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Abstract. *Transportation can be a prohibitive cost in bringing biomass to a preprocessing location or biofuel refinery. One alternative to transporting biomass in baled or loose format to a preprocessing location is to utilize a mobile preprocessing system that can be relocated to the places where biomass is stored and used to preprocess and densify the biomass, which is then shipped to the refinery as needed. Idaho National Laboratory (INL) has a full-scale process demonstration unit (PDU) that includes a Stage 1 grinder, hammer mill, drier, pellet mill, and cooler with the associated conveyance system components. Testing at bench and pilot scales has been conducted to determine effects of moisture on preprocessing, crop varieties on preprocessing efficiency, and product quality. INL's PDU provides an opportunity to test the conclusions made at the bench and pilot scales on full industrial-scale systems. Each PDU component is operated from a central operating station where data is collected to determine power consumption rates for each step in the process. The power for each electrical motor in the system is monitored from the control station for problems and to determine optimal conditions for system performance. The data can then be evaluated to determine how changes in biomass input parameters (for example, moisture and crop type), mechanical changes (i.e., screen size, biomass drying, pellet size, grinding speed, etc.), or other variations affect the power consumption of the system. Sorgum, in four-foot round bales, was tested in the system using a series of six different screen sizes, including 3/16 in., 1 in., 2 in., 3 in., 4 in., and 6 in. The effect on power consumption, product quality, and production rate were measured to determine optimal conditions.*

Key Words: biomass preprocessing, biomass deconstruction, biomass feedstocks, bioenergy, lignocellulosic ethanol

Introduction

Developing a sustainable lignocellulosic bioenergy industry capable of offsetting current fossil fuel consumption is a goal of the United States (U.S.) Department of Energy (DOE). Preprocessing biomass is an essential part of the logistical operation that prepares feedstocks for use in a lignocellulosic ethanol biorefinery. The bulk density and size of loose or even baled biomass makes the use of that material so inefficient that its costs are prohibitive unless further densification is achieved (Hamalinck et al., 2005). Loose harvested biomass has a bulk density ranging from only 50 to 120 kg/m^3, depending on the particle size. Bulk density can be increased substantially (~25%) in chopped or ground biomass by vibrating the biomass holder. To increase density further, the biomass must be mechanically compacted into cubes or pellets (Sokhansanj et al., 1999). One of the objectives of preprocessing is to generate a product that improves handling and transportation efficiencies. Idaho National Laboratory (INL) has assembled a process demonstration unit (PDU) that can be used to test various components necessary to achieve the preprocessing requirements of the lignocellulosic bioenergy industry (see Figure 1).

Figure 1. Loading corn stover onto the PDU.

Three criteria drive the feedstock assembly system: (1) machine capacity (throughput); (2) system efficiency; and (3) quality of the output material. Capacity and efficiency primarily depend on the physical configuration of the equipment and the physical characteristics of the biomass feedstock. Previous INL research has shown that the interaction between machine hardware and biomass structure and moisture can significantly impact the resulting capacity and efficiency of the operation. Efficiency and capacity have also been shown to be directly affected by feedstock moisture content (Yancey et al., 2009).

A standard industrial preprocessing system has several fundamental hardware components that can be iteratively altered to achieve an optimum design, including the following:

- Fractionation mechanism (hammers, knives, shear plates, etc.)
- Biomass feed system (horizontal conveyer, vertical gravity, pneumatic, etc.)
- Output screen size (diameter and thickness) and shape (square, round, etc.)
- Discharge system (belt conveyor, auger conveyor, pneumatic transfer, etc.)
- Power unit or drive system (electric or diesel).

INL has assembled the PDU to test many aspects of biomass preprocessing. The PDU is composed of Stage 1 and Stage 2 grinding or milling components. It also has a pelletizing component for densification.

Safety Emphasis

Like all large-scale grinding and milling equipment, the components of the PDU are potentially hazardous. Prior to operating any of the PDU components, operators received equipment–specific training. Individual components of the PDU are equipped with safety interlocks. Workers operated in compliance with a safety control document equivalent to a health and safety plan, which identified potential hazards and appropriate mitigation of those hazards. Part of those safety controls included establishing safety zones around the equipment and identifying appropriate protective equipment and administrative and engineering controls necessary to ensure safe operation of the PDU equipment.

Methodologies

This study consisted of a series of grinding tests with sorghum in which the screen size of the primary grinder was changed while the energy consumed was monitored during each grind. The table below shows the testing parameters and data collected or monitored for each series of tests.

Table 1. Test Matrix for Sorghum Grinding Test

Number of Bales Tested	Data Collected	Stage 1 Grinder Screen Size	Data Collected	Stage 2 Grinder Screen Size	Data Collected
6	Moisture and Bale Weight	3/16 inch	Moisture and Grinding Energy	¼ inch	Moisture and Grinding Energy
6	Moisture and Bale Weight	1 inch	Moisture and Grinding Energy	¼ inch	Moisture and Grinding Energy
6	Moisture and Bale Weight	2 inch	Moisture and Grinding Energy	¼ inch	Moisture and Grinding Energy
6	Moisture and Bale Weight	3 inch	Moisture and Grinding Energy	¼ inch	Moisture and Grinding Energy
6	Moisture and Bale Weight	4 inch	Moisture and Grinding Energy	¼ inch	Moisture and Grinding Energy
6	Moisture and Bale Weight	6 inch	Moisture and Grinding Energy	¼ inch	Moisture and Grinding Energy

Material

Full-scale grinding studies were conducted at INL to determine optimal operating parameters for the PDU. The PDU comprises the necessary equipment to take bulk biomass in bale format and grind the material, in this case, to a point (1/4-inch or less) at which the biomass can be either pelletized or densified in other forms as desired. In this case, material is pelletized to 1/4-inch pellets using a Bliss pellet mill. The grinding portion of the PDU is composed of a Vermeer BG-480 (henceforth referred to as BG 480) grinder (Figure 2), which has two horizontal grinding drums with swinging hammers. These hammers break down the biomass and force it through metal screens. Four screens screen sizes were used with 3/16-, 1-, 2-, 3-, 4-, and 6-inch screen openings. Each drum is driven by a 200-horsepower electric motor. The ground material is conveyed through two sets of drag chain conveyors to a second-stage grinder or hammermill (manufactured by Bliss Industries), which is powered by a single, 150-horsepower electric motor (Figure 3).

Figure 2. Vermeer BG-480 bale grinder.

Figure 3. Bliss hammermill.

The material is then fed into a metering bin that feeds the milled biomass into the Bliss pellet mill (see Figure 4). The pellet mill is powered by two 150-horsepower electric motors. The pellets are cooled and discharged into trucks to complete the process.

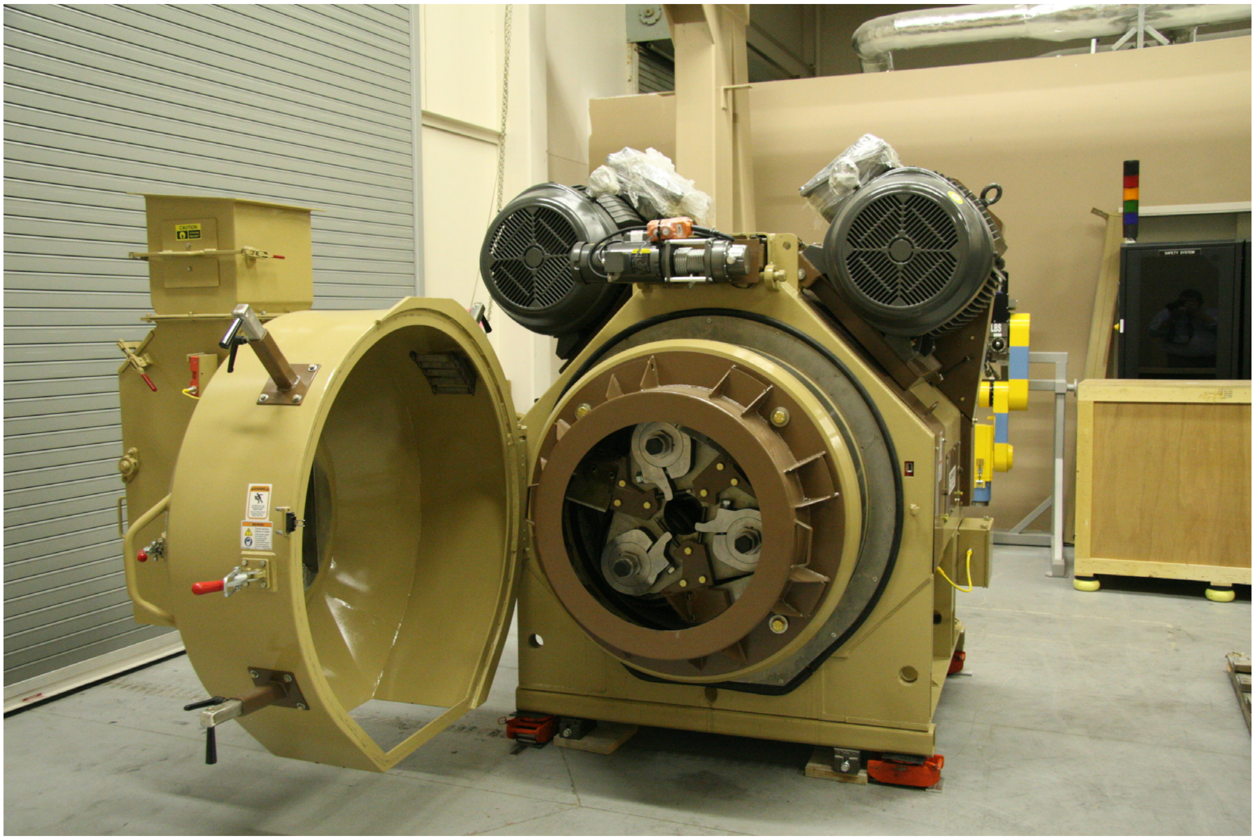


Figure 4. Bliss hammermill.

The focus of this research was to determine optimal parameters for PDU operation, specifically related to screen size selection for the BG-480 when followed by the Bliss hammermill with a 1/4-inch screen. Tests included using a series of six different screen sizes—3/16-, 1-, 2-, 3-, 4-, and 6-inch—in the BG-480 while keeping the screen size in the hammermill constant (at 1/4-inch). The effect on power consumption and production rate were measured to determine which screen combination resulted in the most efficient processing rate (KWhr/DM ton).

Energy sorghum was selected as the test media for the event. The bales were harvested in mid-October 2010 in Hereford, TX; transported to INL on October 28, 2010; and stored under tarps until testing began. The sorghum bales were 4 feet in diameter and 5 feet wide.

Pre-grinding equipment and methods

Prior to grinding, the bales were weighed and core samples collected for moisture analysis. In addition, four core samples were collected from each bale using a 1.5-inch diameter x 18-inch core drill. Cores were collected in the field, placed in Ziploc bags, and refrigerated until the moisture could be measured. The moisture content before grinding was determined per ASABE 358.2 (ASABE. 2006a) standard protocol.

Post-grinding experiment and methods

For each series of tests, six sorghum bales were placed on the infeed of the conveyor of the BG-480. Plastic netting used to wrap the bales was removed prior to placement on the grinder. The grinders and conveyors were started, and grinding start time was measured as soon as the first bale contacted the grinder hammers. This was determined both visually and by observing the current rise resulting from the material entering the grinder.

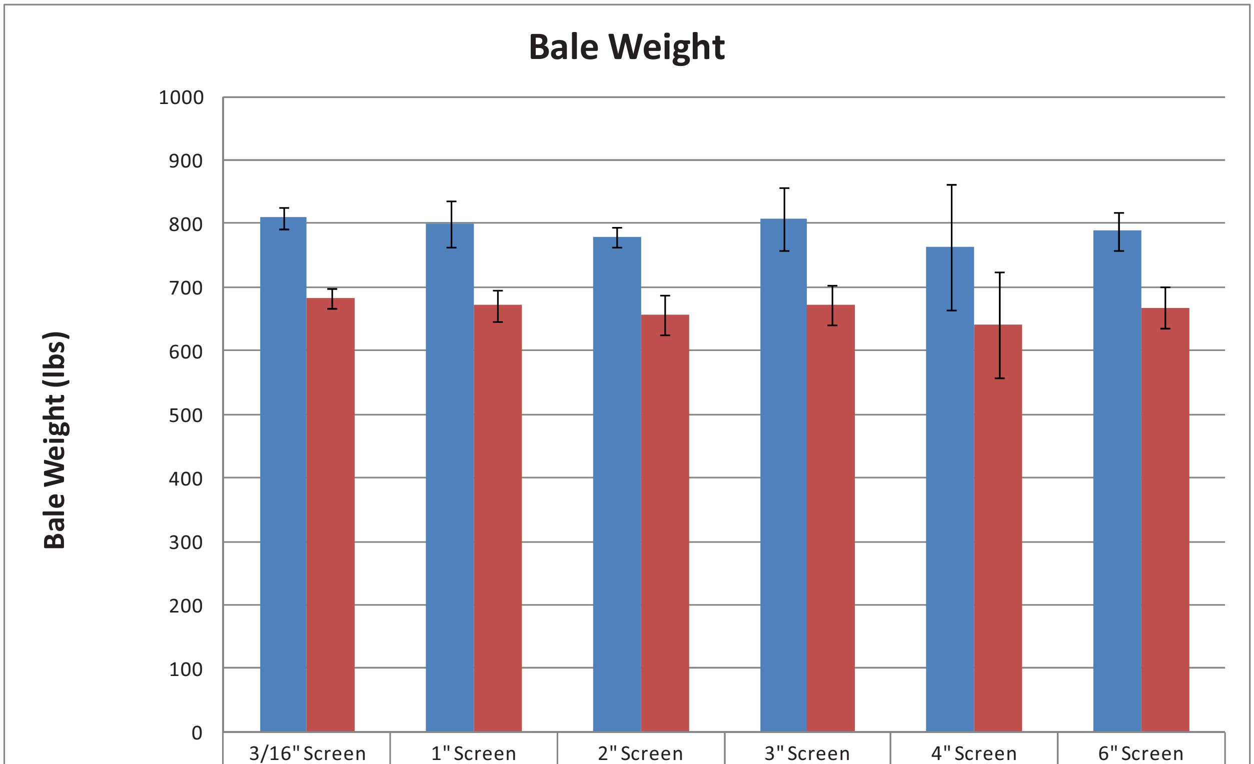
The BG-480, the hammermill, and all associated conveyance motors were connected to a central data logger that monitored current, time, and temperature in and out of the grinder for each motor in the system. Grinding time was measured visually when the bale entered the grinding chamber, and current measured at the grinder first started to increase above baseline operation, which for the BG-480 was about 82 ampere per motor, or 164 ampere total.

Ground sorghum samples were collected after the BG-480 to determine moisture content and bulk density. Two samples were collected from each bale from the conveyor after grinding. Moisture data was collected and compared to grinding efficiency to understand the effect of moisture on grinding efficiency.

Current was also measured at the hammermill and associated conveyors and blower motors. This data was time coded so that it could be correlated with the BG-480 and with each bale that entered the grinder and subsequently entered the hammermill. Samples were also collected after the hammermill, stored in 1-gallon Ziploc bags, and refrigerated until the moisture could be determined.

Results

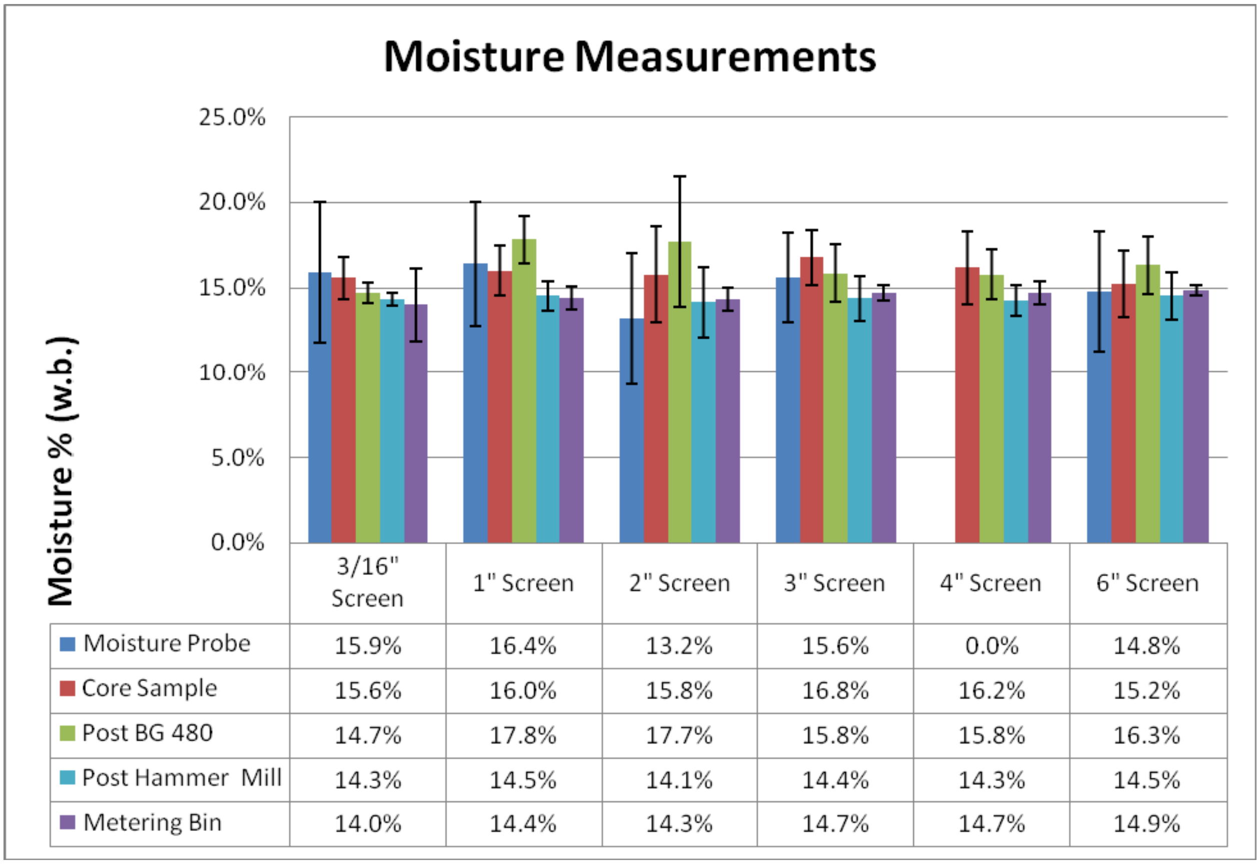
Bale weights and moisture measurements were collected before the bales entered the grinder. Two methods of moisture measurement were used prior to grinding the bales: first, a moisture probe was used to directly measure bale moisture. Second, four core samples were also collected to measure the moisture of each bale. The average bale weight of the six bales in each test is shown in Figure 5. The figure displays the average wet weight and dry weight of the bales for each test. The wet weight of the bales ranged from 764 to 809 lb. The dry weight of the bales ranged from 671 to 683 lbs, an average difference of less than 15 lb. per bale. The tightness of the bale weights between tests provided good uniformity for grinding tests; in other words, the mass ground in each test was consistent between each grind. Differences in grinding energy discussed later in the paper should not be a result of grinding different amounts of biomass in each test, as the weights were essentially equal.



	3/16" Screen	1" Screen	2" Screen	3" Screen	4" Screen	6" Screen
Wet Bale Weight	809	800	778	808	764	788
Dry Bale Weight	683	672	656	672	640	668

Figure 5. Average bale weights for each grinding test.

Prior to grinding the sorghum bales, a moisture probe was inserted into four locations in each bale. The moisture measurements were averaged, and a single value reported from the probe. Core samples were collected from four locations in each bale prior to grinding. Additional samples were collected after the BG-480 ground the material (2 per bale) and after it passed through the hammermill (2 per bale). The ground bale accumulated in the metering bin prior to pelletization. Three samples for each screen test were pulled from the metering bin at 15-minute intervals prior to pelletization. Moisture content was determined for each sample collected. Figure 6 shows the average moisture values for each location in the PDU from which samples were taken and for each screen test. Part of the reason for taking moisture measurements was to determine if any variations in grinding energy could be attributed to moisture. However, typically less than 5% difference in moisture content was noted among the tests or sample locations, so moisture-induced differences would be difficult to detect.



	3/16" Screen	1" Screen	2" Screen	3" Screen	4" Screen	6" Screen
Moisture Probe	15.9%	16.4%	13.2%	15.6%	0.0%	14.8%
Core Sample	15.6%	16.0%	15.8%	16.8%	16.2%	15.2%
Post BG 480	14.7%	17.8%	17.7%	15.8%	15.8%	16.3%
Post Hammer Mill	14.3%	14.5%	14.1%	14.4%	14.3%	14.5%
Metering Bin	14.0%	14.4%	14.3%	14.7%	14.7%	14.9%

Figure 6. Average moisture measurements for the bales in each test.

Sorghum bales were ground using the Vermeer BG-480. The BG-480 is composed of two grinding drums with swinging hammers powered by a 200-horsepower electric motor for each drum. Current data was collected five times per second on each of two motors powering the Vermeer Grinder (BG-480). A series of six tests were conducted using six different screen sizes (3/16, 1, 2, 3, 4, and 6 inch) in the BG-480. Each of the six grinding tests consisted of grinding six round (4-ft diameter x 5 ft tall) sorghum bales. The current data was summed for the two motors and plotted against time. Figure 5 shows the current measured on the Vermeer BG-480 while grinding sorghum using a 1 inch screen. Vertical lines indicate where each of the six bales began or ended for this grinding test. Steady-state grinding tended to occur above 200 amperes, with spikes that occurred in excess of 700 amperes. These spikes occurred as a result of the end of a bale being pulled into the grinder all at once, causing a spike in the current as observed at the end of each bale. Figure 7 also shows the moisture content, dry weight, and KWhr consumed during the grind test for each bale.

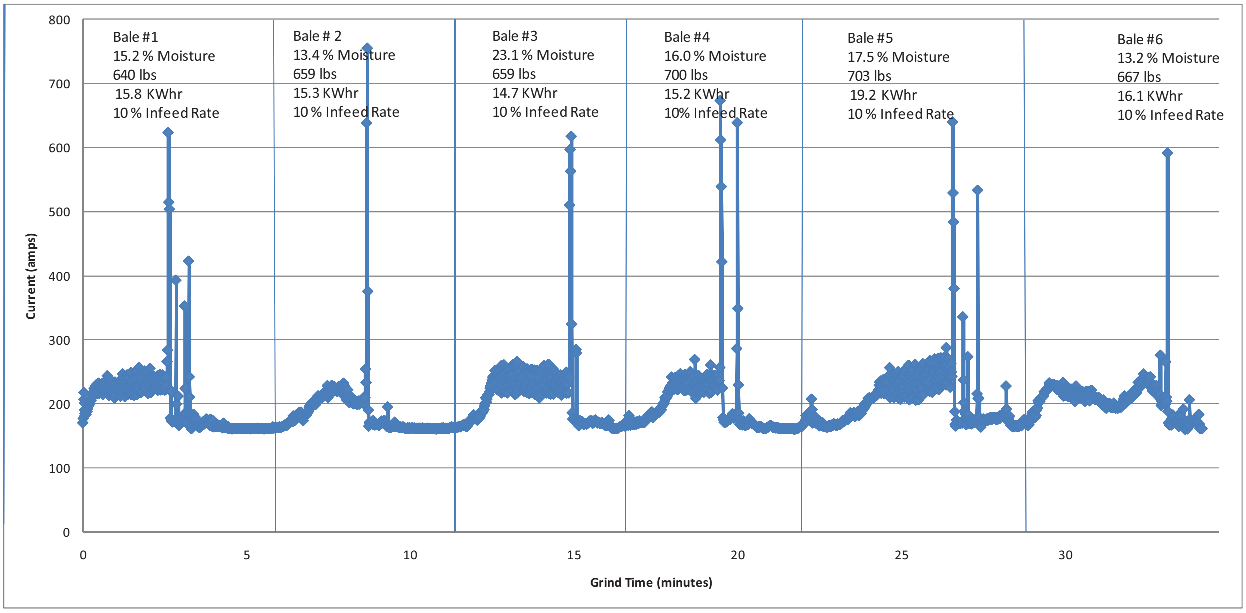


Figure 7. Current data collected from the Vermeer BG-480 using a 1-inch screen.

The ground sorghum left the BG-480 and was conveyed to a Bliss hammermill. The Bliss hammermill has one 150-horsepower electric motor. The hammermill is composed of a single grinding drum with swinging hammers, similar to the BG-480. The Bliss hammermill had a 1/4-inch screen that was used for all of the grind tests. The current was also measured at the hammermill. Figure 8 shows the current (amperes) from the 150-horsepower hammermill. Vertical lines indicate the beginning and end of each of the six bales processed at this screen size. Generally, the average current observed for the hammermill was between 100 and 200 amperes, but spikes near 500 amperes were observed. The surges of material from the BG-480 resulted in the spikes of current at the hammermill.

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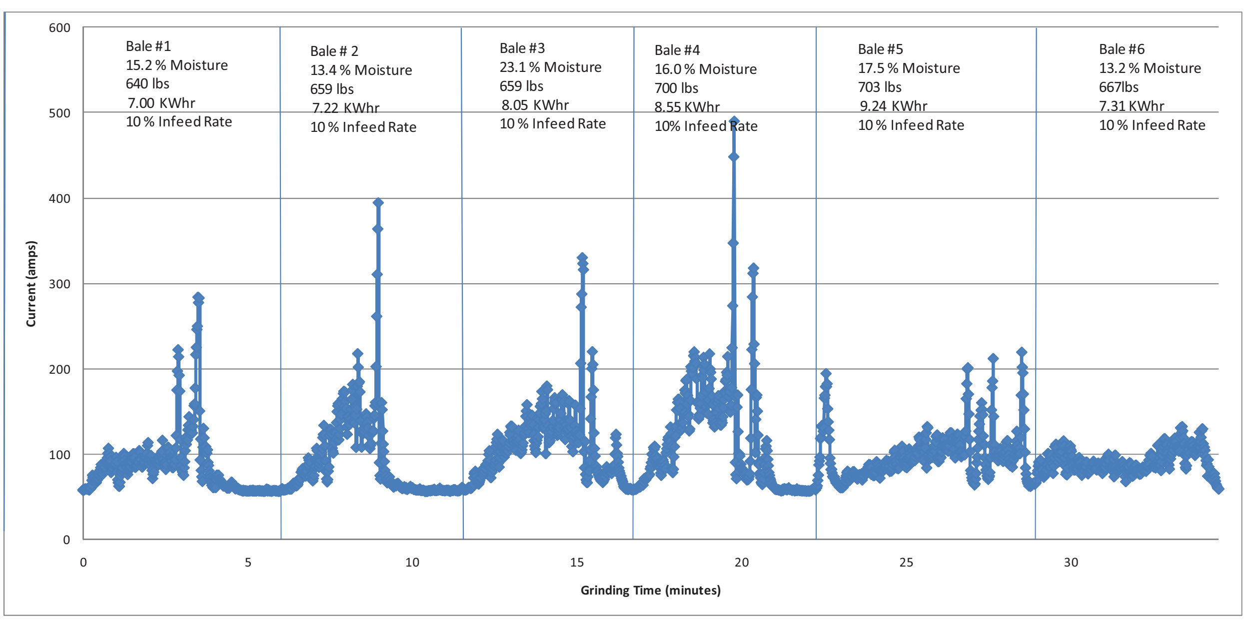

Figure 8. Grinding current for the Bliss hammermill with a 1/4-inch screen.

Grinder Capacity and Efficiency

Grinder capacity was calculated by measuring the time required to grind a bale of known mass. The weight and moisture content for each bale was measured prior to grinding. The dry weight in tons (DM ton) for each bale was calculated using the following equation:

DM ton = Bale wet weight (lb.) *(1-moisture content)/2000.

The capacity was calculated by using the following equation:

Capacity = DM ton * 60 (min/hr)/ grind time (min).

The infeed conveyor speed for the grinder was maintained at 10% of capacity for all of the grinding tests. The BG-480 has a design capacity greater than the hammermill. At 10% infeed rate, the hammermill was maintained at capacity while, in some cases, the BG-480 was operating under capacity. Both the BG-480 and the hammermill operate under a smart-feed capability, which stops and even reverses the infeed if the current spikes above specified set points occur. Figure 9 shows the capacity of the PDU for grinding sorghum with each of the six screens tested. As expected the capacity of the PDU was lowest while using the smallest (3/16-inch) screen. While using the 3/16-inch screen, the capacity was only about 2 DM tons/hour. The highest capacity was achieved with the 2 and 3 inch screens (about 4.3 DM tons/hour), although there was no significant difference observed between the 2-, 3-, 4-, and 6-inch screens. The capacity while using the 3-inch screen was significantly higher than the capacity while using the 1-inch screen.

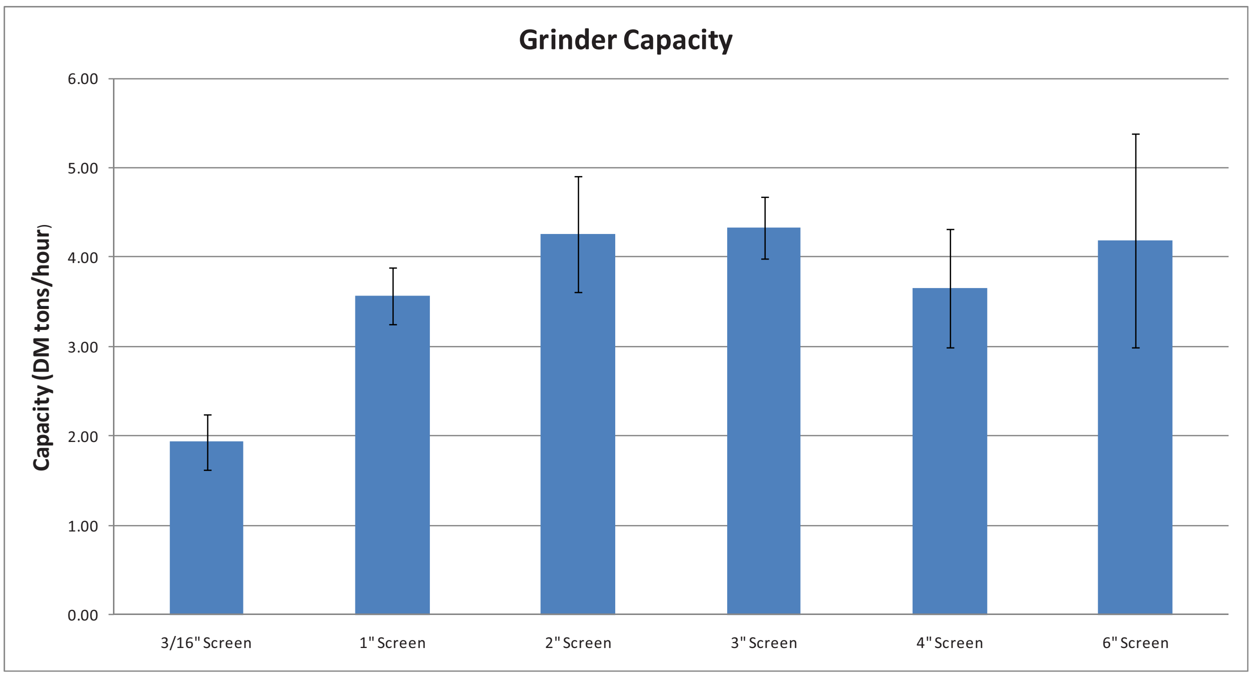

Figure 9. PDU grinding capacity.

Current (ampere) was measured during the duration of the grinding test. The current for the two grinding motors were summed. This value was then converted to KW using the following equation:

KW = I(ampere) x voltage x square root (phase)/1000

where ampere(s) are measured for each time step; volts = 490; and phase = 3.

The instantaneous KW are summed over the duration of the test to obtain kilowatt hour KWhr. The efficiency is then determined by dividing the KWhr/DM ton for each grinding test. The results for each bale were calculated and averaged for each screen size tested (Figure 10). The efficiency of the BG-480 was worst with the 3/16-inch and relatively equal with the 2-, 3-, 4-,and 6-inch screens. The 3-inch screen was significantly better than the 1-inch screen.

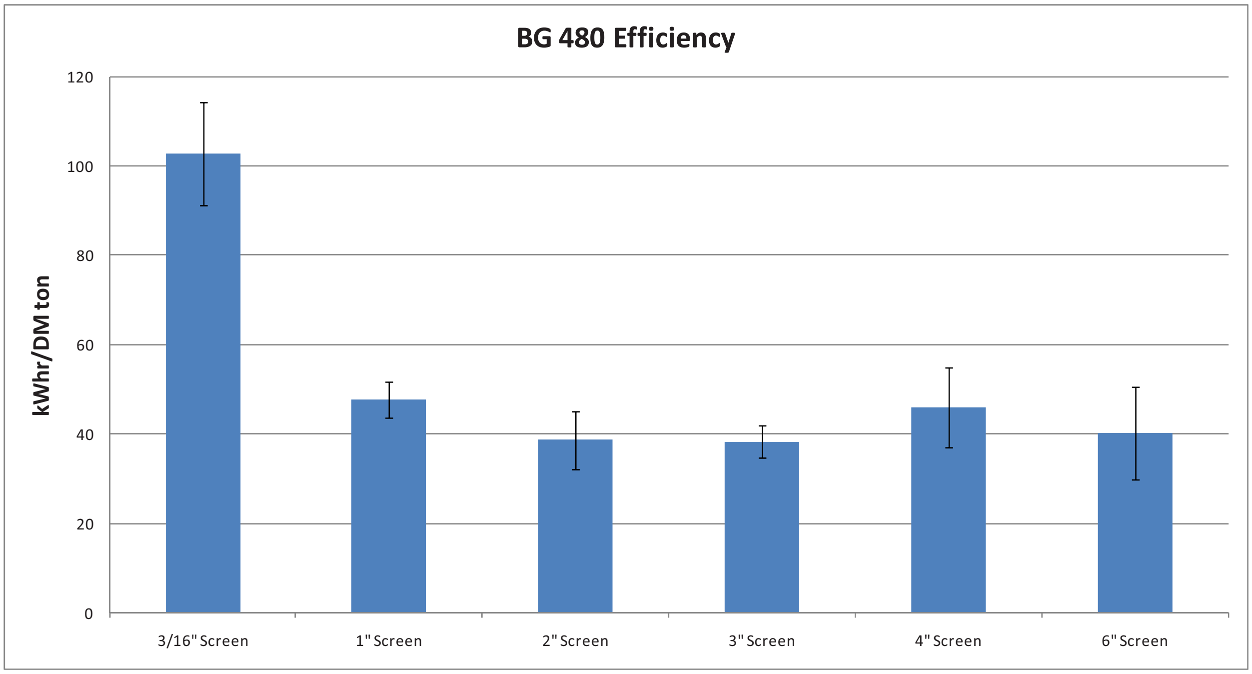

Figure 10. Vermeer BG-480 grinding efficiency.

The current was also recorded for the Bliss hammermill. The efficiency of the hammermill was determined for each of the screen tests conducted. The screen used in the Bliss hammermill was kept constant at 1/4 inch. Figure 11 shows the data from the current measurements taken during each screen test. Each screen size in this figure represents the screen size used in the first stage (Vermeer BG-480 grinder) and would indicate the maximum-sized particle reaching the hammermill. It would be expected that the efficiency would become worse as the screen size in the BG-480 was increased as a result of the additional energy required to grind large-size material at the hammermill. However, what is observed is more of a U-shaped pattern. The efficiency starts out low at the 3/16-inch screen, but improves with the 1- and 2-inch screens, then begins to worsen again. The reason for the poor efficiency with the 3/16-inch screen was that a longer grind time occurred at the BG-480 to accommodate the smaller screen. In essence the hammermill was operating under capacity at the lower screen sizes because the material was not being fed fast enough from the BG-480, although but the BG-480 was operating as fast as it could at that screen size. At the 2-inch screen size, the optimal efficiency was observed. At screen sizes larger than two inches, the efficiency began to deteriorate again. This is a result of larger size material being fed into the hammermill at higher feed rates. The system then becomes limited by the capacity of the hammermill.

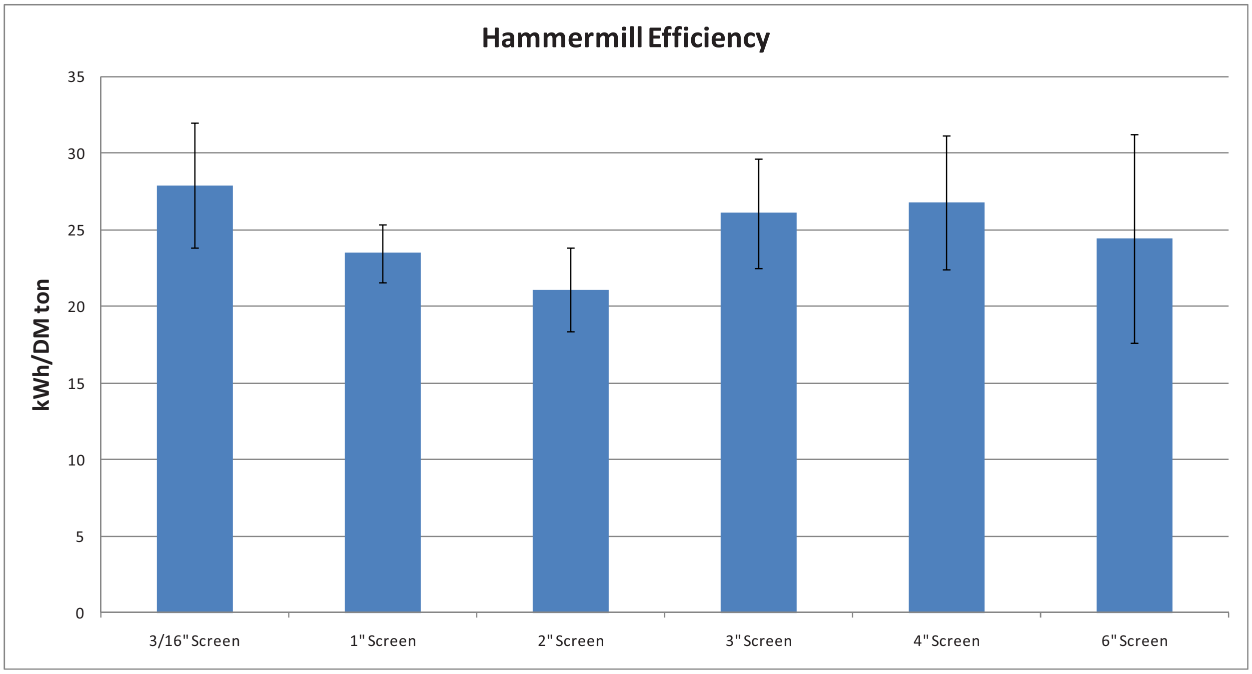

Figure 11. Bliss hammermill grinding efficiency.

Figure 12 combines the efficiency of both the BG-480 and the hammermill. In this figure, the efficiency for the 3/16-inch screen is only respresented with data from the Vermeer BG-480. This is because, with a 3/16-inch screen, only a single-pass grind would be required. For the remaining screen-size tests, the system efficiency is combined with the Stage 1 grinder (BG-480) and the Stage 2 grinder (Bliss hammermill). While significant differences were not observed between screens of 1–6 inches, a difference was observed between 3/16-inch and all other screens. However, the trend continued to show that with the 2-inch screen in the BG-480 and 1/4-inch at the hammermill, the greatest efficiency would be observed.

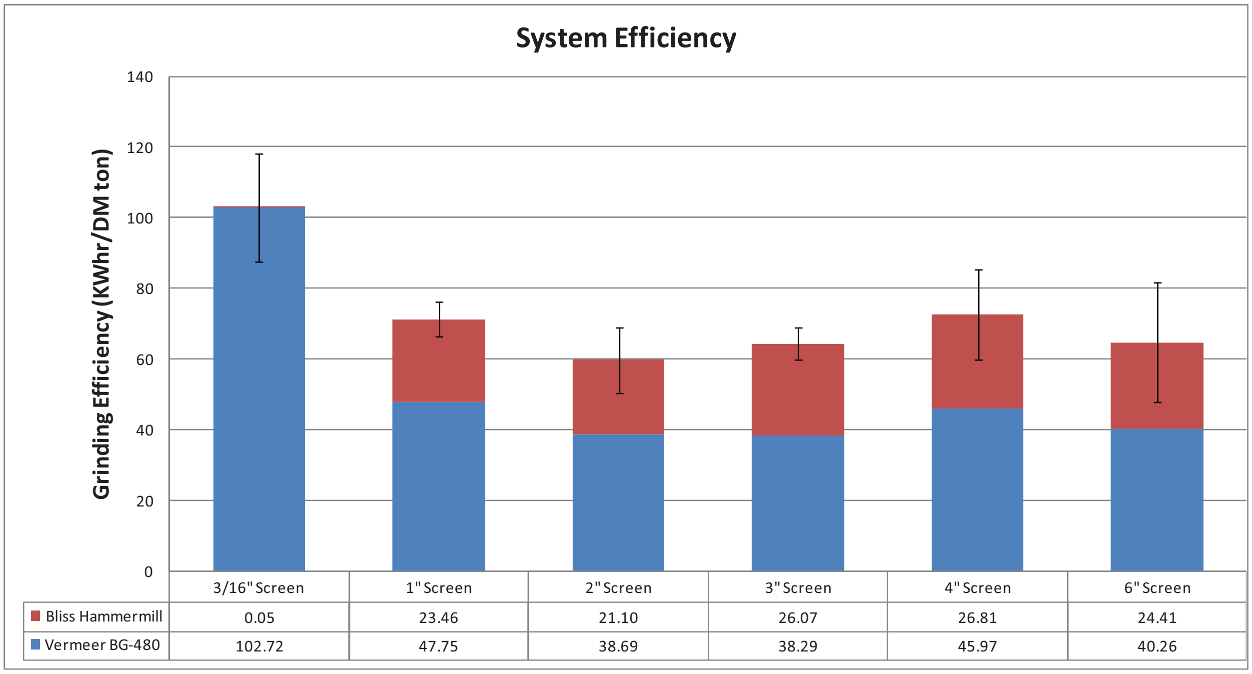

Figure 12. PDU system efficiency.

Discussion and Conclusions

The moisture data collected for the sorghum bales indicates that, in general, the moisture of all bales was fairly consistent. The average bale moisture for 36 bales was 15.9% with a standard deviation of 1.9%. The average bale weight was 797 lb., with a standard deviation of 32 lb. The general tightness in the data for bale weight and moisture suggest that differences in observed efficiency should not be attributed to bale moisture or bale weight.

For each set of screen tests, six bales were loaded onto the infeed of the BG-480. The bales were placed end to end to minimize downtime between bales and maximize the efficiency of the system. The current (amps) data was collected at five times per second. The data shows (Figures 5 and 6) the results of the grinding test with the 1-inch screen. Repeating patterns appeared as each bale moved through the grinder. The grinding energy steadily increased until it reached a steady state at the middle of the bales. At the end of each bale, the last remaining part of the bale was eventually pulled into the grinding drums all at once, causing a sudden spike in the current. This was followed by a drop in energy resulting from the down time that occurred between the end of one bale and beginning of the next. Then this pattern repeated for each bale and each screen test. This made for fairly consistent means of determining the time interval for each bale, which correlated well with the observed start times for the bales.

The current data was then converted to energy in KWhr, which was averaged for the six bales for each run in each screen test. The efficiency was then determined by dividing the KWhr/DMton for each test run. The averages for each run were compared for each stage of grinding and for the system as a whole. With the Vermeer BG-480, the least-efficient screen to use was the 3/16-inch screen. Using this screen also resulted in the lowest capacity of the grinder. This was expected from the BG-480, but it was also the least-efficient grind in the Bliss hammermill. This was because the grind took much longer than in the other runs because the system was limited by how fast the material could be fed into the BG-480 with that screen in place. The most efficient screens were the 2- and 3-inch screens in the BG-480. The most efficient one for the hammermill was the 2-inch screen. For the system as a whole, the 2- and 3-inch screens were very close.

When the screen size was increased beyond 3 inches, the efficiency decreased. At this point, the system became limited by the capacity of the hammermill. As the hammermill reached its capacity, the software controlling the system would reduce the speed of the infeed of the BG-480 so that the flow of material reaching the hammermill would not cause an overload. This resulted in decreased efficiency for the system.

Future Grinder Research Challenges

Due to the number of grinder manufacturers and grinding technologies/options, it is extremely challenging to identify the best possible options for improving grinder capacities and efficiencies while improving the physical and chemical characteristics of every feedstock. The objective of INL's full-scale equipment field testing over the past four years has been to establish baseline performance parameters for multiple feedstock varieties and grinder configurations in order to identify or guide the development of the best preprocessing technologies. The goal of the project discussed in this paper was to analyze the best feed rates for sorghum in a two-stage grinding process. Many other parameters will also affect these same factors. Future testing will be conducted to determine additional parameters to be modified in the full scale PDU system to achieve greater efficiency and capacity.

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U.S. Department of Energy Disclaimer

References – *Please do not use hyperlinks—*

ASABE. 2006a. ASAE S358.2 Moisture measurement - forages. In: ASABE Standards, 608. St. Joseph, MI.: American Society of Agricultural and Biological Engineers.

Hamalinck, C., R. Suurs, and A. Faaij. 2005. International bioenergy transport costs and energy balance. *Biomass and Bioenergy*, 29 (8): 114-134.

Sokhansanj, S. 2006. Overview of the Integrated Biomass Supply Analysis & Logistics (IBSAL). 2006. Aspecial publication Oak Ridge National Laboratory. ORNL/TM-2005/?. 38 pages.

Yancey, N. A., C. T. Wright, C. C. Conner, J. R. Hess. 2009. Preprocessing Moist Lignocellulosic Biomass for Biorefinery Feedstocks. 2009 ASABE Annual Meeting Paper.