TECHNICAL PUBLICATION

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with
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Presented at

Power-Gen International 2010
Orlando, Florida

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ABSTRACT

In recent years, there has been increasing interest regarding the mitigation of emissions and finding feasible, low-cost alternatives to fossil fuels for power generation. Changes to environmental policies are also driving the need for cost effective and readily implemented retrofit technologies in the power generation industry. As a result, the industry has begun to research and implement new fuel technologies that will supplement or even replace currently used fossil fuels such as coal, oil, or gas. Potential new fuel sources include biomass fuels such as wood, straw, switch grass, etc.

Riley Power Inc. (RPI), a Babcock Power Inc. Company, in alliance with Central Power & Lime LLC, evaluated the feasibility of co-firing wood and coal by introducing preprocessed, low moisture wood pellets and raw coal into the pulverizers and combusting the pulverized mixture in suspension. The 150-MWg boiler, owned by Central Power & Lime LLC, located in Brooksville, FL was tested using various blends of pelletized wood and coal for changes in boiler thermal performance, flue gas emissions including NO_X*, and CO, and pulverizer performance. Mixtures of up to 17% wood by weight were pulverized in EL-70 ball-and-race pulverizers and fired in suspension through RPI's Low* NO_X *CCV® DAZ Burners. This paper discusses the results of the testing and subsequent feasibility study.*

INTRODUCTION AND BACKGROUND

The movement towards clean energy has lead to more stringent regulation of flue gas emissions from coal-fired boilers as well as increased the demand for an alternative fuel to coal. As a result, power utility OEM's have begun to evaluate the benefits of suspension firing of renewable fuels such as biomass (e.g. wood pellets, switch grass, etc.). Biomass, which has lower nitrogen content than coal, can potentially reduce NO_x emissions in coal-fired boilers. However, a complete biomass conversion of a coal-fired boiler would require de-rating the unit unless significant modifications to the boiler and fuel handling systems were implemented. This is due to the differences in fuel characteristics, particularly higher heating value, and the difficulty in processing biomass to make it suitable for suspension firing.

To evaluate the possibility of firing biomass fuel without making significant modifications, biomass was mixed with coal at varying blends for full scale test burns, to determine the maximum percentage of biomass that could be processed without significantly affecting the performance of the boiler. If successful, this would result in an overall reduction in the annual consumption of coal by the plant as well as potential reduction in emissions, particularly NO_x at low near term cost or risks to the customer. Central Power and Lime (CP&L), which is equipped with the latest in low NO_x coal combustion technology, participated in a suspension-firing test of a low-moisture wood pellet blended with bituminous coal to determine the impact that varying blends would have on boiler, pulverizer, and emissions performance. The unit's performance was monitored over five tests for blends up to 17% wood pellets by weight. The results of the study are summarized below.

UNIT DESCRIPTION

Central Power and Lime (CP&L) has an opposed fired Babcock and Wilcox (B&W) boiler. Originally owned by American Electric Power, the Twin Branch station was purchased and relocated to Brooksville, Florida and re-commissioned in the early 1980's. The boiler was originally designed to produce 930,000 lb/hr of superheated steam at 1,050°F and 2,080 psig and a reheater with a flow rate 835,000 lb/hr of steam from 670°F and 445 psig to 1,000°F. The boiler is equipped with twelve (12) RPI CCV® DAZ Low NO_x Burners and overfire air system located on the sidewalls of the upper furnace in an opposed-wall configuration burning an Eastern Kentucky bituminous coal supplied by four (4) EL -70 mills. The biomass fuel tested was pelletized wood processed from local southern pine trees, and supplied by pellet manufacturer Green Circle Bio Energy Inc, located in Cottondale, Florida.

BOILER DESIGN

Tests Performed

Five tests were performed during this program. Each test targeted achieving 100% MCR load based on steam flow. Test 1 represented a unit baseline operation with 100% coal, while Test 2, 3, and 4 represented co-firing 8%, 13%, and 17% wood pellets with coal, respectively. Test 2, 3, and 4 were conducted 2 weeks after the initial baseline test (Test 1). To confirm unit operation on coal, an additional test (Test 5) was conducted at the end of wood testing. All fuel blends were measured on a percent by weight basis, and individual fuel proportions were determined by approximate measurements using existing plant equipment. Fuels were mixed in the coal yard at 10, 20, and 30% wood by weight, but these mixtures were further diluted by the preexisting coal in the bunkers, reducing the wood content fired.

Fuels

Table 1 summarizes the fuel constituents of both the coal and wood pellets. Three (3) raw coal and one (1) raw wood pellet samples were taken during testing. Coal sample #1 was assumed to represent the coal from Test 1 only, because the remaining tests occurred 2 weeks later. Coal sample #2 was assumed to represent Test 2 and 3 only, because heavy rain was experienced during the overnight hours between Tests 3 and 4. Coal sample #3 was assumed to represent Test 4 and 5. A single wood pellet sample represented all tests with wood co-firing because the pellets were stored in train cars and only removed for mixing with coal before each test.

The #1 and #2 coal samples had very similar constituents and higher heating value. The #3 sample was similar as well, but showed approximately 30% greater moisture, as was expected. The wood pellet fuel had noticeably different characteristics. Moisture content was similar, but the total ash content was significantly lower. The amount of carbon was significantly lower as well, and this was offset by much greater oxygen content. Therefore the coal had approximately 60% greater energy content by weight. Any coal-wood mixture will require a greater total fuel mass throughput to each mill than coal alone in order to achieve full boiler load. Sulfur and chlorine content was substantially lower as well.

Table 1

Coal and Wood Pellet Fuel Analyses as Fired for Each Test

Fuel Type		Coal					Pellets
Test #		**1**	**2**	**3b**	**4**	**5**	**1-5**
Constituents	Units						
Moisture	% Wt.	4.65	4.98		6.25		4.96
Ash	% Wt.	9.22	8.61		8.85		0.76
Sulfur	% Wt.	0.64	0.61		0.57		0.12
Carbon	% Wt.	73.36	72.85		71.40		49.25
Hydrogen	% Wt.	4.61	4.58		4.37		5.75
Nitrogen	% Wt.	1.34	1.35		1.30		0.12
Oxygen	% Wt.	6.18	7.02		7.26		39.04
Chlorine	% Wt.	0.16	0.17		0.17		219 ppm
HHV	Btu/lb	13,004	13,045		12,735		8,215

Table 2 shows the actual percent wood fired by weight, in addition to the overall heating value. The percent wood fired was determined by sampling the mixed fuels both before and after the pulverizer on multiple mills. A heating value analysis was then performed on these samples, and the result was compared to the heating value of the raw fuels individually. It was found that the calculated percent wood as fired was similar when sampling both before and after the mill. All heating values used for analysis were on a dry-basis, but the values shown in Table 2 were converted back to an as received basis. It is also important to note that the deviation in wood content per test from the desired targets was not a limitation in the fuel system of the boiler, but was due to flow patterns within the fuel bunkers, diluting the wood blend with preexisting coal. Residual wood pellets were also seen on the feeder belts during Test 5, as indicated by a 2% calculated blend.

Table 2

Wood Content and Overall Fuel Heat Content as Fired

Test #	1	2	3b	4	5
% Wood Fired by Wt.	0%	8%	13%	17%	2%
Overall Fuel HHV Fired (Btu/lb)	13,004	12,649	12,405	11,984	12,803

MW Generation, Steam Flow, and Steam Temperature

Table 3 shows the main steam flow generated (expressed as a ratio of design steam flow), and gross generation for each test. It was noted that the unit was unable to produce design steam flow when co-firing the wood pellets. This was due primarily to limitations within the milling system. As shown in Test 2, the MW and steam flow generation dropped immediately with the introduction of just 8% pellets by weight. By making adjustments to mills and classifiers, CP&L was able to improve capacity when firing 13% pellets. MW Generation dropped again when 17% pellets were introduced. Another interesting point is that the ratio of generated MW to steam flow did not remain constant throughout testing. During Tests 3b, 4, and 5, the main steam flow was not proportional to the MW generated, when compared to Tests 1 and 2.

Table 3

Boiler Load Summary

Test #	1	2	3b	4	5
% Pellets as-Fired (by Wt.)	0%	8%	13%	17%	2%
% Steam Flow	103%	86%	105%	91%	96%
Generation (MWg)	147	123	131	114	120
Gross Calculated Turbine Heat Input (MBtu/hr)	530	451	496	445	460

Figure 1 compares the final superheat and reheat steam temperatures measured during testing with the design temperatures for the unit. The results from Test 1 firing 100% coal suggest that the unit runs slightly low on final superheat and reheat steam temperature. Note that for Tests 3b, 4, and 5, the steam temperatures were approximately 30°F less than they were for Tests 1 and 2. This explains why the ratio of generated MW to steam flow was less for these tests than for Tests 1 and 2. In the case of Test 3b for example, the observed steam flow was about the same for Test 1, but the MW generation was 16 MW less. A closer look revealed that the superheat and reheat steam temperatures for Test 3b were 35 and 44°F less respectively. These lower temperatures indicate that the heat input to the turbines was lower as well. This was verified by calculating the gross heat input to the turbines for each test, as shown in Table 3. Note that the gross turbine heat input shares the same trend as the actual generated output of the turbines, even though main steam flow was disproportionately high for some tests. Gross heat input to the turbine was calculated on an approximated basis, and did not include steam take-offs to feedwater heaters or other processes.

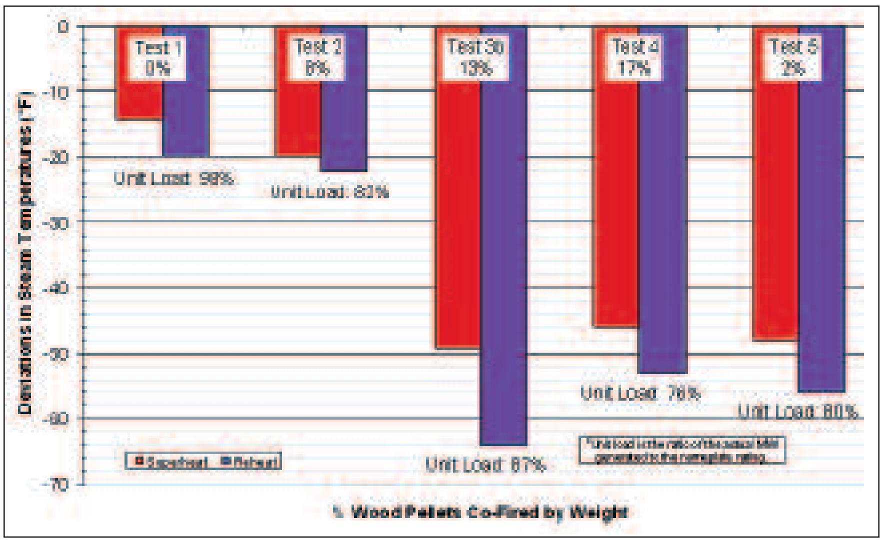

Figure 1. Deviation in Steam Temperatures for Various % Pellets Co-Fired

Decreased steam temperatures are generally the result of one of three issues. This can occur with lower than normal excess air, as by the principals of the heat and mass balance, the flue gas flows would provide less heat for obtaining steam temperature. This was not likely the case because the plant ran the boiler with greater than normal excess air. Increased fouling and slagging of the superheater and reheater surfaces is another factor, by limiting the effectiveness of heat pickup in these sections. A third factor may be that the furnace ran cleaner than normal, with less fouling. This would allow the furnace to pick up more heat, resulting in a lower than normal furnace exit gas temperature. The remaining flue gas would therefore not have enough heat to maintain design superheater and reheater steam temperatures. Note that while the boiler did not make steam temperature, it did generate disproportionately high steam flows.

Fouling and Slagging

When it comes to co-firing biomass, the effects of fouling and slagging in the furnace and on the convective heating surfaces are some of the primary concerns. To preface this section, RPI could not perform furnace observations during the test program. The furnace is a balanced draft design, but furnace pressures had the tendency to become positive. Fuel samples were gathered, but analysis was not performed on the fuel ash to compare known constituents that may be problematic, nor to determine the initial ash deformation temperatures for the various fuel mixtures. Therefore fouling and slagging concerns could only be speculated upon based on other test data such as comparing total ash content in the fuels, checking for increases in draft loss across convective tube bundles, and checking for deviations in tube metal temperatures.

When comparing the fuel analyses it was found that the coal has an ash content that ranges from 8 to 9% by weight, while the wood pellets have a very low ash content on the order of 0.5 to 1% by weight. The wood is from local standing southern yellow pine trees and is not from waste or demolition sources. The manufacturing process also removes the bark (which is used as fuel for the drying process at the manufacturing plant). The bark is a large contributor to the ash content of a wood fuel because dirt often becomes lodged in the bark, and is then added to the pellets once processed. From the standpoint of fuel ash content, fouling and slagging could be reduced due to the significantly lower ash content of these wood pellets. However, the wood ash may contain constituents that are more reactive by nature than the coal ash, and reactive at lower temperatures as well. Furthermore, the unit fired a fuel mixture of approximately 20% wood pellets. The 20% pellet fuel mixture is still primarily coal, and therefore the total fuel ash of the mixtures would only be slightly reduced.

Figure 2 shows a plot of the deviation in convective tube bundle draft loss for Tests 2, 3b, 4, and 5 as compared to Test 1 firing 100% coal. Typically if the fouling of the tube bundles were to increase, the draft loss across each would also increase due to the reduced flow area. The general trend for each bundle type seemed to remain the same across each test: either the draft loss was slightly greater than Test 1, or less. But the change in magnitude did not seem to follow a well-defined pattern. For example, the secondary superheater draft loss was about 0.2 to 0.3 iwc greater for all tests in comparison to Test 1. However, there were only slight changes in the draft loss across this bundle between tests. The deviation in draft loss for 17% pellets was about the same as for 2% pellets. Figure 2 also shows the flue gas mass flow deviations for each test, which identifies that the mass flow remained relatively unchanged between tests. Gas density would also affect the draft loss (based on temperature), but the data at least suggests there shouldn't be much change in draft loss based on flow rate changes. Based on draft loss readings taken across the convective heating surfaces, there was no significant evidence that the surfaces experienced a great degree of additional fouling by co-firing the wood pellets.

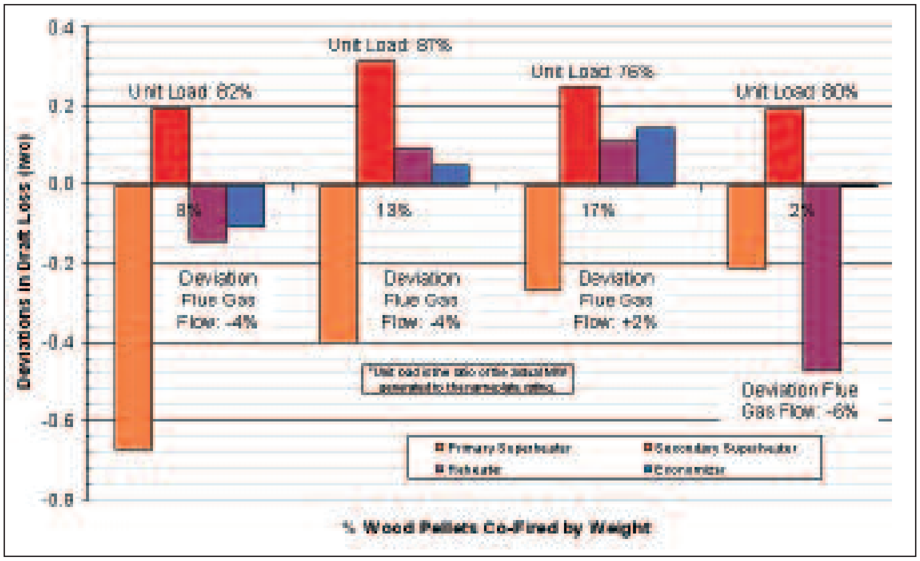

Figure 2. Deviation in Tube Element Draft Loss for Various % Pellets Co-Fired

Figure 3 plots the deviation in convective tube bundle metal temperature for Tests 2, 3b, 4, and 5 as compared to Test 1 firing 100% coal. Typically if the furnace walls were to become fouled, they would absorb less heat. This would therefore increase the furnace exit gas temperature, resulting in higher tube metal temperatures, hotter steam temperatures, and greater spray attemperation flow requirements. With the exception of Test 2, the primary superheater and reheater metal temperatures were much lower than the temperatures measured during Test 1. This may have been a result of the fact that unit load decreased when co-firing the pellets due to capacity issues in the milling system. However, it may provide some positive indication that fouling and slagging was not an issue when co-firing wood pellets.

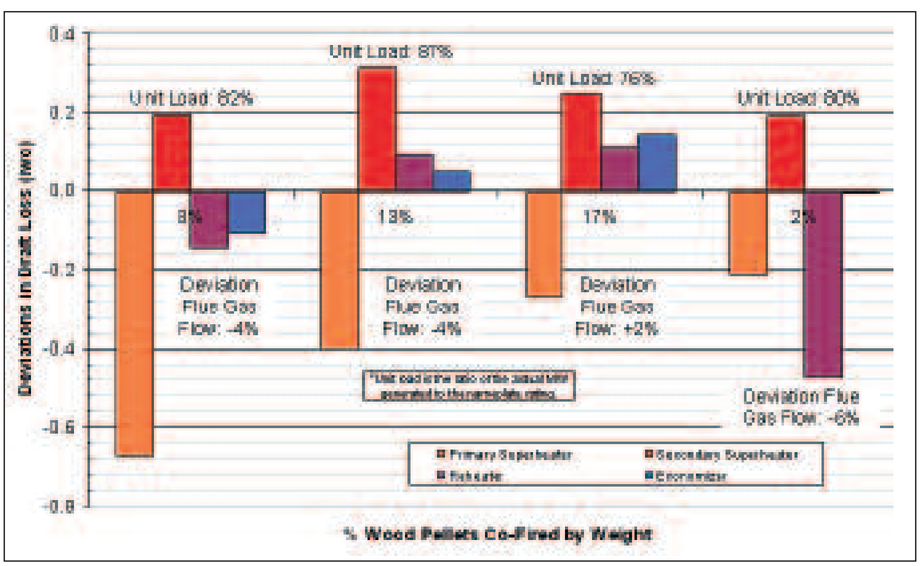

Figure 3. Deviation in Tube Element Metal Temperatures for Various % Pellets Co-Fired

Given a preliminary review of the available test data, fouling and slagging did not appear to be an immediate issue when co-firing wood pellets with coal, in blends less than 20% by weight. It is important to note that varying proportions of wood pellets were co-fired continuously with coal for the better part of four (4) consecutive days. However, data collection during each test was limited to about two (2) hours. Additional test burns with longer durations, as well as additional analysis would be required to fully understand the long terms effects of fouling and slagging when co-firing wood pellets with coal.

PULVERIZER PERFORMANCE

The pulverizer performance aspect of these tests was to determine how well an existing mill system would perform if the fuel was switched from coal to a wood/coal blend. Increasing the proportions of wood in the fuel blend allowed for determination of the effects on mill power, fineness, and other aspects of operation. For these tests, the unit's historian captured the majority of the pulverizer data. Mill data was collected for each test once fuel feed rate and mill motor amperage achieved steady-state conditions. Fineness samples were collected from all three coal pipes on two mills using the ASME PTC 4.2 test method. The coal feeder was put in manual control at a steady feed rate for each fineness test, while the other feeders were adjusted to maintain unit load.

Fuel Delivery

Wood and coal blends were loaded into the coalbunkers once bunkers were nearly empty of coal. The wood-coal mixture was visually confirmed through an observation port at the gravimetric coal feeder. In general, the time required for the blend to reach the feeders was higher than originally estimated. Trace quantities of wood were first observed, with the amount increasing over the next one or two hours. The time between initial sighting of wood in the first feeder and seeing wood in all feeders ranged from two to four hours. This time was dependent on the size and geometry of the bunker, as it was observed that feeders that received the wood-coal mixture first corresponded with the smaller coal bunkers with the steeper sloped walls. Residual coal in the bunkers mixed with the coal/wood blend added to the bunkers resulted in the wood blend being more dilute than the blend that was originally mixed in the coal yard.

Pulverizer Operation

Pulverizer motor amperage increased immediately following the introduction of wood to each feeder. The current increased as the concentration of wood in the mixture increased with each subsequent test, and surged repeatedly as the wood concentration in the mill increased. During the mill current peaks, the mills experienced high vibration as they struggled to clear wood from the grinding area. Motor current limitations forced the feed rate to be reduced in the mills with the greatest percentage of wood, and the load was shifted to other mills.

Particle Accumulation

Following Test 2, one pulverizer, which had experienced significant vibration and throughput limitations was shut down and evacuated for inspection. It was observed that the time to evacuate the mill was significantly longer than normal. Several inches of a sandy wood mixture was found in the lower race surrounding the grinding balls. The material had a HHV of 4,463 Btu/lb and 42% volatiles, both of which indicate it was roughly half wood. About one quarter of the mixture was silicon dioxide, the largest constituent of the coal and wood ash. No hard deposits or plugging was observed in the mills. The proximate analysis and the primary ash constituents are given in Table 4, below.

Table 4

Proximate Analysis of Ash Constituents of Mixture

Proximate Analysis	Percent Composition (as received)
Moisture	0.53
Volatile	41.87
Fixed Carbon	5.71
Ash	51.89
Ash Composition:	
Silicon Dioxide	52.15
Aluminum Oxide	20.39
Ferric Oxide	12.66
Calcium Oxide	8.27

The excessive pulverizer motor amperage and the significant time required to clear the mill indicated that a large inventory of particles was building up in the mill during wood/coal operation. It was thought that this was caused by over-classification of wood particles by the classifier, which is designed to separate much smaller coal particle fines in the pulverizer. This problem has been documented in other papers, including an RPI paper on 100% wood conversion with ball-and-race mills [1]. In an attempt to decrease classification and increase the throughput of the mill, the adjustable segment of each classifier vane was removed. The resulting vanes were about six inches shorter than the original configuration, effectively increasing the diameter of the circulating particles and increasing the classifier cut size. Classifier vanes were in place on all mills for Test 1 and 2, and remained in Mill A on Test 3b. Mill B vanes were shortened for Test 3b, and mill C and D vanes were removed. For Test 4 and 5, vanes were completely removed from all mills.

Primary Airflow

The standard mill exit temperature set point used at this unit (170°F) was not changed for co-firing wood. However, the mill inlet PA temperature was limited to 350 °F to avoid devolatilizing the wood as it entered the pulverizer. Primary airflows and air/coal ratios were increased on some mills to help clear out excessive wood inventory in the mill. The increased airflow allowed the mill to maintain slightly higher fuel throughputs. The increase in primary air across all four mills contributed roughly 1 to 8 percentage points of the total excess air in the boiler, with the highest being during Test 4 when two mills had very high primary airflow. Pressure drop across the mill was also recorded during all tests, and is shown in Table 5. A comparison of Tests 4 and 5 shows a large drop in DP during Test 5, indicating that wood present in Test 4 increased the mill DP significantly compared to coal-only operation. Comparing the coal-only tests (Test 1, before modifications, and Test 5, after classifier modifications had been performed) shows that removal of the classifier vanes reduced the mill DP 5-6 iwc.

Table 5

A/C Ratio, Mill DP, PA Temperatures

			Test 1	Test 2	Test 3b	Test 4	Test 5
Mill A	A/C ratio	lb/lb	2.0	1.9	2.1	1.9	2.1
	Mill DP	iwc	14.8	19.9	20.7	14.1	9.0
	PA Temp	°F	339	301	327	327	326
Mill B	A/C ratio	lb/lb	2.0	2.5	2.1	3.8	2.1
	Mill DP	iwc	16.2	14.9	17.0	16.4	11.0
	PA Temp	°F	349	288	361	239	332
Mill C	A/C ratio	lb/lb	2.0	2.3	2.4	3.5	2.1
	Mill DP	iwc	11.5	12.3	12.0	11.0	7.3
	PA Temp	°F	344	285	278	242	371
Mill D	A/C ratio	lb/lb	2.0	2.0	2.3	2.2	2.1
	Mill DP	iwc	14.1	24.9	19.7	18.3	9.6
	PA Temp	°F	382	306	311	321	391

Coal Fineness

Coal fineness samples were taken on all pipes, and sieved individually according to ASTM D197. Surprisingly, the fineness samples did not appear to contain any wood, even at the highest wood coal mixture of 17%. Wood particles could only be visually distinguished from coal upon close inspection. Once the samples were sieved, the wood particles in the samples became more apparent. The results of the sieving, which indicate the fineness of the whole mixture on a per-mill basis, are shown in Figure 4. Note that these results do not differentiate between the individual wood and coal particle size.

Table 6

Coal and Wood Mixture Fineness

Test		Mill A	Mill C	Mill D
	Fuel Flow (kpph)	26.9	26.8	
1	% Wood	0	0	
	50 mesh	99.8%	99.8%	
	100 mesh	98.7%	97.7%	
	200 mesh	81.6%	76.0%	
	Fuel Flow (kpph)	29.6	21	
	% Wood	11%	4%	
2	50 mesh	99.8%	99.6%	
	100 mesh	98.2%	96.4%	
	200 mesh	78.2%	75.9%	
	Fuel Flow (kpph)		29.1	28.8
	% Wood		16%	11%
3b	50 mesh		94.7%	94.3%
	100 mesh		83.0%	83.5%
	200 mesh		57.4%	59.6%
	Fuel Flow (kpph)	32.9	20.4	
	% Wood	14%	19%	
	30 mesh	99.1%	98.8%	
4	50 mesh	96.1%	92.6%	
	100 mesh	83.7%	80.1%	
	200 mesh	57.8%	54.1%	
	Fuel Flow (kpph)	25.2	25.1	
	% Wood	3%	1%	
5	50 mesh	99.3%	99.5%	
	100 mesh	92.0%	92.4%	
	200 mesh	68.4%	69.8%	

Fineness data for two mills was plotted against wood content for tests performed with and without the classifier blade extensions installed in the mill (see Figure 4). Removal of the blades decreased the fineness significantly as shown in comparison of Test 1 and Test 5. (Note: It was observed during Test 5 that the coal feeders still had trace amounts of wood in the coal entering the pulverizer.) Despite lower coal throughputs in Test 5, the fraction passing 200-mesh decreased from 76-80% to 68-70% and the 50 mesh decreased from 99.8% to 99.3-99.5%.

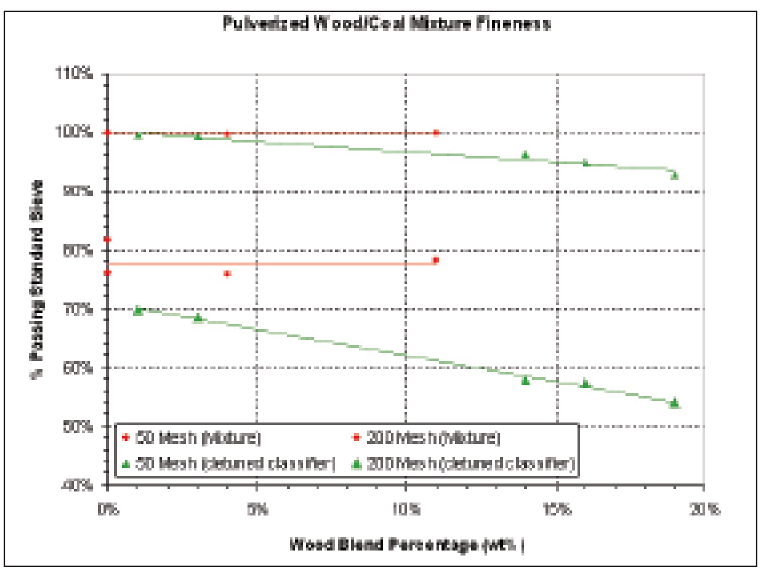

Figure 4. Pulverized Wood and Coal Fineness

Fineness levels remained relatively constant with the classifier blades installed as the classifier effectively trapped the wood particles in the pulverizer until they were ground nearly as fine as the coal particles. (Note: the fuel feed rate for the data plotted was not constant, and likewise the fineness is expected to vary depending on throughput.) However, with the classifier blades removed, the fineness of the mixture drops linearly with the addition of wood. A 19% wood blend, the highest recorded during testing, resulted in 93% passing 50 mesh and 54% passing 200 mesh. A small fraction (1.2%) of particles, all of which were visibly wood, were larger than 30-mesh (600 μm).

From a combustion performance and emissions standpoint, the particle size of the individual coal and wood fractions is more important than the blend fineness because coal needs to be significantly finer than wood particles to achieve stable combustion. The sieve results indicate that the wood is more than sufficiently broken up as all particles are well under 1.5mm, the top size recommended based on RPI's standards on biomass suspension firing. The results do not indicate if the coal fraction meets recommendations for pulverized coal firing (typically 70% through 200 mesh and 98% through 50 mesh).

Further tests conducted on pulverized coal samples from Test 4 were used to calculate the average coal and wood fineness for that test. The higher heating value was determined for each mesh fraction and used to calculate the percentage of wood and coal remaining on each sieve [2]. From this, the "true" wood and coal fineness for Test 4, Mill C was calculated and is presented in Table 7.

Table 7

Wood and Coal Particle Distribution for Test 4

		Wood Particle Size	Coal Particle Size
Mesh Size	μm	% Passing Mesh	% Passing Mesh
30	600	**95%**	**100%**
50	297	**65%**	**100%**
100	149	**39%**	**91%**
200	74	**27%**	**64%**

Figure 5 compares the wood fineness to the wood pellet particle size determined by two methods: dissolving the pellets in water, and grinding in a bench-scale HGI mill. Figure 5 also compares the fineness of the coal fraction to the fineness achieved on the same pulverizer during Test 5, when only a small percentage of wood was present. These results show that the wood pellets, when co-milled with coal, were reduced to particles much smaller than the original composition of the pellets. While less than 15% of the dissolved pellet particles passed 50 mesh before pulverizing, over 60% passed 50 mesh after co-milling with coal. This supports the theory that the wood particles recirculate through the mill many times until they are very fine to escape the classifier, which was de-tuned to decrease classification.

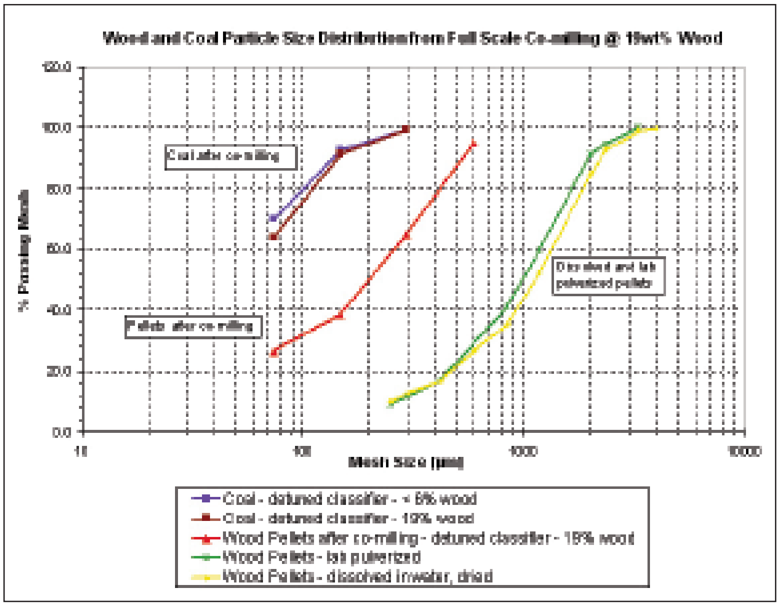

Figure 5. Coal and Wood Particle Size Distributions

The coal fineness decreased when co-milling to approximately 64% through 200 mesh from an estimated 70% through 200 mesh seen in the following test which contained very little wood. Since both tests were performed with the classifier detuned, the decrease in fineness is due to the presence of wood in the grinding section of the mill. The excessive accumulation of wood particles in the grinding segment reduced the grinding efficiency of the pulverizer. The change in coal fineness is significant as it can lead to increased unburned carbon (UBC) in the ash as well as increased NO_x emissions. Quantifying and explaining the changes in UBC and emissions when co-firing with wood requires consideration of both the coal and wood particle size and their effects on combustion.

Mill Power

Mill power was estimated using an electric current reading from one leg of the three-phase mill motors, and power factor (0.92). The mill power increased significantly during co-milling, and pulsed as the mill inventory accumulated large quantities of wood. The average power for each constant-feed rate test period was calculated and divided by mill throughput to determine the specific power demand of the mill. These values were then plotted against the wood content of each wood/coal blend based on the HHV analysis of the raw fuel sample for that individual mill.

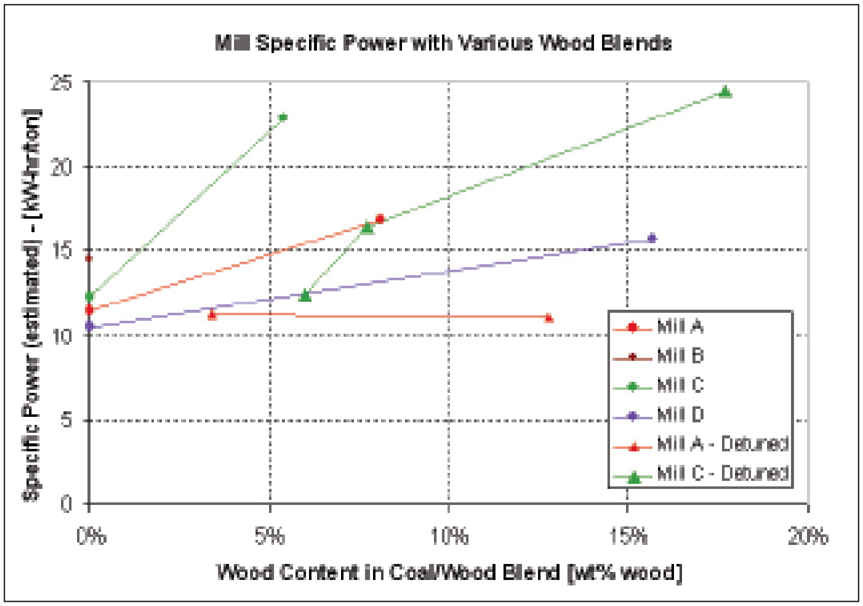

Figure 6. Mill Specific Power vs Wood Content

The graph shows there was a steep increase in specific power when co-milling coal and wood pellets, and the power increased more with higher wood content. This data also shows a significant reduction in power when 'de-tuning' the mills by removing the classifier vane extensions. Removing the vanes reduced the recirculating load in the mill, which in turn reduced specific power and allowed higher throughputs and wood blends to be pulverized. It is also important to note the wide range of specific power between the four mills across all the tests. Much of this variability is likely due to differences in mill wear and condition including the quantity and size of grinding balls, race wear, and grinding load. Primary airflow also affected the mill operation. In general, mills that had been rebuilt recently or had larger grinding balls experienced less vibration and lower power consumption when co-milling.

Pulverizer System Conclusions

The pulverizers successfully handled up to 19% wood pellets by weight, and pulverized the coal and the wood to an acceptable fineness for suspension firing. Reducing classification by removing classifier blade segments proved very effective for increasing throughput and reducing limitations due to excessive mill power demand. Increasing the primary air to the mill also assisted in clearing the mill and maintaining more stable operation. However, overall mill capacity is still considerably lower with a wood/coal blend than with coal alone. Mills with new grinding elements are best suited for co-milling, and have less vibration issues than worn mills. Pulverized wood particle size decreased significantly during co-milling from d_{50} of approximately 1.1 mm (as pelletized) to a d_{50} after milling around 200 μm. Coal fineness was negatively impacted by the presence of wood as well as the de-tuning of the classifier, but did not appear to cause any problems with flame stability or combustion.

EMISSIONS PERFORMANCE

Similar to coal suspension firing, wood suspension firing takes into consideration a lot of the same characteristics needed for coal to produce a sustainable flame in wall fired units. These include the percentage of excess air provided for the combustion process, fuel characteristics such as the amount of moisture in the fuel, heating value and particle fineness, and furnace dimensions that contribute to residence time for a particle to burn in the furnace. A good understanding of these characteristics and how they're related to low-NO_x combustion was needed prior to actual combustion testing of the pellets at CP&L. In general, suspension firing of wood particles tends to be more difficult than suspension firing of coal. In CP&L's case, the unit could not completely convert to wood firing without a de-rating the boiler capacity. Significant modifications to the mill systems and combustion systems would be required to be able to accommodate a larger fuel flow and air flow demand due to the significant decrease in heating value of the fuel and fineness. Mixing a small percentage of wood into the coal stream was the only viable option for this unit.

As part of the test program, the NO_x, CO, and UBC was monitored for each test to determined the impact of co-firing of the wood and coal. An emissions grid was set-up at the economizer outlet of the furnace at 6 port locations evenly distributed across the width of the economizer duct. Each port contained 3 individual probes, which traversed 3 separate depths across the economizer duct. The grid was used to monitor the average NO_x, CO, and O_2 levels at the economizer duct for each test run over the two-hour test period. Unburned Carbon was determined from flyash that was extracted from the economizer outlet over the two-hour test period. This data will be used by RPI to refine our NO_x prediction model for units interested in suspension firing of wood and coal.

NO_x Performance

Figure 7 shows how NO_x emissions for different fuels under similar air staging conditions compare to each other. At similar burner zone stoichiometry, or the ratio of available air to coal at the combustion zone local to the burner front, wood produces lower NO_x emissions than coal [3]. NO_x, which can be broken down into components of thermal and fuel NO_x, is theorized to be lower when burning wood with a burner originally designed to burn coal for several reasons: A) reduced furnace temperatures due to lower HHV of the wood results in lower thermal NO_x formation; B) the amount of fuel-bound nitrogen in wood is lower than coal; and C) higher Oxygen content in the wood allows for reduced excess air to the furnace for combustion. Therefore it is possible to positively affect NO_x emissions in a coal-fired unit by introducing small quantities of wood into the coal stream.

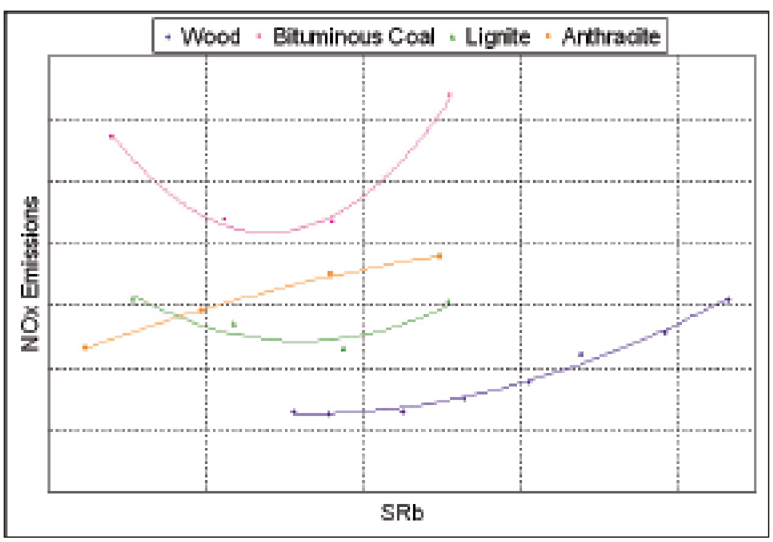

Figure 7. Comparison of NO_x versus Burner Zone Stoichiometry for Different Fuel-types

Recall that there were 5 tests that were conducted with a maximum wood to coal mixture of 17%. Using Figure 7 and RPI's standards, a NO_x prediction was then calculated for each mixture of wood to coal based on a number of known factors such as the basket area heat release for the furnace, fuel analysis of both the coal and the wood and a weighted average of the wood and coal present in the mixture. These predictions were then compared to the NO_x emissions measured at the economizer outlet grid to determine the accuracy of the prediction model used.

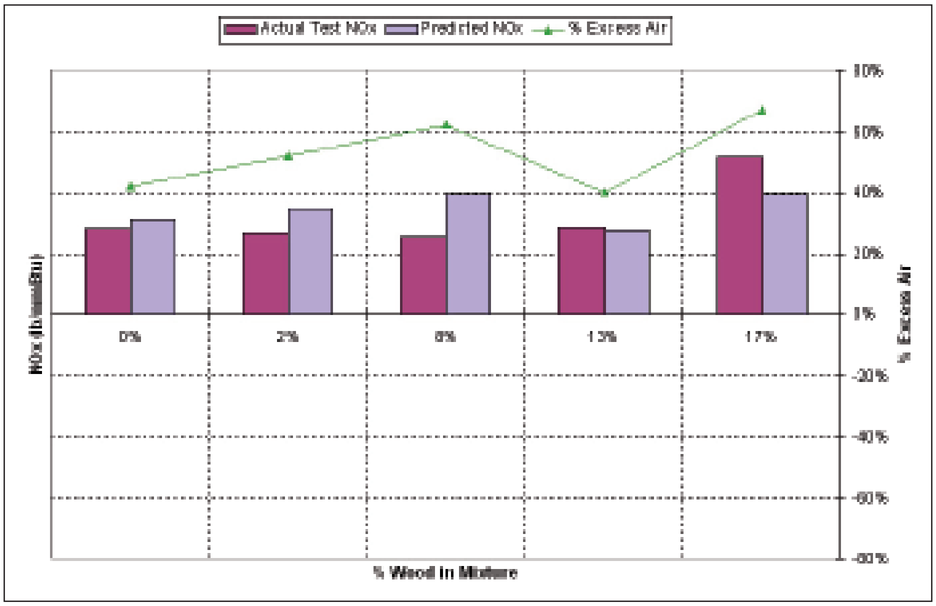

Figure 8. Comparison of NO_x Prediction Versus Actual Measured NO_x

The predicted NO_x compared to the actual NO_x measured for each fuel blend is shown in Figure 8. Also shown on the figure is the percent excess air level measured during testing for each fuel blend. The predicted NO_x deviated from the NO_x measured at the economizer outlet grid by as much as 55% (Test 2 at 8% wood mixture). Because RPI's current wood and coal NO_x prediction model is heavily influenced by excess air, the high O_2 levels measured during each test caused the prediction model to overestimate the NO_x emissions. For Tests 1 and 3, when excess air was observed to be its lowest (approximately 40%), the prediction model estimated very close to the actual NO_x measured (=10% difference), indicating that the RPI's NO_x prediction model was valid for excess air levels less than 40%.

Further review of the NO_x data showed an upward NO_x trend as the percentage of wood pellets increased (see Figure 9.) Note that the predicted NO_x and actual NO_x measured at the economizer outlet grid trended relatively closely for all tests except for during Test 4 (17% wood-coal mixture). Recalling that the classifier settings were changed when the wood concentration was increased in Test 4, the slight decrease in fineness for both the wood and coal, as well as the increase in excess air definitely contributed to the increase in NO_x. However, NO_x emissions appear to increase dramatically when the concentration of wood in coal increases beyond 14%.

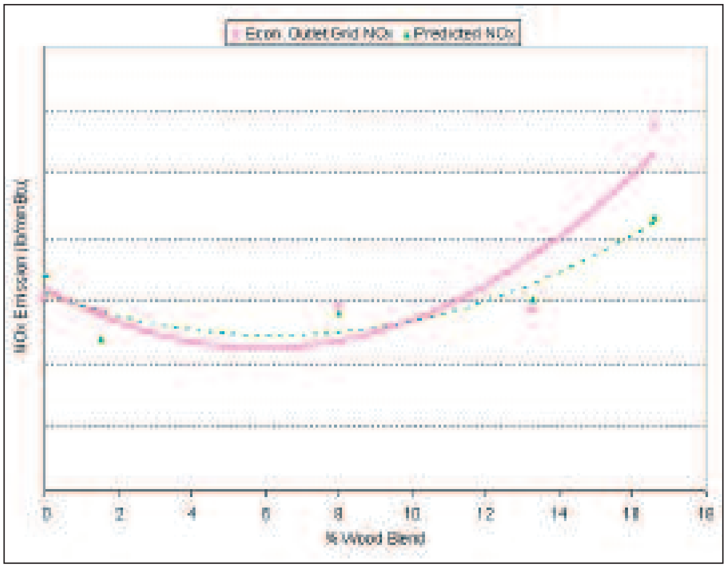

Figure 9. NO_x versus % Wood Blend

Carbon Monoxide Performance

Formation of carbon monoxide (CO) when co-firing wood and coal is governed by burner to burner air and fuel distribution, overall excess air levels and air staging similar to just firing coal on its own, as well as the particle size distribution of the wood and coal. Based on the economizer outlet grid measurements, despite being higher than recommended for low NO_x combustion, O_2 levels were well balanced across the economizer duct with ±5% O_2 from average. With a well-balanced unit, CO cannot form in areas of the duct where pockets of low O_2 may appear. Thus, at high O_2 levels, CO is expected to decrease. Figure 10 shows the CO distribution for each of the five tests. CO emissions increased slightly as the percent wood was increased between Tests 1 and Test 3b. Peak CO emissions were measured at approximately 700 ppmvd (Test 3b), which corresponded with the level of excess air of approximately 40%, the lowest excess air level of the five tests. The sudden decrease in CO shown in Test 4, was again, likely caused by the high excess air measured for that test.

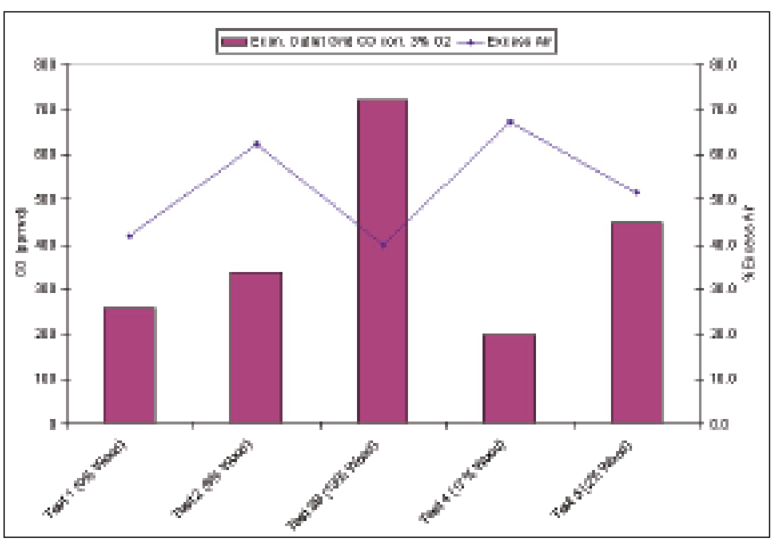

Figure 10. CO Emissions for Each Test

Unburned Carbon in Flyash

Flyash was sampled from the economizer outlet duct during each test and analyzed for percent-unburned carbon (% UBC). Figure 11 shows the change in % UBC for each test. As expected, as the concentration of wood increased with each subsequent test % UBC also increased. The highest level of % UBC occurred during Test 4 at the highest concentration of wood and was found to be approximately 10.8% compared to the baseline % UBC of 5.5% (Test 1). The sharp increase in % UBC was also influenced by the changes in classifier settings implemented prior to Test 4, which in turn reduced the overall fineness of the wood-coal mixture, as previously discussed.

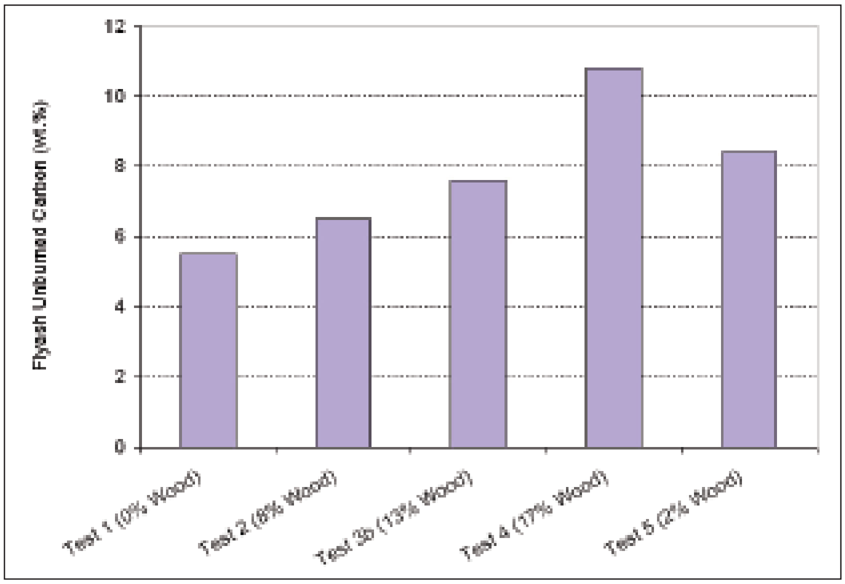

Figure 11. Percent Unburned Carbon versus Wood Concentration

SUMMARY

Based on the findings of this test program, co-combustion of wood and coal in suspension through low NO_x coal burners is a possible alternative to a complete fuel conversion to wood. Although the unit was unable to achieve steady state operation at its rated boiler load due to degradation of mill performance and throughput after the introduction of wood pellets into the pulverizers, steam flow and steam temperatures were stable for each test. To improve mill performance with the introduction of the wood pellets, classifier vanes were removed from the pulverizer allowing for higher throughput of wood and lower the power consumed by the mill during operation. Analysis of the wood pellet determined that the pulverized wood particles were significantly reduced in size. However, coal fineness was also decreased with the introduction of wood. Also, fouling and slagging did not change significantly with the addition of the wood pellets compared to baseline fouling characteristics with coal.

In terms of emissions performance, NO_x, CO, %UBC, all behaved as expected with respect to typical low NO_x operation. Higher than expected excess air level contributed to higher NO_x emissions for each test. However, this did not clearly demonstrate the effectiveness of using wood as a means to further NO_x reduction in the unit. Although, RPI's preliminary NO_x model trended relatively closely to the results observed during testing, testing found that at wood concentrations greater than 14% resulted in increasing NO_x, rather than decreasing. With further tuning of the unit by maintaining low excess air levels more typical of low NO_x combustion, co-firing wood with coal can potentially lead to lower NO_x emissions.

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