Proceedings of the ASME 2018 Power and Energy Conference
PowerEnergy2018
June 24-28, 2018, Lake Buena Vista, FL, USA

PowerEnergy2018-7273

100% TEST BURN OF TORREFIED WOOD PELLETS AT A FULL-SCALE PULVERIZED COAL FIRED UTILITY STEAM GENERATOR

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ABSTRACT

Portland General Electric's (PGE) Boardman plant is a nominal 600 megawatt (MW) coal fired unit that burns sub-bituminous Powder River Basin (PRB) coal from Wyoming. This paper will cover the experience and results of PGE's Boardman plant operating on 100% torrefied wood (TW) pellets at 255 MW consuming almost 5000 tons of pellets. Results were positive and include suitable handing after inclement weathering for months. Pulverizers were able to handle the TW pellets with adjustments, resulting in near 100% combustion efficiency. Particulates were controlled with an electrostatic precipitator (ESP). Topics investigated include torrefied wood production, fuel handling and storage on the front end of the test. Fuel handling, pulverization, combustion, emissions, and ESP performance were monitored during the test and are reported here. Several one mill tests were conducted prior to the 100% test to evaluate and improve mill performance. This test showed that a pulverized coal (PC) boiler can operate on 100% TW fuel with minimal operational changes.

INTRODUCTION

The value of this work is that it is one of the first 100% test burns of TW pellets in a large pulverized coal boiler with positive results. Many questions were answered about production, handling, long term storage, pulverization, combustion and emissions. Several factors outside of Portland General Electric's (PGE's) realm have made the use of a biofuel at the Boardman Coal plant potentially attractive enough to conduct a test burn of a solid biofuel. Due to lack of published papers concerning the full scale use of solid biofuel in a pulverized coal plant, several reviews and reports concerning torrefied wood were used as a basis of understanding. [1-5] Pelletized torrefied wood (TW) was chosen over raw plant material due to its superior handling and pulverization properties. Think of how well a roasted coffee bean grinds compared to a raw green bean. The torrefaction process makes the wood crispier and easier to grind than the raw wood. Torrefaction requires energy to cook the wood, and over torrefaction (over cooking) reduces solid fuel yield. A driver in the use of TW is the use of existing plant infra-structure to accommodate a change in fuel source, e.g., pulverizers, conveyors, etc.

The test included several single mill tests to evaluate and predict the performance of the four mills and burners using 100% TW. As a result of single mill test burns, modifications to the mill's internals and operating conditions were performed on four of the eight mills. The plant was able to operate at near 260 megawatts gross (MWG) on 100% TW for several hours using these four mills. The TW did not grind as small as coal, but its high volatile/reactivity made for good combustion. The electrostatic precipitator (ESP) performed well while maintaining opacity less than 2%.

The TW fuel differs from coal in several combustion aspects. The most significant is it's reactivity in comparison to coal. The TW fuel is high in both volatile matter and oxygen content as indicated by the proximate and ultimate fuel analyses. On site, the high reactivity of TW influenced the manner in which it was stored, handled and pulverized.

The following areas will be covered in this report:

Fuel Quality - Torrefaction Impacts on Fuel Quality - Handling and Storage - Spontaneous Combustion – Pulverizers – Classifiers - Primary Air Systems – Reject Systems – Burners - Combustion Process - Boiler Efficiency – NO_x - SO_2 - ESP Operation

Many of the values reported in this paper are fuel analyses using American Society for Testing and Materials, ASTM laboratory methods. These can be quite accurate +/-

1%. However, a variety of sampling techniques were used that may put some of the values (moisture, HHV) more in the +/- 10% range. Plant data was taken from control room readings where electrical data is accurate to <+/-1%, but measured flows of fuel and air are in the <+/-5% accuracy range.

FUEL QUALITY

The process of torrefaction of wood generally reduces its moisture and volatile content as it increases its heating value. Additionally, the torrefaction process produces a product thatǿs easier to grind. A wide range of TW products were evaluated with four suppliers providing products for the test burn. The TW fuel for the test was made from pine, fir, and other softwoods. Two suppliers of torrefied wood pellets were from Quebec, Canada, and Mississippi, USA. These suppliers provided about 80% of the test fuel with the Mississippi supplier providing almost 75% of the test fuel. The Mississippi pellets consisted of 90% freshly made pellets with about 10% older less torrefied (off-spec) pellets. The wood was first torrefied and then pelletized. The remaining 20% was provided by two local torrefaction facilities, one was a pilot scale laboratory test rig and the other was a tire to carbon black facility converted to produce wood pellets. Both of these local facilities used non-torrefied wood pellets as a feed stock to produce a TW product. The average heating value of the TW delivered to the plant on an ñAs Receivedò (AR) basis was 20,240 MJ/Kg (8,700 Btu/lb). Approximately 5,000 tons of TW fuel was delivered to the plant by late 2016.

The commercially supplied TW pellets were more consistent in heating value and color than the locally produced products. A photograph of the commercial product is shown in Figure 1 and an example of the local product in Figure 2.

Fig. 1 Uniform colored pellets from commercial facility using ground wood as feedstock and then pelletizing.

Fig. 2 Color range of pellets from local producers using wood pellets as feedstock.

Both these products have about the same average heating value, but the local products had a larger standard deviation in the heating value data. It should be noted the plant was unable to differentiate between TW suppliers as the received TW was essentially blended as it was received and stacked out in a prearranged area of the coal yard. They just treated it as the TW biofuel.

Prior to delivery, a layer of sawdust was applied to the yard to isolate the biofuel from coal. This is shown at the base of the fuel pile in Figure 3. This was done to minimize any contamination of the TW fuel with coal. Approximately 400 tons was used for tuning the pulverizers or mills for safe and efficiency grinding of the TW fuel.

Fig. 3 Torrefied wood pellets in storage with sawdust base visible

Due to external factors the test was delayed until mid to late February which resulted in fuel handling issues and deterioration of the TW fuel pre-test. If the fuel was contaminated with coal it was not used. In addition the time to modify four pulverizers for TW fuel only limited the time for the 100% TW fuel test. Compounding this were weather and market issues which limited the 100% test burn to approximately 5 hours. The plant data collected during this period is used for this report.

The average quality of the delivered fuel was as expected; it had a low moisture content and a heating value that exceeded the coal typically consumed by the plant.

Average Fuel Quality Delivered, As Received:

Moisture	8%
Ash	2%
High Heating Value	20,240 MJ/Kg (8,700 Btu/lb)
MAF HHV	22,490 MAF MJ/Kg

Unfortunately, the winter of 2017 was one of the harshest on record and the outside storage of the TW resulted in quality degradation prior to the 100% test. It gained moisture and lost MAF heating value. The loss of MAF heating value is attributed to oxidation. This loss of MAF was significant, at over 900 MJ/Kg compared to typical sub-bituminous PRB coal MAF losses typically in the 200-500 MJ/Kg range. Note the Moisture, Ash and HHV values of the TM after being exposed to the elements:

Average Fuel Quality Tested, As Received:

Moisture	16%
Ash	2%
HHV	17,680 MJ/Kg (7,600 Btu/lb)
MAF HHV	21,560 MAF MJ/Kg

This degraded TW fuel was judged to be suitable for use. The Ultimate and Ash Chemistry data for the test fuel, along with other parameters, are shown in Table 1

The degree of torrefaction can be estimated by using the moisture ash free (MAF) basis heating value. The raw wood itself can have a low MAF value of about 19,800 MJ/Kg (8,500 MAF Btu/lb). When we add the ash and moisture back in to get AR basis the wood itself could run in the AR 9,300 to 14,000 MJ/Kg (4,000 to 6,000 AR Btu/lb) range depending on moisture.

The delivered fuel MAF heating value ranges for the test TW fuel were from a low of 21,170 MJ/Kg (9100 Btu/lb) to a high of 23,260 MJ/Kg (10,000 Btu/lb), with the majority of the fuel in the MAF Btu/lb range of 22,100 MJ/Kg (9,500 Btu/lb) to 22,560 MJ/Kg (9,700 Btu/lb). This range indicates both the degree of torrefaction and potentially any differences in the wood feedstock. Depending on the facility, wood was torrefied at about 300^0 +/-50^0 C to produce a torrefied product in the 21,170 to 23,260 MJ/Kg (9,100 to 10,000 Btu/lb) range. The plant treated all the TW fuel as the same.

Table 1 Average ASTM analyses of 100% test burn TW fuel

Proximate	
Moisture %	14.8
Ash %	1.1
Volatile %	62.2
FC %	21.9
Sulfur %	0.06
MJ/Kg	17,570 (7,555 Btu/lb)
Ultimate	
Carbon %	48.3
Hydrogen %	5.0
Nitrogen %	0.05
Oxygen %	30.8
Chlorine %	0.004
Ash Chemistry	
SiO2	22.2
Al2O3	29.0
TiO2	1.0
Fe2O3	5.6
CaO	17.9
MgO	5.5
K2O	7.8
Na2O	2.3
SO3	4.3
P2O5	2.2
Ash Fusion Temperature Reducing ^{0}C	
ID	1190
ST	1200
HT	1210
FT	1230
HGI = 31	

When MAF Btu/lb is adjusted for ash and moisture, the average fuel quality of the delivered TW test fuel on an As Received, AR basis is 20,240 MJ/Kg (8,700 Btu/lb).

In addition to TW tested, a small portion of Arundo donax grass was torrefied, but this represents only about one percent of the total fuel used.

TORREFACTION IMPACTS ON FUEL QUALITY

A large variety of torrefied wood products were reviewed and two observations were made during the data review. The first observation was the trend of the Hardgrove Grindability Index (HGI) [6] increasing with the degree of torrefaction as indicated by MAF Btu/lb. Figure 4 shows the relationship of HGI and MAF Btu/lb over the wide range of products reviewed. The HGI ranged from 20 to almost 90. This chart contains data from highly torrefied products that were not commercially available.

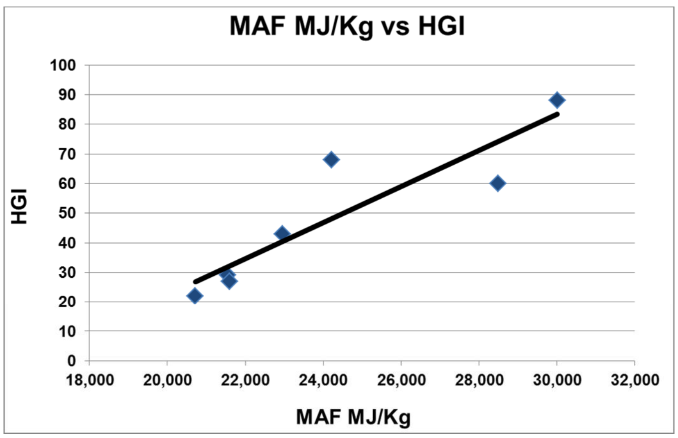

Fig 4. Relationship between MAF heating value and HGI over a wide range of torrefaction.

It is recognized that HGI data is hard to use with biofuels as the test is designed for coal. Reviewed published reports indicated this.[7] Improvements to the test could entail looking at the larger or uncrushed portion rather than the amount of 200 mesh material. The correlation of HGI with MAF heating value did provide some confidence in the HGI value and the mills reaction to the TW fuel certainly indicated a low value. The HGI data for the test fuel was in a narrower range, 21-34, but it also shows a similar trend; that higher MAF heating value products have a higher HGI value or the more the wood is torrefied the crispier it becomes. Figure 5 shows the delivered test fuel data with the trend extended out to help estimate the MAF value that would indicated HGIӧs in the coal range, i.e. greater than 40.

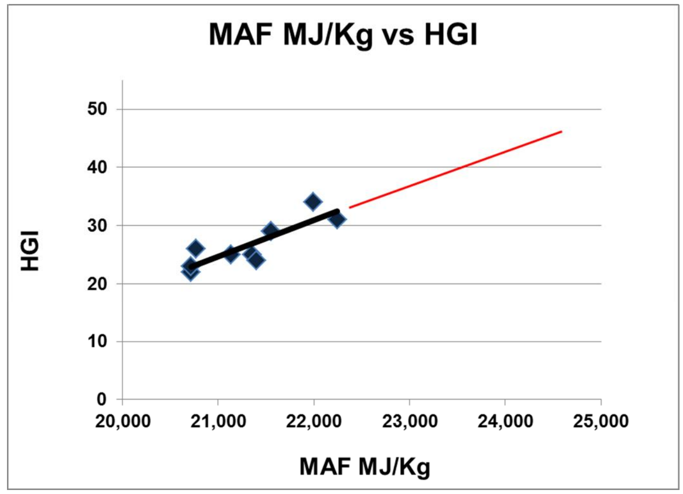

Fig. 5 Relationship of MAF heating value vs HGI for test burn samples showing extension of trend to evaluate where MAF heating value would be for a minimum HGI of 40.

The other observation was the loss of volatile matter associated with higher MAF heating value, implying the more thoroughly the product is torrefied, one sees a reduction in volatile matter. This is shown in Figure 6. This loss in volatile is partially offset by a higher HGI resulting in smaller particles entering the flame.

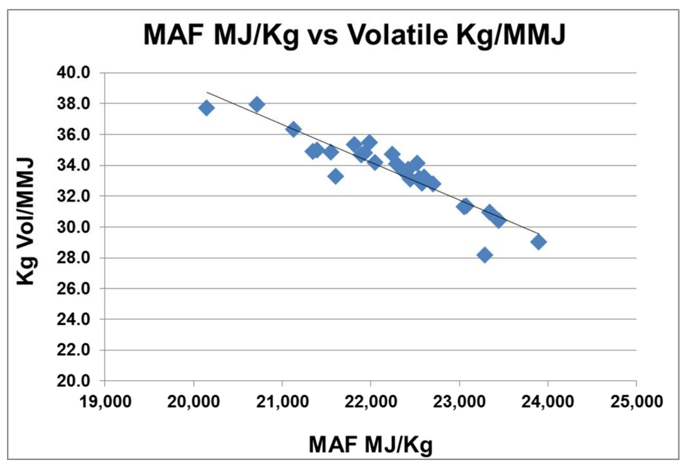

Fig. 6 Relationship between MAF heating value and volatile content; showing loss of volatile content with increased torrefaction.

HANDLING AND STORAGE

TW fuel deliveries were from November 2016 and through yearӧs end. Approximately 5000 tons were delivered with the intention to test in late December 20016. Due to inclement weather and grid restraints, and the time needed to modifying the pulverizers, the test was not conducted until late

February 2017. As previously stated the TW fuel was stored outside in unconsolidated piles as shown in Figure 3.

The impacts of inclement weather starts in December, as temperatures fell and snow increased. The pile shown in Figure 7 shows some of the first snows. Due to the high reactivity of the TW fuel and the long term storage (6-12 weeks) the unconsolidated pile spontaneously combusted. This event could have been exacerbated by the moisture from melting snow and rain. The pile was spread out into the area shown in the foreground of Figure 7. The TW pile was spread out to isolate burning areas and cool the fuel. Because of this, the surface area of the pile was increased exposing more fuel to the degrading effects of the elements. The TW fuel was again piled up for ease of reclamation to the plant.

Fig. 7 First snows of December 2016 before a long hard winter, fuel was not burned until February.

During the prolonged storage the moisture increased from 8% to 15%. The additional surface moisture, and pellet size reduction due to handling, changed the handling characteristics of the fuel, but the station was still able to handle the material safely. The MAF heating value of the fuel was reduced about 930 MJ/Kg (400 Btu/lb) or almost 5%. This is attributed to oxidation of the fuel. Oxygen in TW is hard to measure using the ultimate analyses due to it being calculated ñby differenceò. Oxygen can react with the fuel but does not make a gaseous product. This dilution of the carbon is more apparent in the loss of MAF heating value than the actual oxygen estimate from the ultimate analyses.

The levels of moisture gain during storage are shown in Figure 8. This test is indicative of the durability of the TW pellets as the plant was able to handle and burn this fuel in the degraded form. Figure 9 shows the degradation of both MAF and As Received heating value.

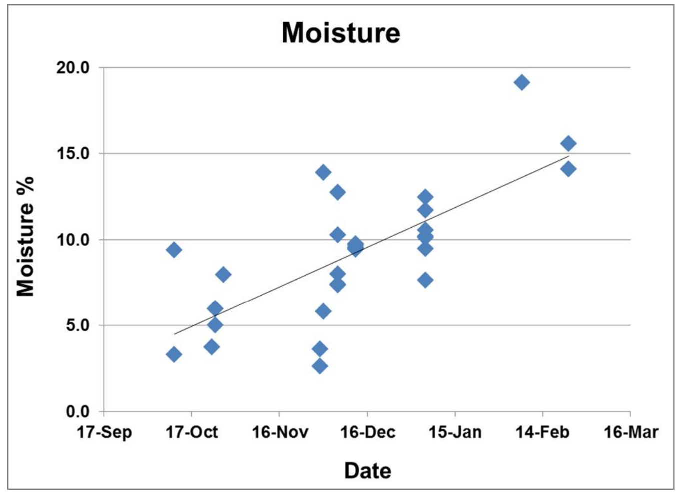

Fig. 8 Shows increase of moisture content of TW fuel during storage.

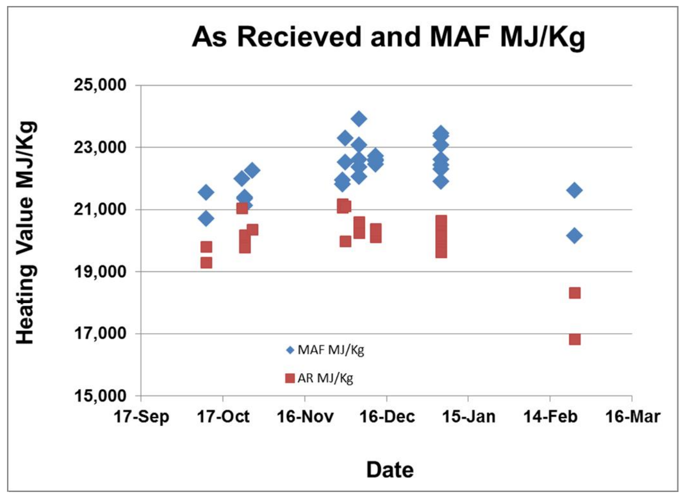

Fig. 9 The loss of both MAF and AR heating value of TW fuel in storage

SPONTANEOUS COMBUSTION

The spontaneous combustion (SPONCOMB) of reactive solid fuels has long been an issue. The author has found two parameters that best illustrate this reactivity, the volatile matter content and the oxygen (by difference) content. It is useful to convert percent values to per heating value by dividing the percent by the HHV. This puts the fuels on a more even footing and indicates how the boiler handles them. Boilers are after all heat machines. A common US term is pounds per million Btus. This report uses Kg/MJ. No matter if expressed in Lbs/MBtu or SI, the relationship is the same, low heating value fuels need more tons to make the same steam.

There is a large difference in the SPONCOMB behavior between the Bituminous C coals of the Illinois Basin

(ILB) coals and the Sub-Bituminous coals of the Powder River Basin (PRB) coals of Wyoming. The bituminous ILB coals can have minor issues if left in an inactive loose or unconsolidated cone pile. Well-groomed compacted piles of ILB coal rarely have SPONCOMB issues. The sub-bituminous PRB coal has much more reactive SPONCOMB behavior. This coal can self-ignite at the mine, on the train, in storage, in dormant silos, in the pulverizer. The upside is PRB coal burns well in the furnace. Special care is taken to groom and compact long term storage piles of PRB coal and still there are fires. Controlling dust and avoiding accumulations of dust are paramount to safe use of PRB coal.

This behavior is explained using the volatile and oxygen levels of these coals. The PRB coal has 30+ percent more volatiles and over two times the oxygen levels of the ILB coal.

	ILB	PRB	TW
Kg Volatile/MMJ	13	17	35
Kg Oxygen/MMJ	2.2	6.1	18

Shown above are the volatile and oxygen levels for the TW fuel. The volatile matter content expressed as Kg Volatile/MMJ is twice that of the problematic sub-bituminous PRB coal. The oxygen values are almost three times that of the PRB coal. These points towards concerns with SPONCOMB and the plant experience confirmed this concern. The plant exclusively burns PRB coal so the staff is well versed on SPONCOM control procedures. This suggests that all plants adopt handling procedures associated with sub-bituminous or PRB type coals if one is confronted with switching to TW fuel. It is not an issue of ñifò it will light off, it is where and when. This was not only shown in the outside storage in inclement weather, but also in the pulverizers. The plant experienced pulverizer fires due to TW being exposed to hot primary air (PA).

PULVERIZERS

The pulverizers were identified as limiting factors due to the low HGI 25-35 of the TW fuel. Several single mill tests were conducted using over 400 tons of fuel to understand how the mills would handle the biofuel. The two main concerns were mill capacity and the potential for fires due to high reactivity fuel. The pulverizers used at the Boardman plant are large vertical spinel mills with three roller or grinding surfaces. They are rated at 67.5 US tons or 61,235 Kg/hr (135 KLbs/hr) of coal flow using coals in the 55+ HGI range. The plant has eight pulverizers and typically needs six for full load operation. The pulverizers are equipped with a modification including an outlet cylinder and a diffuser at the top of the mill. These help with fine grinding and good distribution of the coal to the pipes leading to the burners. This equipment created a large differential pressure (dP) across the mill when the TW fuel was introduced over the entire pulverizer operating range. This resulted in heavy amounts of fuel dropping out of the mill through the pyrite rejection system along with problems with the pulverizer plugging.

The pulverizer was ñ*opened up"* so to say, with the removal of the outlet cylinder and diffuser along with opening the static classifiers to a full open condition. Additionally the reject chutes were removed. This allowed the pulverizer to operate without dP issues up to higher fuel flows. Pulverizers were brought up to 45,500 Kg/hr (100 KLbs/hr) during single mill tests with very high primary air (PA) flow.

Given the low HGI more power was required to grind the TW. Using PRB coal roughly the same amount of power was produced with only 3 mills in operation.

Data below compares mill power.

Fuel	Mills in Serv	AVG Amp	Total Amps	PA Amp
TW	4	48	190	389
Coal	3	40	120	343

It takes more power to grind less fuel for the TW test. It should be noted that fuel flows were also higher for the TW fuel at a similar load, indicating a lower heating value than the PRB coal. The fuel flow for the TW was 153,000 Kg/hr (337 KLbs/hr) verse PRB coal at 145,000 Kg/hr (320 KLbs/hr)

CLASSIFIERS

The mills are equipped with static classifier blades that can be closed off to provide for a finer grind of coal. To maximize mill capacity it was decided to run the mills with the classifiers in the most open position. This did produce a larger TW fuel particle to the furnace, but the high reactivity of the fuel offset this as mill capacity was a limiting factor. Even with the classifiers wide open there was still substantially more mill power usage when grinding the TW fuel. Test results indicated about 25% more mill power needed to grind the TW to a larger size at similar mill tonnage loading. This was true at several mill loading points.

The sizing of the pulverized fuel is dependent on several factors. The mill A/F, fuel HGI, and classifier settings can all influence fuel sizing. The particle sizing of a coal mill is generally set to have less than 1% remaining on a #50 mesh (300um) screen and over 70% passing a #200 mesh (75um) screen. Boardman was near these recommendations on PRB coal. The sizing increased on coal using the TW wide open classifiers settings to 10% retained on the #50 mesh and only

45% passing the #200 mesh screen. The high PA flow and low HGI of the TW fuel future increased the particle sizing to 35% retained on #50 mesh and 30% passing the #200 mesh screen. This represents a fifty fold increase in the large 300 micron sized fuel particles and substantially less fine (<75 microns) fuel particles.

PRIMARY AIR (PA) SYSTEMS

The issue of heavy fuel rejection through the bottom of the pulverizer was a result of low velocity caused by using cool PA to limit the potential of mill fires. The cooler PA inlet temperatures of 38^0 to 88^0 C (100^0- 190^0 F.) verses the typical coal PA inlet temperature of 345^0 C (650^0 F.) for coal made for low velocities through the vane wheel. This allowed the fuel to flow out into the pulverizerȢs pyrite rejection system. Once the PA flow was raised to provide at a minimum velocity of 2135 m/min (7000 ft/min) through the vane wheel area the rejects were minimized. This high PA flow made for high air to fuel ratios (A/F) within the mill compared to coal. The PA flow was set to a minimum of 114,000 Kg/hr (250 KLbs/hr) air flow for the test.

The initial PA flow used was set for coal. PA Flow is measured by weight in (KLbs/hr), not velocity. The velocity of air is heavily influenced by the volume, and hence the temperature. Due to the TW fuel reactivity no hot air was added so the PA inlet temperature was in the 38^0 to 88^0 C (100-190^0 F.) range. This temperature is normally 345^0 C (650^0 F.) when using PRB coal. This PA temperature difference represents about 80% more volume and hence 80% higher velocities when using coal. The initial heavy flow of TW pellets through the mill reject system was resolved by increasing the minimum PA flow to 114,000 Kg/hr (250 KLbs/hr). This represents about a 25% increase in PA flow. This pushed the A/F in the mill to about 2.5; when burning PRB coal, mills typically run at less than 2.0 A/F. The mill fuel flows for four mills were each operated at approximately 39,000 Kg/hr (85 KLbs/hr) for the 100% test. This resulted in a load of about 260 GMW, a suitable low load commercial rating.

The high expected reactivity of the TW fuel and the high safety standards required for the test suggest that when utilizing TW, use as little hot or preheated air as possible for the PA. The pulverizer was operated with no hot or preheated air. The PA inlet temperatures were in the 38^0 to 88^0 C (100 to 190^0 F.) range with the resulting mill outlet temperatures ranging from 27^0 to 35^0 C (80 to 95^0 F.) This low outlet temperature presents a concern with pipe pluggage, but the high velocities from the high PA flow helped prevent this from occurring. While performing initial tests, the plant did experience a plugged coal pipe. Calculations indicate about 5% of the moisture in the fuel was evaporated from the fuel off during pulverization under the above stated conditions.

MILL REJECTION SYSTEMS

Vertical spindle pulverizers have a vane wheel assembly between the PA inlet and the grinding area. The openings on this vane wheel are set to provide a high enough velocity to lift the coal spillage back into the grinding zone. It is low enough velocity to let large dense material like rock and pyrites, (FeS_2, iron sulfide) fall out of the mill and be removed by the pyrite rejection system. This system is generally limited in capacity and subject to pluggage.

The use of cool PA inlet temperatures allowed a large portion of TW pellets to spill out of the grinding zone, through the vane wheel against a low velocity PA, and into the under bowl area. This is then swept into the rejection system. The amount of pellets was excessive and presented both pluggage and fire concerns. Raising the air flow solved this issue.

BURNERS

The low NO_x burners at Boardman rely on low A/F in the mill to reduce the mass flow and primary air velocity. High PA flow tends to make a more oxidizing flame than the designers planned for, hence higher NO_x. The higher velocity adds more turbulence which can also raise NO_x. The high PA flow necessary to minimize mill rejects used about 25% more PA than that required when burning PRB coal. The high velocity pushes the flame front out away from the burner. This can and did interfere with the boiler flame detection or flame scanner system.

The NO_x emissions with TW fuel was at or higher than with coal under similar conditions. The higher PA flow is thought to be a contributor to this.

The flame front being pushed out away from the burner was an issue and the flame scanners had to be tuned for each TW fuel burner. This main flame signal is important as it provides indication related to pulverizer stability. Stable flames allow the plant to remove from service oil igniters. This was accomplished for the majority of the burners. Any oil used during the test was due to control interlock system that limits removal of igniters if there is a weak main flame signal.

COMBUSTION

The combustion of solid fuel particles is primarily impacted by the size and reactivity of the fuel. Low volatile (low reactivity) fuels must be ground finer to ensure burnout in the furnace. High reactivity fuels like the TW can get good combustion even with larger particle sizing. Several papers were reviewed that discussed combustion of TW fuel. [8-11] There were few full scale reports and none found using TW fuel at 100% in a PC unit.

The loss on ignition (LOI) of the ash can approximate the unburnt carbon in the ash. Two samples were taken with LOI's of 7.5% and 11.5 for an average LOI of 9.5%. This represents high combustion efficiency due to the low ash levels of the TW fuel.

The combustion efficiency of the TW fuel during the test burn was 99.92%. This is comparable to the PRB coal where the combustion efficiency was 99.95%.

Two boiler parameters helped achieve this high combustion efficiency. Low load operation results in longer residence time in the furnace, and the higher oxygen values needed at low load also helped burn the fuel. At half load furnace residence time is doubled to that of full load. Keep in mind that the particle size of the TW fuel delivered to the furnace was about twice the size of pulverized coal.

There are two fuel parameters that directly impact the combustion process, the volatiles and the HGI. These tend to balance themselves with the TW fuel as a higher degree of torrefaction lowers the volatile, but increases the HGI.

BOILER EFFICINCY

The boiler efficiency using a heat loss method for the TW biofuel was lower than coal. This is primary due to higher exit gas temperatures observed and excess O_2 used on the biofuel.
The air heater leakage was not considered for this calculation, but should be similar for both cases.

Fuel	Air In	Gas Out	Ex O_2	LOI	B-Eff
TW	43^0 C	152^0 C	5.68%	9.55%	87.1%
Coal	48^0 C	118^0 C	5.11%	2.0%	88.0%

Fuel quality impacted the boiler efficiency in the TW fuels favor due to lower moisture levels. The efficiency improves about 1.0% if the same boiler conditions are used. It is the high exit gas temperature and the lower excess oxygen and LOI that make the coal more efficient.

This lower gas outlet temperature of the coal 118^0 C (244^0 F.) versus the TW fuel 152^0 C (306^0 F) was verified using stack temperature measurements. The cause of this may have to do with deposits in the boiler that limited heat transfer. The short duration of the test did not allow evaluation of ash deposit behavior of biofuel utilization.

NO_x FORMATION

The NO_x levels at the stack were 12% higher versus coal under similar conditions. The nitrogen levels of the TW are substantially lower indicating most of the NO_x is thermal NO_x rather than fuel based NO_x.

Fuel	Fuel Nitrogen Kg/MJ	NO_x Kg/MJ (CEM)
Torrefied Wood	0.03	0.08
Coal	0.40	0.07

The excess oxygen (O2) levels are slightly higher for the TW test, 5.68% versus 5.11% for the coal. Higher O_2 levels tend to increase NO_x. The higher PA flow and more oxidizing conditions may have also impacted NO_x.

The high reactivity of the TW fuel could also influence NO_x by producing fast intense flame. The high NO_x values and low unburnt fuel levels indicate good combustion. This may allow for better tuning for NO_x. No flame tuning was performed during the test.

SO_2 LEVELS

The SO_2 levels reported in Kg SO_2/MJ are substantially lower on the TW fuel. The table below shows the estimated levels based on fuel analyses and the measured values from the stack continuous emission monitor (CEM). The plant uses a sodium bicarbonate product commonly called Trona to remove SO_2 from the flue gas to control sulfur emissions.

Fuel	Fuel SO_2 Kg/MJ	SO_2 Kg/MJ (CEM)
TW	0.05	0.0011
Coal	0.23	0.16

This data indicates that the TW sulfur emissions are less than 1% of the coal emissions. This also indicates the potential effectiveness of the Trona sulfur control additive. The TW fuel analyses, Table 1, indicated that the ash is made of over 30% elements like calcium, magnesium, potassium, and sodium, all which can react with and remove SO_2.

ESP OPERATION

Opacity issues were not observed during the test. The opacity remained low and the electrostatic precipitator (ESP) power levels remained high. Table IX below shows comparison data. CCI estimated bulk fly ash resistivity values also show comparable levels.

Fuel	% Opacity	ESP Powers- KW
TW	1.35	1142
Coal	1.89	1184

The impact of any Trona addition prior to the ESP was not evaluated.

CONCLUSION

In conclusion the Boardman plant showed that a 100% TW fuel could be suitable for a low to mid load range. The pulverizers should use cool PA flow and this will produce a larger particle sized fuel to the boiler. The TW fuel has a high likelihood for spontaneous combustion even when compared to the more reactive PRB coal. The larger fuel sizing to the flame was offset by the high reactivity of the TW fuel to provide good combustion. The pollutants: particulate, NO_x and SO_2 were all controlled within limits. Further testing is required to determine if NO_x can be lowered by burner tuning. The test while challenging showed that TW is a suitable fuel for a pulverized coal unit.

ACKNOWLEDGMENTS

The test was not possible without the efforts and coordination of many people. There were many from the utility company in addition to a team of people to organize and provide test data and expertise. The biofuel supply and production also had many significant people involved in obtaining the test fuel. The author played a small part in this investigation involving fuel quality and combustion aspects. An attempt to identify and show appreciation to others involved is listed here.

<u>Portland General Electric, PGE</u>

The following individuals from PGE are acknowledged for their efforts and expertise:

Dave Rodgers, Boardman Plant Manager
Randy Curtis, Plant Engineer
Dean Mason, Plant Engineer
Hao Liu, Engineer
Robert Hancock, Plant Operator
Dr. Wayne Lie, PGE Corporate

<u>Test Team Consulting and Engineering Services</u>

Storm Technologies, Inc. Albemarle, NC ï Danny Storm ï Provided mill performance testing, fuel and ash samples, and mill and combustion expertise

Black & Veatch, Overland Park, KS ï Una Nowling ï Provided fuel quality expertise and a detailed test burn procedure

Western Research Institute, Laramie, WY ï Jerrod D. Isaak, Nico Wibisono ï Provided pilot scale combustion tests of TW fuel and coal

<u>Fuel Supply and Coordination:</u>

Oregon Torrefaction, LLC ï Matt Krumenauer, CEO

US Endowment for Forestry and Communities ï Carlton Owen, Executive Director

New Biomass Energy of Quitman MS, USA ï Carl Rheuban, President, supplied 75% of test fuel

Idaho National Laboratory INL for providing small torrefier Jim Brewer INL torrefier operator, supplied 11.7% of the test fuel

ReKlaim torrefier supplied 9.6% of the test fuel

Airex Quebec Canada, supplied 4.4% of the test fuel

FUNDING

Portland General Electric
US Endowment for Forestry and Communities
Oregon Torrefaction, LLC

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