**Final Technical Report
August 7, 2009 – December 31, 2012**

**Demonstration of Pressurizing Coal/Biomass Mixtures
Using Posimetric Solids Pump Technology**

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1. ABSTRACT

This document is the Final Technical Report for a project supported by U.S. DOE NETL (Contract No. DE-FE0000507), GE Global Research, GE Energy, and Idaho National Laboratory (INL). This report discusses key project accomplishments for the period beginning August 7, 2009 and ending December 31, 2012. In this project, pressurized delivery of coal/biomass mixtures using GE Posimetric* solids pump technology was achieved in pilot scale experiments. Coal/biomass mixtures containing 10-50 wt% biomass were fed against pressures of 65-450 psi. Pressure capability increased with decreasing biomass content for a given pump design, and was linked to the interaction of highly compressible coal/biomass mixtures with the pump outlet design. Biomass pretreatment specifications for particle size and moisture content were defined based on bench-scale flowability, compressibility, friction, and permeability experiments that mimic the behavior of the Posimetric pump. A preliminary economic assessment of biomass pretreatment and pump operation for coal/biomass mixtures (CBMs) was conducted.

* Posimetric is a registered trademark of the General Electric Company.

2. EXECUTIVE SUMMARY

This document is the Final Technical Report for a project supported by U.S. DOE NETL (Contract No. DE-FE0000507), GE Global Research, GE Energy, and Idaho National Laboratory (INL). This report discusses key project accomplishments for the period beginning August 7, 2009 and ending December 31, 2012.

The project goal was to demonstrate that Posimetric* solids pump technology could deliver mixtures of coal and biomass against a pressure gradient. Successful demonstration of this technology addresses one of the key technical risks related to pressurized gasification for coal/biomass to liquids (CBTL). In the process of achieving this goal, we defined biomass pretreatment specifications that enable successful high-pressure pump operation, and performed an economic assessment of feedstock pretreatment and pump operation for coal/biomass mixtures (CBMs). The CBMs contained no more than 50 wt% biomass, and the project focused on biomass concentrations of 10 wt%, 30 wt%, and 50 wt% (dry basis). GE Global Research collaborated with INL and GE Energy to execute this project, relying on INL's biomass feedstock pretreatment expertise and GE Energy's expertise in Posimetric pump technology.

In the first phase of the project, GE Global Research conducted bench-scale characterization of the coal/biomass mixture material properties that are relevant to operation of the Posimetric pump, including friction, flowability, and gas permeability. Bench-scale characterization of CBMs resulted in definition of biomass particle size specifications and scalable pretreatment methods that yield biomass that is compatible with pressurized Posimetric pump operation. This optimization balanced economics, which favor larger particle sizes, with flowability and permeability, which favor smaller, lower aspect ratio particles. Pretreated biomass aspect ratio was linked to screen size and biomass type. Ultimately, biomass was hammermilled through a 2 mm screen for use in pump trial experiments.

Biomass moisture content was also optimized, based on bench-scale characterization experiments. This optimization balanced economics, which favor wetter biomass, with flowability, which favors drier biomass. Ultimately, biomass moisture content was specified at a maximum of 10 wt% for use in pump trial experiments. However, 15-20 wt% moisture content may be acceptable for some biomass materials. Moisture-related degradation of CBMs in storage was observed in this program in pilot scale experiments, which reinforces the importance of managing moisture content of biomass in storage. To minimize degradation in storage and ensure operable flowability in process equipment, covered biomass storage and quality control and monitoring of biomass moisture content should be employed in CBTL facilities. At the close of this project phase, a go/no-go decision

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was made to proceed to the second phase of the project based on successful achievement of the technical milestones.

In the second phase of the project, 22 unique CBMs (three coals, three biomasses, 2-3 biomass loadings) were tested in a pilot-scale Posimetric pump at a GE Energy facility. The INL team prepared the biomass materials according to the specifications defined in the first phase of the project in sufficient quantity for the trials. The experimental results from these trials, along with relevant mixture property data obtained at the bench scale, were incorporated into a preliminary economic analysis of feedstock handling for CBTL facilities based on Posimetric pump technology.

The pressure capability of the Posimetric pump on CBMs was demonstrated for a range of pump outlet shape factors, biomass loadings, and coal and biomass types. The highest pressure capability achieved in the scope of this program was in excess of 450 psi as demonstrated for 10 wt% biomass mixtures in Illinois #6 coal using an optimal pump outlet shape factor. CBMs based on low-rank coal were found to be quite challenging to feed into the pump inlet, and once inside the pump required inoperably high torque to achieve delivery at atmospheric pressure. This performance was linked to the high moisture content of the low-rank coal, which was correlated with increased compressibility of the material relative to bituminous coal.

Homogeneity of coal/biomass mixtures was monitored throughout the pump trial apparatus, and every possible effort was made to ensure uniform homogeneity of the mixtures during experiments. The effect of mixture inhomogeneity was observed in pump trial experiments, which reinforces the importance of managing this behavior in solids processing equipment.

A preliminary economic analysis of the feedstock handling system for a CBTL facility was performed. CBMs were more costly to process than 100% bituminous coal due to increased feedstock, operating, and capital costs, as well as reduced feedstock energy density. Bituminous CBMs containing 10 wt% biomass were approximately 5-10% more costly than bituminous coal alone. While low-rank CBMs were less costly feedstocks, their high moisture content resulted in higher operating cost for attributed to drying. If feedstock handling systems can be optimized to accommodate high moisture CBMs, these mixtures may become more attractive to process.

3. PROJECT NARRATIVE

The U.S. Department of Energy's National Energy Technology Laboratory (DOE/NETL) is exploring affordable technologies and processes to convert domestic coal and biomass resources to high-quality liquid hydrocarbon fuels. This interest is primarily motivated by the need to increase energy security and reduce greenhouse gas emissions in the United States. Gasification technologies are cleaner, flexible and efficient conversion pathways to utilize coal and biomass resources. A critical technical barrier to adoption of coal/biomass to liquids (CBTL) technology is the ability to deliver solids to a pressurized reactor using a dry conveyance method. The Posimetric pump technology has been demonstrated for coal feedstocks at pressures up to 1000 psig, but has not been demonstrated extensively for coal/biomass mixtures (CBMs).

Figure 1. Project summary.

In this project, GE Global Research characterized the material properties of CBMs that relate to Posimetric pump operation, translated those properties to estimates of pump performance, defined biomass pretreatment specifications for successful pump operation on CBMs, and conducted pilot-scale pump demonstration trials with suitably pretreated CBMs. GE Global Research collaborated with Idaho National Laboratory (INL) and GE Energy to execute this project, relying on INL's biomass feedstock pretreatment expertise and GE Energy's expertise in Posimetric pump

technology. The outcome of this project was pressurized demonstration of the pump for CBMs and an economic assessment of the pump technology and biomass pretreatment methods (Figure 1). Successful demonstration of the Posimetric pump for high-pressure delivery of CBMs addresses one of the key technical risks of dry-feeding technology for pressurized gasification.

3.1. PROJECT OBJECTIVES

The following technical objectives were achieved during this project:

- Identify primary biomass characteristics for dry-feeding CBMs with the Posimetric pump
- Define the most favorable feedstock pretreatment scheme to produce CBMs that are appropriate for use in the Posimetric pump
- Demonstrate operation of the Posimetric pump for CBMs at a reasonable scale
- Perform a preliminary technical and economic evaluation of Posimetric pressurization of CBMs, including feedstock pretreatment

3.2. RELEVANCE AND IMPACTS

Successful development of pressurized coal/biomass feeding technology represents a significant advancement toward large-scale production of low net-carbon fuels using pressurized entrained-flow gasification. Pressurized, entrained-flow gasification is preferred over atmospheric gasification for fuel production due to its high efficiency, low tar formation, and lower capital cost at large scale. The Posimetric pump is a method of delivering solids against a pressure gradient that can potentially offer reduced operating costs and improved gasification efficiency compared to competing technologies like lock hoppers. Posimetric pressurization of CBMs allows for synergistic use of the high energy density of coal and the carbon neutrality of biomass to produce fungible, low net-carbon hydrocarbon fuels from domestic feedstocks at commercially relevant scale.

The Posimetric pump has been developed for coal service and has been demonstrated for a coal/sawdust mixture at 30% biomass loading in pilot-scale trials. While these results suggest the potential for successful demonstration for other CBMs, it is critical to expand the knowledge of pump operation for more diverse CBMs to accelerate growth in low-carbon fuel production. By studying and characterizing the properties of a wide range of CBMs, we gained the required insight to optimize the Posimetric pump design and operation for pressurized CBM gasification and establish the criteria on which a uniform biomass logistics and handling system may be developed.

3.3. EXPERIMENTAL METHODS

3.3.1. Bench Scale Experiments

Coal and biomass were characterized individually by particle size distribution, ultimate and proximate analysis (UPA), and bulk density. UPA data were obtained from Standard Laboratories according to ASTM standard analytical methods. Particle size distribution was measured by sieve analysis and, for high-aspect ratio biomass particles, by image analysis. It is known that, for high-aspect ratio particles, PSD as measured by sieve analysis is biased toward particle width because long, stick-shaped particles can pass through a sieve lengthwise. An alternate method of PSD analysis employed in this project uses computer software to count and measure individual particles in a microscopy image of a dispersed monolayer of particles. In addition to particle size distribution, the particle *shape* distribution can also be measured using this technique. The image analysis technique yields higher fidelity PSD data for high-aspect ratio particles compared to sieve analysis, at the expense of more time needed to perform the analysis. Example micrographs of the corn stover and switchgrass materials used in the above screening experiments are shown in Figure 2. While the two micrographs were taken at different scales, the images have been re-sized herein such that they are approximately on the same scale. An example of the statistical summary of the particle size and shape distribution resulting from the image analysis technique is shown in Table 1.

Figure 2. Examples of micrographs used in the image analysis technique to measure particle size and shape distribution of high aspect ratio biomass.

Table 1. Statistical summary of the particle size and shape distribution of corn stover and switchgrass samples, as derived from image analysis.

STATISTICS	Corn Stover <2mm			Switchgrass <2mm		
	Length (um)	Width (um)	Aspect Ratio	Length (um)	Width (um)	Aspect Ratio
Mean:	1277	462	4.1	1518	423	4.3
Median:	1087	395	3	1373	358	4
Std. Dev.:	711	335	3.4	761	254	2.4
Minimum:	23	23	1.0	305	70	1.2
Maximum:	7158	2125	30.0	8719	1611	15.3
Object Count:	1082			1071		
(based on number)						

For preliminary material characterization experiments, a simple way to control biomass particle size distribution was needed, to allow for systematic assessment of the effect of biomass PSD on mixture properties. To achieve this, we selected a method wherein biomass PSD was synthesized by mixing three biomass materials having fairly uniform particle size. Pulverized pine is available in such discrete particle sizes, and was selected for this approach. Samples of 10 mesh (2000 μm), 40 mesh (425 μm), and 120 mesh (106 μm) pine were procured from American Wood Fibers of Schofield, WI for small-scale screening experiments. These particle sizes were selected to allow for synthesis of a wide PSD, as is typical of the products of conventional grinding processes. The PSDs of these pine materials are shown in Figure 3, and an example of a synthetic PSD that can be created from a mixture of these materials is shown in Figure 4.

Figure 3 is shown as a histogram of particle size to more clearly illustrate the narrow size distributions, while Figure 4 is shown in the conventional cumulative PSD format.

Standard solids flow characterization methods, such as Jenike shear and hopper flow testing, were also performed to evaluate the flowability of CBMs; these results were used to predict how well the solid mixtures flow from the feed hopper into the pump inlet. Hopper flow testing includes measuring the flow rate of solids from a standard-sized hopper. Jenike shear testing was conducted according to ASTM standard method D6218¹.

Figure 3. Particle size distribution of “synthetic” pine constituents.

Figure 4. Synthetic particle size distribution created from a mixture of the pine samples in

Figure 3, compared to actual coal PSDs.

CBMs containing the three major coal types (bituminous, sub-bituminous, and lignite) and three types of biomass (corn stover, wood, and switchgrass) were characterized using a battery of bench-scale tests designed to predict performance in the Posimetric solids pump. The “Stameter”, a proprietary solids testing apparatus, was used to characterize the compressibility, friction, and gas permeability of the mixtures. The Stameter simulates the physical environment experienced by solids during Posimetric pump operation. The Stameter applies compressive force to a sample of solid particles, while an inert gas at modest pressure (<125 psi) is applied to the solids. In this environment, the gas permeability through the compacted solids is measured, as well as the mechanical force required to compact the solids. Because this force measurement includes frictional effects, a separate friction test apparatus is used to measure the solids/wall friction factor. This friction factor is used to separate frictional effects from the compressive force measured in the Stameter when analyzing experimental data. These measurements were used to predict Posimetric pump performance using correlations that have been developed for coal solids.

Experiments were performed for CBMs containing 30 wt% and 50 wt% biomass concentration (dry basis). Early experiments explored the effect of varying biomass particle size distribution (PSD) on key performance metrics, at constant coal PSD and moisture content. From these experiments, a range of operable biomass PSDs was identified. Subsequent samples of biomass, pretreated using conventional, scalable methods, were processed so as to fall within this range of operable biomass PSDs.

Selected PSDs from this range were tested at varying moisture content to assess the impact of high moisture content on key performance metrics. The aim of these

moisture sensitivity experiments was to define the maximum allowable moisture content for biomass feedstocks, to guide selection of biomass pretreatment methods and specifications. As the operable range of biomass characteristics were identified, INL determined the most cost effective biomass preparation method to be used to produce biomass meeting the desired criteria for pilot-scale pump demonstration trials. Throughout the project, INL supplied the pretreated biomass needed for experiments.

The biomass materials used in all experiments were dried to 5-10 wt% moisture to ensure that no degradation occurred in storage (i.e., rotting). Moisture can be present in biomass and coal in two forms. Intrinsic moisture, that which is held within the particle pores, is the moisture that is naturally found within the materials. Surface moisture, that which is present on the surface of the particles, is associated with the method of collection and storage of the materials. Intrinsic moisture is converted to surface moisture during grinding, and typically surface moisture is removed in drying processes. Generally, intrinsic moisture affects flow properties of the solids to a lesser degree than surface moisture. Thus, the approach taken in variable moisture content experiments to control moisture content was to add liquid water in controlled amounts to biomass samples, thus forcing the moisture to be present in surface form. This approach resulted in a more robust maximum moisture content specification, and applied to the biomass feedstock after a drying process.

3.3.2. Pilot Scale Pump Trials

Upon completion of the material characterization phase of the project, pilot-scale pump demonstration trials were conducted for CBMs based on the three major types of coal mixed with three types of biomass at biomass concentrations of 10 wt%, 30 wt% and 50 wt% (dry basis). CBMs containing 10 wt% biomass were added to the test plan after initial results of pump trials for 30 wt% and 50 wt% biomass mixtures were less successful than anticipated. These trials were performed using a test facility operated by GE Energy, and leveraged the Posimetric pump expertise represented therein. A schematic of the pump test apparatus is shown in Figure 5. Mixtures were conveyed to the inlet hopper of the Posimetric pump unit using an atmospheric pressure screw conveyor. The unit is designed such that the outlet geometry can be easily modified to accommodate different feedstock material properties. The unit is fully instrumented with a continuous data acquisition and control system, which includes safety-related interlocks and emergency shutdown capability. Visual monitoring of the material at the pump inlet and outlet during pump operation is possible.

In a typical pump trial experiment, the mixture was fed to the unit against atmospheric pressure until the pump was fully charged with material and the material had begun to develop a compressed solids seal. At this point, pressure in the receiving vessel was gradually increased using compressed nitrogen. Material was fed against this increasing outlet pressure until one or more of the following

conditions was met: the material supply was exhausted, the receiving vessel was full of material, the torque required to rotate the pump reached a maximum operable value, or the gas leakage rate through the pump indicated loss of stable solids seal in the pump. Throughout each experiment, receiving vessel pressure, gas leakage rate, drive torque, feed hopper load, and receiving vessel load (i.e., feedstock mass throughput) were monitored. Spool rotation speed and receiving vessel pressure were among the variables controlled during experiments.

Figure 5. Schematic of the Posimetric pump test apparatus.

4. RESULTS AND DISCUSSION

This program was structured such that experimental work was conducted in two phases. First, bench-scale characterization of CBMs was conducted, as discussed in Sections 4.1 through 4.3. In this phase, the effect of biomass particle size and moisture content on mixture flowability and predicted performance in the Posimetric pump was explored, and specifications for biomass pretreatment were set. Second, pilot scale pump trials were performed for CBMs based on biomass materials generated according to these specifications, as discussed in Section 4.3.4. Finally, the results of these two experimental phases were incorporated into a preliminary economic analysis of Posimetric pump technology for coal/biomass mixture handling, as discussed in Section 4.5.

4.1. FEEDSTOCK CHARACTERIZATION

4.1.1. Coal and Biomass Composition

The coals under consideration for this project covered the major types of coal: bituminous, sub-bituminous, and lignite. A representative coal from each of these classes was selected for experiments. The bituminous coal selected was from the Illinois seam (Illinois #6), the sub-bituminous coal was from the Powder River Basin

(PRB) seam, and the lignite was from Louisiana. Within this period of performance, ultimate and proximate analysis (UPA) data was obtained for each coal sample and is shown in Table 2.

Table 2. Coal UPA results.

Coal Type	Bituminous	Sub-Bituminous	Lignite
Sample ID	Illinois 6	PRB	Lignite
Ultimate Analysis, wt%			
Moisture	8.06	19.54	29.59
Carbon	66.8	56.56	48.02
Hydrogen	4.48	3.69	3.11
Nitrogen	1.27	0.83	0.96
Chlorine	0.11	<0.01	<0.01
Sulfur	2.48	0.96	0.6
Ash	8.76	7.53	7.5
Oxygen (by difference)	8.04	10.88	10.21
Proximate Analysis, wt%			
Moisture	8.06	19.54	29.59
Ash	8.76	7.53	7.5
Volatile Matter	34.99	39.42	30.92
Total Sulfur, wt%	2.48	1.19	0.6
Heating Value, Btu/lb	11,836	9,672	8,192
Heating Value, Btu/lb, MAF	14,230	13,262	13,022

The coals were procured and processed by Vanguard Solutions, Inc., of Ashland, KY to a desired PSD of 95% passing an 18-mesh sieve (1 mm). This PSD was selected based on prior experience with the Posimetric pump². To achieve this desired PSD, the coal was air-dried, crushed in a hammermill through a 16-mesh perforated plate screen. The coal was inerted with nitrogen for shipment, and was double-bagged in 0.004" thick plastic drum liners. After the drums were opened, they were re-inerted with carbon dioxide to prevent oxidation of the coal during storage. PSD of the samples was measured using a RotoTap sieve shaker, and is shown in Figure 3.

The biomasses of interest for this project were selected from the major sources of biomass: wood, herbaceous energy crops, and herbaceous agricultural residues. One biomass of each type was selected for experiments: the wood was pine, the herbaceous energy crop was switchgrass, and the herbaceous agricultural residue was corn stover. Biomass UPA data was collected for the specific materials used for Posimetric pump demonstration trials, and is shown in Table 3. ASTM methods as customary for coal were applied to UPA measurement of biomass.

Table 3. Biomass UPA results.

Biomass	Pine	Switchgrass	Corn Stover
Ultimate Analysis, wt%			
Moisture	16.34	8.72	7.58
Carbon	43.08	43.68	42.28
Hydrogen	4.85	5.03	5.02
Nitrogen	0.12	0.56	0.67
Chlorine			
Sulfur	<0.01	0.05	0.03
Ash	2.5	4.97	7.44
Oxygen (by difference)	33.1	36.99	36.98
Proximate Analysis, wt%			
Moisture	16.34	8.72	7.58
Ash	2.5	4.97	7.44
Volatile Matter	70.48	72.16	72.46
Fixed Carbon	10.68	14.16	12.52
Total Sulfur, wt%	<0.01	0.05	0.03
Heating Value, Btu/lb	7,309	7,233	7,199
Heating Value, Btu/lb, MAF	9,006	8,380	8,471

4.1.2. Biomass Particle Size

Aside from the “synthetic” pine materials, the biomass used in bench-scale experiments was prepared using two different size reduction methods. Early experiments used materials processed in a laboratory-scale knife-mill, while later experiments used materials that had been hammermilled. The particle size of each of these sets of materials was controlled by the screen size that was mounted in the grinding chamber of the equipment. Knife milled samples were prepared using a 2 mm screen, while the hammermilled samples were prepared using a 2 mm screen and a 4.7 mm (3/16”) screen. In this way, the effect of particle size was explored, as was the effect of grinding method on particle size and shape distribution. Biomass particle size and shape data for materials used in early experiments (“synthetic” pine, knife-milled switchgrass and corn stover) and the optimized materials to be used in pump trials are shown in Table 4 and Table 5, respectively.

Table 4. Summary of biomass PSD and shape for materials used in early experiments.

STATISTICS	"Synthetic" Pine 1:1:1			Knife-milled Switchgrass <2mm			Knife-milled Corn Stover <2mm		
	Length (um)	Width (um)	Aspect Ratio	Length (um)	Width (um)	Aspect Ratio	Length (um)	Width (um)	Aspect Ratio
Mean:	467	180	2.7	1543	429	4.3	1141	397	4.5
Median:	447	177	2	1398	364	4	1007	304	3
Std. Dev.:	390	153	1.3	749	253	2.4	583	320	3.6
Minimum:	1	0.5	1.0	381	85	1.2	23	23	1.0
Maximum:	2251	1615	14.0	8719	1611	15.3	3468	1615	23.7
Object Count:	1595			1048			271		

Table 5. Summary of biomass PSD and shape for materials used in pump trial experiments.

STATISTICS	Hammermilled Pine (<2mm)			Hammermilled Switchgrass (<2mm)		
	Length (um)	Width (um)	Aspect Ratio	Length (um)	Width (um)	Aspect Ratio
Mean:	1129	359	3.2	896	322	2.9
Median:	860	290	3	713	269	3
Std. Dev.:	905	253	1.5	655	198	1.6
Minimum:	9	9	1.0	148	51	1.0
Maximum:	5890	1540	11.7	5058	1799	12.0
Object Count:	802			1293		
(based on number)						

4.2. BENCH-SCALE FLOWABILITY CHARACTERIZATION

Flowability of CBMs is an important performance metric on which to assess the suitability of a mixture for use in the Posimetric pump. The flowability of CBMs was evaluated experimentally at the bench scale, and the effect of biomass particle size, loading, and moisture content were assessed. Flowability is primarily characterized by hopper flow tests; specific CBMs to be used in pump demonstration trials were also characterized by Jenike shear testing. Flowability of CBMs was compared against that of a pure coal benchmark.

4.2.1. Effect of Biomass Particle Size and Shape

Screening experiments using the “synthetic PSD” approach for controlling biomass particle size distribution were conducted to evaluate the effect of biomass particle size on coal/biomass mixture flowability. The data shown in Table 6 exemplify the results of these experiments, and also include Stameter screening experiment results for the same mixtures. The trends apparent in this data are comparable to those for PRB and lignite coal mixed with “synthetic” pine. From this data, it is clear that biomass particle size had a noticeable effect on coal/biomass mixture flowability. For a given biomass loading, the flowability declined as biomass particle size decreased. Further, as biomass particle size decreased, the permeability of the mixture, as expressed in terms of estimated gas leakage rate, also decreased.

Table 6. Summary of Stameter and hopper flow screening DOEx results for mixtures of Illinois #6 coal with pine.

weight percent				Relative to Coal		Hopper Flow Rate (ft/min)
100um Pine	425um Pine	2000um Pine	Illinois #6 < 1mm	Est. Leakage @ 500psi (cfm) [95% CI = +/-0.5]	Material Friction Force (psi) [95% CI = +/-0.5]	
-	-	-	100	1.0	1.0	1.0
30	-	-	70	1.3	1.6	no flow
-	30	-	70	4.9	0.6	1.6
-	-	30	70	3.5	0.5	1.8
50	-	-	50	1.2	1.4	no flow
-	50	-	50	6.7	0.9	1.6
-	-	50	50	6.0	0.4	1.8

CBMs were generally found to have comparable, and in some cases higher, hopper flow rates relative to 100% coal. For flowable CBMs, the increase in hopper flow rate was largely an effect of the increased particle size of the biomass relative to coal. However, mixtures containing large fractions of the finest pine particles bridged in the test hopper, thereby failing the flowability test. As shown in Figure 6, coal/pine mixtures containing more than approximately 20% 100 μ m pine particles failed the hopper flow test. Because as pine particle size decreases, gas leakage decreases (positive effect), flowability decreases (negative effect), and feedstock preparation cost increases (negative effect), optimization of pine PSD with respect to these opposing performance metrics was necessary.

Figure 6. Effect of pine PSD on flowability of Illinois #6/pine mixtures.

Additionally, experiments with more realistic biomass materials, namely high aspect ratio particles, revealed another aspect of how particle size affects flowability. CBMs based on switchgrass that had been knife-milled to pass a 2 mm screen bridged readily in the test hopper. However, when this switchgrass was sieved to remove

particles exceeding 700 μm in size, mixture flowability improved significantly. This result suggested that there exists an upper limit to flowable particle size for high aspect ratio particles, which are naturally more likely to bridge or rathole in solids flow equipment. The data shown in Table 7 indicates that sieving reduced the mean aspect ratio of the particles, while also reducing the mean and maximum particle length. While there is an economic benefit to use of large biomass particles (reduced grinding cost), this benefit must be balanced against the observed flowability risk and the increase in mixture permeability with increasing particle size.

Table 7. Comparison of particle size and shape of knife-milled switchgrass before and after sieving.

STATISTICS	Knife-milled Switchgrass < 2mm			Sieved SG<700 μm		
	Length (μm)	Width (μm)	Aspect Ratio	Length (μm)	Width (μm)	Aspect Ratio
Mean:	1543	429	4.3	1394	412	3.9
Median:	1398	364	4	1251	371	3
Std. Dev.:	749	253	2.4	832	239	3.0
Minimum:	381	85	1.2	7	7	1.0
Maximum:	8719	1611	15.3	5276	1622	51.0
Object Count:	1048			1003		

4.2.2. Effect of Biomass Moisture Content

Moisture content is known to affect solids flowability. Bench scale flowability experiments were conducted for mixtures of high-moisture biomass with each of the three coals of interest to quantify the effect of biomass moisture content on flow properties and to define a maximum moisture content specification for feedstock preparation. Hopper flow tests were conducted for pine, switchgrass, and corn stover. Experiments focused on mixtures containing 50 wt% biomass in order to define a maximum moisture content specification in the limiting case. Because biomass' effect on mixture properties increased with increasing biomass content, a moisture content specification set for 50 wt% biomass mixtures represented a conservative specification for mixtures containing less than 50 wt% biomass.

Grinding-type size reduction processes for biomass tend to operate best on dry biomass materials. Dry biomass is generally more amenable to the shattering mechanism by which grinding reduces particle size. Generally, grinding biomass containing greater than 20 wt% moisture will result in a significantly reduction in grinding equipment capacity, thereby increasing grinding cost. Further, biomass moisture content should be maintained below this level to prevent degradation (e.g., rotting) in storage³. Thus, flowability experiments focused on biomass materials containing up to 20 wt% moisture. The flowability of 50 wt% biomass mixtures of high moisture biomass with coal as a function of biomass moisture content is shown in Figure 7. The scatter within the data reflects the use of 3 different coals in the mixtures.

Within the range of moisture content studied, switchgrass was the most robust to added moisture content. Mixtures of coal and switchgrass containing up to and including 20 wt% moisture in the biomass were flowable in hopper tests, with good stability. Pine mixtures were slightly less robust to high biomass moisture content; mixtures of coal and pine containing up to and including 15 wt% were flowable with good stability. Coal/pine mixtures comprised of pine having 20 wt% moisture bridged in the hopper. Corn stover mixtures were the most sensitive to high moisture content; while mixtures of coal and corn stover containing up to and including 20 wt% moisture were flowable, intermittent bridging was observed, indicating poor flow stability.

Figure 7. Effect of biomass moisture content on 50 wt% biomass mixture flowability. The dotted line shows the decline in flowability with increasing moisture.

Based on these results, an upper specification for biomass moisture content was established at 10 wt% for use in this project, which was intended to be robust to the range of moisture sensitivity observed in different types of biomass. For some biomass materials, 15 wt% or 20 wt% moisture may be acceptable. Because of the observed variation in limiting moisture content, it may be more sensible in commercial practice to monitor coal/biomass mixture flowability for materials that fall within the 10-20 wt% moisture range.

4.2.3. Optimized Biomass for Flowability

By conducting flowability experiments on a wide range of biomass particle size, shape, and moisture content, a thorough understanding of the biomass properties required for acceptable flowability was developed. Given this information, biomass

pretreatment methods were investigated to identify a scalable mode of preparing biomass for pilot scale pump trials, as discussed in Section 4.2.1. Hopper flow data for CBMs containing biomass that was optimized for flowability is shown in Table 8, expressed relative to 100% coal benchmarks. The particle size distributions of the biomass materials listed in Table 8 are shown in Table 5, with the exception of the corn stover material, which is shown in Table 4.

Table 8. Summary of hopper flow rate data for CBMs compared to 100% coal. HM = hammermilled; KM = knife-milled

Biomass / Coal	Hopper Flow Rate (ft/min)		
	Illinois #6 < 1mm	PRB < 1mm	Lignite < 1mm
100% coal	1.0	1.0	1.0
70/30 coal / Pine <2mm HM	1.1	1.0	2.1
70/30 coal / SG <2mm HM	1.1	1.2	2.0
70/30 coal / CS <2mm KM	1.3	1.4	2.3
50/50 coal / Pine <2mm HM	0.8	0.8	1.6
50/50 coal / SG <2mm HM	0.9	0.9	1.6
50/50 coal / CS <2mm KM	1.2	1.2	2.3

The effect of biomass particle size, shape, and moisture content on coal/biomass mixture flowability were evaluated and quantified at the bench scale. This information was used to define biomass pretreatment specifications for moisture content, and contributed to those for particle size and shape. Biomass materials that enabled acceptable coal/biomass mixture flowability were then tested in the Stameter to assess the mixtures' permeability, compressibility, and friction performance. Hopper flow rate measurements were also used in pump performance estimate calculations. Stameter experiments and pump performance estimate calculations will be discussed in the next section of this report.

4.3. BENCH-SCALE STAMETER CHARACTERIZATION

Stameter experiments were conducted as the primary method of characterizing the behavior of CBMs in a system that simulates Posimetric pump operation. The key measurements resulting from Stameter experiments are gas leakage rate, a measurement of permeability, and force, a measure of material friction properties, as a function of sample size, which correlates to the pump outlet design geometry. The results of these experiments, which were conducted at moderate pressure, were used to build feedstock-specific models to predict pump performance for a given material at high pressure. The pump performance models predict gas leakage rate, pump drive torque, and material mass throughput at high pressure for a given feedstock and a given pump outlet design. These predictions were compared to the operating window of the pump, including the available pump outlet design configurations for the pump test unit, to assess if a material is suitable for pilot-scale testing.

4.3.1. Effect of Biomass Particle Size and Shape

As discussed in a previous section of this report, a “synthetic” method of precisely controlling particle size distribution was used for initial screening experiments. Through this approach, the effect of particle size on Stameter performance was evaluated and quantified. As shown in Table 6 above, biomass particle size directly affects the permeability of the coal/biomass mixture. Upon examination of Table 6 the following observations are made:

1. Mixtures of Illinois #6 with pine particles between 100-2000 μ m in size had higher projected gas leakage rate than Illinois #6 alone.
2. Estimated leakage rate increased with increasing pine particle size.
3. Estimated leakage rate increased with increasing pine concentration, especially for larger pine particles.

We turn to a review of particle packing literature to explain these observations, since interparticle voidage provides the path by which gas permeates through a particulate bed. For beds of uniform particle size, larger particles have higher voidage than smaller particles. The addition of smaller particles in sufficient volume to a bed of larger, uniformly sized particles reduces bed voidage because the smaller particles fill in the voids between the larger particles⁴. This behavior is the reason why beds having wide particle size distributions tend to have lower voidage than beds of uniform particle size. In these screening experiments, coal is a wide particle size distribution of relatively small particles, and the pine fractions are narrow PSDs of relatively large particles. We expect coal to have low voidage, and based on the literature we expect that adding pine to this coal will increase the voidage of the mixture relative to coal alone. Both of these expectations are consistent with the above observations.

Table 6 also includes the drive force related to the friction of the mixture against the walls of the Stameter tube for a selection of mixtures in the design space. This value correlates to the torque that is required to rotate the pump during operation. Evaluation of the friction measurements within the mixture space indicates that the frictional forces between the Stameter tube walls do not vary significantly with pine particle size or concentration. This observation was unexpected, however it suggests that the pump may not require more torque to operate for an Illinois #6/pine mixture than for Illinois #6 alone. Thus the critical variable to optimize for this system is the permeability of the mixture. Mixture permeability can be optimized through control of the biomass particle size distribution. Further, the pump outlet can be designed to compensate for high material permeability.

While the data discussed herein was collected for mixtures of a specific coal and “synthetic” pine, the trends and conclusions are representative of, though not exactly equal to, the other two coal types. As will be discussed, the trends that are observed for these “synthetic” mixtures also apply to more realistic biomass materials (knife-

milled or hammermilled pine, switchgrass, and corn stover), and also incorporate the effects of biomass particle shape on predicted pump performance.

After screening experiments on “synthetic” pine-based CBMs were performed, experiments were conducted on knife-milled samples of switchgrass and corn stover, the particle size distributions of which are shown in Table 4. Because the knife-milled switchgrass caused poor flowability of 50 wt% biomass CBMs, Stameter experiments for this biomass loading were conducted on sieved samples of knife-milled switchgrass, as shown in Table 7. A summary of the pump performance estimates resulting from these experiments is shown in Table 9. These results are representative of those obtained for switchgrass with each of the other two coals of interest. Further, these results are comparable to those of <2 mm hammermilled switchgrass, which was subsequently used in pump trials.

Table 9. Pump performance estimates for Illinois #6/knife-milled switchgrass mixtures.

650psi outlet Pressure		Illinois #6	70/30 Illinois #6 / SG<2mm (KM)			50/50 Illinois #6 / SG<700um (KM, sieved)		
Bulk Density	lb/ft ³	1	0.6			0.5		
Hopper Flow Rate	ft/min	1	1.4			0.9		
Mass Throughput	lb/hr	1	0.8			0.4		
			Standard Design	Meet Leakage Spec	Current Design Limit	Standard Design	Meet Leakage Spec	Current Design Limit
Pump Outlet Shape Factor	-	1.0	1.0	2.2	3.2	1.0	3.0	3.2
Pump Drive Torque	ft-lb	1.0	0.7	1.2	2.1	0.5	0.8	0.9
Gas Leakage Rate	scfm	1.0	3.6	1.6	1.1	4.9	1.6	1.5

The pump performance estimates were prepared for three different pump outlet designs: the standard design, a design such that the leakage rate specification was met (that the coal/biomass mixture has less than approximately 50% greater permeability than 100% coal), and the current pump outlet design limit. The space that was bounded by the pump outlet design to meet the leakage specification and the current design limit is the predicted operation space for the coal/biomass mixture at high pressure. This predicted range of operable pump outlet design defined the pump outlet designs to use in experiments.

As observed in screening experiments, the permeability of coal/switchgrass mixtures was higher than that of 100% coal at the standard pump design, but the torque requirement was less than that of 100% coal. As the pump design was expanded to accommodate higher mixture permeability, the torque increased to a level that was comparable to that of 100% coal. At the current design limit, the torque requirement for the 30 wt% biomass mixture exceeded that of 100% coal, and the permeability approached a comparable value to 100% coal. At this same limit, the torque requirement for the 50 wt% biomass mixture approached that of 100% coal and the leakage rate approached the specification.

4.3.2. Effect of Biomass Moisture Content

High biomass moisture content affects the flowability of CBMs, and also affects permeability and friction properties as measured using the Stameter test methods.

An example of how moisture content affects Stameter results is shown in Figure 8, which depicts Stameter results for 50 wt% biomass mixtures of Illinois #6 coal with corn stover at ~7 wt% ("dry" for storage stability) and 15 wt% moisture content. This data set is selected for discussion because corn stover was found to be more sensitive to high moisture content than pine or switchgrass in flowability experiments. Further, the effect of high moisture content biomass is more readily distinguished in a 50 wt% biomass mixture than a 30 wt% biomass mixture. Thus, the conclusions derived from this dataset are conservative estimates of the maximum operable biomass moisture content with regard to Stameter and flowability performance.

The data shown in Figure 8 suggests that 15 wt% biomass moisture content does not significantly impair Stameter performance. Statistical analysis of the raw data using a paired t-test approach^{5,6} indicates there is no statistically significant difference between the low moisture and high moisture data sets, as shown in Figure 9. The paired t-test analyzes the differences between pairs of data sets and determines if the differences are statistically significant. The mean difference between the paired data sets and the 95% confidence interval of the difference is compared to the hypothesized mean difference (mean = 0, or no difference between the data sets). In the example shown in Figure 9, the mean difference and its 95% confidence interval span the hypothesized mean (0), which means that, statistically, there is no difference in the force or leakage rate measured in Stameter experiments between mixtures of Illinois #6 and low moisture and high moisture corn stover mixture. This reinforces the observation that moisture content's limiting effect on coal/biomass mixture performance is on flowability of the mixture. This observation was confirmed in pump trial experiments, as discussed in a later section of this report.

Figure 8. Drive force and gas leakage rate as a function of pump outlet shape factor for 50 wt% biomass mixtures of Illinois #6 coal with equilibrium and high moisture corn stover.

Figure 9. Results of paired t-test analysis of the difference between Stameter results for 50 wt% biomass mixtures of Illinois #6 coal with low moisture vs. high moisture corn stover.

Because the mixtures studied herein were the most sensitive to high biomass moisture content in flowability experiments, we can infer that there should be no statistical difference in performance for other CBMs based on biomass having 15 wt% moisture. This result indicated that coal/biomass mixture performance in the Stameter should be robust to moisture content within the 10-20 wt% range. In commercial practice, it may be more sensible to monitor coal/biomass mixture flowability for materials that fall within this range, as flowability appeared to be the limiting factor in defining the moisture content limit.

4.3.3. Optimized Biomass for Pump Trials

By conducting flowability and Stameter experiments on a wide range of biomass particle size, shape, and moisture content, a detailed understanding of the biomass properties required for acceptable performance was developed. Given this information, biomass pretreatment methods were investigated to identify a scalable mode of preparing biomass for pilot scale pump trials, as discussed in a previous section of this report. A summary of the pump operating space for each coal/biomass mixture is shown in Figure 10. The data suggests that all CBMs studied herein were expected to be operable within the current design limits of the pump test unit. It is of further note that all CBMs studied had sufficiently high permeability as to preclude high-pressure (650 psi) operation using the standard pump design. The predicted operable pump outlet shape factor tended to increase with declining coal quality, which was related to differences in the flowability, permeability, and friction properties between the three coal types. The particle size distributions of the biomass materials listed in Figure 10 are shown in Table 5, with the exception of the corn stover material, which is shown in Table 4.

Figure 10. Summary of pump operating space with regard to pump outlet shape factor for optimized CBMs. Green shading indicates strong likelihood of success; yellow shading indicates possible success.

In the bench-scale experiment phase of this program, the effect of biomass particle size, shape, and moisture content on coal/biomass mixture flowability were evaluated and quantified. This information was used to define biomass pretreatment specifications for moisture content, and contributed to those for particle size and shape. Biomass materials that enabled acceptable coal/biomass mixture flowability were then tested in the Stameter to assess the mixtures' permeability, compressibility, and friction performance. These results, along with hopper flow rate measurements, were used to estimate pump performance at high pressure. The experimental results and analysis suggested that each of the 18 candidate CBMs was anticipated to be operable in the Posimetric pump test unit. The permeability of all CBMs tested was higher than that of coal alone, and as such it was expected that modified pump outlet designs would be needed to achieve pressurized operation. Such pump outlet modifications were available for use in pump trials, and will be discussed in the next section of this report.

4.3.4. Validation of Mixture Properties for Pump Trials

Biomass particle size specifications were communicated to INL to guide development of scalable biomass pretreatment methods. An initial sample of hammermilled biomass was prepared and tested. Experimental results indicated that a finer particle size should be specified to meet mixture flowability and permeability requirements. A second iteration on biomass processing conditions was conducted, resulting in a final specification for biomass materials to be used in pump trial experiments. Validation of the properties of materials prepared to this specification is presented in this section.

4.3.4.1. Particle Size Distribution

Biomass meeting the final particle size specification was prepared by hammermilling through a 2 mm screen. Hammermilling is more easily scaled up to relevant capacities for commercial applications, and can be adapted for a wide range of feedstocks and target particle sizes. Previous samples used in bench scale screening experiments were knife milled through a 1/16" screen or hammermilled through a 3/16" screen. Knife milling tends to be limited to small-scale (e.g., laboratory) applications. Comparison of hammermilled pine samples at the coarser and finer size specifications confirmed a significant decrease in particle size in finer samples. Particle size distribution data for these hammermilled pine samples are shown in Table 10, and are similar to that of hammermilled switchgrass at the same particle size specifications.

Table 10. Particle size distribution data per image analysis of hammermilled pine at two size specifications (<3/16" and <2 mm).

STATISTICS	Hammermilled Pine <3/16"			Hammermilled Pine <2mm		
	Length (um)	Width (um)	Aspect Ratio	Length (um)	Width (um)	Aspect Ratio
Mean:	3248	820	4.7	1129	359	3.2
Median:	2698	702	4	860	290	3
Std. Dev.:	2783	523	3.0	905	253	1.5
Minimum:	295	76	1.1	9	9	1.0
Maximum:	42832	2902	20.6	5890	1540	11.7
Object Count:	567			802		
(based on number)						

The PSDs encompassed a similar range of particle sizes, but the recent pine sample has a smaller mean particle size compared to the initial sample (1129 μm vs. 3248 μm , based on image analysis as described above. Both materials are comprised of high-aspect ratio particles, but the finer material has a smaller average aspect ratio. This reduction in particle aspect ratio resulted in improved flowability of the material, as will be discussed in the next section.

4.3.4.2. Flowability

Flowability, as characterized by hopper flow, was evaluated for mixtures of coal with dry pine and switchgrass. These validation experiments focused on the 50 wt% biomass mixtures only, since based on prior results, if a 50 wt% biomass mixture was flowable, the 30 wt% biomass mixture at the same coal and biomass PSDs was also flowable.

Table 11. Hopper flow rate and bulk density of 50 wt% biomass mixtures, relative to 100% coal values.

	Pine <2mm		Switchgrass <2mm	
	Bulk Density, kg/m ³	Hopper Flow Rate, m/s	Bulk Density, kg/m ³	Hopper Flow Rate, m/s
Illinois #6	0.4	0.85	0.4	0.86
PRB	0.4	0.83	0.4	0.92
Lignite	0.5	1.65	0.4	1.59

The results of hopper flow experiments for 50 wt% biomass pine- and switchgrass-based coal mixtures are shown in Table 11. Mixture performance data is expressed relative to that of 100% coal. Each coal/biomass mixture was found to be flowable in the hopper test environment. As in previous experiments, the bulk density of the mixtures decreased with increasing biomass content. While a number of these mixtures were less flowable (have lower hopper flow rate) than 100% coal, their flow properties were believed to be adequate.

4.3.4.3. Stameter Characterization and Predicted Pump Performance

Stameter performance for CBMs based on hammermilled pine and switchgrass was evaluated and high-pressure pump performance was predicted. Pump performance was predicted for 650 psi delivery pressure, per the target delivery pressure for the pilot scale phase of this program. Experiments focused on 50 wt% biomass mixtures, since, similar to flowability, if a 50 wt% biomass mixture had acceptable performance, the 30 wt% biomass mixture based on the same coal and biomass also had acceptable performance. The results from this work on more finely hammermilled pine-based mixtures are shown in Table 12. While the data shown herein are specific to pine, the results are representative of those observed for switchgrass that was pretreated in a similar manner (hammermilled to <2 mm). The data are expressed relative to 100% coal, and includes results for two conditions: at constant pump outlet shape factor typical for 100% coal operation, and at a pump outlet shape factor chosen such that the leakage rate was no more than 50% greater than that of 100% coal operation.

Table 12. Summary of calculated pump performance estimates for 50 wt% pine mixtures at 650 psi outlet pressure.

		100% Coal	50/50 Illinois #6/Pine<2mm		50/50 PRB/Pine<2mm		50/50 Lignite/Pine<2mm	
Bulk Density	lb/ft ³	1.0		0.4		0.4		0.5
Hopper Flow Rate	ft/min	1.0		0.8		0.8		1.3
Mass Throughput	lb/hr	1.0		0.3		0.4		0.7
			Standard L/D	Meet Leakage Spec.	Standard L/D	Meet Leakage Spec.	Standard L/D	Meet Leakage Spec.
Pump Outlet Shape Factor	-	1.0	1.0	4.0	1.0	3.2	1.0	3.2
Pump Drive Torque	ft-lb	1.0	0.5	1.0	0.5	1.1	0.5	0.8
Gas Leakage Rate	scfm	1.0	7.0	1.7	5.0	1.5	5.7	1.8

As in previous experiments, projected leakage rates of CBMs were higher than those of 100% coal. However, the leakage rates of these new mixtures were significantly higher than those observed for CBMs containing more finely ground biomass. While this effect of particle size was directionally consistent with prior observations, the pump outlet design was expected to require further optimization to ensure high-pressure pump operation for this particular particle size. These pump performance estimates suggested that the biomass hammermilling process used herein with a 2 mm screen yielded biomass that would be appropriate for use in pump trial experiments.

4.4. PILOT SCALE PUMP TRIAL EXPERIMENTS

The pump trial experiments that were conducted in this program are summarized in Table 13. These experiments reflect optimization of pump outlet shape factor, as discussed in Section 4.4.2, the effect of compressibility on pump performance, as discussed in Section 4.4.3, the challenges encountered when handling low-rank coal/biomass mixtures, as discussed in Section 4.4.4, and successful high pressure operation obtained for 10 wt% biomass mixtures using a new pump design prototype, as discussed in Section 4.4.5.

Table 13. Summary of pump trial experiment results.

Coal	Biomass	Loading (C/B,wt%)	Pump Outlet Shape Factor			
			1.60	1.80	2.40	3.20
Illinois 6	Pine	70/30			removed from test plan due to sticky agglomerate formation	
		50/50				
PRB	Pine	70/30				
		50/50				
Lignite	Pine	70/30	high torque max P = 0psig sticky agglomerates		removed from test plan due to sticky agglomerate formation	high torque max P = 0psig sticky agglomerates
		50/50				
Illinois 6	Switchgrass	90/10		operable torque max P = 450psig	operable torque max P = 168psig	
		70/30	low torque seal unstable max P = 0psig		operable torque max P = 65psig	high torque max P = 20psig
		50/50			operable torque max P = 70psig	
PRB	Switchgrass	90/10			could not convey to pump	
		70/30			could not convey to pump	
		50/50			removed from test plan to accommodate 90/10 mixtures	
Lignite	Switchgrass	70/30			could not convey to pump	
		50/50			removed from test plan to accommodate 90/10 mixtures	
Illinois 6	Corn Stover	90/10		operable torque max P = 457psig	operable torque max P = 109psig	
		70/30	low torque seal unstable max P = 0psig		operable torque max P = 195psig	high torque max P = 23psig
		50/50			operable torque max P = 75psig	
PRB	Corn Stover	90/10			could not convey to pump	
		70/30			could not convey to pump	
		50/50			high torque max P = 15psig	
Lignite	Corn Stover	70/30			high torque max P = 0psig	
		50/50			removed from test plan to accommodate 90/10 mixtures	

4.4.1. Coal/Biomass Mixture Storage Stability

As discussed previously, biomass moisture content was optimized to minimize its negative effects on flowability and handling properties. Another potential impact of high moisture content is acceleration of biomass degradation in storage. Useful observations on the storage stability of CBMs were made as pump trial experiments were initiated. Due to schedule constraints on the pump test facility, pump trial experiments for this program were delayed. Thus, the CBMs obtained for these experiments were held in storage for a period of 2-3 months. As discussed above, CBMs were double-bagged, packaged with dry, inert gas, and placed in sealed metal drums for shipment and storage. Under these conditions, most of the CBMs were stable, however those comprised of lignite and corn stover began to decompose.

Figure 11. Photograph of lignite/corn stover mixture after 2-3 months in storage.

As shown in Figure 11, mixtures of lignite and corn stover were moldy and significantly agglomerated after this storage period. The decomposition was attributed to moisture released from the lignite during grinding. Lignite is a high moisture coal, as evident from ultimate and proximate analysis results reported in Section 4.1.1. The observed feedstock degradation was only observed for mixtures of lignite with corn stover, which suggests that corn stover is more sensitive to moist degradation than switchgrass or wood. This may be due to differences in lignin content, since lignin, a biopolymer that confers rigidity to plant matter, is resistant to biodegradation⁷. Compositional data reported in the literature⁸ for corn stover, wood, and switchgrass indicate that corn stover contains less lignin than wood or switchgrass. Because of the decomposition, the lignite/corn stover mixtures were

deemed unusable for testing, and a fresh sample of mixture was obtained for experiments.

Feedstock degradation is a potentially costly phenomenon that should be avoided in a large-scale gasification application. The observations discussed herein illustrate the importance of moisture control for biomass during storage, especially for herbaceous feedstocks such as corn stover. In addition to the chemical changes that result from degradation, high moisture content feedstocks are more difficult to handle in process equipment, as shown in bench scale flowability studies discussed in Section 4.2.2. Dry storage facilities for biomass should be incorporated into the design for a CBTL facility; this accommodation was incorporated into the economic assessment conducted in this program. Further, it is not recommended that CBMs be stored for long periods of time, particularly for high moisture coals, unless the mixture has been sufficiently dried so as to prevent moist decomposition of the biomass.

4.4.2. Pump Outlet Shape Factor Optimization

As discussed in a previous section, the models developed in the bench scale experiment phase of this program indicated that the pump should be configured for a higher pump outlet shape factor to enable pressurized delivery of CBMs. As shown in Figure 10, models predicted that different CBMs could be pressurized using pump outlet shape factors in the range of 1.6-3.2. The pump trial campaign began with experiments to determine the appropriate pump outlet shape factor(s) to employ for CBM demonstration trials.

As shown in Figure 10, the smallest pump outlet for which acceptable pump performance was predicted for any coal/biomass mixture was 1.6, and pump performance predictions were satisfactory for only a few CBMs at this pump outlet shape factor. Pump trial experiments confirmed these predictions. At this condition, CBMs did not form a stable pressure seal in the pump during operation. The data shown in Figure 12 illustrates how this behavior was detected during pump trials. This graph shows a test performed with a 30 wt% switchgrass mixture with Illinois #6 for a pump outlet shape factor of 1.6, and is representative of test data observed for other CBMs in this pump configuration. As gas pressure was applied in the pump outlet and the pump forces material through the outlet, the mixture should compress to build a stable plug, thereby reducing gas vent flow rate through the pump. In this case, the material did not compress enough to form a pressure seal, as evident by the increasing vent flow rate with increasing gas outlet pressure. This set of experiments demonstrates that pump performance models were reasonably accurate in predicting pump capability at this end of the design range, where pump performance is limited by the permeability of the coal/biomass mixture.

Figure 12. Example of operating data for a coal/biomass mixture in which a stable pressure seal was not achieved, as exhibited by increasing vent flow with increasing outlet pressure.

Similar experiments were conducted for outlet shape factors of 3.2 and 2.4. At a pump outlet shape factor of 3.2, which corresponds to the largest possible outlet shape in the pump test unit, a stable pressure seal was achieved for CBMs, and the pump pressure capability improved significantly relative to the smallest pump outlet. However, the torque required to operate the pump exceeded the torque capability of the test unit. Experiments conducted at a pump outlet shape factor of 2.4 were more successful. At this condition, pressure sealing performance remained operable, however the torque required to operate the pump at pressure remained too high, and limited the maximum delivery pressure achieved in experiments. At this shape factor, outlet pressures of up to 195 psig were achieved for CBMs as shown in Table 13. The majority of pump trial experiments were conducted at this pump outlet shape factor. However, late in the program a few experiments were conducted at a pump outlet shape factor of 1.8, wherein the highest pressures achieved in the program were observed. These experiments will be discussed in Section 4.4.5.

The relationship between torque and gas outlet pressure, as a function of pump outlet shape factor, was found to be consistent with pump performance predictions. As gas outlet pressure increased, the resistance to flow increased, which resulted in an increased torque requirement. Similarly, as the pump outlet shape factor increased, the resistance to flow increased, resulting in an increased torque requirement. These relationships, derived from experimental data generated from pump trials, are shown in Figure 13.

Figure 13. Relationship between torque and gas outlet pressure as a function of pump outlet shape factor.

4.4.3. Effect of Compressibility on Pump Performance

An unexpected observation was made in pump trials related to the effect of biomass loading on torque and gas vent flow during pump operation at pressure. In bench scale experiments, permeability of CBMs increased with increasing biomass content. However, as is shown in Figure 14, the gas vent flow during pump trials was lower for a 50 wt% switchgrass mixture with Illinois #6 than for a 30 wt% switchgrass. This behavior is attributed to increased compressibility of the 50 wt% biomass mixture compared to the 30 wt% biomass mixture. As the outlet gas pressure increased, the resistance to solids flow through the pump increased, which resulted in increased torque and increased compressive force experienced by the mixture. This increase in compressive force resulted in more efficient particle packing, and thus decreased gas permeation through the solids. This behavior is evident in Figure 14 in the decline in vent flow (red line) and increasing torque (blue line) with increasing gas pressure for the 50 wt% biomass mixture. For the 30 wt% biomass mixture, the vent flow (purple line) remained stable until a threshold degree of compression was achieved, at which point the material began to compress and vent flow declined with increasing outlet gas pressure. The data shown in Figure 14 is shown as an example; similar behavior was observed for other combinations of coal and biomass as well.

Figure 14. Vent flow and torque behavior as a function of biomass content in mixtures of Illinois #6 coal with switchgrass.

These experiments demonstrated that pump performance models were less accurate at this end of the design range, where pump performance is limited by the frictional behavior of the coal/biomass mixture. This discrepancy is attributed to the fibrous character of the biomass content and its effect on deformation and compressibility. As material flows from the pump body into the pump outlet, it experiences a change in the cross-sectional shape. In order for the material to pass through this transition, it must deform. The fibrous, high aspect ratio biomass particles interlock under compression to a greater degree than the roughly spherical coal particles, and thus resist this deformation to a greater degree. The magnitude of this effect is dependent on the type of biomass and the loading of biomass in the mixture, but is significant for all CBMs. The bench scale experiments were conducted in a geometry that does not include such a transition, and thus cannot quantify this particular aspect of biomass' impact on pump performance. Because this behavior is geometry-specific, it must be studied in the scope of pump trials, rather than at the bench scale. Future work should address how to quantify this type of behavior at the bench scale to improve pump design practices for biomass-based materials.

4.4.4. Low-Rank Coal-Based Mixtures

4.4.4.1. Coal/Pine Mixture Performance

CBMs comprised of lignite and pine were very difficult to convey to the pump feed hopper using the atmospheric pressure screw conveyor because the mixtures formed plugs in the screw. The team overcame this issue by implementing a

negative-pressure (vacuum) pneumatic conveyor to transport the feedstock into the pump feed hopper. As the material was compressed in the pump, its handling performance continued to decline. The material became stickier with increasing compression and formed plugs inside the pump and at the pump outlet. This behavior was evident from unexpectedly high torque during pump operation against atmospheric pressure, as shown in Figure 16. After this experiment, sticky agglomerates of the coal/biomass mixture were found in the pump outlet, as shown in Figure 15.

Figure 15. Photographs of sticky agglomerates of 30 wt% biomass lignite/pine mixture in the pump outlet.

Figure 16. Unacceptably high torque observed during pump operation at atmospheric pressure for 70/30 w/w lignite/pine mixture, at two pump outlet shape factors.

This behavior was attributed to the release of a sticky resin from the pine fraction of the mixture as the material was compressed in the pump. Resin release was not observed the bench-scale experiments conducted previously in this program. While the pine used in the bench scale phase of the program was prepared according to the same particle size and moisture content specifications as that prepared for these pump trials, the two pine samples came from different batches of feedstock. Due to this behavior, pump trial experiments were refocused on mixtures based on herbaceous biomass.

4.4.4.2. Effect of Coal Moisture Content on Mixture Compressibility

As shown in Figure 17, in an experiment on 30 wt% biomass mixture of lignite and corn stover, the torque quickly increased as the pump was operated against atmospheric pressure. The sealing capability of the coal/biomass mixture could not be tested, as the torque against atmospheric pressure exceeded the limits of operation. Similar behavior was observed for 50 wt% biomass mixture of PRB and corn stover, which suggested that coal moisture content may contribute to the behavior.

Figure 17. Pump operation data for 30 wt% biomass mixture of lignite and corn stover at pump outlet shape factor of 2.4.

To explore this effect, bench-scale experiments to evaluate the material properties under frictional and compressive loads were conducted as a function of coal moisture content. Frictional behavior was studied using a custom test fixture that allows for isolation of friction forces between two materials. The fixture can be used to study friction between a sample of compressed solids and a metal coupon, or within a sample of compressed solids. The test was conducted to capture the friction coefficient after breakaway (i.e., while the two surfaces are sliding against each other). In addition, durometer hardness of the compressed samples from the friction

experiments was measured. Compressive behavior was studied using a separate test fixture that allows for measurement of compressibility under varying load.

Bench-scale friction testing was conducted on as-received (“wet”) and dried 30 wt% corn stover mixture with lignite. Because lignite is a high moisture coal, the net moisture content of the coal/biomass mixture was approximately 30 wt%, and is notably higher than that of the Illinois #6-based CBMs studied previously. The dried lignite/corn stover mixture was approximately 9 wt% moisture. As shown in Figure 18, negligible difference in breakaway friction coefficient as a function of moisture content was observed for the lignite/corn stover mixture. However, friction coefficient decreased with increasing load, which is unusual given the more typical behavior of Illinois #6-based mixtures, wherein friction coefficient remains approximately constant with increasing load. This friction coefficient describes the behavior between the coal/biomass mixture and the internal surfaces of the pump.

Figure 18. Measured friction coefficient for 70/30 coal/corn stover mixtures at increasing applied load against carbon steel as a function of moisture content.

Internal friction, or friction within a compressed solids sample, was also evaluated for wet and dried 30 wt% corn stover mixed with lignite, and was compared to that of a naturally low-moisture 30 wt% corn stover mixed with Illinois #6. The results, shown in Figure 19, are similar to those for friction coefficient between CBMs and carbon steel. Breakaway friction coefficients of the CBMs were similar in magnitude; however a modest increase in lignite/corn stover friction coefficient with decreasing moisture content is evident. Friction coefficients of the lignite/corn stover mixtures also decreased with increasing load, in contrast to the load-independent behavior of Illinois #6/corn stover mixture. Lower internal friction coefficient can contribute to

increased Poisson's ratio⁹, and thus increase the load on the mixture at the pump internal surfaces (increasing torque requirement).

Figure 19. Measured internal friction coefficient of 70/30 w/w coal/corn stover mixtures at increasing applied load as a function of moisture content.

Hardness of the compressed CBMs was measured by durometer after each friction coefficient measurement. The results shown in Figure 20 indicate that dried lignite/corn stover mixture becomes harder than wet mixture under compression, and its hardness is similar in magnitude to that of Illinois #6/corn stover mixture. The appearance of the compressed dried lignite/corn stover mixture was similar to that of compressed Illinois #6/corn stover mixture. The hardness of wet lignite/corn stover mixture was relatively insensitive to increasing load. Very little moisture was observed to have been squeezed out of the samples during compression at all moisture levels tested.

Figure 20. Durometer hardness of compressed 70/30 w/w coal/corn stover mixtures at increasing applied load as a function of moisture content.

Coal moisture content clearly affected the material properties of CBMs. Internal friction coefficient and compressed sample durometer hardness increased with decreasing moisture content; lignite/corn stover mixtures behaved more like Illinois #6/corn stover mixtures upon drying. Both of these observations were consistent with the inoperably high torque that was observed during pump startup for high moisture CBMs. However, the dependence of friction coefficient on applied load was not consistent with expected coal/biomass mixture behavior, and warranted further study through compressibility experiments.

The compressibility of CBMs was measured as a function of moisture content. In these experiments, a compressive load was applied and the change in sample volume and the degree to which the sample resisted compression were monitored. As shown in Figure 21, compressibility increased with increasing moisture content, and the rate at which the load increased in the sample (the sample resisted compression) increased with increasing moisture content. The high moisture lignite/corn stover mixture compressed to approximately 90% of its original volume, and built up load abruptly as it approached this limit. The dried lignite/corn stover

mixture compressed less, and built up load more gradually as the sample was compressed. The Illinois #6/corn stover mixture compressed even less, and also built up load more gradually as the sample was compressed.

Figure 21. Compressibility of 70/30 w/w coal/corn stover mixtures.

The compressibility results suggest that moisture content of CBMs affects how the mixtures “spring back” against applied load. An analogy can be made to Hookean spring behavior¹⁰. Springs having larger spring constant exert greater resistive force at the same deflection. Similarly, low moisture CBMs exert greater resistive force at a given deflection than high moisture CBMs. Further, at a given load, the degree of spring deflection decreases with increasing spring constant. Similarly, low moisture CBMs compress to a lesser degree than high moisture CBMs. This behavior is consistent with the observed pump performance: during pump startup, high moisture CBMs compress under applied load, and once they are fully compressed, they resist further load, thereby resulting in a sharp increase in applied torque to operate the pump, even in the absence of applied gas pressure. Low moisture CBMs compress more gradually under applied load, and thus allow for an operable torque requirement at a range of applied gas pressure. Some evidence of “springback” was

observed in pump trials: when pump rotation was stopped, lignite/corn stover mixture continued to extrude out of the pump outlet. Further work is needed to conclude that this “springback” behavior is a significant contributor to the jamming behavior observed in the pump for low-rank coal/biomass mixtures. In order to conduct such experiments, development of suitable test fixtures is necessary; thus it is recommended that this work be pursued under a future project.

These bench-scale material characterization experiments illustrate the effect of moisture content on CBMs, and suggest that drying high moisture CBMs (i.e., those based on PRB or lignite) can improve their handling behavior in the pump. However, as coal is dried beyond its equilibrium moisture content, the risk of self-ignition due to self-heating increases. Dried coal will re-equilibrate its moisture content by absorbing moisture from the environment. As moisture is absorbed, the latent heat of vaporization is released, causing a rise in temperature in the coal that can reach the ignition temperature of the coal. If the coal is mixed with a material that has a lower ignition temperature than coal (e.g., biomass), the risk of self-ignition is higher due to the lower mixture ignition temperature. In addition, the data suggests that the differences in behavior of low-rank coal/biomass mixtures compared to high-rank CBMs are not completely a function of coal moisture content; in other words, dried low-rank coal/biomass mixtures behave more similarly to high-rank CBMs, but not identically so. At a commercial scale, drying low-rank coal/biomass mixtures may be quite costly. As an alternative, a design concept is being developed that would allow the pump to adapt to the range of compressibility observed in high and low moisture CBMs.

4.4.4.3. Effect of Coal Moisture Content on Handling Performance

CBMs based on low-rank coals (PRB, lignite) were generally difficult to handle in the pump test rig equipment. Each mixture of low-rank coal with biomass could not reliably be fed to the pump inlet using the atmospheric pressure screw conveyor. As noted in Section 4.4.4.1, lignite/pine mixtures formed plugs in the screw conveyor, which warranted use of a vacuum-assisted pneumatic transfer method to feed the material to the pump. Alternatively, a manual method was employed to feed the material into the pump inlet hopper for later experiments. In all experiments attempted with low-rank coal/biomass mixtures, pressurized delivery could not be established due to high torque requirements, as discussed in previously in this section. This behavior was attributed to the increased compressibility of low-rank coal-based mixtures, which is linked to the coal moisture content as shown in Section 4.4.4.2. Future work is recommended to develop improved methods of handling low-rank coal/biomass mixtures, to enable pressurized delivery of those mixtures. This work should address drying the CBMs, employing atmospheric pressure handling techniques that are robust to the increased compressibility of high moisture CBMs, and developing a pump design that can adapt to highly compressible, high moisture CBMs.

4.4.5. Performance of 10 wt% Biomass Mixtures

In pump trial experiments focusing on 30 wt% and 50 wt% biomass mixtures with coal, as discussed in Sections 4.4.2 through 4.4.4, pressurized delivery was achieved for mixtures of Illinois #6 coal with switchgrass and corn stover. However, the maximum pressures achieved in these trials were at most one third that of the target value of 650 psi. Two approaches were taken to increase the maximum pressure capability demonstrated within this program. First, experiments with 10 wt% biomass mixtures were added to the test plan. These experiments will be discussed in Section 4.4.5.2. Second, experiments on these mixtures using a prototype pump outlet design were added to the test plan. This prototype pump outlet design was developed under a separate, GE-internal effort that was operating in parallel to this program. These experiments will be discussed in Section 4.4.5.3 and 4.4.6.

4.4.5.1. Properties of 10 wt% Biomass Mixtures

The 10 wt% biomass mixtures were prepared according to the same specifications and methods used for the 30 wt% and 50 wt% biomass mixtures. Upon receipt of the mixtures, material properties such as bulk density and moisture content were measured. The properties of these mixtures were directionally consistent with those of the 30 wt% and 50 wt% mixtures; for example, bulk density of the 10 wt% biomass mixtures was higher than that of the 30 wt% and 50 wt% biomass mixtures. The moisture content of the 10 wt% biomass mixtures with Illinois #6 was higher than expected, due to increased moisture content of this particular batch of coal. The effects of this increased moisture content were evident in the pump trial experiment results, as discussed in Section 4.4.5.2. The as-received properties of the 10 wt% biomass mixtures compared to the 30 wt% biomass mixtures of the same coals and biomasses are shown in Table 14.

Table 14. Summary of as-received properties of 10 wt% biomass mixtures compared to 30 wt% biomass mixtures.

Coal	Biomass	Biomass concentration, wt%	Tapped Bulk Density, lb/cuft	Moisture Content, wt%
Illinois 6	Switchgrass	30	36.3	6.2
Illinois 6	Switchgrass	10	46.3	12.6
PRB	Switchgrass	30	33.2	18.8
PRB	Switchgrass	10	43.9	23.4
Illinois 6	Corn Stover	30	35.5	6.5
Illinois 6	Corn Stover	10	45.4	12.3
PRB	Corn Stover	30	27.1	19.1
PRB	Corn Stover	10	41.4	23.6

4.4.5.2. Pump Performance with 10 wt% Biomass Mixtures

As shown in Figure 22 and Figure 23, the maximum pressures achieved for 10 wt% biomass mixtures were well below the target delivery pressure for this program (650 psi). A stable seal of solids was generated during pump startup, and continuous feeding of solids was achieved during the experiments. The maximum pressure achieved for the 10 wt% corn stover mixture with Illinois #6 was lower than anticipated because of slightly higher than anticipated moisture content, as shown in Figure 24.

Figure 22. Pump trial results for 10 wt% switchgrass mixtures with Illinois #6 at a pump outlet shape factor of 2.4.

The results of pressure test experiments using 10 wt% biomass mixtures are consistent with the trend of pressure capability with biomass concentration. The maximum pressure achieved in pump trial experiments increased with decreasing biomass concentration. This trend is illustrated in Figure 24, which compares the ratio of pump torque to outlet pressure at peak outlet pressure. This data also implies the effect of moisture content on pump performance, as elevated moisture content in the 10 wt% corn stover mixture with Illinois #6 led to less favorable performance (lower maximum outlet pressure and higher torque:pressure ratio).

Figure 23. Pump trial results for 90/10 Illinois #6/corn stover at a pump outlet shape factor of 2.4.

Figure 24. Trend of pump performance (ratio of operating torque to outlet pressure) with biomass concentration.

These results are consistent with the trends established in previous experiments of pressure capability with biomass concentration and coal moisture content. While high moisture coals were more challenging to handle, even low moisture CBMs could not be delivered against the target pressures using the pump configuration

employed. This result suggested that optimization of coal material properties would be insufficient to enable solids delivery at pressures >500 psi. To address this, proof of concept experiments employing a new pump design prototype were conducted.

4.4.5.3. Proof of Concept with New Pump Outlet Prototype

A proof of concept experiment to explore the utility of a new pump outlet design modification was conducted using 10 wt% biomass mixtures with Illinois #6. This prototype was designed to allow for greater control over the formation of a solids seal in the pump during startup and shutdown. Such control is expected to enable greater pressure capability for certain materials, including highly compressible CBMs. A prototype of this device was installed to the pump outlet. The shape of this device confers some degree of restriction to the solids flow exiting the pump, and can be modulated to accommodate different types of materials.

Initial test results indicated that the outlet modification device, in its first design iteration, was too restrictive to solids flow from the pump. In this initial test, the torque quickly increased to an inoperable level under atmospheric outlet pressure. Because stable pressurized delivery had been achieved in earlier experiments with 10 wt% biomass mixtures with Illinois #6 using the standard pump outlet design, it was clear that this behavior was a result of the new outlet design. Further design iterations of this outlet design modification are needed, and development of this device will continue in the future under a separate program.

After these initial tests, the outlet design prototype was removed from the pump unit, which resulted in a change in the effective pump outlet shape factor. This new pump outlet shape factor was approximately 1.8. Pump trials continued for 10 wt% biomass mixtures with this new outlet shape factor. For the CBMs tested, pressure capability increased significantly relative to prior experiments with 30 wt% biomass mixtures at higher pump outlet shape factor. As shown in Figure 25 and Figure 26, delivery pressures of 450 psi were attained for 10 wt% biomass mixtures with Illinois #6, which approaches the target delivery pressure for this program (650 psi). A stable solids seal was generated during pump startup, and continuous feeding of solids was achieved during the experiments. The maximum pressure achieved for the 10 wt% corn stover mixture with Illinois #6 was 457 psi and that for the 10 wt% switchgrass mixture with Illinois #6 was 450 psi.

Figure 25. Pump trial data from 10 wt% switchgrass with Illinois #6 mixture at pump outlet shape factor of 1.8.

Figure 26. Pump trial data from 10 wt% corn stover with Illinois #6 mixture at pump outlet shape factor of 1.8.

The coal/biomass mixture exiting the outlet pipe tended to agglomerate, which prevented the material from flowing smoothly into the pressurized receiving vessel. It is believed that this behavior contributed to the rise in torque near the end of these experiments, and greater pressure capability may be possible if the behavior is addressed. Further pump design modifications may include a de-agglomerating device at the outlet to mitigate this behavior.

Figure 27. Agglomerated 10 wt% corn stover with Illinois #6 mixture exiting the pump after 457 psi delivery.

Figure 28 and Figure 29 illustrate total vent flow vs. outlet pressure of the Posimetric pump during these experiments. As outlet pressure increased, vent flow through the outlet plug is reduced, indicating greater stability and compression of the material in the outlet. This behavior was consistent with expected pump performance at elevated pressures. These experimental results suggested that the pump design can be optimized for high pressure coal/biomass service, and that continued development of the pump outlet design modification is warranted.

Figure 28. Vent flow vs. outlet pressure for 90/10 w/w Illinois #6/switchgrass experiment.

Figure 29. Vent flow vs. outlet pressure for 10 wt% corn stover mixture with Illinois #6 experiment.

4.4.6. CBM Homogeneity

It is well known that solids mixtures, particularly those derived from materials having different particle sizes, are prone to segregation¹¹. Homogeneity of CBMs is important for robust operation of the Posimetric pump, as well as for a gasifier. The potential impact of mixture inhomogeneity in the Posimetric pump includes insufficient development of a solids seal, nonuniform solids throughput, and poorly controlled operating torque.

During the FY11 Advanced Fuels Peer Review, the Review Panel made the following recommendation to the team:

R1: Determine how to achieve homogeneity of the CBMs at larger scales.

The project team should find a way to control the gross homogeneity of CBMs to ensure optimum pump performance and reliability.

The risk of mixture inhomogeneity was identified early in the development of the project, and mitigation steps were incorporated into the proposed scope of work. Since this recommendation was made, the following actions have been taken to address the risk:

- Mixtures were prepared using methods specifically designed to ensure homogeneity of the CBMs prior to shipment to the test facility.

- Upon receipt from the vendor, mixtures were monitored for homogeneity, and were re-dispersed as needed to correct segregation that may have occurred during shipment.
- During the pump trials, homogeneity of mixtures was monitored visually at the pump outlet, and the uniformity of pump performance (torque, gas leakage rate, solids mass throughput) was monitored throughout the test to detect any effects of mixture inhomogeneity on pump performance.

Segregation of solids mixtures can be the result of a mismatch in particle size, due to percolation of fine particles through the spaces between larger particles. As shown in bench-scale experiments, permeability of CBMs decreased with decreasing biomass particle size. In order to achieve pressurized pump operation, the biomass particle size was specified such that 70 wt% of the biomass passed a 1 mm sieve. The coal particle size specification was 95 wt% passing a 1 mm sieve. This significant overlap in particle size distribution limits the potential for mixture segregation by particle size.

CBMs were prepared using a procedure designed specifically to ensure mixture homogeneity and accurate composition (coal:biomass mass ratio). Coal and biomass were carefully metered into lined shipping containers (drums), using empirically determined equipment settings that ensured continuous metering of coal and biomass at uniform feeding rates. Once the drums were filled, the mixtures were inerted with nitrogen and the plastic drum liners were sealed. The drums were then rotated on a drum roller for 30 minutes, and every 5 minutes the drum was inverted. In this way, the CBMs were prepared to a target composition and thoroughly dispersed.

Upon receipt of the mixtures from the vendor, each barrel of mixture was rotated on a drum blender to redisperse the material and reverse any segregation that may have occurred during shipment. Representative samples were taken from each drum of each mixture for particle size analysis by sieving.

During each pump trial experiment, the uniformity of pump performance was monitored, in an effort to identify if material inhomogeneity contributed to poorly controlled operating torque, insufficient solids seal development, or nonuniform solids throughput. In addition, coal/biomass mixture particle size distribution, moisture content, and bulk density were monitored before and after each pump trial. While some variation in torque, leakage rate, and solids throughput was typically observed during pump trials, this variation was not indicative of the negative effects of gross mixture segregation. The mixture property data, a typical example of which is shown in Figure 30, supports this observation; negligible changes in particle size distribution, moisture content, and bulk density were observed.

Figure 30. Coal/biomass mixture property data collected before and after pump experiments, illustrating little change in mixture properties.

In contrast, the data shown in Figure 31 and Figure 32 illustrates an example of a run condition wherein material inhomogeneity may have contributed to poor pump operation. In this test, a stable seal could not be generated in the pump as the outlet pressure was established, which was unexpected given past experience with the mixture components (Illinois #6 coal and switchgrass biomass) at higher biomass concentrations. The data shows that the outlet plug was not stable as indicated by the wide swings in torque (Figure 31) and the vent flow/outlet pressure relationship (Figure 32). This data also suggests possible difficulty in feeding the material uniformly into the pump. Inspection of the mixture properties (Figure 33) indicates that significant material attrition occurred during this test. These observations suggest a possible effect of mixture inhomogeneity. Mixture inhomogeneity was not detected from visual inspection of the material exiting the pump during the test.

Figure 31. Pump trial data illustrating the effects of coal/biomass mixture

inhomogeneity on pump performance.

Figure 32. Pump trial data illustrating the effects of coal/biomass mixture inhomogeneity on pump performance.

Figure 33. Coal/biomass mixture property data collected before and after pump experiments, illustrating a significant change in mixture properties.

After this experiment, this mixture, 10 wt% corn stover mixed with Illinois #6, was redispersed according to the standard procedure for mixture handling described above. The pump trial experiment was repeated, and yielded the experimental data shown in Figure 26 and Figure 29. This second experiment reflects the performance expected of this mixture given past experience with Illinois #6/corn stover mixtures of higher biomass concentrations and 10 wt% switchgrass mixture with Illinois #6. It is unclear why the mixture performed so differently in the pump at first; however

performance was restored upon redispersion of the mixture, which reinforces the importance of maintaining a homogeneous mixture. As this technology is further developed, solids handling practices and equipment should continue to be defined with management of mixture homogeneity in mind.

4.5. ECONOMIC ASSESSMENT

To quantify the economic impact of using the Posimetric pump for high-pressure delivery of CBMs, a preliminary economic evaluation was performed. The preliminary economic analysis of coal/biomass dry-feeding leveraged the experimental results generated in the program related to biomass pretreatment and Posimetric pump operation. INL performed the analysis related to biomass pretreatment, while GE analyzed the Posimetric pump results and integrated these separate analyses into an overall estimate of coal/biomass mixture handling and pressurization using the Posimetric pump. A schematic of the conceptual feedstock handling system (based on herbaceous biomass) is shown in Figure 34, which illustrates the structure of the economic analysis.

Figure 34. Schematic of herbaceous feedstock handling system for CBTL facility.

4.5.1. Biomass Feedstock Cost

The economics of commercial-scale biomass pretreatment were determined using INL's Feedstock Supply System Logistics Model. This tool uses an engineering-economic approach for cost estimation of biomass handling and pretreatment systems and includes the effects of equipment, labor, consumables/supplies, taxes, and energy as presented by the American Society of Agricultural Engineers (ASAE 2001). This cost estimation tool also reflects other calculations and correlations based on research at INL to capture process step interface dynamics and logistics. The equipment required for biomass pretreatment was determined based on the desired particle size and the moisture content for each coal/biomass mixture as defined in the experimental phase of this program and discussed above. Biomass pretreatment equipment includes grinders, mills, screening systems, driers, solids conveyance equipment, and solids mixers to create uniform CBMs.

The biomass feedstock supply system model was developed based on an annual supply of 800,000 dry metric tons of biomass for a biomass conversion facility (CBTL plant). This feedstock is sourced from within a radius of 50 miles from the CBTL facility according to what is referred to as a "conventional" feedstock supply arrangement. In such a system, which is reflective of current practices for biomass harvesting, biomass is collected at the point of harvest, processed into a form that is suitable for transport, transported to a CBTL facility, and dried and ground to the specifications for the CBTL process. Cost reduction and other supply chain optimization is believed to be attainable through adoption of an advanced feedstock supply system^{12,13,14}, wherein biomass of different types is accumulated at regional preprocessing depots, and is subsequently transported to central biomass distribution facilities. This model, which resembles the grain commodity system, is currently under development. For the purpose of this economic analysis, costs reflecting the conventional biomass supply system are used, to yield a conservative estimate of biomass feedstock cost and to reflect the capabilities of current biomass logistics infrastructure.

Separate analyses were conducted for woody and herbaceous biomass to account for the differences in biomass harvest and pretreatment methods needed for the different biomass types. The cost of biomass as delivered to the plant gate of a CBTL facility reflects capital, operating, and transportation costs associated with biomass harvest and collection, preprocessing, transportation and handling, and grower's payment as illustrated in Figure 34 and shown in Figure 35. Plant receiving, storage, queuing, and in-feeding processing costs will be included in the operating costs for the plant. The plant-gate feedstock cost is used as an input to the CBTL feedstock handling economic model. These costs are shown in Figure 35 a) and b) for woody and herbaceous biomass. Further details of these analyses are documented in separate reports, and are provided in Appendix I and II of this report.

Woody biomass		Herbaceous biomass	
Cost Summary in 2007 USD		Cost Summary in 2007 USD	
	\$/dry metric ton		\$/dry metric ton
Feedstock Cost for Analysis	\$ 57.30	Feedstock Cost for Analysis	\$ 49.35
In-Plant CapEx	\$ 5.25	In-Plant CapEx	\$ 1.40
In-Plant OpEx	\$ 19.45	In-Plant OpEx	\$ 1.25
Total Feedstock Cost	\$ 82.00	Total Feedstock Cost	\$ 52.00
Total Logistics Cost	\$ 66.80	Total Logistics Cost	\$ 36.10
Total Grower Payment	\$ 15.20	Total Grower Payment	\$ 15.90
Harvest & Collection		Harvest & Collection	
Total Cost Contribution	\$ 19.40	Total Cost Contribution	\$ 13.80
Capital Cost Contribution	\$ 5.65	Capital Cost Contribution	\$ 5.20
Operating Cost Contribution	\$ 13.75	Operating Cost Contribution	\$ 8.60
Plant Receiving, Storage, Queuing, & In-Feed Processing		Storage and Queuing	
Total Cost Contribution	\$ 24.70	Total Cost Contribution	\$ 2.65
Capital Cost Contribution	\$ 5.25	Capital Cost Contribution	\$ 1.40
Operating Cost Contribution	\$ 19.45	Operating Cost Contribution	\$ 1.25
Preprocessing		Preprocessing	
Total Cost Contribution	\$ 12.20	Total Cost Contribution	\$ 10.65
Capital Cost Contribution	\$ 4.20	Capital Cost Contribution	\$ 1.80
Operating Cost Contribution	\$ 8.00	Operating Cost Contribution	\$ 8.85
Transportation & Handling		Transportation & Handling	
Total Cost Contribution	\$ 10.50	Total Cost Contribution	\$ 9.00
Capital Cost Contribution	\$ 3.55	Capital Cost Contribution	\$ 1.50
Operating Cost Contribution	\$ 6.95	Operating Cost Contribution	\$ 7.50

a)

b)

Figure 35. Plant-gate feedstock cost estimates for a) woody and b) herbaceous biomass.

As illustrated in Figure 34, herbaceous biomass (switchgrass or corn stover) is harvested and field dried, resulting in material containing typically 15-20 wt% moisture content, depending on weather conditions during harvest. This material is baled for transport by truck to the CBTL facility. Within the CBTL facility, the bales are ground to the particle size distribution specification established in the bench-scale phase of this program. While biomass grinding equipment lies within the plant gate of the CBTL facility, for this analysis the costs are included within the biomass feedstock cost shown in Figure 35.

Figure 36. Schematic of woody feedstock handling system for CBTL facility.

As illustrated in Figure 36, woody biomass is harvested and ground for transport, resulting in material that may contain as much as 60 wt% moisture and is sized according to the particle size distribution specification established in the bench-scale phase of this program. This biomass is transported to the CBTL facility, where it is dried to the moisture content specifications defined in the bench-scale phase of this program. While this drying operation occurs within the CBTL facility, for this analysis the costs are included within the biomass feedstock cost shown in Figure 35. The increased cost of woody biomass relative to herbaceous biomass is primarily due to the active drying required for woody biomass, since the herbaceous biomass is dried in the field (i.e., by the sun). The operating cost of harvest is the second largest contributor to this cost difference, and is a reflection of the difference in efficiency of harvesting processes for wood compared to those for herbaceous biomass. Herbaceous biomass is typically planted in uniform rows, whereas woody biomass is grown in groups of trees that are not necessarily uniformly dispersed.

4.5.2. Feedstock Handling and Pressurization for CBTL Facility

This economic analysis quantified the incremental cost of incorporating biomass capability into the feedstock handling and pressurization systems of a CBTL facility, relative to coal-only service. The baseline for this economic analysis, that of a dry solids handling and pressurization system for a 100% coal facility, was derived from

an analysis performed under a separate DOE contract¹⁵. The cost of incorporating biomass handling capability was added to this baseline, given the experimentally-generated estimates of pump performance. The contributions of feedstock, operating, and capital costs to the total incremental cost of biomass capability were quantified, and the sensitivity of these costs to the type of coal, type of biomass, and concentration of biomass were estimated. These results are shown in Figure 37 in terms of \$/MJ of feedstock delivered. These units were selected to better illustrate the effect of biomass' energy density on the economics of feedstock handling.

The economic analysis was performed assuming a basis of a constant pump size; the physical size of the Posimetric pump was held constant, and feedstock throughput was estimated based on the experimental results of this program. Addition of facilities and equipment for dry biomass storage and generation of uniform CBMs was captured in the incremental cost of biomass service for the conceptual system, as shown in Figure 34.

Figure 37. Summary of feedstock and feedstock handling and pressurization costs for CBMs relative to 100% coal.

4.5.2.1. Effect of Bulk Density on Capacity

The mass throughput of CBMs and the accompanying energy feed rate was compared to that of 100% coal service to assess biomass' potential impact on capacity of the feedstock handling system. Because pump size was held constant, the volumetric throughput of feedstock through the handling system was also held constant. As shown in Figure 38, this resulted in a reduction in estimated coal/biomass mixture mass throughput, due to the decrease in bulk density with increasing biomass content. In addition, the energetic feed rate of CBMs to the gasifier was less than that of 100% coal, since biomass is less energy dense than coal.

Figure 38. Feedstock mass throughput for CBMs relative to 100% coal at constant volumetric throughput.

4.5.2.2. Feedstock Cost

In this assessment, feedstock cost is large relative to the operating and capital costs of the feedstock handling system for a CBTL facility, as is evident from Figure 37. Average coal spot prices for the year 2011, as obtained from the Energy Information Administration (EIA)¹⁶, were used for this analysis, as shown in Table 15. Coal was assumed to be transported by rail from the mine to a hypothetical CBTL facility

located in southern Indiana. Coal transportation costs were accounted for using a cost factor that was based on assumed transportation distance, average spot prices for diesel fuel¹⁷, and estimated locomotive fuel mileage.

Table 15. Coal spot prices and delivery cost factors used in economic analysis.

Coal Type	Sample ID	Spot Price, \$/ton		Mine Location	Transportation Cost Factor	Plant Gate Price, \$/ton	
Bituminous	Illinois 6	\$	51	Illinois	1.1	\$	56
Sub-Bituminous	PRB	\$	14	Montana	3	\$	42
Lignite	Lignite	\$	17	North Dakota	2	\$	34

As is evident from comparison of Figure 35 and Table 15, biomass is generally more costly than coal. Thus, as more biomass is incorporated into the feedstock blend, the average price of feedstock increases relative to 100% coal for a given coal type. When the costs are reported in terms of \$/MJ of feedstock delivered, this effect is amplified, since the energy density of biomass is less than that of coal.

Of the coals studied, PRB and Lignite are significantly less costly than Illinois #6, which results in lower feedstock cost in those cases relative to Illinois #6. However, as will be discussed in the next section, the operating cost associated with processing lower-quality coals is higher than that for Illinois #6, due to the need for drying.

4.5.2.3. Operating Cost

Operating conditions identified in pump trial experiments were translated into estimates of operating costs for a commercial-scale dry feeding system based on the Posimetric solids pump. For example, pump drive torque was used to estimate the power required to operate the pump. Operating cost for the coal grinding, drying, atmospheric pressure conveyance, and Posimetric pump operation for 100% coal were extracted from the aforementioned 100% coal dry-feeding analysis¹⁵. As discussed in Section 4.5.1, the cost of biomass grinding and drying is included within the biomass feedstock costs. Utility costs were based on 2011 average electricity and natural gas prices as obtained from the EIA^{18,19}. Operating costs include energy to dry coal to <20 wt% moisture, power to operate the coal mill, power to operate the coal/biomass mixing equipment, in-plant biomass receiving, storage, queuing, and in-feed processing (as shown in Figure 35) and power to operate the Posimetric pump. Note that operating cost related to biomass feedstock harvest and pretreatment is included in the biomass feedstock cost, as discussed in Section 4.5.1.

As shown in Figure 37, operating costs for Illinois #6/biomass mixtures are moderately higher than those for 100% Illinois #6 coal. Operating costs for in-plant feedstock handling of woody biomass is greater than that of herbaceous biomass due to the higher drying requirements noted in Section 4.5.1. Similarly, operating cost for CBMs based on lower-quality coals is significantly higher than that for Illinois #6 coal and Illinois #6/biomass mixtures due to the drying requirements for the lower

rank coals. Both PRB and lignite must be dried to reach the 20 wt% moisture requirement for the handling system, while the as-received moisture content of Illinois #6 meets this specification. As discussed in Section 4.4.4, low-rank coal/biomass mixtures were much more difficult to handle due to high moisture content, but that drying the coal may improve the mixture handling behavior. If feedstock handling systems can be optimized to accommodate high moisture coal/biomass mixtures, low-rank coal/biomass mixtures may potentially be less costly than Illinois #6/biomass mixtures due to reduced feedstock cost.

4.5.2.4. Capital Cost

Capital cost for coal/biomass mixture handling was estimated as follows. The bulk of the handling equipment needed for a CBTL facility is identical to that needed for a coal gasification facility. Thus, the equipment costs for a 100% coal facility were extracted from the aforementioned low-rank coal dry-feeding analysis¹⁵. This included equipment for coal grinding, drying, atmospheric pressure conveyance, the Posimetric pump, and associated supporting equipment (e.g., blowers, pressure vessels, control systems). Equipment needed for biomass handling (mixers, coal and biomass metering equipment, covered biomass storage) was added to this estimate based on vendor cost estimates. Capital cost for this equipment did not vary significantly with coal type or biomass type. The increase in capital cost observed with increasing mixture biomass content is due to the need for larger covered biomass storage with increasing mixture biomass content.

5. CONCLUSIONS AND RECOMMENDATIONS

Bench-scale characterization of CBMs resulted in specification of biomass particle size and scalable pretreatment methods that yield biomass that is compatible with pressurized Posimetric pump operation. This optimization balanced economics, which favor larger particle sizes, with flowability and permeability, which favor smaller, lower aspect ratio particles. Pretreated biomass aspect ratio was linked to screen size and biomass type. Ultimately, biomass was hammermilled through a 2 mm screen for use in pump trial experiments.

Biomass moisture content was also optimized, based on bench-scale characterization experiments. This optimization balanced economics, which favor wetter biomass, with flowability, which favors drier biomass. Ultimately, biomass moisture content was specified at a maximum of 10 wt% for use in pump trial experiments. However, 15-20 wt% moisture content may be acceptable for some biomass materials. Moisture-related degradation of CBMs in storage was observed in this program in pilot scale experiments, which reinforces the importance of managing moisture content of biomass in storage. To minimize degradation in storage and ensure operable flowability in process equipment, covered biomass storage and quality control and monitoring of biomass moisture content should be employed in CBTL facilities.

Bench-scale mixture characterization methods and the resulting models of pump performance adequately predict the permeability performance of CBMs in the Posimetric pump. Addition of biomass to coal results in increased permeability due to increased average particle size, which translates to the need for higher pump outlet shape factor than that needed for 100% coal to manage increased gas vent flow through the solids seal.

Pressure capability of the Posimetric pump on CBMs was demonstrated for a range of pump outlet shape factors, biomass loadings, and coal and biomass types. The highest pressure capability achieved in the scope of this program was in excess of 450 psi as demonstrated for 10 wt% biomass mixtures in Illinois #6 coal using an optimal pump outlet shape factor. CBMs based on low-rank coal were found to be quite challenging to feed into the pump inlet, and once inside the pump required inoperably high torque to achieve delivery at atmospheric pressure. This performance was linked to the high moisture content of the low-rank coal, which appears to cause increased compressibility of the material relative to bituminous coal. Comparison of the pump trial results with the predicted pump performance derived from the bench-scale experiments indicated that the bench-scale experiment protocol may need to be modified to better characterize the impact of the compressibility of highly compressible CBMs. Improved characterization of this behavior will result in more accurate estimates of torque requirements to operate the pump at pressure and the maximum pressure capability of the pump.

Homogeneity of coal/biomass mixtures was monitored throughout the pump trial apparatus, and every possible effort was made to ensure uniform homogeneity of the mixtures during experiments. The effect of mixture inhomogeneity was observed in pump trial experiments, which reinforces the importance of managing this behavior in solids processing equipment.

An analysis of the contribution of feedstock and solids handling to CBTL economics was performed. Bituminous coal/biomass mixtures containing 10 wt% biomass were estimated to be 5-10% more costly than bituminous coal alone, which reflects increased biomass feedstock cost (which includes pretreatment and transportation costs), increased capital cost for equipment needed to accommodate biomass handling, and reduced bulk and energy density of biomass compared to coal. Compared to 100% bituminous coal, low-rank coal/biomass mixtures are comparably or more costly; while low-rank coal is a less costly feedstock, its higher moisture content requires additional drying expense. If feedstock handling systems can be optimized to accommodate high moisture coal/biomass mixtures, low-rank coal/biomass mixtures may become more economically attractive than bituminous coal/biomass mixtures due to lower feedstock cost.

6. FUTURE WORK

Beyond this project, future work to develop Posimetric pump technology for use with coal/biomass mixtures should focus on optimization of the pump outlet design. The results obtained from this program suggest that further design optimization is possible to enable greater control over the development of the solids seal during pump operation on highly compressible solids. To advance the development of Posimetric pump technology for dry-feeding CBMs, the following items should be addressed in future efforts:

- Continue to develop pump outlet design to accommodate highly compressible solids
- Optimize feedstock handling systems to be robust to high moisture content coal and coal/biomass mixtures
- Develop feedstock handling systems that are robust to or actively manage/prevent segregation of coal/biomass mixtures

7. LIST OF ACRONYMS AND ABBREVIATIONS

CBM	Coal/Biomass Mixture
DOE	US Department of Energy
DOEx	design of experiments
EIA	Energy Information Administration
GE	General Electric Company
INL	Idaho National Laboratory
NETL	National Energy Technology Laboratory
PRB	Powder River Basin
PSD	particle size distribution
R&D	research and development
SCFM	standard cubic feet per minute
UPA	ultimate and proximate analysis

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9. APPENDIX I: WOODY BIOMASS FEEDSTOCK SUPPLY SYSTEM

WOODY BIOMASS FEEDSTOCK SUPPLY SYSTEM

INL/EXT-12-25020

CBTL DESIGN CASE SUMMARY

Conventional Feedstock Supply System—Woody

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Erin M Searcy

February 2012

WOODY BIOMASS FEEDSTOCK SUPPLY SYSTEM

2012 DESIGN CASE SUMMARY

Conventional Feedstock Supply System—Woody

A conventional woody feedstock design has been developed that represents supply system technologies, costs, and logistics that are achievable today for supplying woody biomass as a blendstock with coal for energy production. Efforts are made to identify bottlenecks and optimize the efficiency and capacities of this supply system, within the constraints and consideration of existing local feedstock supplies, equipment, and permitting requirements.

The feedstock supply system logistics operations encompass all of the activities necessary to move woody biomass from the production location to the conversion reactor ready for blending and insertion (Figure 1). This supply system includes operations that are currently available such that costs and logistics are reasonable and reliable. In fact, depending on the quality of woody material needed, a second material stream consisting of slash (the limbs and tops of trees) can be fed through the chipper to decrease total system dry matter loss, or can be discarded to remove higher ash containing bark. The system modeled for this research project includes the use of the slash stream since it is a more conservative analysis and represents the material actually used in the experimental part of the project. A schematic of the system is shown in Figure 1.

Figure 1. INL researches material properties and equipment performance from the point of harvest to infeed into the conversion reactor. The Conventional woody biomass feedstock supply system incorporates existing or near-term equipment and practices.

Conventional Feedstock Supply System—2011

A baseline set of parameters have been established so that the modeled supply system design can feed conversion facilities that have similar demands as previously reported thermochemical¹ pathways (Table 1). Thus the modeled design uses transpirationally² dried fir and pine (Northwest US varieties) as a feedstock to supply a conversion facility that depends on a year-round biomass delivery schedule with 800,000 dry metric (DM) tons of biomass annually.

Table 1. The Conventional woody biomass supply system scenario is scaled to support current baseline thermochemical conversion facility designs.

	Woody Biomass
Plant Operation Size (delivered tons ^a)	800,000 DM ton/yr
Feedstock Harvested Annually ^b	1,403,500 DM ton/yr
% Supply Area Under Cultivation	100
% Cropland in Supply Area Cultivated	100
% Farmer Participation	100
Acres Harvested Annually	59,095
Feedstock Supply Radius	50 miles

a. U.S. short ton = 2,000 lb.

b. Extra tonnage harvested to account for supply system losses.

In the Conventional scenario, fir and pine trees are harvested and piled in the forest. The trees are transpirationally dried prior to being moved to the landing, where they are stacked and loaded into a flail debarker to remove bark and limbs. The delimbed, debarked trees are fed into a chipper, which ejects material into a chip van for transport to the conversion facility. A second material stream is created by feeding the limbs through the chipper, which reduces dry matter losses in the system. At the conversion facility, chips are received and placed into storage. Stored chips are then queued for additional preprocessing and blending prior to insertion.

The modeled conversion size specification is a nominal particle size of 3/16-inch (based on grinder screen size). Through experimentation, this size of particles has exhibited satisfactory flow and blending characteristics necessary for a suitable blendstock with coal. Table 2 shows the mean particle size of the pine material compared with corn stover (CS) and switchgrass (SW). The mean particle size is 0.735 mm with a distribution represented in Figure 2.

¹ Phillips S, A Aden, J Jechura, D Dayton, T Eggeman (2007) Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass, NREL Technical Report, TP-510-41168, National Renewable Energy Laboratory, Golden, Colorado.

² "Transpiration" refers to natural drying as a result of water loss by evaporation in terrestrial plants

WOODY BIOMASS FEEDSTOCK SUPPLY SYSTEM

Table 2. Particle characteristics. X_c min represents the geometric mean diameter (d_{gw}) with the geometric mean diameter standard deviation (S_{gw}) shown in parenthesis. The sphericity (SPHT) and aspect ratio are also listed, where the aspect ratio is the ratio between X_c min and X_{re} max.

Particle Characteristics	CS	SW	PC
X_c min (S_{gw}), mm	0.582 (0.817)	0.678 (1.122)	0.735 (0.771)
X_{re} max (S_{gw}), mm	1.351 (2.076)	1.744 (2.857)	1.652 (1.784)
1/SPHT ^b	2.456 (0.164)	2.784 (0.052)	2.525 (0.029)
Aspect Ratio ^b	0.475 (0.007)	0.431 (0.002)	0.470 (0.002)

^a Number enclosed in the parenthesis were standard deviation with $n = 3$

^b Aspect ratio and SPHT are dimensionless parameters.

Figure 2. Particle size distribution. The derivative of the cumulative passing size distribution, %/mm, (Rhodes & Ebooks, 2008), (4a) and cumulative passing, % (4b) of nominal 3/16-inch pine grind.

Conventional Design Costs

Costs for the conventional woody biomass design used in this project were modeled using the feedstock supply system model developed at INL. A baseline scenario was established using metrics that are consistent with current thermochemical conversion pathway reports since these reports use woody biomass as the feedstock source. These costs include labor, fuel, material, and equipment (comprised of owner and operating costs) for all operations necessary to move the biomass from standing in the forest to the point of blending with other feedstock or directly feeding the conversion process. The modeled costs are shown in Table 2.

Conventional Feedstock Supply System—2011

Table 2. Unit operation costs in a Conventional Feedstock Supply System (2007 USD per dry matter (DM) ton*), for the scenario using mixed pine as a feedstock.

Cost Summary in 2007 USD	
	\$/DM ton
Total Feedstock Cost	82.00
Total Logistics Cost	66.80
Total Grower Payment³	15.20
Harvest & Collection	
Total Cost Contribution	19.40
Capital Cost Contribution	5.65
Operating Cost Contribution	13.75
Preprocessing	
Total Cost Contribution	12.20
Capital Cost Contribution	4.20
Operating Cost Contribution	8.00
Transportation & Handling	
Total Cost Contribution	10.50
Capital Cost Contribution	3.55
Operating Cost Contribution	6.95
Plant Receiving, Storage, Queuing, & In-Feed Processing	
Total Cost Contribution	24.70
Capital Cost Contribution	5.25
Operating Cost Contribution	19.45

* Grower payment estimates provided by Oak Ridge National Laboratory

Summary

This Conventional woody design is a baseline design for meeting the material specification targets set forth in the CBTL Project between INL and GE Global Research. This analysis reveals key parameters and unit operations that contribute to the cost of a conventional woody design. The challenges faced by this design, in terms of cost, are driven by the logistics of the system where moving large quantities of a bulky, unstable, non-flowable material is inherent. Despite these challenges, the technology exists that will allow for relatively large amounts of woody material to be harvested, collected, preprocessed, and delivered to a conversion facility as a standalone feedstock or as a blendstock for energy production.

³ Langholtz, M., Graham, R.C., Eaton, L., Perlack, R., Hellwinckel, C., De la Torre Ugarte, D., in review. Price Projections of Feedstocks for Biofuels and Biopower in the U.S. Energy Policy.

WOODY BIOMASS FEEDSTOCK SUPPLY SYSTEM

Motivation for a Commodity-Driven System

The U.S. DOE aims to displace 30% of the 2004 gasoline use with biofuels (60 billion gal/yr) by 2030. Of those 60 billion gallons, 15 billion are projected to come from grains, and the remaining 45 billion from lignocellulosic resources. This means that of the 700 million DM tons of biomass required annually, 530 million DM tons will come from a diverse variety of herbaceous and woody lignocellulosic biomass resources (also referred to as “cellulosic” biomass). In order for the biofuels industry to be a self-sustaining enterprise, the lignocellulosic feedstock supply system logistics (all processes involved in getting the biomass from the field to the conversion facility) cannot consume more than 25% of the total cost of the biofuel production.

While national assessments⁴ identify sufficient biomass resource to meet the production targets, much of that resource is inaccessible using current biomass supply systems because of unfavorable economics. Therefore, conventional biomass supply systems are incapable of meeting these long-term biomass use goals. Increasing the demand for lignocellulosic biomass introduces many logistical challenges to providing an economic, efficient, and reliable supply of quality feedstock to the biorefineries.

The design report, *Uniform-Format Solid Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Biocrude from Lignocellulosic Biomass*, documents an approach to address these logistic challenges by implementing a strategy of incremental change from existing biomass supply systems to economic and reliable commodity-scale supply systems that provide uniform, aerobically stable, quality-controlled feedstocks to biorefineries. This approach has been demonstrated and proven successful for feed grains. For woody resources, these design increments are termed “Conventional,” which reflects current practice and was presented in this case study, “Pioneer Uniform,” which uses current or very near-term technologies and offers incremental improvements over the Conventional Bale system, and “Advanced Uniform,” which meets all cost and supply targets and requires some conceptual equipment, such as a single-pass harvester, to provide a commodity-scale bulk liquid feedstock.

The Pioneer Uniform design enables the transition from the Conventional to the Advanced Uniform supply system by developing the supply chain infrastructure required for forward-deployed preprocessing. The Advanced Uniform system brings biomass of various types (i.e., herbaceous, woody) and physical characteristics (i.e., bulk densities, moisture content) into a standardized format early in the supply chain. This uniform material format allows biomass to be handled as a commodity that can be bought and sold in a market, vastly increasing its availability to the biorefinery and enabling large-scale facilities to operate with a continuous, consistent, and economic feedstock supply. The commodity-scale system also releases biorefineries from contracting directly with local farmers for biomass feedstocks. Figure 3 shows a schematic of the end-state commodity supply system for all types of lignocellulosic biomass resources.

⁴ Perlack RD, LL Wright, AF Turhollow, RL Graham, BJ Stokes, DC Erbach (2005) Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply, DOE/GO-102005-2135.

Conventional Feedstock Supply System—2011

Figure 3. The Advanced Uniform-Format feedstock supply system resembles the grain commodity system, which manages crop diversity at the point of harvest and/or the storage elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources.

10. APPENDIX II: HERBACEOUS BIOMASS FEEDSTOCK SUPPLY SYSTEM

HERBACEOUS BIOMASS FEEDSTOCK SUPPLY SYSTEM

INL/EXT-12-25021

CBTL DESIGN CASE SUMMARY

Conventional Feedstock Supply System—Herbaceous

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February 2012

HERBACEOUS BIOMASS FEEDSTOCK SUPPLY SYSTEM

2012 DESIGN CASE SUMMARY

Conventional Feedstock Supply System—Herbaceous

A conventional bale feedstock design has been established that represents supply system technologies, costs, and logistics that are achievable today for supplying herbaceous feedstocks as a blendstock with coal for energy production. Efforts are made to identify bottlenecks and optimize the efficiency and capacities of this supply system, within the constraints of existing local feedstock supplies, equipment, and permitting requirements.

The feedstock supply system logistics operations encompass all of the activities necessary to move herbaceous biomass feedstock from the production location to the conversion reactor ready for blending and insertion (Figure 1). This supply system includes operations that are currently available such that costs and logistics are reasonable and reliable. The system modeled for this research project includes the uses of field-dried corn stover or switchgrass as a feedstock to annually supply an 800,000 dry metric (DM) ton conversion facility (Table 1). A schematic of the system is shown in Figure 1.

Figure 1. INL researches material properties and equipment performance from the point of harvest to infed into the conversion reactor. The Conventional Bale biomass feedstock supply system incorporates existing or near-term equipment and practices.

In order to establish a baseline system, a set of parameters has been established so that the modeled supply system design can feed conversion facilities based on previously reported biochemical¹ pathways (Table 1). Even though the current project is not focused on biochemical conversion as the end use of the feedstock, the design, and thus the feedstock modeled, can be used to feed a thermochemical or direct combustion facility without any changes to the base assumptions. Thus, the modeled design uses field-dried corn stover or switchgrass as the feedstocks to supply a conversion facility that depends on a year-round biomass delivery schedule with 800,000 DM tons of biomass annually.

¹ Aden A, M Ruth, K Ibsen, J Jechura, K Neeves, J Sheehan, B Wallace, L Montague, A Slayton, J Lukas (2002) Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover, NREL/TP-510-32438, <http://www.nrel.gov/docs/fy02osti/32438.pdf>

2011 Conventional Feedstock Supply System

Table 1. The Conventional Bale–Corn Stover/Switchgrass supply system scenario is scaled to support current baseline conversion facility designs.

	Corn Stover/Switchgrass
Plant Operation Size (delivered tons ^a)	800,000 DM ton/yr
Feedstock Harvested Annually ^b	842,100 DM ton
% Supply Area Under Cultivation	50%
% Cropland in Supply Area Cultivated in Corn	50%
% Farmer Participation	50%
Acres Harvested Annually	261,900
Feedstock Supply Radius	45.4 miles

a. U.S. short ton = 2,000 lb.

b. Extra tonnage harvested to account for supply system losses.

In the Conventional Bale scenarios, stover/switchgrass is left in the field after harvest. It is then windrowed and dried in the field and later baled. The baled material is stacked at roadside where it is covered and stored until needed at the conversion facility. The stored bales are transported via truck to the conversion facility, where they are received and undergo further processing and blending to meet specifications for the conversion process.

In order for the baled material to meet conversion specifications it is size-reduced at the conversion facility prior to blending. The modeled conversion size specification is a nominal particle size of 3/16-inch (based on grinder screen size). Through experimentation, this size of particles has exhibited satisfactory flow and blending characteristics necessary for a suitable blendstock with coal. Table 2 shows the mean particle size of the corn stover (CS) and switchgrass (SW) material compared with pine (PC). The mean particle size for corn stover is 0.582 mm and for switchgrass is 0.678 mm with a distribution represented in Figure 2.

Table 2. Particle characteristics. X_c min represents the geometric mean diameter (d_{gm}) with the geometric mean diameter standard deviation (S_{gm}) shown in parenthesis. The sphericity (SPHT) and aspect ratio are also listed, where the aspect ratio is the ratio between X_c min and X_c max.

Particle Characteristics	CS	SW	PC
X_c min (S_{gm}), mm	0.582 (0.817)	0.678 (1.122)	0.735 (0.771)
X_c max (S_{gm}), mm	1.351 (2.076)	1.744 (2.857)	1.652 (1.784)
1/SPHT ^b	2.456 (0.164)	2.784 (0.052)	2.525 (0.029)
Aspect Ratio ^b	0.475 (0.007)	0.431 (0.002)	0.470 (0.002)

^a Number enclosed in the parenthesis were standard deviation with $n = 3$

^b Aspect ratio and SPHT are dimensionless parameters.

HERBACEOUS BIOMASS FEEDSTOCK SUPPLY SYSTEM

Figure 2. Particle size distribution. The derivative of the cumulative passing size distribution, %/mm, (Rhodes & Ebooks, 2008), (4a) and cumulative passing, % (4b) of nominal 3/16-inch pine grind.

Conventional Design Costs

Costs for the conventional bale design used in this project were modeled using the feedstock supply system model developed at INL. A baseline scenario was established using metrics that are consistent with current biochemical conversion pathway reports, since these reports use herbaceous biomass as the feedstock source. These costs include labor, fuel, material, and equipment (comprised of owner and operating costs) for all operations necessary to move the biomass from standing in the field to the point of blending with other feedstock or directly feeding the conversion process. The modeled costs are shown in Table 2.

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Table 2. Unit operation costs in a Conventional Feedstock Supply System (2007 USD per dry matter (DM) ton*), for the scenario using cornstover/switchgrass as a feedstock.

Cost Summary in 2007 USD	
	\$/DM ton
Total Feedstock Cost	52.00
Total Logistics Cost	36.10
Total Grower Payment²	15.90
Harvest & Collection	
Total Cost Contribution	\$13.80
Capital Cost Contribution	\$5.20
Operating Cost Contribution	\$8.60
Storage and Queuing	
Total Cost Contribution	\$2.65
Capital Cost Contribution	\$1.40
Operating Cost Contribution	\$1.25
Preprocessing	
Total Cost Contribution	\$10.65
Capital Cost Contribution	\$1.80
Operating Cost Contribution	\$8.85
Transportation & Handling	
Total Cost Contribution	\$9.00
Capital Cost Contribution	\$1.50
Operating Cost Contribution	\$7.50

* Grower payment estimates provided by Oak Ridge National Laboratory

Summary

This Conventional Bale design is a baseline design for meeting the material specification targets set forth in the CBTL Project between INL and GE Global Research. This analysis reveals key parameters and unit operations that contribute to the cost of a conventional herbaceous bale design. The challenges faced by this design, in terms of cost, are driven by the logistics of the system where moving large quantities of a bulky, unstable, non-flowable material is inherent. Despite these challenges, the technology exists that will allow for relatively large amounts of herbaceous material to be harvested, collected, preprocessed, and delivered to a conversion facility as a standalone feedstock or as a blendstock for energy production.

² Langholtz, M., Graham, R.C., Eaton, L., Perlack, R., Hellwinckel, C., De la Torre Ugarte, D., in review. Price Projections of Feedstocks for Biofuels and Biopower in the U.S. Energy Policy.

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Motivation for a Commodity-Driven System

The U.S. DOE aims to displace 30% of the 2004 gasoline use with biofuels (60 billion gal/yr) by 2030. Of those 60 billion gallons, 15 billion are projected to come from grains, and the remaining 45 billion from lignocellulosic resources. This means that of the 700 million DM tons of biomass required annually, 530 million DM tons will come from a diverse variety of herbaceous and woody lignocellulosic biomass resources (also referred to as “cellulosic” biomass). In order for the biofuels industry to be a self-sustaining enterprise, the lignocellulosic feedstock supply system logistics (all processes involved in getting the biomass from the field to the conversion facility) cannot consume more than 25% of the total cost of the biofuel production.

While national assessments³ identify sufficient biomass resource to meet the production targets, much of that resource is inaccessible using current biomass supply systems because of unfavorable economics. Therefore, conventional biomass supply systems are incapable of meeting these long-term biomass use goals. Increasing the demand for lignocellulosic biomass introduces many logistical challenges to providing an economic, efficient, and reliable supply of quality feedstock to the biorefineries.

The design report, *Uniform-Format Solid Feedstock Supply System: A Commodity-Scale Design for Bulk Solid Lignocellulosic Biomass*, documents an approach to address these logistic challenges by implementing a strategy of incremental change from existing biomass supply systems to economic and reliable commodity-scale supply systems that provide uniform, aerobically stable, quality-controlled feedstocks to biorefineries. This type of approach has been demonstrated and proven successful for feed grains. For herbaceous lignocellulosic resources, these design increments are termed “Conventional Bale,” which reflects current practice and was presented in this case study, “Pioneer Uniform,” which uses current or very near-term technologies and offers incremental improvements over the Conventional Bale system, and “Advanced Uniform,” which meets all cost and supply targets and requires some conceptual equipment, such as a single-pass harvester, to provide a commodity-scale bulk solid feedstock.

The Pioneer Uniform design enables the transition from the Conventional Bale to the Advanced Uniform supply system by developing the supply chain infrastructure required for forward-deployed preprocessing. The Advanced Uniform system formats biomass of various types (i.e., corn stover, switchgrass) and physical characteristics (i.e., bulk densities, moisture content) into a standardized format early in the supply chain. This uniform material format allows biomass to be handled as a commodity that can be bought and sold in a market, vastly increasing its availability to the biorefinery and enabling large-scale facilities to operate with a continuous, consistent, and economic feedstock supply. The commodity-scale system also releases biorefineries from contracting directly with local farmers for biomass feedstocks. Figure 3 shows a schematic of the end-state commodity supply system for all types of lignocellulosic biomasses resources.

³ . Perlack RD, LL Wright, AF Turhollow, RL Graham, BJ Stokes, DC Erbach (2005) Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply, DOE/GO-102005-2135.

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Figure 3. The Advanced-Uniform format feedstock supply system resembles the grain commodity system, which manages crop diversity at the point of harvest and/or the storage elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources.