1, based on re-analysis of the phase 1 results.

For the dry wood, the CO rate with co-firing seems to increase at a rate between that of coal alone and green wood co-firing. The break point seems to be a little lower, perhaps 3.8% O2 overall boiler O2.

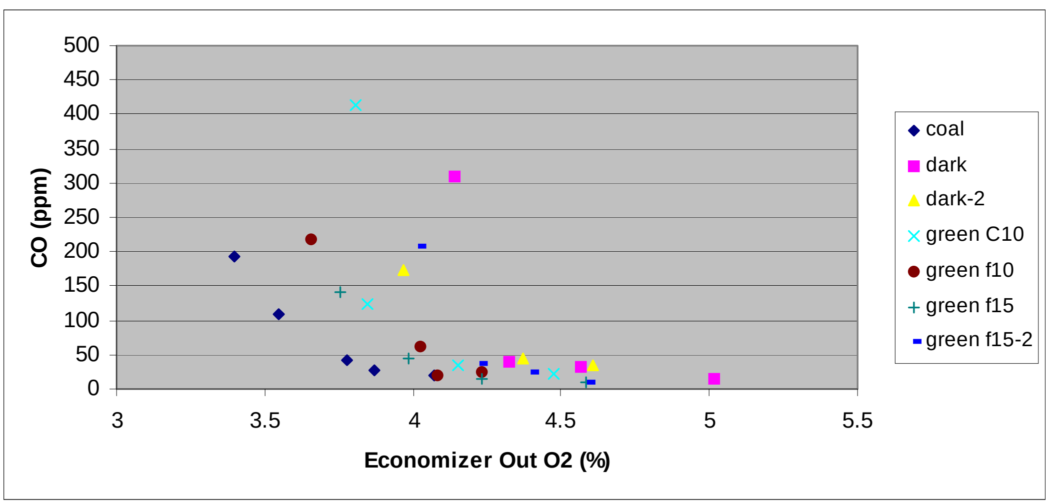

Fig 21: Carbon Monoxide emissions co-firing with green wood versus Economizer out O2

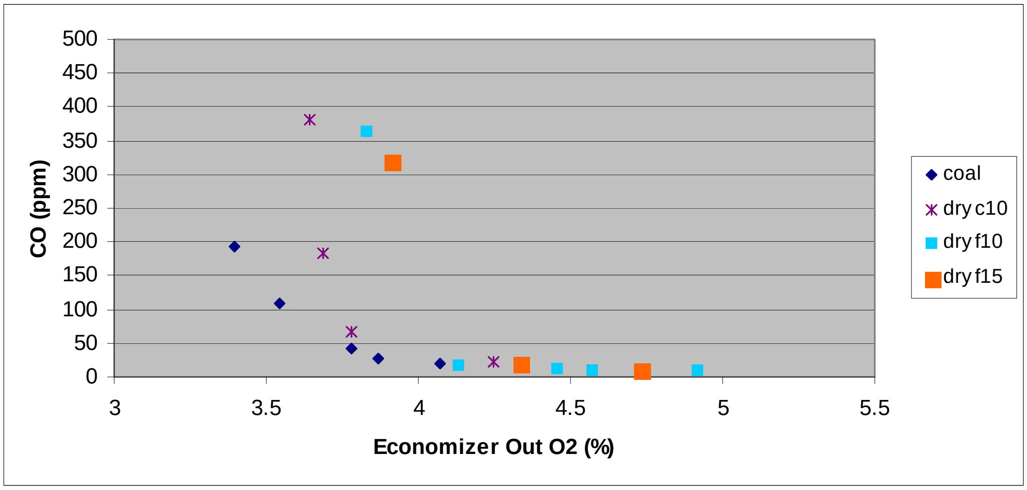

Fig. 22: Carbon Monoxide emissions co-firing with dry wood versus Economizer out O2

Opacity

Opacity measurements taken with plant instrumentation during these tests are shown plotted with economizer outlet O2 in Fig 23 below. The opacity readings were fairly scattered over a range between 0 and 4 percent. Coal only opacity averaged about 1.3%. moisture content of the wood did not seem to be a factor in opacity, green and dry wood having average opacity of about 2.0 and 2.2% respectively.

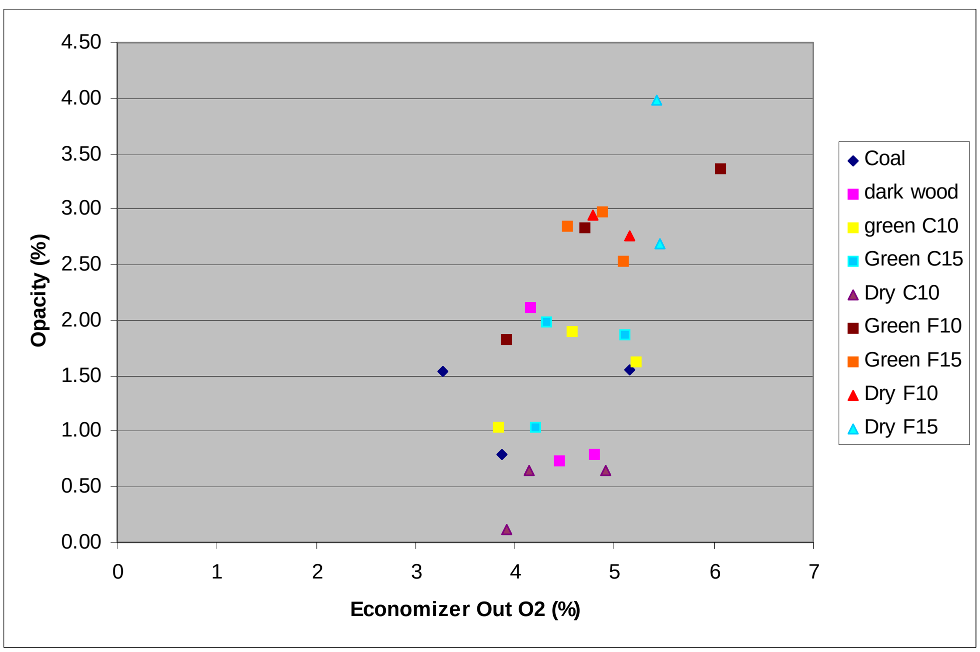

Fig 23. Opacity versus economizer outlet O2

However, the fineness of the wood particles seemed to have a distinct effect. Coarse wood co-firing had an average opacity of 1.2%, about the same as coal alone. Opacity co-firing fine green or dry wood averaged over twice that value at 2.9% opacity (Figure 24).

The cause of the higher opacity with fine wood is believed to be the resulting finer ash particles resulting when they burn. As coal and wood particles burn, the ash from each fuel particle tends to remain separate as it passes through the boiler and ESP. Wood particles have little ash and therefore result in finer ash particles. Fine wood grind results in even finer ash particles, and these are believed to affect the opacity reading. Fine ash particles have been shown to increase opacity in cases where particulate loading is unchanged or even reduced, because the finer particles produce higher scattering of the opacity meter light.

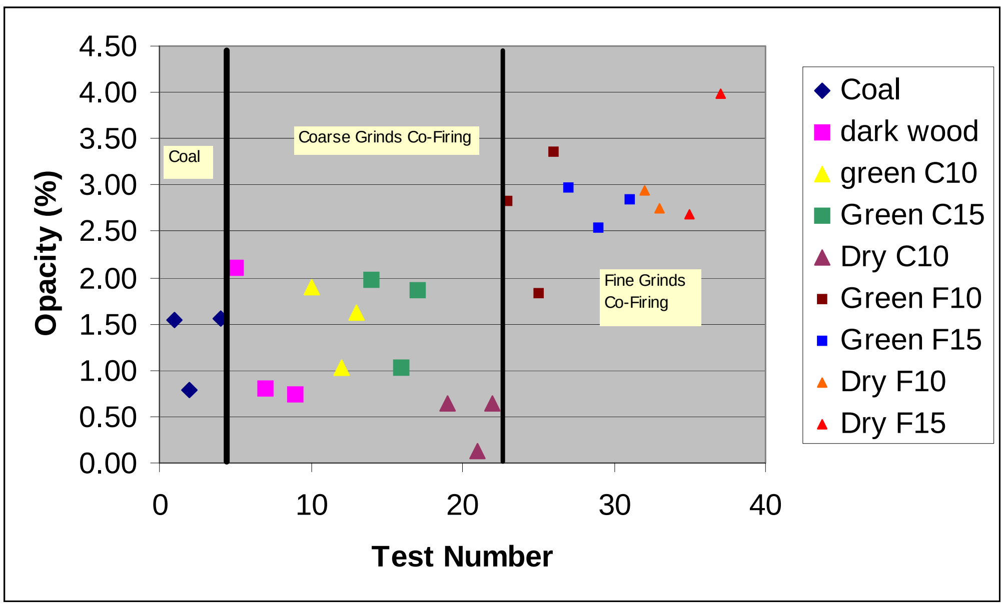

Fig 24: Fine grind wood co-firing has slightly higher opacity

Conclusions

Based on the Phase 2 tests of April and May, 2008, the following conclusions were made:

- Co-firing tests of 8% up to 15% by weight were successfully completed with dry, 35% moisture and 65% moisture wood.
- Coal for co-firing in phase 1 had different volatile and hardness characteristics than the synfuel used in phase 1. Day-to day phase 2 coal properties seemed more variable than in phase 1.
- Wood for most of the phase 2 tests was different than for phase 1. In addition to reduced moisture, the wood was mostly hardwood.
- The wood was processed in a hammer mill, which resulted in quantities of fine material to make the wood meet top size specifications. As a result, dusting initially was a problem with the dry wood, but use of existing water sprays successfully resolved the issue
- For the dry wood, the increase in mixed fuel bulk density for bunker and feeder rate issues were similar to the phase 1 results. The phase 2 green wood was less dense than the other woods and resulted in lower mixed fuel bulk densities.
- Phase 2 mill amps appeared to be directly related to the percentage dry wood component of the fuel mix. Amps increased with wood addition at about the same rate as in phase 1, but were lower overall because the phase 2 coal was softer than the phase 1 synfuel.
- The lower moisture of the phase 2 wood cleared up problems of mill pressure and temperature and unit derate that occurred in phase 1.
- Unit maximum load was successfully achieved co-firing 15% green and 15% dry wood. Phase 2 mill amps were lower than in phase 1, probably due to change to softer coal. Softer coal helped to avoid derate due to amps
- Unit control issues were resolved with simple control tuning. Following adjustments, the controls were shown to operate in a stable manner co-firing both phase 1 and phase 2 woods.
- Substantial slagging occurred during these tests. Slag build up is believed to have affected temperatures, boiler efficiencies, and other factors in the tests
- Serious questions remain regarding the accuracy of unburned combustible results
- Moisture losses with dry wood were increased by the use of the dust suppression sprays.
- Unlike phase 1, a measurable NOx reduction was seen with co-firing in phase 2. This may be related to differences in the volatile contents of the phase 1 and phase 2 coals. It may also be related to higher fraction of fines in the phase 2 wood.
- CO in phase 2 closely paralleled the results with co-firing in phase 1.

Acknowledgements

The authors wish to recognize the contributions of GreenFuels, LLD of Jasper, AL, who obtained and provided the dry and green wood for this test phase. They processed the wood to size specifications and delivered it in a timely way for these tests. It is because of their support and hard work that this project phase was possible.

A special thanks to Ron Hunter and the staff of Alabama Power's Environmental Labs for the many fuel and ash analyses they performed in support of these tests

Support of the management and personnel of Plant Gadsden is greatly appreciated, and necessary to the success of this project. In particular, fuel handling was required to modify their normal routines, and they offered new and fresh solutions to fuel handling problems. Loretta Aultman provided support with data, and Lee Wood and Jerry Reagan provided insights into resolving the controls problems.

References

Boylan, D. M., Roberts, G. K., Zemo, B. R., and Johnson, T. W. "Co-Milling Green Wood Chips at Alabama Power Company's Plant Gadsden Unit 2," Southern Company Test Report, June, 2008.

Abbreviations

C10 = Coarse wood 10%
C15 = Coarse wood 15%
F10 = Fine wood 10%
F15 = Fine wood 15%
Dark wood = phase 1 wood in phase 2 test

	dark wood	preliminary	Green C	Green C	Green C	??	Green F	dry fine	Green F	Green C	Dry Coarse	Green C	dark wood
Dry Basis													
Ash, dry	0.45	1.22	1.24	1.53	1.59	1.9	2.04	0.75	1.22	0.5	0.41	1.08	8.13
Heat of Combustion, dry	7899	8275	8336	8213	8365	8337	8174	7801	8267	8114	7801	8169	11336
Carbon, dry	51.32	49.67	50.06	49.69	50.29	49.76	49.79	49.87	50.08	49.56	50.01	49.94	64.8
Hydrogen, dry	5.77	5.75	5.66	5.81	5.84	5.75	5.73	5.78	5.78	5.8	5.85	5.77	5.1
Nitrogen, dry	0.07	0.07	0.12	0.14	0.16	0.11	0.13	0.16	0.14	0.05	0	0.17	1.01
Oxygen, dry	42.37	43.26	42.9	42.82	42.04	42.47	42.3	43.43	42.77	44.08	43.72	43.03	19.91
Fixed Carbon, dry	20.55	18.37	18.58	18.39	19.9	18.96	18.23	19.07	18.84	19.29	19.04	14.71	53
Volatiles, dry	79	80.41	80.18	80.08	78.51	79.14	79.73	80.18	79.94	80.21	80.55	84.21	38.87
Sulfur, dry	0.02	0.03	0.02	0.01	0.08	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.05
As Received													
Moisture, Total	61.98	39.97	36.07	39.27	40.63	26.68	27.25	8.36	23.27	7.58	7.26	45.13	42.8
Ash, as received	0.17	0.73	0.79	0.93	0.94	1.39	1.48	0.69	0.94	0.46	0.38	0.59	4.65
Heat of Combustion, as received	3003	4967	5329	4988	4966	6113	5947	7149	6343	7499	7235	4482	6484
Carbon, as received	19.51	29.82	32	30.18	29.86	36.48	36.22	45.7	38.43	45.8	46.38	27.4	37.07
Hydrogen, as received	2.19	3.45	3.62	3.53	3.47	4.22	4.17	5.3	4.43	5.36	5.43	3.17	2.92
Nitrogen, as received	0.03	0.04	0.08	0.09	0.09	0.08	0.09	0.15	0.11	0.05	0	0.09	0.58
Oxygen, as received	16.11	25.97	27.43	26	24.96	31.14	30.77	39.8	32.82	40.74	40.55	23.61	11.39
Carbon Fixed, as received	7.81	11.03	11.88	11.17	11.81	13.9	13.26	17.48	14.46	17.83	17.66	8.07	30.32
Volatiles, as received	30.04	48.27	51.26	48.63	46.61	58.03	58	73.48	61.34	74.13	74.7	46.21	22.23
Sulfur, as received	0.01	0.02	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.6
General													
Heat of Combustion, MAF	7935	8377	8441	8341	8500	8498	8344	7860	8369	8155	7833	8258	12339
Sulfur, lbs/mm Btu	0.025	0.036	0.024	0.012	0.096	0.012	0.012	0.013	0.012	0.012	0.013	0.012	0.926
nitrogen	0.0333	0.040266	0.018765	0.020048	0.100685	0.016359	0.016815	0.013988	0.015765	0.013335	0.013822	0.022311	0.925355
Sieve Analysis-Retained on 004M	64.44	17.71	12.27	13.94	9.48	8.25	4.65	4.85	8.08	10.1	12.32	11.92	0.2
Sieve Analysis-Retained on 006M	20	18.71	17.71	16.36	13.71	19.32	13.94	7.68	13.13	13.94	12.32	17.78	0.2
Sieve Analysis-Retained on 008M	8.89	15.29	14.49	13.94	13.31	16.5	15.15	14.34	18.59	16.57	15.96	15.35	3.02
Sieve Retained on Catch	6.67	48.29	55.53	55.76	63.51	55.94	66.26	73.13	60.2	59.39	59.39	54.95	96.57
Ignited as Oxide													
Aluminum Oxide, ignited									6.29	2.41			27.28
Barium Oxide, ignited									0	0			0.405
Calcium Oxide, ignited									35.75	38.91			2.05
Copper Oxide, ignited									0.03	0.02			
Iron Oxide, ignited									3.82	2.29			12.55
Magnesium Oxide, ignited									4.11	2.64			1.2
Nickel Oxide, ignited									0.03	0.04			
Phosphorus Oxide, ignited									1.11	1.53			0.94
Potassium Oxide, ignited									15.56	14.45			2.99
Silicon Oxide, ignited									29.96	33.93			49.23
Sodium Oxide, ignited									0.53	0.51			0.23
Sulfur Trioxide, ignited									2.3	3			1.64
Strontium Oxide, ignited									0.169	0.193			0.177
Titanium Oxide, ignited									0.46	0.14			1.27
Manganese Oxide, ignited									0.99	0.08			

Appendix 1 Wood Properties

wood type	Coal	Coal	coal	dark	dark	dark	gc	gc	gc	gc	gc	gc
% wood	0	0	0	10	10	10	10	10	10	15	15	15
% wood energy	0	0	0	0.03	0.03	0.03	0.046	0.046	0.046	0.07	0.07	0.07
Test #	1	2	4	5	7	9	10	12	13	14	16	17
Dry Basis												
Ash, dry	16.68	16.71	16.89	15.73	17.51	18.59	17.01	17.32	17.59	15.52	16.25	16.13
Heat of Combustion, dry	12633	12560	12498	12760	12317	12187	12271	12263	12107	12621	12232	12427
Carbon, dry	70.43	70.65	69.59	71.17	69.07	67.83	68.97	68.11	68.03	70.85	68.49	69.31
Hydrogen, dry	4.38	4.42	4.37	4.44	4.33	4.22	4.44	4.39	4.44	4.54	4.53	4.5
Nitrogen, dry	1.47	1.44	1.39	1.44	1.33	1.39	1.41	1.38	1.34	1.44	1.38	1.39
Oxygen, dry	5.12	3.92	5.63	4.56	5.68	5.34	6.55	6.19	6.13	5.75	7.5	6.76
Fixed Carbon, dry	56.64	56.6	55.98	56.97	55.52	54.8	55.52	54.37	54	56.19	57.13	54.73
Volatiles, dry	26.68	26.69	27.13	27.3	26.97	26.61	27.47	28.31	28.41	28.29	26.62	29.14
Sulfur, dry	1.92	2.86	2.13	2.66	2.08	2.63	1.62	2.61	2.47	1.9	1.85	1.91
As Received												
Moisture, Total	4.25	4.33	4.5	7.34	9.58	9.01	7.65	7.54	7.47	8.54	9.73	10.24
Ash, as received	15.97	15.99	16.13	14.58	15.83	16.92	15.71	16.01	16.28	14.19	14.67	14.48
Heat of Combustion, as r	12096	12016	11936	11823	11137	11089	11332	11338	11203	11543	11042	11154
Carbon, as received	67.44	67.59	66.46	65.95	62.45	61.72	63.69	62.97	62.95	64.8	61.83	62.21
Hydrogen, as received	4.19	4.23	4.17	4.11	3.92	3.84	4.1	4.06	4.11	4.15	4.09	4.04
Nitrogen, as received	1.41	1.38	1.33	1.33	1.2	1.26	1.3	1.28	1.24	1.32	1.25	1.25
Oxygen, as received	4.9	3.75	5.38	4.23	5.14	4.86	6.05	5.72	5.67	5.26	6.77	6.07
Carbon Fixed, as receive	54.23	54.15	53.46	52.79	50.2	49.86	51.27	50.27	49.97	51.39	51.57	49.13
Volatiles, as received	25.55	25.53	25.91	25.3	24.39	24.21	25.37	26.18	26.29	25.87	24.03	26.16
Sulfur, as received	1.84	2.74	2.03	2.46	1.88	2.39	1.5	2.41	2.29	1.74	1.67	1.71
General												
Heat of Combustion, MA	15162	15080	15038	15142	14932	14970	14786	14832	14691	14940		14605
Sulfur, lbs/mm Btu	1.52	2.277	1.704	2.085	1.689	2.158	1.32	2.128	2.04	1.505		1.512

Appendix 2 – Fuel Analyses

Wood type	dc	dc	dc	gf	gf	gf	gf	gf	df	df	Coal last da
% wood	10	10	10	10	10	10	15	15	10	15	0
% wood energy	0.062	0.062	0.062	0.046	0.046	0.046	0.07	0.07	0.062	0.096	
Test #	19	21	22	23	25	26	27	29	32	34	
Dry Basis											
Ash, dry	18.48	21.44	17.04	16.13	17.06	14.48	14.41	15.8	14.58	15.53	13.18
Heat of Combustion, dry	11932	11558	12099	12471	12197	12766	12699	12536	12752	12560	13230
Carbon, dry	66.76	65.13	68.02	70.04	69.17	70.94	70.88	69.79	71.42	70.16	73.73
Hydrogen, dry	4.41	4.26	4.48	4.57	4.53	4.6	4.63	4.53	4.6	4.6	4.59
Nitrogen, dry	1.34	1.32	1.34	1.42	1.42	1.46	1.47	1.38	1.43	1.41	1.5
Oxygen, dry	7.05	5.77	7.12	6.14	5.97	6.89	6.98	6.29	5.93	6.81	4.3
Fixed Carbon, dry	52.4	51.08	52.97	54.64	53.43	55.5	55.58	54.98	56.04	54.32	59.05
Volatiles, dry	29.12	27.48	29.99	29.23	29.51	30.02	30.01	29.22	29.38	30.15	27.77
Sulfur, dry	1.96	2.08	2	1.7	1.85	1.63	1.63	2.21	2.04	1.49	2.7
As Received											
Moisture, Total	5.39	5.72	5.3	6.04	6.48	6.24	5.71	7.45	6.72	7.63	6.81
Ash, as received	17.48	20.21	16.14	15.16	15.95	13.58	13.59	14.62	13.6	14.35	12.28
Heat of Combustion, as r	11289	10897	11458	11718	11407	11969	11974	11602	11895	11602	12329
Carbon, as received	63.16	61.4	64.41	65.81	64.69	66.51	66.83	64.59	66.62	64.81	68.71
Hydrogen, as received	4.17	4.02	4.24	4.29	4.24	4.31	4.37	4.19	4.29	4.25	4.28
Nitrogen, as received	1.27	1.24	1.27	1.33	1.33	1.37	1.39	1.28	1.33	1.3	1.4
Oxygen, as received	6.67	5.44	6.74	5.77	5.58	6.46	6.58	5.82	5.53	6.29	4.01
Carbon Fixed, as receive	49.58	48.16	50.16	51.34	49.97	52.04	52.41	50.88	52.27	50.18	55.03
Volatiles, as received	27.55	25.91	28.4	27.46	27.6	28.15	28.3	27.04	27.41	27.85	25.88
Sulfur, as received	1.85	1.96	1.89	1.6	1.73	1.53	1.54	2.05	1.9	1.38	2.52
General											
Heat of Combustion, MA	14869	14706	14928	14837	14888	14929	14869	15238			
Sulfur, lbs/mm Btu	1.363	1.517	1.277	1.284	1.763	1.6	1.186	2.041			

Appendix 2 – Fuel Analyses (Continued)

	wood type	Coal	Coal	coal	dark	dark	dark	gc	gc	gc	gc	gc	gc
	% wood	0	0	0	10	10	10	10	10	10	15	15	15
	% wood energy	0	0	0	0.03	0.03	0.03	0.046	0.046	0.046	0.07	0.07	0.07
	Test #	1	2	4	5	7	9	10	12	13	14	16	17
ESP Lower	*Dry Basis*												
	Loss on Ignition @750 C	18.05	18.8	14.29	15.31	15.21	18	13.12	13.21	15.22	14.22	20.65	18.7
	Ash, dry	81.95	81.2	85.71	84.69	84.79	82	86.88	86.79	84.78	85.78	79.35	81.3
	Carbon, dry	19.97	20.81	17.27	17.57	17.57	20.28	16.14	15.85	17.96	16.96		20.56
	Hydrogen, dry	0	0	0	0	0	0	0	0	0	0	0.09	0
	Nitrogen, dry	0.21	0.16	0.12	0.13	0.15	0.2	0.09	0.17	0.15	0.13	0.25	0.17
	As Received												
	Moisture, Total	0.35	0.53	0.41	0.42	0.4	0.4	0.28	0.29	0.34	0.34	0.38	0.3
	Ash, as received	81.66	80.77	85.36	84.33	84.45	81.67	86.64	86.54	84.49	85.49	79.05	81.06
	Carbon, as received	19.9	20.7	17.2	17.5	17.5	20.2	16.09	15.8	17.9	16.9	19.7	20.5
	Hydrogen, as received	0	0	0	0	0	0	0	0	0	0	0.09	0
	Nitrogen, as received	0.21	0.16	0.12	0.13	0.15	0.2	0.09	0.17	0.15	0.13	0.25	0.17
ESP Upper	*Dry Basis*								10.31				
	Loss on Ignition @750 C	12.38	10.74	7.68	7.55	8.55	9.36	11.08	7.97	12.84	7.15	6.47	11.74
	Ash, dry	87.62	89.26	92.32	92.45	91.45	90.64	88.92	92.03	87.16	92.85	93.53	88.26
	Carbon, dry	12.27	9.68	6.77	6.49	7.82	8.98	10.08		12.72	6.59	6.01	11.46
	Hydrogen, dry	0.06	0.03	0.11	0.08	0.05	0.03	0.03	0.05	0.04	0	0	0.05
	Nitrogen, dry	0.14	0.12	0.08	0.08	0.09	0.1	0.13	0.13	0.15	0.09	0.07	0.14
	As Received												
	Moisture, Total	0.26	0.25	0.32	0.25	0.2	0.23	0.27	0.15	0.19	0.14	0.17	0.17
	Ash, as received	87.39	89.04	92.02	92.22	91.27	90.43	88.68	91.89	86.99	92.72	93.37	88.11
	Carbon, as received	12.24	9.66	6.75	6.47	7.8	8.96	10.05	10.29	12.7	6.58	6	11.44
	Hydrogen, as received	0.06	0.03	0.11	0.08	0.05	0.03	0.03	0.05	0.04	0	0	0.05
	Nitrogen, as received	0.14	0.12	0.08	0.08	0.09	0.1	0.13	0.13	0.15	0.09	0.07	0.14

Appendix 3 – Fly Ash Analyses

	wood type	dc	dc	dc	gf	gf	gf	gf	gf	df	df
	% wood	10	10	10	10	10	10	15	15	10	15
	% wood energy	0.062	0.062	0.062	0.046	0.046	0.046	0.07	0.07	0.062	0.096
	Test #	19	21	22	23	25	26	27	29	32	34
ESP Lower	*Dry Basis*										
	Loss on Ignition @750 C	16.19	19.05	18.23	13.02	17.92	13.96	13.89	16.39	16.24	16.38
	Ash, dry	83.81	80.95	81.77	86.98	82.08	86.04	86.11	83.61	83.76	83.62
	Carbon, dry	18.45	21.06	20.46	15.66	20.04		16.95	19.04	18.75	19.25
	Hydrogen, dry	0	0	0	0	0	0	0	0	0	0
	Nitrogen, dry	0.17	0.22	0.21	0.16	0.17	0.03	0.12	0.17	0.17	0.16
	As Received										
	Moisture, Total	0.29	0.28	0.3	0.36	0.21	0.48	0.31	0.2	0.25	0.24
	Ash, as received	83.57	80.72	81.52	86.67	81.91	85.63	85.84	83.44	83.55	83.42
	Carbon, as received	18.4	21	20.4	15.6	20	0.85	16.9	19	18.7	19.2
	Hydrogen, as received	0	0	0	0	0	0	0	0	0	0
	Nitrogen, as received	0.17	0.22	0.21	0.16	0.17	0.03	0.12	0.17	0.17	0.16
ESP Upper	*Dry Basis*										
	Loss on Ignition @750 C	10.3	11.06	7.78	7.33	11.89	6.66	6.83	10.37	9.36	8.97
	Ash, dry	89.7	88.94	92.22	92.67	88.11	93.34	93.17	89.63	90.64	91.03
	Carbon, dry	10.14	10.54	6.92	6.77	11.46	5.59				
	Hydrogen, dry	0	0	0	0	0.03	0	0	0	0	0
	Nitrogen, dry	0.12	0.14	0.08	0.08	0.15	0	0	0	0	0
	As Received										
	Moisture, Total	0.17	0.15	0.18	0.14	0.25	0.36	0.28	0.31	0.28	0.33
	Ash, as received	89.55	88.81	92.05	92.54	87.89	93	92.91	89.35	90.39	90.73
	Carbon, as received	10.12	10.52	6.91	6.76	11.43	Not Detecte	Not Detecte	Not Detecte	Not Detecte	Not Detecte
	Hydrogen, as received	0	0	0	0	0.03	0	0	0	0	0
	Nitrogen, as received	0.12	0.14	0.08	0.08	0.15	0	0	0	0	0

Appendix 3 – Fly Ash Analyses – (Continued)

wood type		Coal	Coal	coal	dark	dark	dark	gc	gc	gc	gc	gc	gc
% wood		0	0	0	10	10	10	10	10	10	15	15	15
% wood energy		0	0	0	0.03	0.03	0.03	0.046	0.046	0.046	0.07	0.07	0.07
Test #		1	2	4	5	7	9	10	12	13	14	16	17
Dry Basis													
Loss on Igni	ASTM D 514	4.88	1.69	0.15	0.09	-0.02	-0.03	1.43	0.85	0.01	-0.47	10.96	2.14
Ash, dry	ASTM D 514	95.12	98.31	99.85	99.91	100.02	100.03	98.57	99.15	99.9946	100.47	89.04	97.86
Carbon, dry	ASTM D 537	8.5	0.66	0.14	0.2	0.58	0.06	0.61	0.35	0.16	0.14	0.53	0.3
Hydrogen, d	ASTM D 537	0	0	0	0	0	0	0	0	0	0	0.15	0
Nitrogen, dr	ASTM D 537	0.03	0	0	0	0.04	0	0	0	0	0.02	0	0
As Received													
Moisture, To	ASTM D 330	10.99	26.92	0.46	0.36	0.39	0.55	33.77	22.56	1.39	1.16	25.7	31.37
Ash, as rece	ASTM D 514	84.67	71.84	99.39	99.55	99.63	99.48	65.28	76.78	98.6	99.3	66.16	67.16
Carbon, as r	ASTM D 537	7.57	0.48	0.14	0.2	0.58	0.06	0.4	Not Detecte	Not Detecte	Not Detecte	0.39	0.21
Hydrogen, a	ASTM D 537	0	0	0	0	0	0	0	0	0	0	0.11	0
Nitrogen, as	ASTM D 537	0.03	0	0	0	0.04	0	0	0	0	0.02	0	0

Appendix 4 – Bottom Ash Analyses

wood type	dc	dc	dc	gf	gf	gf	gf	gf	df	df
% wood	10	10	10	10	10	10	15	15	10	15
% wood energy	0.062	0.062	0.062	0.046	0.046	0.046	0.07	0.07	0.062	0.096
Test #	19	21	22	23	25	26	27	29	32	34
Dry Basis										
Loss on Ignition @750 C	7.53	3.16	-0.57	8.41	19.89	6.05	16.97	4.33	5.26	1.19
Ash, dry	92.47	96.84	100.57	91.59	80.11	93.95	83.03	95.67	94.74	98.81
Carbon, dry	1.62	1.92	0.18	4.37	2.04	2.49	12.19	3	2.09	0.75
Hydrogen, dry	0	0	0	-0.22	-0.44	0.21	0.86	-0.25	-0.16	0
Nitrogen, dry	0	0	0	0.12	0	0	0.3	0.04	0.02	0.07
As Received										
Moisture, Total	47.26	48.56	0.46	57.79	49.64	57.28	51.52	43.88	46.34	22.64
Ash, as received	48.77	49.81	100.11	38.66	40.34	40.14	40.25	53.69	50.84	76.44
Carbon, as received	0.85	0.99	Not Detecte	1.84	1.03	1.06	5.91	1.68	1.12	0.58
Hydrogen, as received	0	0	0	-0.09	-0.22	0.09	0.42	-0.14	-0.09	0
Nitrogen, as received	0	0	0	0.05	0	0	0.15	0.02	0.01	0.05

Appendix 4 – Bottom Ash Analyses – (Continued)