INL/EXT-13-28203

Bench-Scale Dense Phase Biomass Feed Insertion Tests

Corrie Nichol
Rick Wood
Richard Boardman

October 2012

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-13-28203

Bench-Scale Dense Phase Biomass Feed Insertion Tests

Corrie Nichol, Rick Wood, Richard Boardman

October 2012

Idaho National Laboratory
Biofuels and Renewable Energy Technologies Division
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy
Efficiency and Renewable Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

SUMMARY

The objective of this work is to provide the technical data needed to understand whether representative agriculture, woody, and energy crops could be inserted with the established conveyance, grinding, and transport lines in an existing power plant. This report considers the material properties and processing steps necessary to render biomass compatible with conventional coal fired boilers in a cofiring scenario.

CONTENTS

FIGURES

TABLES

ACRONYMS

DOE	Department of Energy
INL	Idaho National Laboratory
RTTS	Reconfigurable Thermal Treatment System
PC	Pulverized Coal
THC	Total Hydrocarbons
HHV	Higher Heating Value

Bench-Scale Dense Phase Biomass Feed Insertion Tests

1. Introduction

Biopower is defined as the production of power directly from the combustion of biomass. This method of producing power from a renewable source provides a viable technology in the near term for displacing coal and other fossil fuels for power production, as well as enabling the development of an infrastructure for the production and delivery of a commodity feedstock material of sufficient consistency and quality that it can be adopted largely for other end uses, including the production of liquid fuels, etc.

The objective of this work is to provide the technical data needed to understand whether representative agricultural residue, woody biomass, and purpose grown energy crops could be inserted into the established conveyance, grinding, and transport lines in an existing power plant. This report considers the material properties and processing steps necessary to render biomass compatible with conventional coal fired boilers in a cofiring scenario. This has many implications in regards to the specifications the biomass material must meet. Specific areas considered for this report are summarized below:

1. Energy content
2. Ash composition
3. Material grindability
4. Air entrained material flowability

1.1 Energy Content

The energy content of biomass is typically significantly lower than coal, and depending on the biomass type, can also vary significantly. For cofiring with coal, this can limit the amount of material that can be cofired without reducing the performance and efficiency of the boiler. These properties can also pose a challenge to the boiler feed systems, which are designed for the energy density of coal, and must feed a larger solid fraction to achieve burner stoichiometry.

1.2 Ash Composition

Problematic properties of biomass can include a higher overall ash content. Biomass may also produce ash that is more corrosive and more prone to agglomeration and adhesion on boiler tubes (reducing the efficiency and performance of the boiler).

1.3 Grindability

Coal tends to be brittle, and fracture readily. In pulverized coal power plants, it is typically ground in ball mills, or other pulverizers wherein the grinding modality is optimized for brittle materials such as coal. Biomass typically doesn't grind well under these conditions, and must therefore be treated if it is to be co-fed with coal into the power plant grinding and feed systems.

Raw biomass also exhibits substantially different grinding behavior than does coal. Raw biomass typically requires a vastly different grinding modality to reduce it to an optimal particle size. This can include cutting and chopping, as well as hammer milling to achieve appropriate particle size distributions for combustion.

1.4 Air Entrainment and Flowability

In coal fired boilers, pulverized coal is entrained in air flowing through the grinder, and ultimately into the boiler where it is burned. If biomass is to be cofired with coal, it must perform similarly in the feed systems of coal boilers. This includes demonstrating that the material will entrain in air, and will not settle out in delivery tubes.

Three possibilities exist for the combustion of biomass in a PC boiler. First, the biomass can be handled completely separately from the coal, including size reduction, feed tube transported to dedicated burners, and combusted in specific zones within the boiler. Second, the biomass can be size reduced, and inserted with the coal into the coal feed tubes, where it is co-combusted with the coal in the boiler. The third option, which is the most attractive to a boiler owner, is to render the biomass in a format that can be fed with coal directly into the grinding apparatus, and is then completely compatible with coal in the boiler. It is expected that the analysis of these options will demonstrate that it is possible to economically produce material that is compatible with coal, and can be fed as described in option three above.

This report summarizes testing conducted at INL to determine the effectiveness of new technologies such as leaching, torrefaction, and densification to render biomass more compatible with coal boilers, and to do so at the least cost possible.

2. Work Summary

For this report, the following biomass types were tested: 1) Pine, 2) Switchgrass, 3) Corn stover, 4) Arundo Donax, and 5) Leached Arundo Donax. These materials were ground and dried prior to further processing.

Each type of material was torrefied to two levels, 230°C and 270°C, both with a 30 min. residence time. During torrefaction, data were collected, including analyzing the gas composition released during torrefaction, and overall mass yield of the torrefaction process.

Switchgrass was used as a test case to determine the optimal levels of binder additives (two binders were tested) to produce a suitable pellet. Samples of each material at each torrefaction temperature were pelleted. Pelletization energy was recorded for each material. Pellets were then dried and sifted to remove fines, and tested in a pellet durability tester. Pellet bulk density was also measured.

Pellets were then subjected to an "impact ball mill" grinding test. These tests include 100% coal, 80% coal/20% biomass, and 100% biomass. The resulting particle size distribution was recorded as a measure of the ability to grind and entrain the material in the flow and delivery apparatus of a coal boiler.

Material thermochemical properties were also analyzed to determine the heating value and ash composition of each sample.

3. Results

Results obtained from the testing are summarized below. The test sections are each presented with a brief description of the testing or operation, and the results obtained during the processing.

3.1 Torrefaction

Material was torrefied in the INL Reconfigurable Thermal Treatment System (RTTS) (Figure 1). This system enables the controlled torrefaction of biomass as it moves through a reactor column. Temperature and residence time is controlled to obtain the desired level of thermal treatment.

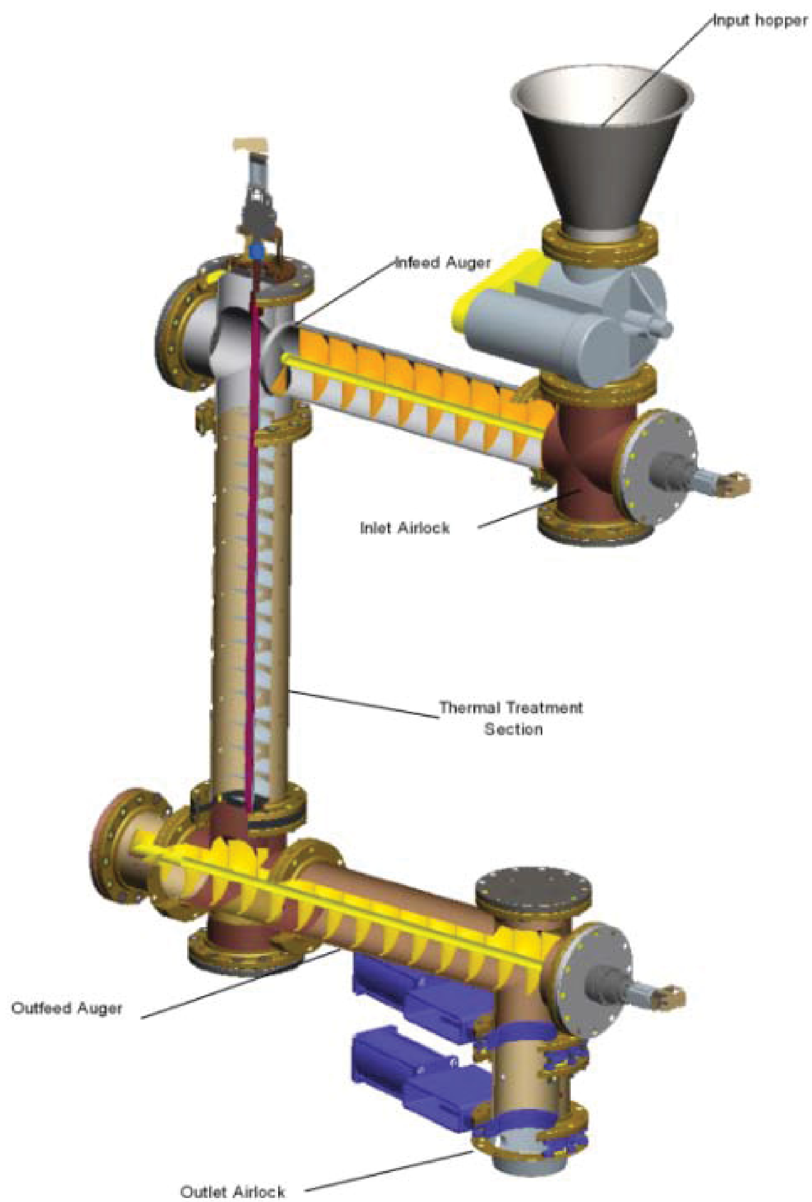

Figure 1: INL Reconfigurable Thermal Treatment System (RTTS).

During torrefaction, data were collected to enable characterization of the process parameters. The data collected included the temperature within the reactor vessel, analyzing the gas composition released during torrefaction, and overall mass yield of the torrefaction process. These data are presented in Table 1.

Table 1: Gas analyzer data collected during torrefaction.

Material	Target Temp.	Temp. (°C)		O_2%		CO%		CO_2%		H_2%		THC ppm		CO%		CH_4%	
		Avg	St. Dev.	Avg	St. Dev.	Avg	St. Dev.	Avg	St. Dev.	Avg	St. Dev.	Avg	St. Dev.	Avg	St. Dev.	Avg	St. Dev.
Switchgrass*	180	176.2	1.725	0.46	0.067	0.27	0.018	1.23	0.048	**	**	1831	212.7	0.071	0.0136	0.009	0.0020
Switchgrass*	230	212.5	2.203	0.74	0.047	2.14	0.267	5.93	0.330	**	**	**	**	2.031	0.7664	0.117	0.0248
Switchgrass	270	285.0	20.665	0.39	0.213	0.86	0.096	1.55	0.123	0.16	0.036	2959	955.1	0.645	0.2279	0.028	0.0086
Southern Pine	180	178.0	0.000	2.46	0.140	0.03	0.004	1.89	0.033	**	**	1272	60.3	**	**	0.039	0.0045
Southern Pine	230	216.7	0.683	5.16	0.140	0.16	0.001	3.07	0.149	**	**	802	129.3	0.005	0.0058	0.021	0.0007
Southern Pine	270	261.7	3.204	1.79	0.462	2.64	0.640	14.46	0.433	0.86	0.336	5986	1584.3	2.066	0.6197	0.128	0.0563
Arundo Donax	180	195.5	5.665	4.73	8.232	2.15	1.583	5.36	3.541	**	**	5259	3091.8	1.736	1.1832	0.037	0.0159
Arundo Donax	270	291.2	8.902	1.06	0.021	1.06	0.072	2.08	0.175	**	**	5037	745.7	0.853	0.1238	0.045	0.0103
Leached A.D.†	230	239.9	0.458	0.18	0.029	4.59	0.028	10.31	0.087	**	**	9679	297.9	3.924	0.0220	0.060	0.0047
Leached A.D.†	270	283.6	1.284	0.01	0.014	11.38	1.178	19.27	1.157	**	**	9918	219.4	9.908	0.2673	0.435	0.1117
Corn Stover	180	--	--	11.84	1.268	0.20	0.002	0.45	0.043	**	**	326	26.0	0.115	0.0054	0.006	0.0008

* These data rely on a small data set due to the limited data available at steady state.

** Below detectible limits.

† This material torrefied in a different reactor due to the smaller amounts available.

Table 1 reports values from three separate gas analyzers. Analyzer one returns values for O_2, CO, CO_2, and H_2. Analyzer two reports total hydrocarbons (THC), and analyzer three reports CO and CH_4. Because of this, two values for CO% are reported in the table, and the values vary slightly. This reflects the different sensitivity ranges of the analyzers used, where the CO/CH_4 analyzer is less sensitive at the lower ranges, and is therefore less accurate.

Table 2: Mass balance for the torrefaction process.

Material	Target Temp.	Mass Balance (kg)				Solid Yield (%)
		Mass In	Mass Out	Total Waste	Mass Loss	
Switchgrass	180	653.52	555.35	36	62.17	85%
Switchgrass	230	266.84	213.08	22.06	31.7	80%
Switchgrass*	270	65.08	63.08*	0*	2*	*
Southern Pine	180	1023.35	1004.55	12.9	5.9	98%
Southern Pine	230	742.31	718.13	19.7	4.48	97%
Southern Pine	270	466.07	343.98	34.24	87.85	74%
Arundo Donax	180	575.13	503.955	6.04	65.135	88%
Arundo Donax	270	138.83	117.62	5.89	15.32	85%
Leached A.D.	230	3.7	2.635	0.3	0.765	71%
Leached A.D.	270	3.17	2.04	0.55	0.58	64%
* Steel ball processing aids inadvertently included in mass output measurement.						

During torrefaction, the mass yield of the process at each temperature was captured (Table 2). The mass of material inserted into the torrefier was measured, as was the mass exiting (the mass of torrefied material). The waste value accounts for several waste streams captured as a result of torrefaction. Waste was collected from the process in the form of condensed liquids, some tars, and some solid particulate captured in the filters and left in the chamber of the torrefier. This was all summed, and recorded. The total mass loss represents mass that was unaccounted for. This mass exited the torrefier in the form of light volatiles and gases that were vented from the process. The solid yield was calculated by dividing the mass out by the mass in.

For the processing of herbaceous biomass, it was found that the inclusion of steel balls assisted in flow and mixing in the torrefaction reactor. For one of the runs, (switchgrass at 270) some of these steel balls were not separated out of the output stream, and the mass reflects the presence of some of these processing aids, resulting in inaccurate mass output measurements.

3.2 Binder Additive

Torrefied material is difficult to form into pellets. The torrefaction process drives off light volatile compounds in the biomass, and increases the glass transition temperature of the remaining lignin in the material, which plays a key role in the formation of durable pellets. Materials at each of the torrefaction levels were tested with and without binder additives to determine the ability to produce a densified feedstock pellet to improve the transportation logistics of torrefied biomass.

For this test, two binders were utilized. The binders are soy oil based, and one contains a lignin additive to improve binder effectiveness. To enable another point of comparison, some of the samples were tested with raw material as a binder. For these tests, torrefied material was mixed with a small quantity of raw material (of the same type), and pellets were made. These tests were restricted to less than 10% by mass of raw material so as to not counteract the benefits attained during torrefaction. For the materials tested, a mass fraction of roughly 8% was used, as it appeared to provide the most benefit to pellet production, and didn't improve significantly at higher mass fractions.

Torrefied feedstock material was first tested without binders to determine the required pellet energy and relative pellet durability. Binders were then added to some of the torrefied material at a level expected to be a mid-range weight percentage of binder material, and the material was pelleted. The pellets were observed during operations, and the amount of binder was adjusted accordingly. The optimal binder amount was then used for subsequent testing. Those results are presented below.

3.3 Pelleting and Tests

For this testing, a single pellet mill and die was used for all materials tested. The result is that the pellet formation was not optimized for any material or material condition. As a result, the pellet durability and formation energy recorded do not exhibit clear trends as would be expected. Future work will focus on the optimal pellet die parameters necessary for the formation of good pellets.

3.3.1 Pellet Mill/Die Description

The pellet mill used for these tests is a Colorado Mill Equipment (CME) model ECO-10. For this work, the die used was an 8 mm pellet diameter, and an effective length of 22 mm, resulting in an L/D ratio of 2.75. Manufacturers recommend a die with a specific L/D ratio for the material being processed, for example, one manufacturer recommends an L/D ratio for ground Corn of 12, and for alfalfa of 8, and for rye grass of 9. Higher L/D ratios are typically reported to form more durable pellets. The die used for this work is not optimized for any of the materials selected, and so the results of the pellet density and durability are not optimal. It is expected that further testing with optimal die configurations will yield better pellet properties and better understanding of the densification energy required.

3.3.2 Pelleting Results

Using the CME Pellet Mill, the ability to form good pellets, and the energy required for pellet formation were recorded. Some of the materials tested presented significant challenges to form good pellets. It is worth noting that the pellet forming die was not optimized for any particular material, and the production of pellets with material specific dies may enable the formation of more consistent pellets. The results presented here form the basis of a relative comparison between the pellet quality and durability of the materials tested.

After completion of pelleting work, the pellets were dried and sifted to remove fines. The resulting pellets were tested in a pellet durability tester. This equipment tumbles the pellets for a given time, and the mass of pellets is compared to the mass of fines generated. This ratio is recorded as the pellet durability.

Pellet bulk density was determined by placing a known mass of pellets into a known geometry circular container. The pellets are leveled, and the height of the pellets in the container is measured, and a bulk density is then calculated.

Table 3: Densification testing results.

Material	Torr. (°C)	Binder Type	(Wt%)	Pellet Yield (%)	Bulk Dens. (g/cm^3)	Pellet Durability Avg.	St. Dev.	Dens. En. (KWhr)	Energy Consumed per Pellets Produced
Southern Pine	0		0%	23.9%	0.1346	0.8470	0.0231	0.1310	0.3613
Southern Pine	230		0%	21.1%	0.3307	0.8716	0.0102	1.2300	5.5395
Southern Pine	270	GG1	1%	16.9%	0.3984	0.4872	0.0215	0.6700	0.6678
Southern Pine	270	GG2	4%	38.3%	0.4128	0.5518	0.0120	1.1500	1.1226
Southern Pine	270	Raw	8%	26.3%	0.3808	0.7911	0.0065	0.9600	1.5805
Southern Pine	270		0%	46.5%	0.4156	0.7896	0.0137	1.4800	1.2867
Corn Stover	0		0%	76.5%	0.4233	0.8688	0.0143	0.7100	0.4332
Corn Stover	230		0%	6.9%	0.2090	0.3339	0.0113	0.8250	5.2953
Corn Stover	230	GG1	1%	40.8%	0.3987	0.6044	0.0138	1.0700	1.0536
Corn Stover	270		0%	34.3%	0.4806	0.7441	0.0665	1.1100	1.6082
Corn Stover	270	GG1	2%	36.9%	0.4291	0.3415	0.0108	0.6800	0.9001
Corn Stover	270	GG2	2%	41.5%	0.4318	0.3297	0.0167	0.6200	0.7279
Switchgrass	0		0%	76.9%	0.3977	0.9165	0.0063	0.7500	0.3903
Switchgrass	230		0%	40.3%	0.5669	0.8435	0.0151	1.7800	1.9685
Switchgrass	230	GG1	1%	73.5%	0.5707	0.9096	0.0078	1.2300	0.7345
Switchgrass	270		0%	16.7%	0.3041	0.5333	0.0179	0.7600	2.0440
Switchgrass	270	GG1	1%	16.9%	0.2962	0.3437	0.0136	0.6700	1.6363
Switchgrass	270	GG1	2%	20.0%	0.3147	0.3449	0.0216	0.7000	1.4402
Switchgrass	270	GG1	4%	32.0%	0.3203	0.3119	0.0211	0.6800	0.8299
Switchgrass	270	GG2	2%	22.6%	0.3133	0.3963	0.0164	0.6900	1.2945
Arundo Donax	0		0%	39.1%	0.3556	0.6926	0.0208	0.5200	0.5101
Arundo Donax	230		0%	15.9%	0.2761	0.3996	0.0196	0.6100	1.5076
Arundo Donax	230	GG1	1%	44.6%	0.4489	0.4009	0.0052	0.5000	0.4612
Arundo Donax	230	GG2	1%	30.3%	0.3630	0.2066	0.0110	0.4000	0.5306
Arundo Donax	230	Raw	8%	41.8%	0.2837	0.5436	0.0207	0.7300	0.6984
Arundo Donax	270		0%	33.2%	0.3912	0.3031	0.0171	0.3800	0.4602
Arundo Donax	270	GG1	2%	28.4%	0.3942	0.1133	0.0137	0.3700	0.5873
Arundo Donax	270	GG2	2%	41.5%	0.3917	0.2023	0.0250	0.4900	0.4514
Arundo Donax	270	Raw	8%	48.2%	0.3614	0.4140	0.0203	0.5300	0.4774
Leached A. D.	0		0%	75.6%	0.4027	0.8858	0.0273	0.4600	0.3280
Leached A. D.	230		0%	40.8%	0.3903	0.5866	0.0131	0.7400	0.7744
Leached A. D.	270		0%	46.5%	0.5025	0.5581	0.0111	0.3700	0.5771
Leached A. D.	270	GG2	2%	37.2%	0.5035	0.4808	0.0154	0.5500	1.0267

The summary table (Table 3) contains a large amount of data, and trends in the data are not immediately apparent. For example, the densification energy does not seem to follow any specific trend as the torrefaction temperature is increased.

After testing as described above, correlation coefficients were calculated to statistically quantify the effect of various binders and other parameters on pellet production. Correlation coefficients near zero indicate no correlation, and correlations near an absolute value of 1 indicate exact correlation between input parameter and output result. The correlation coefficients are summarized in Table 4.

Table 4: Correlation coefficients for various input/output parameters.

Input Parameter	Output Parameter	Correlation Coefficient
Torrefaction Temperature	Densification Energy/Pellets Produced	0.2308
Overall Binder Performance	Pellet Durability	-0.1948
	Pelleting Process Yield	-0.0380
	Densification Energy/Pellets Produced	-0.1578
Binder 1	Pellet Durability	-0.5661
Binder 2		-0.4604
Raw Biomass		-0.1960
Binder 1	Pellet Bulk Density	-0.0303
Binder 2		0.1438
Raw Biomass		-0.1225
Binder 1	Pelleting Process Yield	-0.1140
Binder 2		-0.0274
Raw Biomass		0.0182
Binder 1	Densification Energy/Pellets Produced	-0.2159
Binder 2		-0.1986
Raw Biomass		-0.1776

This summary table demonstrates that the correlations that exist are often small, and some are of no statistical significance, for example, the addition of binders had no real effect on the pelleting process yield. The value of many of the other correlation coefficients is small, demonstrating only small correlation between the parameters analyzed, and indicating that other factors had an effect on the output parameter variation.

Some interesting trends can be identified based on these data. As biomass torrefaction temperature is increased, the energy to densify the biomass slightly increases (as would be expected based on previous work where densification of torrefied biomass is more difficult). In conjunction with this, as the level of binder increases, the densification energy slightly decreases (a benefit of the binders is reduced densification energy).

Surprisingly, the statistical analysis demonstrates that overall, the addition of those binders tested reduced the overall pellet durability. This is where the strongest interactions are noted when individual binders are selected for analysis.

3.4 Impact Ball Milling

Because the grinding modality in a typical coal fired boiler relies on impact, such as for a ball mill, the pellets produced in the testing outlined above were subjected to a similar laboratory scale test.

A bituminous coal sample was first ground in the impact ball mill to a mean particle size of approximately 90 micron. The parameters required to mill the coal to this level were then used to grind samples of biomass pellets, and biomass/coal mixtures.

Particle size testing was performed on each sample using a Camsizer™ digital image processing system. For each material tested, the theoretical sieve size was calculated for which a volume percentage of the total sample passes through the sieve. Three volume percentages of material were specified for reporting: 50%, 16%, and 84%. In addition to particle size quantification, the Camsizer™ was also programmed to report the sphericity and aspect ratio of the particles in each test. A lower value for the aspect ratio indicates more elongated particles. A factor for 1/sphericity increasing from unity designates a particle with a corrugated/irregular surface. The resulting particle size distribution was measured for each sample ground, and the results are presented in Table 5 and Table 6.

Samples of each biomass material were also characterized, and the particle size is recorded in the tables as well. This characterization was conducted to provide some insight as to the effect on particle size that the pelleting and subsequent re-grinding of the biomass has. It was expected that the final particle size distribution of the raw biomass samples after pelleting and re-grinding would be similar to the particle size distribution of the biomass prior to pelleting. This test has demonstrated that the particle size distribution for raw pelleted and re-ground biomass seems to range from roughly 2/3 to 1/2 the size for the raw unprocessed biomass. The torrefied biomass, in comparison, has a substantially reduced particle size, typically around 1/3 the pre-procesed biomass size distribution. This is consistent with published results which demonstrate an increase in friability and grinding efficiency for torrefied biomass. The resulting material is more brittle, and performs more like coal upon grinding in this impact ball mill type grinder.

Because the goal of this research is to produce a biomass material with properties that render it completely compatible with coal in a coal fired boiler, some grinding tests were conducted with biomass and coal mixes. These tests are shown in Table 5. Previous work has suggested that a co-firing ratio of up to 10% raw biomass can be accomplished without derating the boiler, and ratios of as much as 20% or more can be accomplished if the biomass has been torrefied to increase its energy density. Three tests were conducted where biomass was milled with coal, one with 10% (by mass) of biomass, one with 20% southern pine torrefied at 230°C, and one with 20% southern pine torrefied at 270°C. The results demonstrate that the mean particle sizes of each test are near the target of 90 micron. The largest variation is demonstrated in the screen size to pass 84% of the ground material. For the raw sample, this is near the coal sample at 0.240 mm, but higher mix ratios with torrefied biomass demonstrate substantially larger screen sizes necessary to pass 84% of the material. Further replications of this testing, including the performance of co-milling with herbaceous biomass are suggested to better characterize the grinding performance of other biomass types when milled with coal. Also, given the milling action of a coal pulverizer, wherein particles are transported out of the mill when the correct particle size is achieved, and larger particles continue to be ground, future investigations will consider the tendency of biomass particles to accumulate in a coal pulverizer, possibly reducing its efficiency and throughput.

Table 5 and Table 6 also demonstrate that the mean particle size for the untreated biomass samples (without binder) is larger for the 270°C torrefied biomass than for the 230°C. It has been noted that electrostatic forces between sufficiently small particles can cause some agglomeration, even in the absence of binders (which tend to exacerbate the tendency of the biomass to agglomerate). Future work will focus on the utilization of a physical screen type size characterization method, which may be more able to mechanically break up the agglomerations, resulting in a more accurate particle size distribution.

Table 5: Particle size results for Southern pine and corn stover.

Material	Torr. (°C)	Binder		Sieve Size at which cum. % material passes through (mm)			1/Sphericity	Aspect Ratio	Notes
		Type	(Wt%)	50%	16%	84%			
Coal	0			0.098	0.051	0.278	1.357	0.674	
Southern Pine*	0			1.197	0.481	2.186	1.835	0.423	Some fibers
Southern Pine	0			0.542	0.116	2.152	2.475	0.528	Some whole pellets
Southern Pine*	230			0.779	0.153	1.966	1.883	0.460	Some fibers
Southern Pine	230			0.380	0.099	2.196	2.288	0.539	Some whole pellets
Southern Pine*	270			0.528	0.125	1.500	1.585	0.477	
Southern Pine	270			0.218	0.064	1.971	1.757	0.590	
Southern Pine	270	Raw	8%	0.207	0.068	0.865	1.761	0.584	
Southern Pine	270	GG1	4%	2.105	0.812	4.338	1.855	0.644	Moderate agglomeration
Southern Pine	270	GG2	4%	1.832	0.755	3.884	1.712	0.658	
90/10 Coal/S.P.	0			0.093	0.050	0.240	3.077	0.543	
80/20 Coal/S.P.	230			0.109	0.054	0.839	1.527	0.608	
80/20 Coal/S.P.	270			0.107	0.052	1.618	1.534	0.629	
Corn Stover*	0			0.742	0.247	1.905	2.188	0.454	Some fibers
Corn Stover	0			0.455	0.098	3.171	2.278	0.534	Some whole pellets
Corn Stover*	230			0.377	0.146	0.942	1.901	0.492	Some fibers
Corn Stover	230			0.136	0.056	1.533	1.776	0.572	
Corn Stover	230	GG1	1%	1.210	0.272	3.657	2.410	0.581	Minor agglomeration
Corn Stover*	270			0.259	0.088	0.836	1.721	0.527	
Corn Stover	270			0.239	0.067	6.278	2.370	0.565	
Corn Stover	270	GG1	2%	0.718	0.193	2.841	1.818	0.632	
Corn Stover	270	GG2	2%	0.714	0.146	3.393	1.916	0.625	Minor agglomeration

*These samples were not pelletized before characterization.

Table 6: Particle size results for switchgrass and Arundo Donax.

Material	Torr. (°C)	Binder		Sieve Size at which cum. % material passes through (mm)			1/Sphericity	Aspect Ratio	Notes
		Type	(Wt%)	50%	16%	84%			
Switchgrass*	0			0.975	0.278	3.838	6.667	0.359	Some fibers
Switchgrass	0			0.638	0.139	3.389	2.660	0.543	Some whole pellets
Switchgrass*	230			0.442	0.144	1.475	2.618	0.402	Some fibers
Switchgrass	230			0.194	0.070	0.603	1.751	0.583	
Switchgrass	230	GG1	1%	1.001	0.180	4.939	2.519	0.578	
Switchgrass*	270			0.620	0.173	2.061	2.841	0.412	Some fibers
Switchgrass	270			0.544	0.085	5.070	2.315	0.573	
Switchgrass	270	GG1	1%	1.220	0.175	5.912	2.545	0.554	Minor agglomeration
Switchgrass	270	GG1	2%	0.923	0.129	4.186	2.137	0.589	Minor agglomeration
Switchgrass	270	GG1	4%	1.793	0.521	4.330	1.919	0.633	Minor agglomeration
Switchgrass	270	GG2	2%	1.089	0.273	3.153	1.931	0.625	Minor agglomeration
Arundo Donax*	0			0.459	0.117	1.307	2.037	0.403	Some fibers
Arundo Donax	0			0.258	0.080	1.275	1.953	0.554	
Arundo Donax*	230			0.344	0.112	1.091	1.957	0.427	Some fibers
Arundo Donax	230			0.293	0.074	4.139	2.257	0.563	
Arundo Donax	230	Raw	8%	0.474	0.095	4.578	2.370	0.559	
Arundo Donax	230	GG1	1%	0.861	0.167	3.356	2.198	0.604	
Arundo Donax	230	GG2	1%	0.868	0.185	3.234	2.128	0.606	Minor agglomeration
Arundo Donax*	270			0.364	0.103	1.152	1.821	0.452	Some fibers
Arundo Donax	270			0.227	0.066	3.470	1.957	0.580	
Arundo Donax	270	Raw	8%	0.228	0.072	2.199	1.689	0.606	
Arundo Donax	270	GG1	2%	0.798	0.286	2.236	1.799	0.635	Moderate agglomeration
Arundo Donax	270	GG2	2%	1.165	0.322	3.331	1.898	0.630	Minor agglomeration
Leached A.D.*	0			0.680	0.243	1.984	2.475	0.426	Some fibers
Leached A.D.	0			0.233	0.084	0.677	1.869	0.534	Some fibers
Leached A.D.	230			0.175	0.061	2.324	1.799	0.585	
Leached A.D.	270			0.104	0.049	2.332	1.531	0.619	
Leached A.D.	270	GG1	2%	0.484	0.084	2.831	1.825	0.621	
*These samples were not pelletized before characterization.									

For all biomass samples, the average particle size was larger than the 98 μm coal sample. A few samples came close to this average size: corn stover and switchgrass which had been torrefied at 230°C and pelletized without adding a binder. The blends of coal and Southern pine were also very close to the average particle size of the coal sample alone; however, the sieve size at which 84% of the material was able to pass through was somewhat larger than for coal alone. Because biomass tends to be significantly more reactive than coal, it is reasonable to assume that these particle sizes will result in favorable combustion properties, although further testing is required to verify this assumption.

Using raw biomass as the binder for pelletization seemed to result in the least change in particle size properties compared to pelletizing a given material without a binder. In all cases, the use of binder 1 (GG1) and binder 2 (GG2) as binders resulted in an increase in the average particle size. In fact, all of the samples which exhibited minor to moderate agglomeration were pelletized using one of these binders. Testing with switchgrass also indicates that using more binder results in a larger average particle size and potentially increases the tendency for agglomeration of the milled material.

In all cases, the average particle size of the torrefied biomass was similar to or smaller than non-torrefied biomass. For southern pine and Arundo Donax, increasing the torrefaction temperature from 230°C to 270°C resulted in a somewhat smaller average particle size. The opposite effect was observed when increasing the torrefaction temperature for corn stover and switchgrass.

Note that for some of the biomass samples, the biomass particles tended to agglomerate and form larger particles, resulting in a larger apparent particle size distribution. This is illustrated in the photographs obtained from the Camsizer™, as shown in Figure 2.

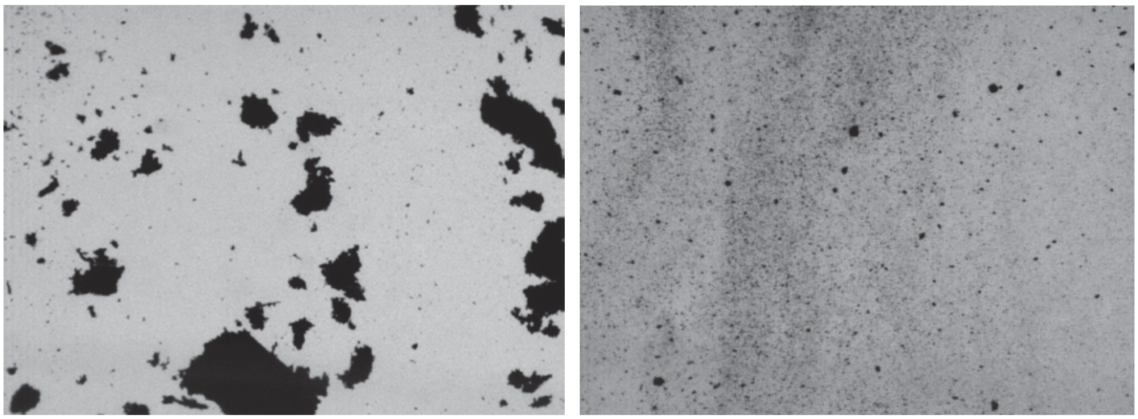

Figure 2: Camsizer™ images showing agglomeration of Arundo Donax (270°C torrefaction, 2% GG1 binder) (left image) compared to coal (right image).

Figure 3 shows photographs of two types of biomass with higher percentages of binder additives. The effect illustrated in Figure 2 as seen by the Camsizer™ are also apparent in the photographs, where the material is clearly seen to form larger agglomerates which the optical sizing process is unable to distinguish or dissociate into fundamental particle sizes. It is expected that a sufficiently turbulent flow feed system would cause these agglomerated particles to dissociate, but again, more testing is required to confirm this assumption. Given that these binder materials had little positive effect on the formation and durability of pellets, a more suitable binder material must be sought for this process.

Figure 3: Photographs of 270° torrefied Southern Pine with 4% binder (left), and 270° torrefied Arundo Donax with 2% binder (right).

For some samples, particularly those that were not torrefied, some pellets made it through the milling process virtually intact (see Figure 4). Of the biomass types tested, only Arundo Donax did not exhibit this effect.

Figure 4: Switchgrass sample showing that some pellets made it through the milling process intact.

As can be seen from the results of this testing, significant work remains to be done to improve pre-processing techniques which will result in the desired particle size properties for biomass materials being ground in coal grinders. In addition, flow-loop and fluidization testing is recommended to determine the optimal biomass properties to allow pulverization and feeding in existing coal-fired power plant systems. Future work will also consider the optimal biomass particle size at a given pretreatment condition for combustion, and this will inform the decisions about what percentage of biomass cofiring can be achieved without retrofit of an existing coal boiler.

3.5 Suitability for Use in a Coal Boiler

In order to determine the suitability of firing a specific biomass in a given coal boiler design, combustion testing in a representative boiler will likely be required. However, it is possible to perform an initial screening of material based on defined specifications for the fuel. In 2010, EPRI drafted a preliminary specification for pelletized, torrefied biomass based on experience with coal boilers. This specification was updated to revision 3 in 2012 (ETDS-001 Rev. 3 - 10/2012). The testing and analyses performed by INL allow a comparison of results to a subset of these specifications, as shown in Table 7.

Woody biomass easily met the 20 wt% ash requirement, as did all of the tested herbaceous biomass types. For Arundo Donax, leaching was shown to reduce ash content by a few percent. A higher torrefaction temperature resulted in higher ash content of the finished fuel due to increased mass loss of volatile material during torrefaction. It may be possible to reduce ash content in the herbaceous biomass types further by modifying the leaching process.

The minimum specification for volatile matter is 60 wt%. The purpose of this specification is to ensure that combustion occurs early enough in the specified sections of the boiler. This specification was met for most of the biomass tested. For corn stover and Arundo Donax, however, torrefaction at 270°C resulted in volatile matter content below this specification. Combustion testing is needed to ensure that this specification is properly framed. Biomass is typically much more reactive than coal, and the extent to which this has an effect on the combustion of biomass with coal should be characterized. This will allow a better understanding of the importance of this specification, and the level at which it should be set, to ensure desired combustion properties.

Table 7: Suitability of resulting biomass properties for direct fire in a coal boiler.

Material	Torr °C	Binder		Ash	Volatile Matter	HHV	Bulk Density	Energy Density	Mechanical Durability	N	S	Cl	Na + K
		Type	wt%	wt.%, dry	wt.%, dry	Btu/lb, daf	lb/ft^3	kBtu/ft^3	% intact	wt.%, dry	wt.%, dry	wt.%, dry	ppm, dry
Proposed EPRI Specification:			< 2*	< 20	> 60	8,500 - 12,000	45 - 55	400 - 700	85.0 - 97.5	< 1	< 0.6	< 0.03	< 4,000
Southern Pine	0			2.40	86.02	8,935	8.41	75	84.7	0.462	0.007	0.15	3,435
Southern Pine	230			2.88	84.81	8,981	20.65	185	87.2	0.474	0.014		
Southern Pine	270			0.91	78.25	9,406	25.95	244	79.0	0.521	0.013		
Southern Pine	270	Raw	8%	0.82	79.41	9,545	23.78	227	79.1	0.525	0.011		
Southern Pine	270	GG1	4%	0.81	79.90	9,844	24.87	245	48.7	0.511	0.011		
Southern Pine	270	GG2	4%	0.94	78.50	10,008	25.77	258	55.2	0.512	0.031		
Corn Stover	0			6.51	80.32	8,385	26.43	222	86.9	0.804	0.042		
Corn Stover	230			6.99	77.40	8,648	13.05	113	33.4	0.866	0.041		
Corn Stover	230	GG1	1%	7.79	77.78	8,823	24.89	220	60.4	0.829	0.050		
Corn Stover	270			13.32	52.98	10,859	30.00	326	74.4	1.151	0.061		
Corn Stover	270	GG1	2%	12.76	54.74	11,018	26.79	295	34.1	1.139	0.034		
Corn Stover	270	GG2	2%	12.96	55.00	11,080	26.96	299	33.0	1.125	0.062		
Switchgrass	0			5.42	81.81	8,169	24.83	203	91.7	0.958	0.065		
Switchgrass	230			6.40	77.63	9,016	35.39	319	84.4	0.838	0.085		
Switchgrass	230	GG1	1%	5.69	78.67	8,943	35.63	319	91.0	0.899	0.072		
Switchgrass	270			9.25	70.51	9,839	18.98	187	53.3	1.047	0.098		
Switchgrass	270	GG1	1%	7.67	71.06	9,791	18.49	181	34.4	1.113	0.088		
Switchgrass	270	GG1	2%	7.76	71.51	9,850	19.64	193	34.5	1.119	0.088		
Switchgrass	270	GG1	4%	7.45	72.80	9,854	20.00	197	31.2	1.122	0.087		
Switchgrass	270	GG2	2%	7.78	71.47	9,836	19.56	192	39.6	1.115	0.068		
Arundo Donax	0			12.96	75.01	8,473	22.20	188	69.3	2.010	0.306	5.05	25,483
Arundo Donax	230			13.59	70.40	9,107	17.24	157	40.0	2.199	0.286		
Arundo Donax	230	Raw	8%	13.96	71.23	9,188	17.71	163	54.4	2.392	0.318		
Arundo Donax	230	GG1	1%	17.80	61.37	10,131	28.03	284	40.1	2.300	0.325		
Arundo Donax	230	GG2	1%	17.39	61.59	10,001	22.66	227	20.7	2.327	0.294		
Arundo Donax	270			16.59	57.47	10,294	24.42	251	30.3	2.589	0.330		
Arundo Donax	270	Raw	8%	17.36	58.93	10,084	22.56	228	41.4	2.578	0.366		
Arundo Donax	270	GG1	2%	16.60	59.07	10,597	24.61	261	11.3	2.442	0.294	5.26	34,305
Arundo Donax	270	GG2	2%	17.79	59.44	10,595	24.45	259	20.2	2.460	0.332	4.83	33,199
Leached A.D.	0			8.76	79.21	8,408	25.14	211	88.6	1.731	0.159	0.73	5,204
Leached A.D.	230			11.90	71.95	9,510	24.37	232	58.7	1.878	0.124		
Leached A.D.	270			18.40	48.62	11,802	31.37	370	55.8	2.408	0.126		
Leached A.D.	270	GG2	2%	16.01	55.95	11,508	31.43	362	48.1	2.194	0.129		

Red values indicate that the material does not meet the specification proposed by EPRI.
*This specification applies only to binders that differ from the biomass material.

The heating value specification of 8,500 – 12,000 Btu/lb (HHV, dry, ash-free basis) is established to ensure that biomass fed to the boiler closely matches that of coal to enable co-firing without de-rating the boiler. In every material tested, torrefaction was able to improve the heat content of the biomass to achieve this specification.

Bulk density of the torrefied pellets is important to ensure seamless transport and feeding of material in systems that were originally designed for coal. Unfortunately, the bulk density for all pellets tested fell well below the lower specification of 45 lb/ft3. Hence, flow and feed testing of these materials will be required to determine if they can be transported, stored, and fed with existing coal plant equipment. Because of the low bulk density of the pellets, the energy density specification was also not met for all materials tested.

None of the pellets produced met the minimum specification for mechanical durability of 95% intact. In fact, other than raw biomass, the binders selected resulted in less durable pellets. Hence, additional research and testing is required to improve pellet durability via the inclusion of other types of biomass binders.

A maximum nitrogen content of 1 wt% is specified to limit NO_X emissions during combustion (i.e., fuel NO_X). All of the Southern Pine, and some of the agricultural residues met this specification, and the leached Arundo Donax came close to meeting this specification. Further, nitrogen bound in the biomass does not appear to be volatile, as it increases as the torrefaction temperature is increased. Combustion testing is recommended to determine the fate of nitrogen bound in the biomass. Results of such testing may allow the specification to be relaxed.

All materials tested met the maximum sulfur specification of 0.6 wt%. As shown in the results of these tests, leaching of Arundo Donax is capable of reducing the sulfur content.

Chlorine content is an important fuel specification, as excessive chlorine can contribute to accelerated corrosion within the boiler. None of the biomass materials tested met the required maximum chlorine specification of 0.03 wt%. For these analyses, only southern pine and Arundo Donax were tested. The decision to limit these tests was based largely on previous experience which had demonstrated that this sample of Arundo Donax was particularly high in inorganics, and we wanted to characterize this, in conjunction with the leaching experiment to demonstrate the potential capabilities of a leaching operation. Southern pine was tested as well to demonstrate the comparison of Arundo Donax to a commonly characterized material (a baseline material).

Excessive sodium and potassium content in the fuel can cause fouling in the boiler; hence, a maximum specification of 4,000 ppm has been proposed. While Southern pine was able to achieve this specification, Arundo Donax was not. It was shown, however, that leaching was very effective at reducing alkali content in the biomass. With further development of the leaching process, it may be possible to achieve the alkali specification for Arundo Donax.

While the data presented is not exhaustive (only one leaching process was tested, only small samples of select biomass types were included, etc.) general trends do emerge as a result of the data.

First, as biomass (of whatever type) is torrefied, it is possible to increase the energy density significantly. Judicious selection of torrefaction process parameters is able to increase the energy content to the level of some types of coal.

Second, leaching can significantly improve the biomass properties, particularly in reducing the presence of chlorine, sodium, potassium, and overall ash content. Further research and testing should focus on optimizing the harvest and collection practices to minimize initial ash content (i.e. the inclusion of dirt contamination in the initial collection of biomass), and in the optimization of the leaching process parameters, including the leachate, as well as testing other herbaceous sources of biomass.

Third, future research should focus on the development and testing of the specifications against which the biomass has been compared. This would enable a more complete understanding of the specific requirements that a biomass type must achieve to be well suited for co-firing. This may require some boiler specific testing and modeling to determine the performance of these materials in the specific case considered.

4. Conclusions

This analysis has demonstrated the potential for the correct combination of pre-processes to render biomass compatible for co-firing in PC boilers. This work has focused on demonstrating the series of pre-processing operations that are necessary to enable biomass to be used as a drop-in fuel for PC boilers.

While the biomass tested did not demonstrate compete compatibility with the specification that was selected, it was shown that these processes in the correct combination can render biomass compatible with coal. As stated previously, more research must be conducted to determine the specific processes necessary to render biomass compatible with coal. These areas of research include further work in the selection and testing of binder materials, appropriate torrefaction procedures for biomass not tested here, leaching process parameters, and coal boiler specifications and tests.

This testing also demonstrates that there are several types of biomass that may represent a best path forward for initial biopower development. These include woody biomass such as southern pine, and many herbaceous biomass types, perhaps combined with a leaching process. The development of a biomass feedstock based on these materials could enable rapid realization of necessary specifications, and would enable subsequent development to enable the upgrading of lower grade feedstock materials.