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Properties and bulk drying of biomass

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by

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ABSTRACT

A converted trailer-based peanut dryer was tested to determine its suitability and performance for drying biomass materials. These small-scale drying devices are capable of transporting, storing and dry biomass after harvest. Corn stover was dried from a range of initial moisture content of 14 to 31% down to 6%. Corn cobs were dried from 22% to 9% moisture content. Based on the test results, the energy requirement of the trailer is very high. Among the tests, test 12/2/2009 (Half load stover) was found to be the test with the highest energy requirement and Test 11/17/2009 (Full load cobs) required the least amount of energy. Air leaks and environmental conditions greatly influenced the energy requirements of the system. In the trailers present state, it was able to dry biomass adequately; however design modifications are needed to solve handling and logistical issues. Recommended modifications were listed based on the results and observations from the experiment. These modifications apply to the three main operational categories of the drying process: loading, drying and unloading. With these modifications in place, it is projected that drying efficiency and handling issues can be improved. Based on the experiment, bulk handling of biomass is a pertinent issue for its overall acceptance. Material properties of biomass such as friction coefficient are essential for designing machines and equipments that can improve processing efficiency. A method to determine the friction coefficient of corn residue was developed based on procedures used for grain. The method was capable of determining static and dynamic friction coefficient of corn harvest residues on different types of surfaces. HDPE and oak was found to be the material with the smallest and highest static friction coefficient respectively. This result was also true for the dynamic friction coefficient.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Biomass as an energy source is an attractive alternative to fossil fuel due to its abundance and closed carbon-cycle nature. It is seen as a solution to the over-reliance on fossil fuel and a major player in the mitigation of global warming, while at the same time meeting the ever-growing demands of the world's population. Biomass is defined as organic material of recent biological origin (Brown, 2003). In other words, biomass residues and wastes are materials of biological origin arising as by-products and wastes from agriculture, forestry, forest or agricultural industries, and households (Hoogwijk et al., 2003).

In response to a number of global problems, biomass is used to provide various energy services (heat, light, mobility, etc) and produce biomaterials as substitutes to the existing petro-chemical based products. Furthermore, biomass also has an advantage over other kinds of renewable energy due to its flexibility and suitability for a wide range of energy demands and its ability to be stored (Sims, 2004). Biomass energy conversion can be achieved through various processes and can be derived from many types of sources. These many kinds of processes obviously involve different routes to produce the desired product and they also require different types of pre-processing to prepare the materials prior to conversion. The common concern in pre-processing is the moisture content of the materials and moisture removal is often done through drying.

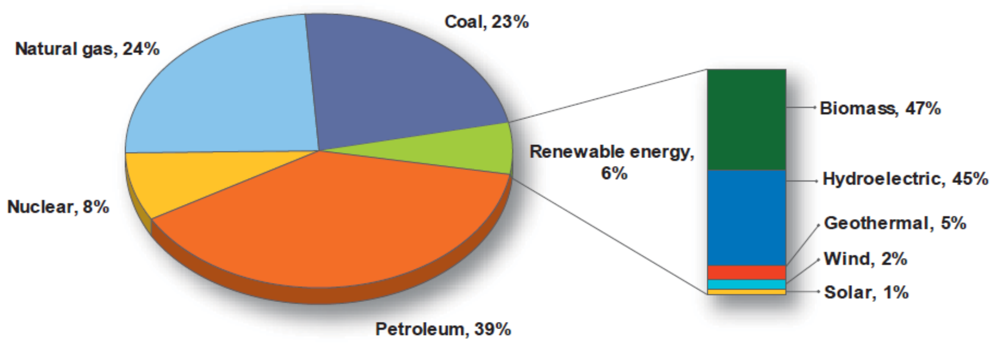
Preparation of biomass as feedstock to a biorefinery requires drying to remove moisture from the raw materials. This can be achieved either passively by utilizing dry ambient air, or actively by heating the drying air through an external heat source. Removal of moisture is essential in order to ensure high combustion efficiency. Moisture in the biomass also affects the net energy density of the biomass because of the weight of the moisture and the required energy to drive off the moisture. High moisture biomass also impacts the storage of biomass as higher moisture results in greater risk of composting and mold formation.

Thesis Organization

This thesis is divided into five main chapters, including the general introduction in Chapter One and general conclusions in Chapter Five. In Chapter Two, a technical paper titled: "Drying biomass in a semi-trailer dryer" will be included. The evaluation of drying biomass materials in a converted semi-trailer was done to determine its efficiency in terms of drying energy consumption and energy cost. In Chapter Three, a list of modification recommendations will be presented. These recommendations are based on the findings in Chapter Two and the modifications are intended to improve the drying efficiency of the trailer-dryer and subsequently to reduce drying costs. In Chapter Four, a procedure to measure friction coefficients of corn harvest residue on different surfaces will be presented. Bulk handling of biomass is a challenge due to its low bulk density and this was apparent during the experiment in Chapter Two. Determining material characteristics such as friction coefficients, will aid design and development of better machinery and equipment that can efficiently handle bulk quantities of biomass.

Literature Review

In 2003, biomass contributed nearly 3.1×10^{15} kJ to the energy supply of the United States, which is nearly 3 percent of the total U.S. energy consumption of about 109×10^{15} kJ (EIA, 2004). Biomass has surpassed hydropower as the single largest renewable energy source (Figure 1). More than half of this renewable energy is generated from the forest products industry. The breakdown of biomass contribution to the overall renewable energy consumption in the U.S. can be summarized as: 13% of renewably generated electricity, 97% of the industrial renewable energy use, 84% and 90% of renewable energy consumption in the residential and commercial sectors respectively and 2.5% of transport fuel use (Perlack, 2005). However, renewable energy consumption for transportation has increased almost 40% from 3.39×10^{14}kJ in 2004 to 8.3×10^{14}kJ in 2008 (EIA, 2008). Clearly, with the ever-growing demand for energy and volatile nature of fossil fuel supply, renewable energy has become a significant player in meeting these needs and furthermore this is a partial solution that is readily available through the application of existing technology and abundant supply.



Biomass Consumption	Million dry tons/year
Forest products industry	
Wood residues	44
Pulping liquors	52
Urban wood and food & other process residues	35
Fuelwood (residential/commercial & electric utilities)	35
Biofuels	18
Bioproducts	6
Total	**190**

- Forestlands and agricultural lands contribute 190 million dry tons of biomass - 3% of America's current energy consumption.

Source: EIA, 2004a & b

Figure 1. Summary of biomass resource consumption (EIA, 2004a & b)

The use of bio-energy around the world is similar in terms of its magnitude and proportion in relation to conventional sources. As of 2009, biomass and waste supplies around 16.7% of the global demand for primary energy as compared to only 10% in 2005 (Schuber and Blasch, 2010). The White Paper (European Commission, 1997) identified bioenergy as a major contributor for the total projected increase of renewable energy sources between 1995 and 2010. This is further influenced by the Kyoto Protocol that requires the European Union (EU) to reduce its greenhouse gas emission by 8% compared to 1990, mainly by substituting renewable energy sources such as bioenergy for fossil based fuels. On the other hand, China has the third largest coal supply in the world and a majority of its energy will be generated from coal for the foreseeable future, with renewable energy very much in the backseat. Biomass use is largely attributable to the continuing widespread use of traditional biomass which is for cooking and heating (BP, 2005).

A large portion of the bioenergy used is in the heat sector, which is the traditional use of biomass. Firewood, charcoal and animal dung are still important sources of energy for about 38% of the world's population in 80 newly industrializing and developing countries (IEA, 2006). Modern biomass in the form of power, heat and fuel only represents about 14.5% of the said total, with biofuels for the transport sector (2.2%) and electricity from bioenergy (34.5%) (Schubert, 2010). These numbers are expected to rise as more countries are promoting its use and obviously its global appeal is also enhanced when climate-related and economic goals are put into the mix. This rise is also propelled by state specific promotion measures in many different countries that influence market prices, which in turn translates into incentives for increased use and production of bioenergy (Schubert, 2010).

Biomass Resources

The resource base for biomass is categorized into two main types: agricultural resources and forest resources. The potential of obtaining vast quantities of these biomass materials for the generation of bio-energy can be seen in the breakdown illustrated in Figure 2. The primary contributors for the agriculture resources are crop residues from major crops such as corn stover, small grain straw and others, grains (corn and soybeans) used for ethanol, biodiesel and bioproducts, perennial grasses and perennial woody crops. Primary constituents of forest resources are logging residues from conventional harvest operations and residues from forest management and land clearing operations, removal of excess biomass (fuel treatments) from timberlands and other forestlands, and fuel wood extracted from forestlands. Unlike dedicated bio-energy corps, biowaste and residues are not produced specifically for use as an energy resource. They are actually a result of an economic activity and production of goods in almost all sectors of the economy (Cherubini et al., 2009). Both of these supply chains require different methods of collection and transportation to respective biorefineries. The importance of minimizing the moisture content is apparent, as moisture filled biomass in inefficient to transport - where moisture is being transported instead of valuable dry mass of the material.

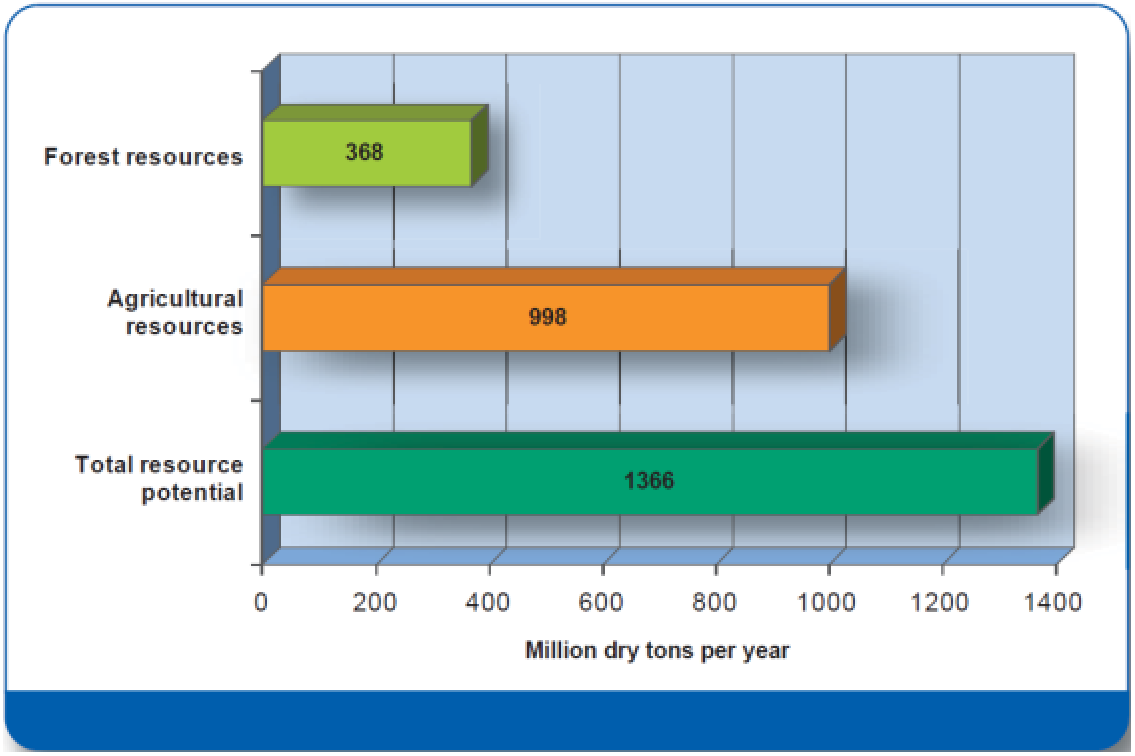


Figure 2. Annual biomass resource potential from forest and agricultural resources (EIA, 2004a & b)

Agriculture resources such as corn stover are collected on-site during harvesting along with the grains and the collection number is very much limited to the technical harvest efficiency of the combine harvester (Petrolia, 2006). Collection is also limited to the farming practices in terms of tillage and crop rotation, in order to maintain a certain level of soil nutrients for farming. These materials are collected and baled prior to transportation. Unlike agriculture resources, forest resources are not by-products of harvesting and it is either collected at timber processing plants or from municipal councils. Moisture contents of these materials are higher than those of agriculture resource. Depending on the conversion process, the materials are then subjected to some form of drying, either through passive air-drying or active heat powered drying to reduce the moisture content prior to transporting or pre-processing into feedstock. Ideally, moisture content of less than 20% is required for thermal conversion, however bioconversion can utilize feedstocks with higher moisture content (McKendry, 2001).

Moisture Content and Drying Methods

The growth of biomass as a replacement for fossil fuel is steadily increasing. The huge amount of potential biomass sources also bodes well for growth. New techniques and improvement of older ones should mitigate the stigma of bio-energy being less efficient and less energy-dense as compared to its fossil fuel counterparts. These two factors are heavily linked with the amount of moisture in the material. Adequate and efficient drying ensures better biomass conversion efficiency and better net mass (overall weight with minimum moisture) of biomass being stored and transported to biorefineries. Table 1 lists the moisture contents of various kinds of biomass derived from various agriculture and non-agriculture resources. Note the varying amounts of moisture in many types of different food, forest and agriculture waste. Due to the variety of sources of biomass, unless bio-refineries are set up at every collection location, which is not economically viable, moisture removal is essential to ensure the maximum bulk volume is supplied to bio-refineries.

In terms of the relation between energy content and moisture content, Table 2 depicts this relation and also in relation to coal. These numbers are the average calorific values of agricultural feedstocks such as logs, briquettes, chips and pellets. Biomass has significantly better energy yield in terms of mega joules per kilogram (MJ/kg) at lower moisture levels. It is also important to note that at lower moisture content, biomass has slightly better energy content compared to coal. This is a good indication of the potential of biomass to replace to fossil-based fuel however, this analogy does not take into account of the energy density of the biomass in terms of how much biomass is needed to produce comparable amount of usable fuel stock.

Table 1. Moisture content by weight of several biomass feedstocks as received

Feedstock	Moisture Content by Weight (%)
Forest Products	
Fuel chips [6]	45-55
Pine sawmill waste [1]	11
Construction waste [2]	12-17
Bark [6]	30-60
Pulp & paper mill sludge [5]	50-70
Agricultural Wastes	
Rice husks [1]	10 (as received) 8.5 (air dried)
Corn cob [4]	10
Soy hulls [3]	9
Lactating cow manure [4]	88 (as excreted) 98 – 99.7 (from milk house or parlor)

(1) "Biofuel Database," Commonwealth Scientific and Industrial Research Organisation, www.det.csiro.au/science/energyresources/biomass.htm
(2) "Biomass," Institute for Environmental Research and Education, www.iere.org/documents/biomass.pdf
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(6) Bruce, D.M. and M.S. Sinclair, *Thermal Drying of Wet Fuels: Opportunities and Technology*, 1996, EPRI TR-107109

Table 2. Energy content of bioenergy (Spitzer, 2004)

Biomass Type	Calorific Value (MJ/kg)
Biomass (0% water)	17-20
Biomass (20% water)	13-15
Biomass (60% water)	5-7
Coal	25-30
Lignite	12-15

Current Drying Processes

Table 4 depicts the various types of conversion technologies that are available today and their current development status. This table gives insight to how much biomass-based bioenergy has matured over the years and what kind of facility incorporates these kinds of technology. These processes do involve pre-treatment in the form of drying to prepare the materials prior to processing. Processes, such as anaerobic digestion and fermentation, do not usually require any drying because the conversion process occurs in a liquid or semi-liquid form and moisture is required to aid the metabolic digestion or fermentation. A process that requires the feedstock to be burned such as incineration, gasification or pyrolysis, however, does require the feedstock material to be at certain levels of moisture to ensure optimum energy generation.

Table 3. Biorenewable conversion technologies and current status (Roos, 2008)

Technology	Technology Status	Possible Products	Facility type
Anaerobic digestion	Mature	Power, heat, soil amendments, and other co-products	Dairies, food processors, confined animal feedlots, wastewater treatment facilities
Ethanol Fermentation	Mature	Ethanol	Agricultural and food processing industries
Incineration	Mature	Power, heat, soil amendments, and other co-products	Wide range of facility types, including forest products, agricultural and food industries.
Biomass Gasification	Demonstration emerging into commercialization	Power, heat, combustible syngas, chemical feedstocks, hydrogen, biochar, soil amendments	Wide range of facility types, including forest products, agricultural and food processing industries
Biomass Pyrolysis	Demonstration emerging into commercialization	Power, heat, liquid fuel bio-oil, combustible syngas, chemical feedstocks, soil amendments, biochar	Forest products industries
Lignocellulosic Conversion	R&D and Demonstration	Cellulosic ethanol, chemical feedstocks, hydrogen, other co-products	Biorefineries, especially in the forest products industry.

There are two main types of drying that can be applied to the feedstock, namely; passive drying and active drying. Adoption of these methods is influenced by the type of materials that needs to be dried, geographic considerations and most importantly economic viability.

Passive Drying

The process of passive drying, drying without external heat source, is highly dependent on the ambient conditions in order for the biomass to dry and reach equilibrium moisture content. Passive drying is often slow and is uncontrolled. The drying is influenced by these factors:

i. Vapor pressure and relative humidity – The drying air exerts a saturation vapor pressure when it holds a maximum amount of vapor. When the water vapor present in the biomass is less than this maximum, then the drying air will take up more moisture. The ratio of actual vapor pressure to the saturation vapor pressure at a given temperature is called relative humidity (RH) and is normally expressed as a percentage form. When wet biomass is exposed to unsaturated air (>100% RH), evaporation on its surface removes moisture from the biomass. The rate of evaporation is dependent on the vapor pressure difference between the air closest to the biomass surface and that of the more mobile air above this zone.

ii. Air movement – Stagnant air around the biomass will result in the drying air becoming saturated and evaporation of moisture from the surface of biomass to stop. Even when there is a continuous stream of air passing over the biomass, the layer of air closest to the surface of the biomass moves relatively slowly with higher vapor pressure than the main stream. This 'boundary layer' equates into an increase in airspeed can therefore be regarded as equivalent to a reduction of the humidity barrier at the biomass surface. When dealing with large volumes of biomass, stacks or piles of biomass is normally left dried in the open. Although this factor is mainly influenced by the management and arrangement of said biomass in a drying yard, external climate factors also play a hand in ensuring the biomass receives enough aeration.

In passive drying, the process is comparatively slower than active drying and requires a larger area to store the material while waiting for it to dry. Also, conditions, such as drying temperature, humidity and airflow are beyond the control of the user. Some materials, such as tree trimmings or husks and stalks, can be allowed to dry naturally by storing in a covered, open area or by taking advantage of open-air solar drying. The final moisture content of air-dried materials usually varies from about 15 to 35%, depending on the size and characteristics of the material and ambient conditions (Roos, 2008). However, the slow uncontrolled nature and large space requirement make this option undesirable for high volume, high efficiency biomass feedstock enterprises.

Active Drying

Unlike passive drying, active drying is a form of drying that offers the user better control over the entire process. This kind of drying is also bound by the same principles as in passive drying, albeit in this case the user has more control over conditions such as drying temperature and air movement. Active drying is a more widely used technique in the biomass industry.

There are many types of dryers used in drying biomass, including direct- and indirect fired rotary dryers, conveyor dryers, cascade dryers, flash or pneumatic dryers, superheated steam dryers and microwave dryers. The type of dryer that is chosen depends on the biomass material's characteristics, the opportunities for integrating the process and dryer and the environmental controls needed or already available (Amos, 1998). Selecting the appropriate dryer depends on many factors including the size and characteristics of the feedstock, capital cost, operation and maintenance requirements, environmental emissions, energy efficiency, waste heat sources available, available space, and potential fire hazard (Roos, 2008). These dryers are normally associated to feedstock derived from forest resources, where the amount of moisture to be removed is larger (60 to 20% or 0%).

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CHAPTER 2. DRYING BIOMASS IN A SEMI-TRAILER DRYER

A paper to be submitted to *Applied Engineering in Agriculture, ASABE.*

A.S. Bujang, C.J. Bern, T.J. Brumm, J.C. Askey

Abstract

Drying pretreatment is often a necessary operation prior to utilizing of biomass. With the availability of smaller scale drying devices, such as a converted semi-trailer based system that can transport, store and dry biomass after harvesting, it is important to gauge the suitability and performance of such a system in achieving this goal. A converted semi-trailer-based system was tested and found to achieve reasonable drying capability for corn cobs and corn stover. Corn stover tests were dried from a range of intial moisture content of 14 to 31%, down to around 6%. Corn cobs were dried from 22 to 9% moisture content. Overall, the system was capable to dry biomass adequately; however, energy required for drying was very high. Major modifications are needed to solve some handling and logistical issues.

Keywords. *Biomass, Advanced Trailer Dryer, Drying*

Introduction

In response to a number of global problems, biomass is increasingly used to provide energy for processing heat and electric power generation and to provide biomaterials as substitutes for petro-chemicals. Furthermore, biomass also has an advantage over other kinds of renewable energy due to its flexibility, storability, and suitability for a wide range of energy demands (Sims, 2004). With the shift towards reducing emissions and carbon footprint, the closed carbon nature of biomass further enhances its attractiveness.

Biomass energy conversion can be achieved through various processes and can be derived from many types of biomass sources. These processes involve different routes to produce the desired product and they also require different types of pre-processing to prepare materials for conversion. A common concern in pre-processing is biomass moisture content and moisture removed through some sort of drying process.

Drying biomass prior to combustion can improve steam generation efficiency by 60 percentage points in processes such as gasification and incineration (Roos, 2008). Roos also reported that biomass is normally dried to less than 20% moisture[1] prior to pelleting. In direct combustion boilers, drying biomass improves energy efficiency, increases steam production, reduces ancillary power requirements, lowers emissions and improves boiler operation (Frea 1984, Fredrikson 1984, Hulkkonen et al. 1995, Intercontinental Engineering Ltd 1980, Linderoth 1992, MacCallum et al 1981, Wardrop Engineering Inc, 1990). Moisture in biomass also reduces net energy density per unit mass, and more energy is needed to drive off excess moisture. Moisture in biomass also increases the rate of deterioration during storage. Even if biomass is not converted to energy through combustion processes, it is still important to remove excess moisture prior to transportation or storage in order to maintain the cost-effectiveness of a biorefinery.

Corn Biomass

The potential of using corn residues as bioenergy feedstock is immense, however, harvest and storage of corn stover and cobs remain a challenge. Drying of corn residue is commonly done through field drying prior to baling. Shinners et al. (2003) reported average ratios of mass of stover harvested to total stover dry matter yield are about 53, 56 and 33% for chopped, wet baled and dry baled stover, respectively. Shinners and Binversie (2007) also reported that total moisture in stover was in the range of 47 to 67% when corn kernel moisture was 30%. Sokhansanj et al. (2002) summarizes field drying moistures of corn residues in Table 4, and it is evident that through field drying, when grain moisture was 35%, the cobs and stalks moisture content was high at 55% and 82% respectively. Although there is a large difference of moisture between the grain and corn residue, this difference is diminished when the grain moisture is lower. Therefore, in field drying, the relationship between moistures of grain and corn residues is not linear., even at low grain moisture, there is considerable amount of moisture left in the residue. Field drying and baling of the residue does not thoroughly dry the materials and it would be advantageous to find a method of drying as part of a suitable post-harvest processing technique to prepare these materials as bioenergy feedstocks. There is a need to investigate and develop drying methods that can provide suitable and cost-effective drying.

There are few studies of drying stover and cobs reported in the literature. Loewer et al. (1982) reported on the feasibility of drying corn biomass for use as combustion fuel for drying corn, where it was found that sufficient energy exist in all the component of corn biomass which is limited by its

[1] All moistures are % wet basis

moisture content. Zabaniotou (2000), investigated the efficiency of drying *Erica Arborea*, a type of foresty biomass, in a rotary dryer as a preparation method before pyrolysis.

Table 4. Moisture contents of corn crop at harvest and after field drying (Sokhansanj et al., 2002)

Component	Before Drying	Field Drying
Corn kernel	34	15
Cob	55	19
Husk	47	24
Stalks and leaves	82	33

Advanced Trailer Converted Semi-trailer Peanut Dryer

Advanced Trailer and Equipment of Georgia specializes in converting semi-trailers into dryers and marketing them to the peanut industry in the region. These trailers are able to transport, dry, and store peanuts direct from harvest. The specifications and key elements of the trailer dryer system are depicted in Figures 3 and 4.

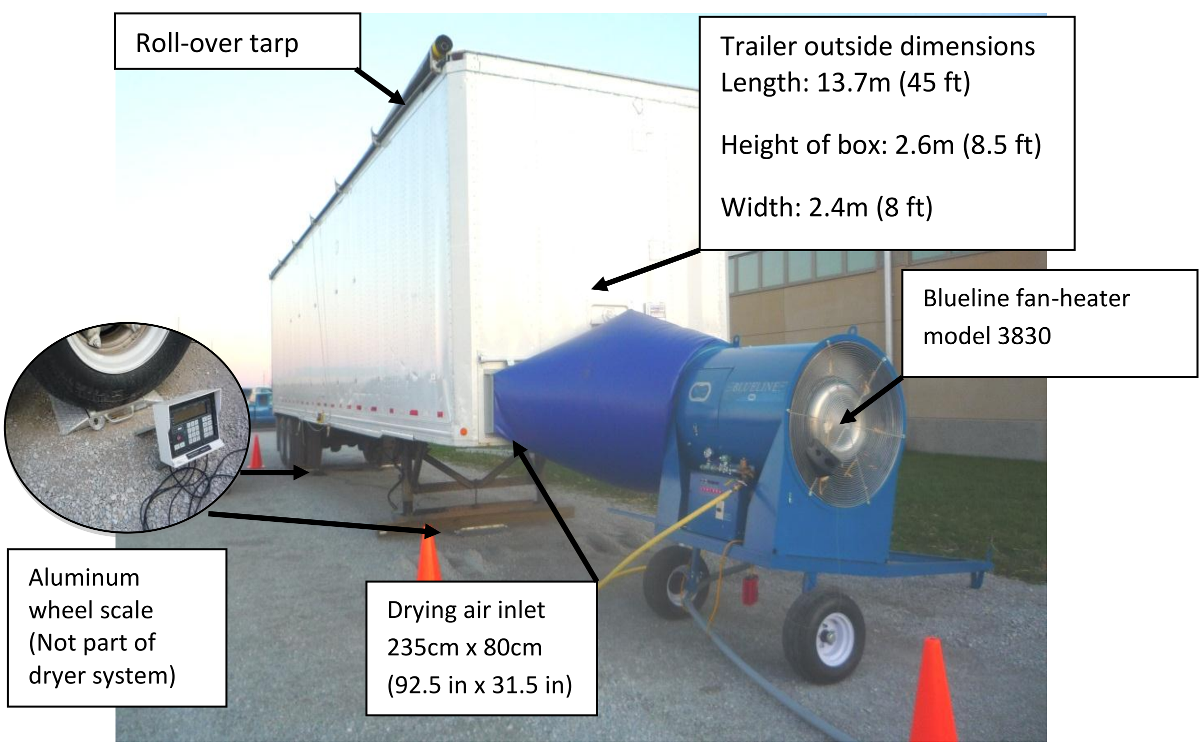

Figure 3. Advanced Trailer dryer system

This technology may find suitable application for drying, transporting and storing biomass after harvest. This venture is a good example of the importance of small companies in supplying biomass feedstock equipment. Therefore, a study is needed to evaluate dryer performance for drying corn stover and cobs after harvest. Key performance indicators, such as energy requirements and management considerations, need to be evaluated.

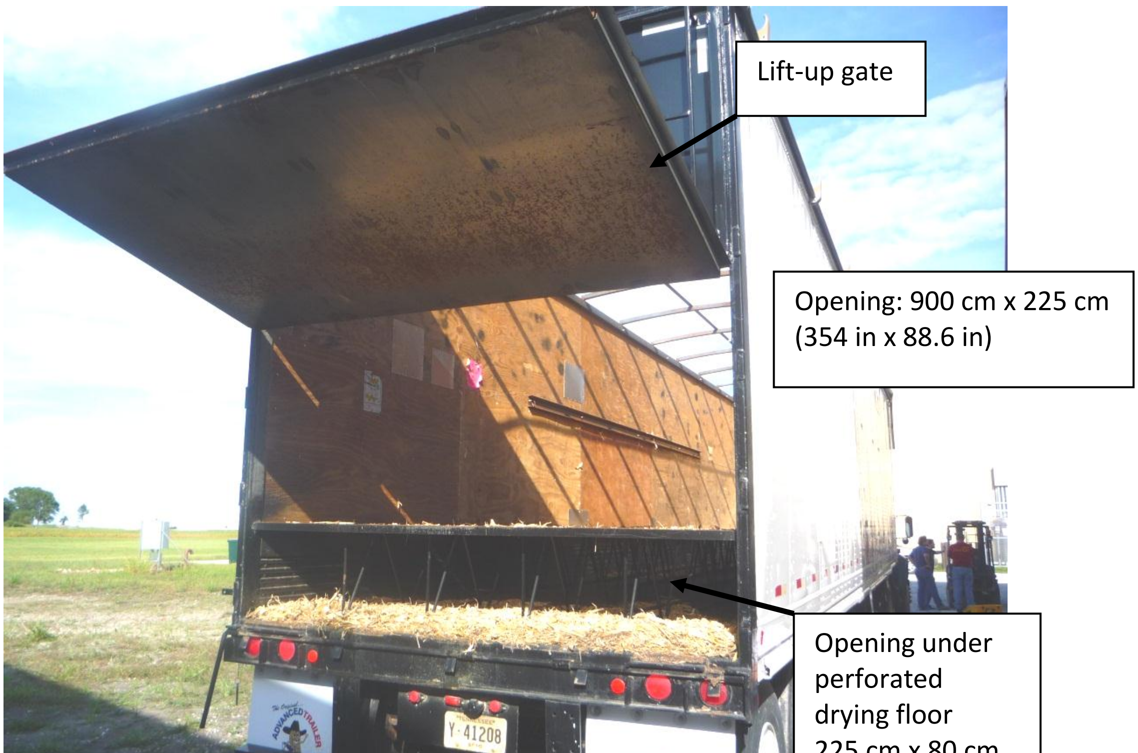

Figure 4. Rear of semi-trailer

Objective

The objective of this research was to measure the performance in terms of drying energy requirement of an semi-trailer-based peanut dryer system for drying corn stover, corn cobs and eucalyptus woodchips.

Procedures

Experimental Design

The experiment was carried out during the fall of 2009 at the ISU Bio Century Research Farm (BCRF) 16 km west of the Iowa State University campus in Ames using *Advanced Trailers* semi trailer dryer systems. A system consisted of a modified semi-trailer and a Blueline fan-heater (Figure 1). *Advanced Trailers* has been granted a US patent 7,770,556 on the trailer and a second patent is pending. The experiment involved drying several batches of biomass materials using direct-fired natural gas. The dryer system was equipped with instruments to measure drying parameters. An Aluminum Wheel Scale (Schrran Engineering Inc., Griswold, Iowa) electronic load cell system connected to a Weigh Tronix indicator (Model 640XL, Avery Weigh Tronix, Freemont, MN) was used to measure trailer weights (Figure 1). Air temperature in the drying biomass was measured by using thermocouples embedded into the biomass and connected to a Rofles portable manual data logger (Model KF-200, Rofles@Boone, Boone, IA). Temperatures were manually read and recorded.

Natural gas volume was measured by calibrating the Alliant Energy revenue meter. The calibration procedure and relevant data from the calibration process can be seen in Appendix A.

A natural gas Blueline fan-heater model 3830 (Cook Industrial Electric Co. Inc. Cordele, GA) was used to heat the drying air (Figure 1). The rated burner output range was 370,000 to 2,100,000 kJ/h (350,000 to 2,000,000 Btu/h). The fan was a 96.5-cm (38-in)-diameter axial design using an 18 to 20 kW (25 to 27 hp) output motor with a rated speed of 1750 rev/min (Appendix C). The drying air temperature rise was 9 to 20°C depending on airflow. Gas pressure was set at 26 kPa (4 psi) throughout the experiment.The dryer was connected to 230-V, 3-phase electrical service. Electrical energy was measured using a watt-hour meter.

Relative humidity and ambient temperature data were collected from a cooperative observer for the National Weather Service, adjacent to the BCRF. Daily data were uploaded to the Iowa Mesonet website (http://mesonet.agron.iastate.edu/agclimate/index.phtml) under station number Ames 8WSW. Materials were dried day and night, drying was stopped during rain. After drying, dried materials were transported to the ISU composting facility for disposal and the cycle was repeated for the next batch of biomass material.

Moisture Content Determination

Sampling for initial moisture content was done by digging 1-1.5 ft into the materials in the trailer. Four locations along the length of the trailer was chosen as sampling sites. Three samples were taken at each location and oven moisture test were done on each samples. Prior to the oven test, each sample was thoroughly mixed and a sub-sample was taken and weighted. Oven moisture tests (103°C, 24 h) were then done on each sub-samples and thry were conducted following ASABE Standard S358.2 (ASABE Standards, 2008).

Moisture content for the material during and after drying was determined by calculation, based on the initial moisture content and the weight of water that was removed. The moisture content (M_f) was calculated using:

$$\Delta W = W_f – W_o = (1/100\text{-}M_f)(M_f – M_o)W_o$$

Where: ΔW = Change in weight

W_f = Final weight

W_o = Initial weight

M_f = Final moisture content (% wet basis)

M_o = Initial moisture content (% wet basis)

Biomass Materials

Corn cobs, corn stover and eucalyptus chips were dried. In general, corn stover includes materials that are left in field after corn grain harvest and consists of leaves, stalk, husks and cobs. The corn cob is the central core of the maize and it is sometimes categorized separately from corn stover. The material properties of stover are similar to straw in terms of its physical characteristics, having low water content during harvest and being bulky. In present experiment, corn cobs and stover were sourced from nearby private and university-owned farms.

Corn was harvested by a modified John Deere 9860 Combine, developed by ISU to harvest biomass. This combine was designed to harvest corn grain and at the same time separate cobs from other material leaving the combine. Eucalyptus woodchips are residues from the processing of eucalyptus trees into pulpwood and firewood. They were obtained from Frontline BioEnergy, LLC (Ames, Iowa) and average length of the material was about 4 cm (1.5 in). Table 5 summarizes characteristics of materials used in the experiment.

Material composition was determined by obtaining the weight fraction of the different materials in the sample. Each sample was physically separated according to the type of material: stalk and husks, cobs, leaves and other materials. These categorized sub-samples were then weighed and their fractional weights were calculated. This was done in triplicates. The sample lot used for this experiment was the same as the one used for moisture content determination.

Table 5. Characteristics of biomass materials used

Experiment Number	Material	Variety	Date Harvested	Initial Moisture Content (%)	Final Moisture Content (%)	Material Composition (Mass fractions average, %) [C]
11/1/2009, Stover half load	Corn stover	Dekalb 111 day corn	10/26/2009	31	7	Cobs: 28.0 %, Stalk/husk: 25.4 %, Leaves: 42.0 %, Other [A]: 4.6 %
11/10/2009, Stover full load	Corn stover	Dekalb 111 day corn	11/7/2009	25	6	Cobs: 33.3 %, Stalk/husk: 36.2 %, Leaves: 29.8 %, Other [A]: 0.8 %
12/2/2009, Stover half load	Corn stover	Crow's 111 day corn	11/18/2009	14	6	Cobs: 15.5 %, Stalk/husk: 34.1 %, Leaves: 49.9 %, Other [A]: 0.5 %
11/17/2009, Cobs full load	Corn cobs	Dekalb 111 day corn	10/26/2009	22	9	Cobs: 95.3 %, Stalk/husk: 2.9 %, Leaves: 0.7 %, Other [A]: 1.2 %
9/23/2009, Eucalyptus	Eucalyptus woodchips	Eucalyptus amplifolia	Not available	55	31	Not available
10/7/2009, Eucalyptus	Eucalyptus woodchips	Eucalyptus amplifolia	Not available	51	16	Chips: 86.2 % Other [B]: 13.8%

[A] Other: Unrecognizable debris, dirt, grain, twigs

[B] Other: Leaves, bark, dirt

[C] Data are available in Appendix D

Bulk Density

Bulk density was calculated dividing the weight (kg) of the material and the volume (m^3) the material occupies in the trailer. The weight was observed from the electronic scale and the volume was calculated by multiplying the width (2.4m) and the length (13.7m) of the trailer and the height of the material. Because the level of the material in the trailer is not uniform, measurement was taken at 4 points along the sides of the trailer and averaged to give an approximate height of the materials. The height of the material was the average height of the 4 points. The measurement was done by measuring the length of the top of the material and the top of the trailer and subtracting this number by the height of the trailer (2.6m). Measurements data can be seen in Appendix B.

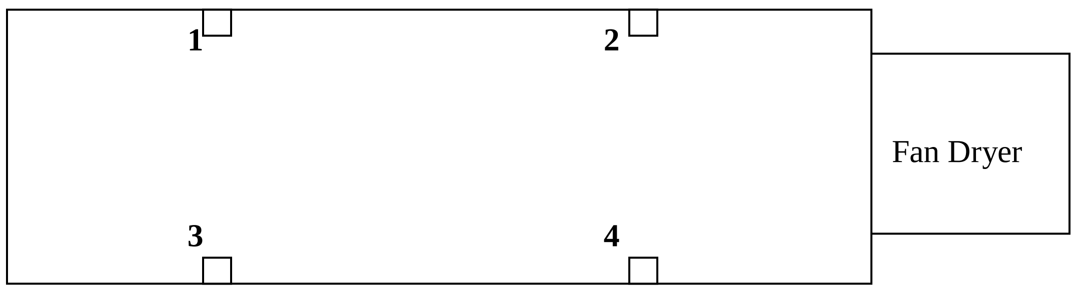

Figure 5. Overhead view of the position of height measurement sampling

Results and Discussion

Figures 6 and 7, show moisture and bulk density values during drying. The complete data set from the drying experiments can be found in Appendix B. Moisture content decrease tended to be linearly with time for all materials. For these tests, drying was allowed to continue until material moisture reached near equilibrium with the drying air. Drying could be stopped at higher moisture levels for specific applications.

Moisture Content

Eucalyptus woodchips require longer time to drive out the moisture as water molecules in woody carbonaceous materials are harder to remove with low heat static drying. Therefore a compromise on the final moisture content level is needed to ensure that drying cost is kept within an acceptable and viable range. The data points used in Figure 6 was standardized to 24 hours for corn stover/cobs tests and 29 hours for the eucalyptus tests. This is to ensure direct comparisons can be made between tests.

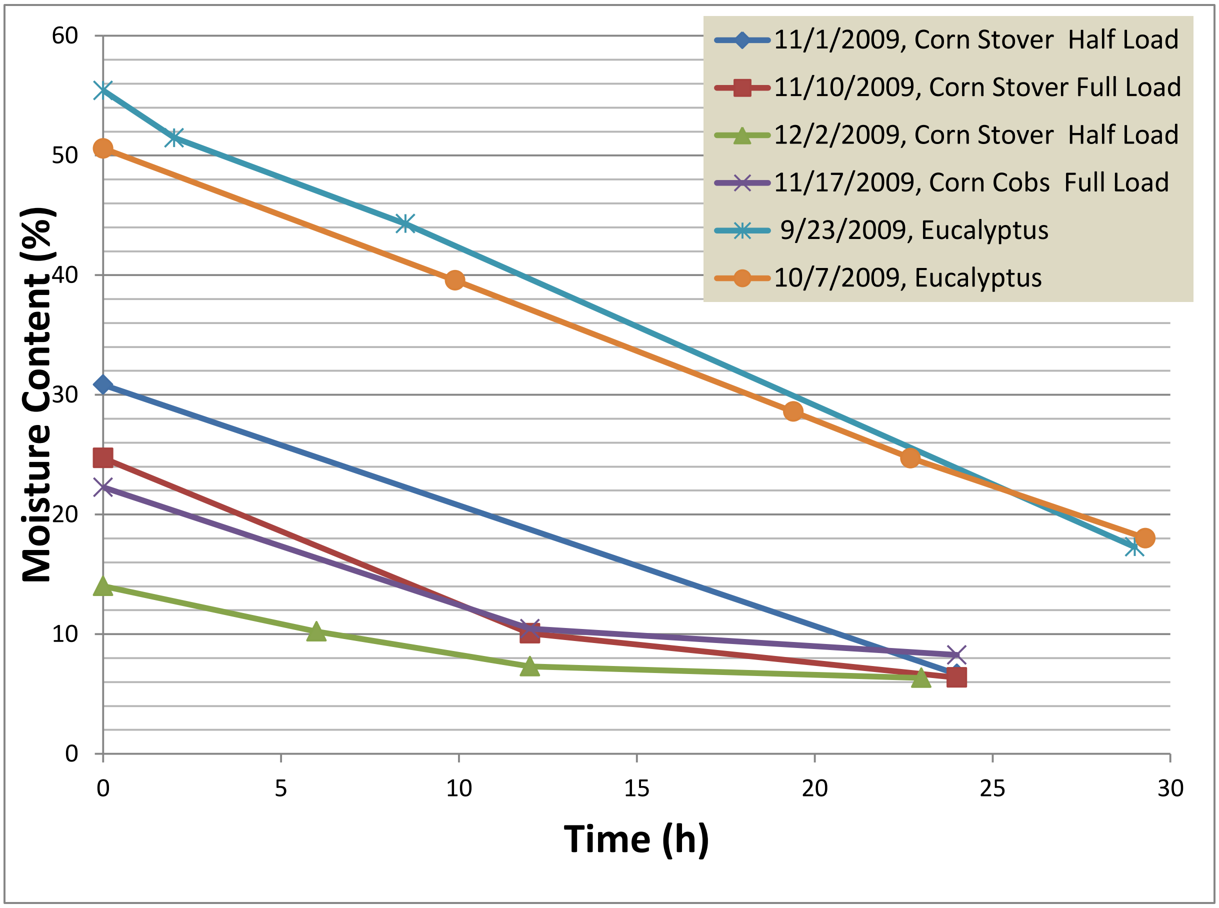

Figure 6. Moisture content vs time. Data points are the average of nine moisture tests.

Bulk Density

Drying materials were loaded into the trailer from the top and then manually levelled with minimal packing. The level decreased during drying and indicating that the overall volume and mass of the material decreased as water was being driven out. Therefore, the drying also slightly decreased the bulk density of the materials. Table 6 shows the summary of material depth and weights during drying. There is some variation in the bulk density that was calculated due to average value of height that was used in the calculations. The error bars in Figure & shows that for test 12/2/2009, the variation is relatively less than that of the other three experiments. The level of material in this experiment was observed to be more uniform than the other.

Table 6. Summary of material height, weight and bulk density.

Drying Test	Initial Weight (kg)	Final Weight (kg)	Initial Depth, m (in)	Final Depth, m (in)	Initial Bulk Density (kg/m3)	Final Bulk Density (kg/m3)
11/1/2009, Stover half load	2400	1800	1.1 (43.3)	0.9 (35.4)	78.2	68.4
11/10/2009, Stover full load	5900	4800	2.0 (78.7)	1.9 (74.8)	104.4	92.4
12/2/2009, Stover half load	2100	1800	1.1 (43.3)	0.9 (35.4)	67.3	68.8
11/17/2009, Cobs full load	10200	8600	2.1 (82.7)	1.9 (74.8)	175.6	162.3

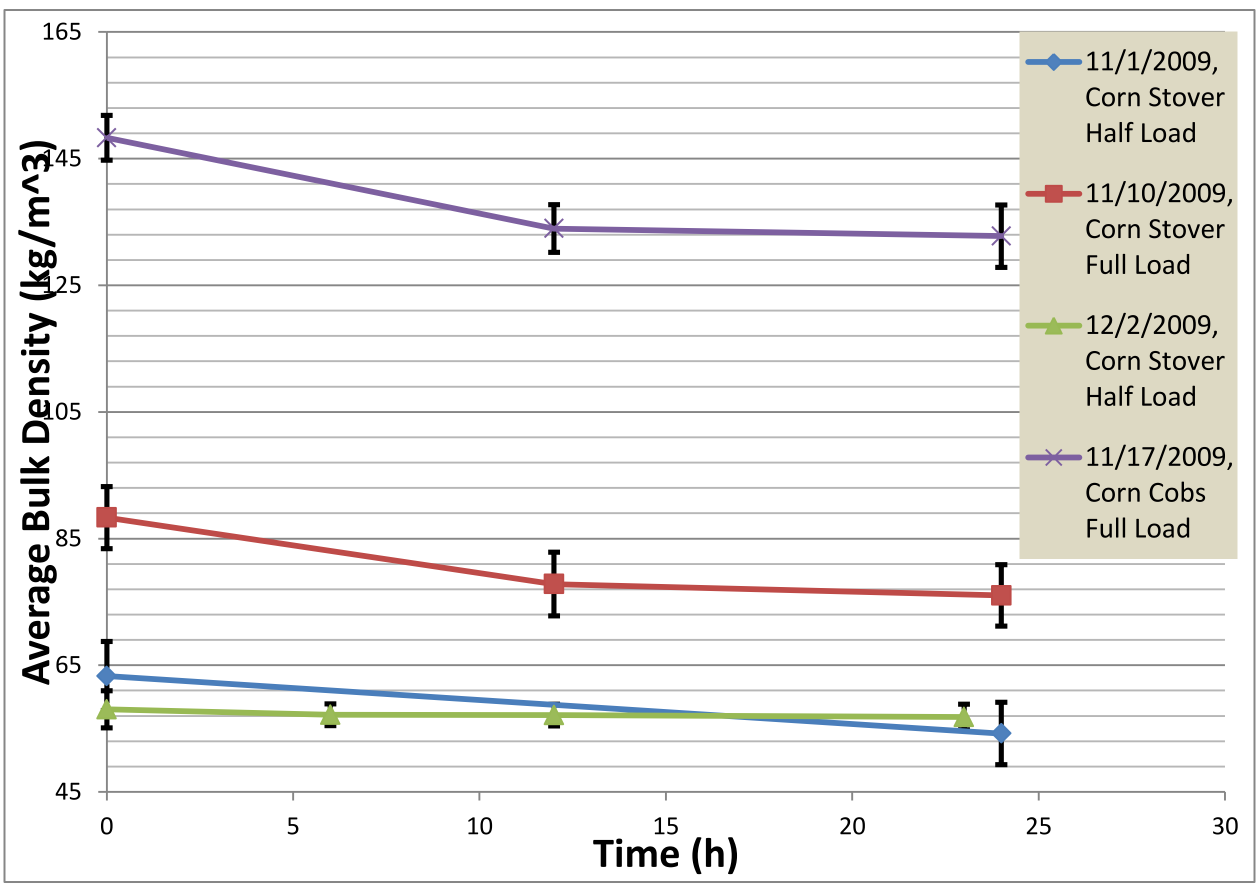

Figure 7. Bulk density versus time

Drying Results

Table 7 shows drying results from the experiment. A full load of corn cobs (11/7/2009) has the best drying characteristics since it has the most water removed and required the least amount of energy per kg of water removed. The half loads of stover on the other hand had the least energy efficient drying results where much more energy was required to remove comparable amounts of water to that of corn cobs. The reason for this may be that it was dried to only 9% compared to 6% for the stover as residual moisture remaining in the materials require more energy to vaporize. However it is worth noting that biomass energy conversion only requires moisture content to be <10% (Roos, 2008). Total input energy values tended to be very high. Air leaks around the trailer no doubt contributed to this. The drying cost for the experiments can be seen in Table 8. The costs conform to the total energy input in Table 7, where the highest cost was attributed to Test 3 (12/2/2009), which has the highest energy input with the least amount of water removed.

Table 7. Summary of drying results (Latent heat of vaporization of water = 2492 kJ/kg water removed)

Drying test	Initial weight, kg (lb)	Water removed, kg (lb)	Initial moisture, %	Final moisture, %	Natural gas input energy, kJ/kg water removed	Electrical input energy, kJ/kg water removed	Total input energy, kJ/kg water removed
11/1/2009, Stover half load	2400 (5300)	630 (1400)	31	6	36900	4170	41000
11/10/2009, Stover full load	5900 (13000)	1160 (2500)	25	6	20100	1930	22000
12/2/2009, Stover half load	2100 (4600)	170 (400)	14	6	130000	15600	145000
11/17/2009, Cobs full load	10200 (22500)	1600 (3400)	22	9	16200	1600	16600
9/23/2009, Eucalyptus	11100 (24000)	4700 (10400)	55	17	5500	n/a	5500
10/7/2009, Eucalyptus	8100 (18000)	1800 (4000)	50	18	8800	n/a	8800

Table 8. Drying energy cost

Drying test	**Moisture %**		**Drying energy cost*, ($/Mg dry matter/ % pt)**
	Begin	End	
11/1/2009, Stover half load	31	6	$4.09
11/10/2009, Stover full load	24	6	$2.00
12/2/2009, Stover half load	14	6	$11.72
11/17/2009, Cobs full load	22	8	$1.50

* Natural gas = $6.16 /1000ft3 (http://www.eia.doe.gov/)
Electricity = $0.043 /kWh (https://www.alliantenergy.com/)

Airflow

Table 9 and Figure 8 summarize material depth and total fan airflow during drying. A Magnehelix® pressure gauge model 2005 (Dwyer Instruments Inc, Michigan City, IN) was connected to a pressure tap under the drying floor midway between the front and rear of the trailer. Airflows were read from the fan curve (Appendix C). There were slight differences between pressure readings from full-load and half-load tests. This slight difference was not seen when the conversion from the fan curve was made. From the table, we can see the relation between the readings and the characteristics of the drying materials. Readings for half loads were less than full loads and there was slight variation as seen in comparison between Tests 2 and 4. The corn cobs have more spaces between cobs for air to flow through compared to the more interlocking nature of stover that restricted the airflow slightly more. However, through this observation, there was negligible difference of airflow throughout the duration of the drying period, although depth difference from the start to finish indicated natural compression of the materials, it did not affect the airflow through it. Overall, the airflow of the drying air was not channelled totally from the dryer through the material. There were many leaks throughout the structure of the trailer especially at the back where the door was located.

Table 9. Airflow and material depths during drying

Drying Test		Fan Airflow, m^3/min (cfm x 1000) [a]						Material depth	
		0 h	6 h	12 h	18 h	24 h	>24h	Start m, (in)	Finish m, (in)
1	**11/1/2009, Stover half load**	1.3 (45.5)	-	-	-	1.3 (46)	1.3 (46)	1.1 (43.3)	0.9 (35.4)
2	**11/10/2009, Stover full load**	1.3 (44.7)	-	1.3 (44.7)	-	1.3 (44.7)	1.3 (44.7)	2.0 (78.7)	1.9 (74.8)
3	**12/2/2009, Stover half load**	1.3 (45)	1.3 (45)	1.3 (45)	-	1.3 (45)	-	1.1 (43.3)	0.9 (35.4)
4	**11/17/2009, Cobs full load**	1.2 (42.1)	-	1.3 (44.7)	-	1.2 (42.7)	1.3 (44.9)	2.1 (82.7)	1.9 (74.8)

[a]Airflow calculated from fan curve in Appendix C

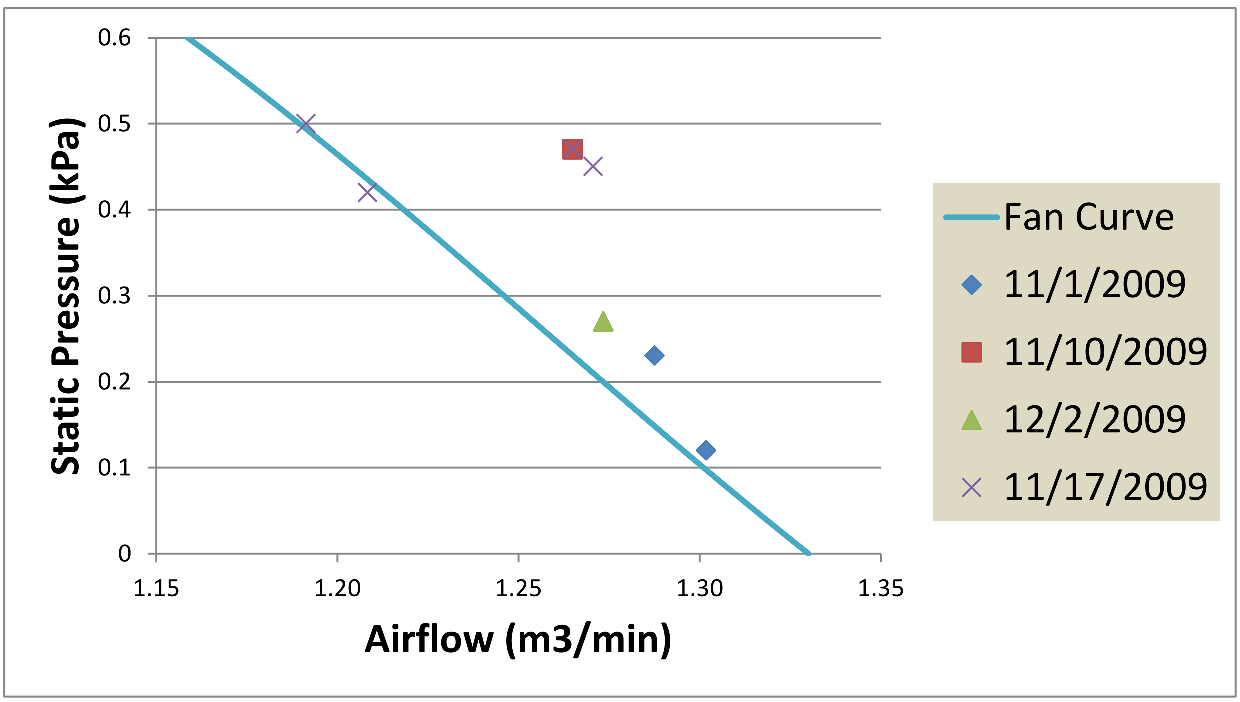

Figure 8. Graph of airflow and pressure readings during drying (Data are in Appendix C)

Table 10 summarizes the observed ambient temperature and relative humidity along with the energy required during drying. The highest energy requirement was observed for Test 3 where the corresponding ambient temperature was the lowest and the relative humidity was the highest. This was expected as more energy was needed to heat up the drying air to dry the material and to overcome the effects of high humidity on moisture evaporation from the drying material. However, when assessing the performance of the dryer/trailer, referring to Test 4, the drying energy requirement was the lowest and at the same time it was during the time where the ambient temperature was second lowest and the humidity was the second highest among the four tests. This may be due to the way the materials are packed up in the trailer, as a full load of cobs may have resulted in a better dry airflow distribution between the cobs.

In Table 11, a summary of the work done by a research team from the University of Idaho is presented (Gallagher et al., 2010). The experiment was set up in similar conditions and a total of 11 tests were done, where white fir chip mix was dried from a moisture content of 50% (wet basis) to a final moisture content of <20% (wet basis). Only three tests were selected in this summary because the heater and fan were used during drying, whereas in the other eight tests, drying was done with ambient air. From the results, the drying energy added was lower than than the results obtained in this paper. This is due to the different ambient temperatures and the amount of water removed from the drying material was also substantially higher.

Table 10. Effects of environmental conditions on drying

	Drying test	**Average ambient temp, °C**	**Average drying air temp, °C**	**Average ambient relative humidity, %**	**Average ambient wet bulb depression, °C**	**Drying energy added kJ/kg**
1	**11/1/2009, Stover half load**	12	20	55	5	41000
2	**11/10/2009, Stover full load**	8	18	60	4	22000
3	**12/2/2009, Stover half load**	1	9	85	1	145000
4	**11/17/2009, Cobs full load**	5	14	75	2.5	16600

Table 11. Drying energy summary from similar test done at University of Idaho (Gallagher et al., 2010)

Test	Ave. Day High Temp (°C)	Ave. Night Low Temp (°C)	Duration (h)	Electrical Consumption (kWh)	Input Electrical Energy (kJ)	Input Heat Energy (kJ)	Water Weight Removed (kg)	Drying Energy Added (kJ/kg)
Run 1	29	8	52	1997	7.19E+06	2.13E+07	9100	3100
Run 2	32	10	75	2880	1.04E+07	3.07E+07	7100	5700
Run 10	7	-12	72	2765	9.95E+06	5.74E+07	6000	11000

Challenges

The fall 2009 harvesting season was a challenging period for carrying out biomass drying. High rainfall and cloudy days caused corn to not dry normally prior to harvest. Harvesting schedules were delayed and drying times were increased. As a result, the number of tests that could be carried out was reduced. Obviously a trailer that was designed to handle flowable and aggregated materials, such as peanuts, would have some problems when dealing with clumpy materials such as corn stover and cobs. Loading the material was one of the main problems. The open top of the trailer had steel cross beams and woven straps that run the length of the trailer, as seen in Figure 9. This hindered the loading process, where cobs and stover loaded from the top required manual raking to ensure that the materials dropped to the bottom. This also affected the bulk density of the materials in the trailer and eventually the distribution of the dry air and the effects of irregular density were even more pronounced when handling corn stover due to the clumpy nature of the material.

Figure 9. Loading corn stover.

Loading-unloading Sled

Unloading materials after drying was also a major issue affecting the overall suitability of the trailer to drying corn cobs and stover. In peanut drying, the unloading was done by placing the trailer at a certain degree of inclination. We did not have an inclined dump mechanism available to use. The clumpy-ness of the material was more evident after drying and as shown in Figures 10 and 11, the material retains the form of the trailer even after the gate was opened. The design of the gate also complicated the unloading process as it only allowed one-half of the height of a full load to pass through. A laborious and time consuming effort was required to manually rake out the material. We doubt that an inclined dump mechanism would be effective with corn cobs and corn stover.

Figure 10. Low flowability of dried material.

Figure 11. Laborious manual raking required to unload material.

To partially overcome the problems during unloading, a wooden sled was designed and constructed to drag out the material from the back of the trailer (Figure 12). This device was built slightly lower than the height of the clearance at the gate and was placed at the front of the trailer prior to loading material. The sled was hooked up to a telescopic handler by a chain that would pull the sled out and the materials with it. Figure 13 illustrates this process. Unloading was easier when half load of materials were involved as this sled easily pushes out most of the materials without much labor. The technical drawing for the wooden sled can be found in Appendix E.

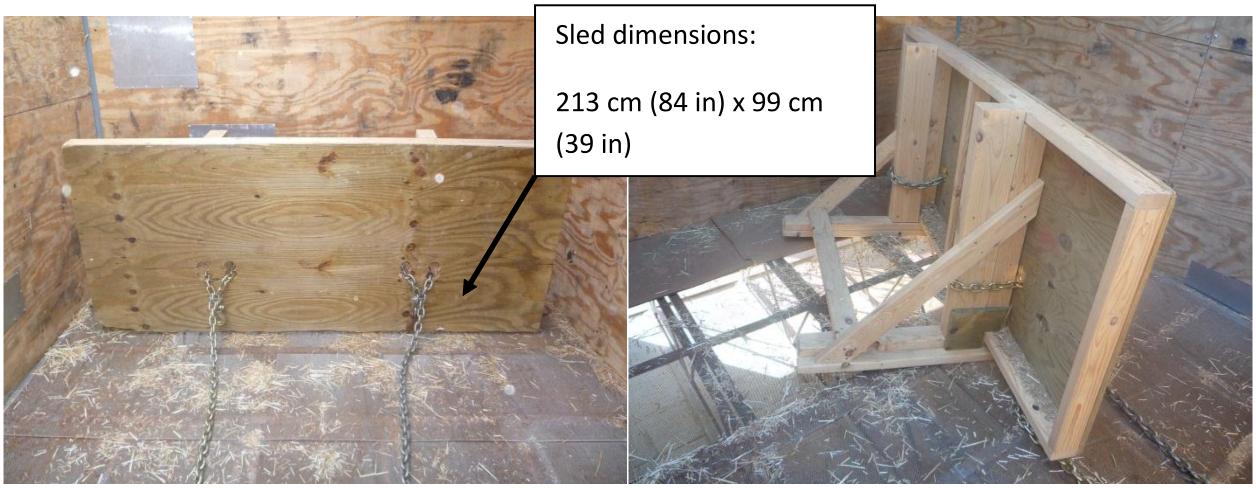

Figure 12. Wooden sled with chains that was hooked on to a tractor

Figure 13. Unloading aided by wooden sled.

Conclusions

The Advanced Trailer semi-trailer-based peanut dryer system was effective in drying wet corn cobs, corn stover and woodchips. However, the energy requirement was very high. Test 12/2/2009 (Half load stover) was found to be the test with the highest energy requirement and Test 11/17/2009 (Full load cobs) required the least amount of energy. Plugging numerous air leaks around the trailer would decrease the drying energy requirements. Environmental conditions also influence the energy requirement. In the trailer's present configuration, loading and unloading corn cobs and stover was not convenient.

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CHAPTER 3. RECOMMENDATIONS FOR THE MODIFICATION OF ADVANCED TRAILER PEANUT DRYER

Based on the conclusions from experiments in Chapter Two, The Advanced Trailer Dryer System would benefit from modifications to improve its ability to handle bulk quantities of clumpy biomass and overall energy efficiency. The following recommendations are divided into the main stages of a drying process, which is loading, drying and unloading.

Loading

The tarp support bars are a major impediment to the loading process (Figure 14). This problem is exacerbated when dealing with clumpy biomass materials. In practice, loading materials using dump-carts was a time-consuming process and required at least two workers to spread out the materials into the trailer. Loading materials directly from the harvester was also not practical. In addition, compaction of the material to increase bulk density was also impossible due to these bars.

Recommendations:

1. Open top design. There are trailers, such as those used in garbage disposal and quarry operations, that have open top designs. In these designs, the support bars are eliminated and the tarp can still be used by switching the orientation of the roll-over tarp (Figure 15)

Figure 14. Tarp support bars requires manual intervention during loading.

Figure 15. Open-top trailer (Mountain Tarp, 2011)

2. Reducing the number of support bars and removing the horizontal strap. The support bars are used to support the weight of the tarp and water or snow on top of it. Since the duration of storage and drying of these materials is short, perhaps they can be eliminated. However, further study is needed to assess the overall strength of trailer box when a full load of material is dumped into the trailer without the full complement of the support bars.

Drying

The drying process is the most critical aspect of the trailer-dryer. The overall effectiveness of the dryer is judged based on the efficiency of utilizing energy in the drying process.

Recommendations:

1. Plugging air leaks/gaps. The most obvious flaw of the trailer was the air leaks around the entire drying plenum under the trailer floor. Air leaks were also apparent around the rear door. Therefore, with the recommended door type in place, it should have no air leaks. Air leaks reduce the static pressure of the drying air and reduce the ability of the dryer to channel

hot drying air to the material. It is important to locate and identify all possible air leaks in the plenum and plugging it by using epoxy or silicone materials.

2. Dual dryer attachment point. The existing design only permits the dryer to be hooked up from the front (truck) end. Considerable time is needed to unhook the truck and then move the dryer into position and then latching it to the trailer before any drying takes place. With a dual dryer attachment point, the dryer can be latched to the trailer from the back with the trailer still attached to the truck. This would save turn-over time or eliminate the need for the truck to be unhooked from the trailer.

Unloading

The unloading process was the most time consuming and labor intensive part of the experiment in Chapter Two. Based on the findings, the trailer requires essential modifications in order to improve this process.

Recommendations:

1. Full/Width Back Doors. The existing design is suitable for unloading of aggregated materials, such as peanuts, where gravitational force induced by the inclination of the trailer on an inclined-dump mechanism, allow the peanuts to flow out freely from the trailer. When handling clumpy materials such as corn harvest residues, the material retains the shape of the trailer and moving the materials out by gravity is not suitable. Furthermore the half-gate door also impedes the flow of materials especially when the load is higher than the opening of the gate. Therefore, a full/wide door design that is common to most trailers and storage containers is preferred.

2. Live-floor design. This design features a conveyor system on the floor of the trailers that enables the materials to be unloaded without inclining the whole trailer and eliminates the need for such expensive mechanism/system. Such design is used on trucks/trailer that transport scrap metals, quarry and construction materials.

3. Eliminate cross chains. The existing design has support chains designed to support the walls of the trailer that were placed in the middle of the trailer. The elimination of these chains would facilitate the unloading of materials.

4. Unloading sled. The use of this device was tested during the experiment in Chapter Two and it is the cheapest and easiest way of solving a large portion of the unloading problem. Details and drawing of the sled can be seen in Appendix E. This device would be much more useful if the doors at the back of the trailer are changed to the full/wide door. This would enable the sled to be used for the unloading of full loads of materials.

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CHAPTER 4. METHOD TO DETERMINE FRICTION COEFFICIENTS OF CORN HARVEST RESIDUES ON DIFFERENT SURFACES

Introduction

The potential of biomass as an alternative to fossil-fuel based sources is well documented. In the United States, the goal of producing 36 billion gallons of biofuel by the year 2022 is mandated by the Energy Independence and Security Act 2007 (Sissine, 2007). According to Sokhansanj and Wright 2002, over 500 million tons of bio-based feedstock will be required annually by 2020 to supply the needs of the United States without increases in imported energy. From a technological perspective, one of the key challenges in achieving this goal lies in improving existing pretreatment practices of supplying biomass to biorefineries. Plants have natural barriers that protect non-starchy polysaccharides from microbial and enzymatic deconstruction. Overcoming this natural protective mechanism or biomass recalcitrance is a major hurdle in unlocking the vast wealth of non-starchy biomass that can be used for bioconversion. Physical pretreatment, specifically physical size reduction of biomass is a key step to overcome the recalcitrance of lignocelluloses. Currently, this process is a major contributor to the overall processing cost for ethanol production (Zhu et al., 2008).

Due to their abundance and close proximity to biorefineries, corn harvest residues are an ideal strategic feedstock (Hettenhaus and Wooley, 2000). Currently, corn residues are collected by existing machinery for grain harvest. Although some aspects of the machinery have been modified to handle biomass harvesting and collection, operating efficiency is still very low to supply a large bioethanol industry. Sokhansanj et al. (2002) concluded that experience and technical data on harvesting and post-harvest processing of corn stover are very limited and there is high inefficiency of collection due to losses during shredding, windrowing and pick-up. This dearth in knowledge can also be related to the scarcity of literature on the physical and mechanical properties of biomass, such as the coefficient of friction, angle of repose and compressive strength. Currently, biomass mechanical properties in literature are mostly limited to the study of biomass grinds (Shaw and Tabil, 2006; Mani et al., 2004; Mani et al., 2006). However, in order to design better and higher efficiency machinery and collection practices, knowledge of the mechanical and physical properties of harvested biomass prior to physical pretreatment is essential.

Design of biomass harvesting and collection machinery is currently based properties derived from grains such as corn and wheat. Likewise, the methods used to determine properties, such as coefficient of friction, can be adapted from procedures used for grains and wheat due to the similarity of their physical properties. Tsang-Mui-Chung et al. (1984) investigated the method of measuring coefficients of friction for grain and Brubaker and Pos (1965) determined the static friction of grains on different surfaces. The studies done on wheat are more extensive and cover a multitude of aspects in actual field practices. Moore et al. (1984) determined the friction of wheat on corrugated metal surfaces, where the coefficient of friction is dependent on the how the grain is positioned in the bin and how fast the bin is emptied. Thompson et al. (1988) studied the variation in the apparent coefficient of friction of wheat on galvanized steel and found that friction behavior of material on galvanized steel is different from other surfaces and requires a wearing-in process to account for the variation.

In this particular study, the goal is to obtain a procedure that can be used to measure static and dynamic coefficient of friction of biomass material on different surfaces. This will help designers of machinery and equipment that handle bulk volumes of harvested biomass to determine the best source of material based on the data that was obtained. The coefficient of friction is a dimensionless scalar value that describes the ratio of friction between two bodies and the force pressing them together. A low value of friction coefficient means that there is no or little friction between the two materials and the value increases as the friction increases. Dry materials have values of friction coefficient between 0.3 to 0.6. Static coefficient of friction is the ratio of force that must be overcome to enable the object to move on the surface and the dynamic friction coefficient is the ratio of forces when the two surfaces are moving (or sliding) in relation to each other.

Objective

To develop a procedure to determine static and dynamic friction coefficients of corn harvest residue on different surfaces using a scaled-up wheat friction apparatus.

Materials and Methods

Test Apparatus

The apparatus is a scaled-up version of a test apparatus that was used to determine the coefficient of friction of wheat (Ross et al., 1987). This apparatus was scaled up 5.4 times based on the ratio of average lengths of corn cobs and wheat (35.3mm/6.5 mm). The structure is made of 2 x 6 dimension lumber and 0.75–in thick particle board. It consisted of 3 frames, a bottom plate that was attached to one of the frames, and a top pressure plate (Figure 16). Test material was placed into the apparatus up to the second frame. Strips of test material were placed between the bottom frame and the middle frame (Figure 17). The apparatus had outside dimension of 101 cm (40 in) wide x 215 cm (85.75 in) long. The technical drawings for the whole apparatus can be found in Appendix A.

Figure 16. Scaled-up coefficient of friction test apparatus

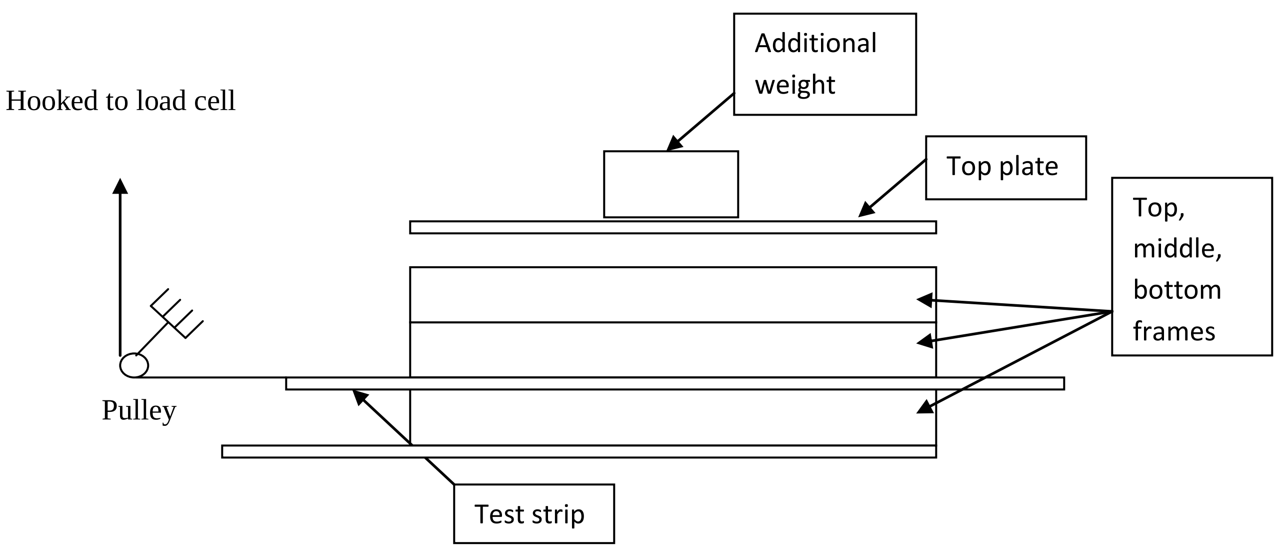

Figure 17. Schematic diagram of apparatus setup

Material Testing Station

The test apparatus was connected by a metal cable to a 500-lb load cell. The force measured by the load cell is fed to a software program onboard the MTS, model SINTECH 60/D ® material testing workstation (MTS Systems, Eden Prairie, MN). The software program used was Testworks ® 3 that runs on a Windows 3.1 workstation (Figure 18).

Figure 18. The Material Testing System onboard a Windows 3.1 workstation.

Trial Run Test Material

As a proof of concept, a trial run was completed to test the procedures that were developed for this purpose. The material consisted of corn grain harvest residue that was collected from a prototype John Deere 9750 single-pass dual-stream combine October 2, 2010. The corn variety was Dekalb DKC 52-59 VT3 that was planted on April 15 at 32,200 seed per acre on the Bruner Farm, 16km west of Iowa State University campus.

Moistureasdf Content

Moisture content for the procedure obtained from oven moisture tests (103°C, 24 h) and were conducted following ASABE Standard S358.2 (ASABE Standards, 2008). The average moisture content of the three samples was 17.8%.

Bulk Density

Bulk density of the material being tested can be estimated by weighing the material placed into the test apparatus and dividing it by the volume of the material. The volume was calculated by ensuring that the material was properly loaded into the test apparatus according to the procedure.

Experimental Procedure

The procedure was developed by Al-Mahasneh and Lane (1997) and was adapted for the determination of friction coefficient in this experiment. The main change was the use of additional weights to be placed on the apparatus during the experiment.

Based on the method used by Ross et al. (1987), test material was subjected to additional weights on top of the top plate to generate adequate grain pressure on the test material. This ensured that there was adequate horizontal force by the material acting on the test surface so that the force that was needed to overcome the friction can be calculated. For the scaled-up test, an equivalent weight of 1.5-m depth of test material was chosen as the assumed horizontal force, since bulk materials are often moved and transported in this volume. The additional weights to be added corresponding to the test strips used are summarized in Table 12. Calculations can be seen in Appendix B. Seven types of materials that are sometimes used as building materials to handle the test materials were chosen. The choices were two types of plastic surfaces: HDPE (High-density polyethylene) and UHMW (Ultra-high-molecular-weight polyethylene), Three types of metal surfaces: GS (Galvanized steel), MS (Mild steel) and SS (Stainless steel), and two types of wood surfaces: oak and pine, both in the direction of the wood grain. Test strips are all 234 cm (96in) long and each type has different width and thickness due to limitations of material supply. Dimensions can be seen in Table 12 as well. For the galvanized steel and stainless steel strips, the thickness of the individual strip was a composite of 2 ply of the metal sheet with a layer of pine in between. This was to provide support to the metal sheets and prevent it from warping as using a single ply of metal sheet would be too thin and the strip would not be flat on top of the test material during test.

Table 12. Additional weights for corresponding test strips

Test Strip	Additional Weight, kg	Thickness, cm	Width, cm
High-density polyethylene, HDPE	101.0	1.5	42.0
Ultra-high-molecular-weight polyethylene, UHMW	101.1	1.5	42.0
Galvanized steel, GS	93.8	1.5	42.5
Mild steel, MS	98.1	0.2	42.0
Stainless steel, SS	95.2	1.4	42.5
Oak	101.7	1.2	36.0
Pine	99.9	1.7	40.0

A. MTS and computer setup

1. Attach the 500-lb load cell to the MTS crosspiece and plug in the load cell cable into the MTS at the back of the crosspiece.
2. Turn on the MTS machine and then the computer.
3. Click on ‘TEST’ icon.
4. Click on ‘CALIBRATE’.
5. Select ‘500 lb Interface cell’.
6. Click ‘OK’, then ‘EXIT’.

B. Apparatus setup

1. Fill the bottom of the frame with test material, level the material with a long strip and remove excess material (Figure 20).

2. Place the test strip on the test material and make sure the strip does not come into contact with the frame. Hook up test strip to load cell with a cable and be sure to align the strip and the base of the MTS machine (Figure 21).
3. Place the second and third frames on top of the bottom frame and fill with test material up to the level of second frame (Figure 22).
4. Place the pressure plate on top of the test material (Figure 23).
5. Place additional weights on top of the pressure plate (Figure 24).

Figure 19. Bottom frame

Figure 20. Fill test material up to frame level

Figure 21. Test strip on bottom material

Figure 22. Place second and third frame

Figure 23. Place pressure plate

Figure 24. Place additional weights

C. Machine Operation

1. On the computer screen, select application method. Click on 'METHOD" then 'COEFFICIENT OF FRICTION'.
2. Click 'SAMPLE' icon and name the experiment and sample number.
3. Click 'INPUTS' and choose 'CALCULATION'. Select 'SLED WEIGHT' and enter amount of weight on the plate (Total weight = top plate + additional weight).
4. Exit 'SLED WEIGHT".
5. Select 'TEST' and click on 'CROSSHEAD SPEED'. Enter 130 mm/min (5 in/min).
6. Still under 'TEST', select 'EXT LIMIT HI' and enter 50 mm (2 in).
7. Exit 'INPUTS'
8. Using hand control, move load cell up until the pre-load force on the screen is approximately 2 to 5-kg (5 to 10-lb).
9. Zero the crosshead position by clicking 'ZERO' on the screen.
10. Click 'RUN' and enter a crosshead speed of 130 mm/min (5 in/min).
11. As observed by Thompson et Al., 1988, to obtain a correct reading and to ensure the material goes through a wearing in period, steps 8 to 10 are repeated at least 3 times.
12. After wearing in process is done, run the test by repeating steps 8 to 10 and then noting down the values for Static Coefficient of Friction, Dynamic Coefficient of Friction.
13. Click next to prepare to run next replication.

D. Material set-up in between tests

1. Remove all the materials from the apparatus and weigh the material to calculate bulk density based on the known apparatus volume. Record the weight.
2. Mix material thoroughly before refilling the apparatus for a test apparatus. Once mixed, steps B1 to B5 is repeated to set up material for the next test.
3. Steps C8 to C13 are repeated.

Results And Discussion

From the results obtained, the experiment (Table 13, Figures 25 and 26) in contact with material other than grain (M.O.G.) at 17.8% moisture content, we were able to determine the static and dynamic coefficients of friction for all the test strips. All the results except for galvanized steel conform to the expected results where plastic surface (HDPE) was the least resistant to frictional forces and wood surfaces (oak and pine) were the highest valued coefficients. For galvanized steel, the results were not as expected due to the 'slip-stick' phenomena (Bucklin et.al., 1996) and the effect was more pronounced as this was a new strip of metal without any wear. The summary of results can be seen in Table 13 and Figures 25 and 26. The test for UHMWP was not done because the test strip was deformed and warped. This deformity might result in incorrect results as the test strips need to be flat and slides smoothly across the test materials. Test datasheet can be seen in Appendix C.

Table 13. Summary of Static and Dynamic Coefficient of Friction

Test Strip	**Coefficient of Friction**		**Bulk density, kg/m^3**	**Bulk density std. dev.**
	Static	Dynamic		
Oak	0.44	0.21	52.2	8.96
Pine	0.41	0.22	52.9	1.64
Mild steel	0.40	0.25	52.9	1.69
Stainless steel	0.37	0.31	54.3	4.98
Galvanized steel	0.66	0.34	54.1	2.35
HDPE	0.23	0.16	55.2	2.72

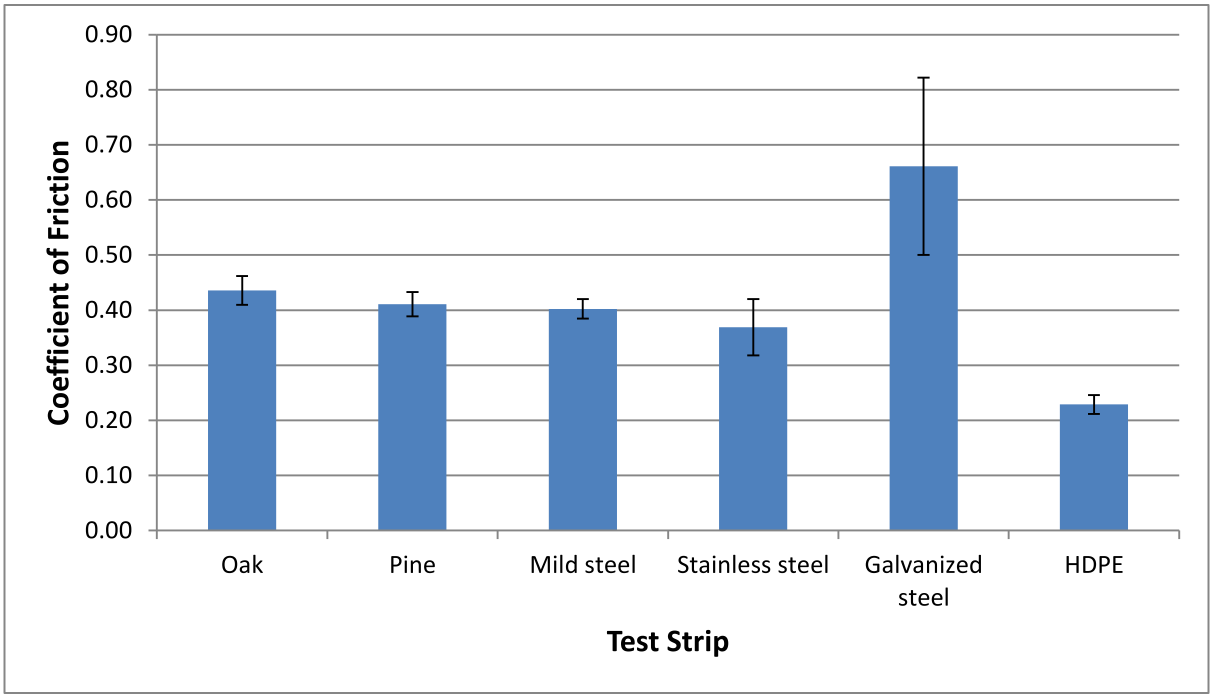

Figure 25. Static coefficients of friction of 17.8% moisture content M.O.G. for all test strips for 3 replications

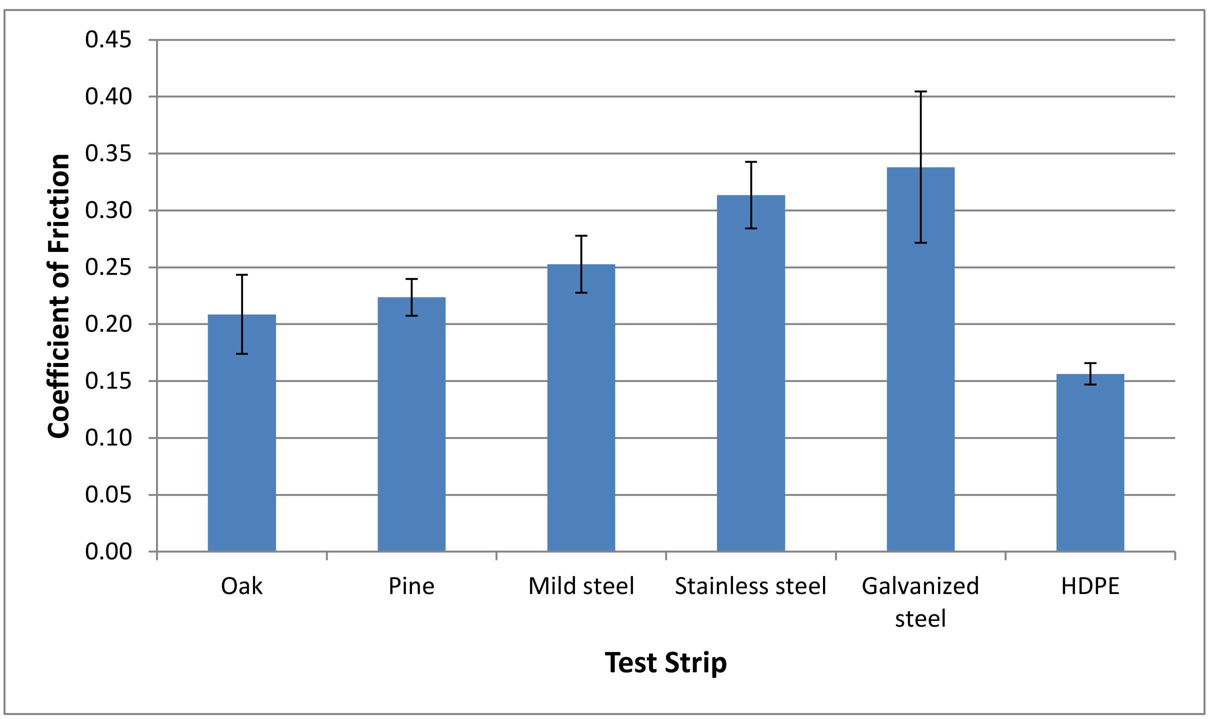

Figure 26. Dynamic coefficients of friction of 17.8% moisture content M.O.G. for all test strips for 3 replications

Statistical analysis was done to determine whether there is a significant difference in means of all the results obtained for all the test strips. Based on a one-way ANOVA procedure, all test strips were found to be significantly different from each other at F = 0.0003 and a coefficient of variation of 17.1 %. As for the dynamic coefficient of friction tests, the ANOVA table provides evidence to support the conclusion of a statistically significant difference among all tests at an F = 0.0004 and a coefficient of variation of 14.2%. The ANOVA tables can be found in Appendix D.

The experiment was initially designed measure the values of coefficient of friction of three types of corn harvest residues: corn stover, corn cobs and material other than grain (M.O.G.), on seven different types of test surfaces. The experiment will also compare the measurement taken from three different moisture contents (10 %, 17.81%, 25% wet basis). However, the test station of the MTS Sintech 60/D ® suffered hardware failure. Repair duration and cost were beyond the period and budget of the experiment. The experiment was subsequently terminated.

Conclusions

This procedure can be used to estimate the values of coefficient of friction of biomass on different surfaces. HDPE and oak was found to be the material with the smallest and highest static friction coefficient respectively. This result was also true for the dynamic friction coefficient. The slip-stick phenomena was found to affect the friction coefficient of M.O.G. on galvanized steel.

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CHAPTER 5. GENERAL CONCLUSIONS

Conclusions

Densification and handling of bulk quantities of biomass remains a challenge for biomass to be regarded as a feasible alternative to fossil fuels. Corn residue is an obvious choice as biomass feedstock due to its abundance and close-proximity to biorefineries. Drying of biomass as a pretreatment prior to bioconversion is seen as an essential step in the densification process. Harvest and collection of residues are currently done with existing machines designed for grain harvest and the current practices of field drying and baling have many issues.

This dissertation examines a potential system that can be used to store, transport and dry harvested biomass. The Advanced Trailer Peanut Dryer system was tested and evaluated to dry corn stover, corn cobs and eucalyptus woodchips. Based on these test, drying characteristics and overall energy efficiency was determined. The system was found to be effective in drying wet corn cobs, corn stover and eucalyptus woodchips. However, in the system's current configuration, loading and unloading of materials are not convenient. Overall energy efficiency is also negatively affected by numerous air leaks around the trailer.

Based on the testing, modifications were recommended to improve the capability of the system to handle bulk quantities of biomass and drying energy efficiency. A list of recommendations was suggested for the three main operation components of the system (loading, during drying and unloading).

In relation to the testing of the drying system, material handling of bulk quantities of leafy biomass such as corn stover and corn cobs was found to be very challenging. Existing machinery and equipment were not design specifically to handle biomass of such nature and utilizing it is at a high cost of time, labor and efficiency. Therefore, material characteristics such as friction coefficient of corn harvest residue are important in order to design more suitable machinery and equipment. A procedure to determine the friction coefficient of corn harvest residue was developed based on procedures used for grain. This procedure was found to be suitable in determining friction coefficient of corn harvest residue on different surfaces at different moisture contents.

Recommendations for future research

Based on the modifications that were suggested, further testing can be done to evaluate the system's performance after all or some of these modifications were carried out. The results can be compared with those prior to the modifications to see if the overall drying energy efficiency can be improved.

Further tests to determine the friction coefficient of biomass materials should be carried out to predict the behavior of biomass during bulk handling based on material characteristics of grain or other similar materials. These tests can be done for corn harvest residues at different moisture contents and can be extended to other types of biomass such as switchgrass or kenaf.

APPENDIX A: NATURAL GAS MEASUREMENT

Natural gas volume was measured through calibration of Alliant Energy's revenue meter. The dryer gas burner was connected to a meter that registers the total volume being used by the whole facility. Therefore, calibration of the meter was carried out by measuring the time needed to advance one digit on the meter register. All drying was done at the maximum setting of the dryer pressure regulator which was at 0.2kPa (4 lb/in^2). At this setting, the burner required 60 minutes to advance one digit on the gas meter, with all other gas outlets in the building closed. The corresponding single digit on the meter represents 1000 ft^3 of gas used; therefore gas consumption was 27.5 m^3 (1000 ft^3/h).

APPENDIX B: DATA FROM DRYING EXPERIMENT

Test Number : 11/1/2009

Drying Start Date and Time	11/1/2009	2:55 PM
Drying End Date and Time	11/3/2009	4:20 PM
Drying Material	Corn Stover	
Corn Hybrid	Dekalb 111 day corn	
Harvest Location	Kent Berns Dairy Compost Field	
Date Harvested	10/26/2009 -10/29/2009	
Harvesting Machine Model	John Deere 9860 Combine	

NOTE:				
1. Half load stover				
2. Gas flow conversion	1000/1.08	ft^3/hr		
3. Heating value of natural ga	1028	Btu/ft^3		
4. Electrical energy conversic	3412.3	Btu/kwh		
5. Btu to kJ conversion	1.05506	kJ/Btu		
6. Trailer Length	45	ft	14	m
7. Trailer width	8	ft	2	m

DATA COLLECTION												
PARAMETER	At Zero			INITIAL			24 hr			49.42 hr		
WEIGHT, lbs [kg]	5380.0	2445.5		5380.0	2445.5		3986.4	1812.0		3961.3	1800.6	
WATER WEIGHT REMOVED, lbs [kg]	0	0.0		0	0.0		1393.6	633.5		1418.7	644.9	
RELATIVE HUMIDITY (%)	63.3			63.3			37.5			57.3		
NATURAL GAS FLOW (hr)	49.42											
NATURAL GAS CONSUMPTION (ft^3)	22160.66											
CUMULATIVE ELECTRICITY CONSUMPTION (kWh)	0			0			733			**1405**		
STATIC PRESSURE, in.H2O [kPa]	0	0		0.91	0.227		0.5	0.125		0.5	0.125	
TRAILER TEMPERATURE POINTS (F)/(°C)	T1	54.0	12.2	T1	54.0	12.2	T1	83.0	28.3	T1	87.0	30.6
	T2	76.0	24.4	T2	73.0	22.8	T2	72.0	22.2	T2	64.0	17.8
	T4	54.0	12.2	T4	62.0	16.7	T4	73.0	22.8	T4	70.0	21.1
	T3	72.0	22.2	T3	68.0	20.0	T3	64.0	17.8	T3	59.0	15.0
	T4	53.0	11.7	T4	70.0	21.1	T4	75.0	23.9	T4	76.0	24.4
	T5	76.0	24.4	T5	73.0	22.8	T5	66.0	18.9	T5	66.0	18.9
		64.2	17.9		66.7	19.3		72.2	22.3		70.3	21.3
AMBIENT TEMPERATURE, F [°C]	62.9	12.2		62.9	17.2		50.8	10.4		46.3	7.9	
INLET PLENUM TEMP, F [°C]	67	19.4		89.4	31.9		72	22.2		68.9	20.5	
MIDDLE PLENUM TEMP, F [°C]	60	15.6		73	22.8		73	22.8		70	21.1	
NATURAL GAS PRESSURE, psi [kPa]	3	20.7		4	27.6		4	27.6		4	27.6	
STOVER DEPTH, ft [m]	3.67	1.12		3.67	1.12		3.25	0.99		3.08	0.94	
VOLUME ft^3 [m^3]	1319.95	31.29		1319.95	31.29		1169.95	27.74		1109.96	26.31	
BULK DENSITY, lb/ft^3 [kg/m^3]	4.08	78.15		4.08	78.15		3.41	65.33		3.57	68.43	
Moisture Content (%)	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%
Dryer End				14.40	10.00	30.56	8.20	7.60	7.32	7.80	7.40	5.13
2				11.00	7.80	29.09	7.00	6.60	5.71	7.80	7.40	5.13
3				11.20	7.60	32.14	5.80	5.40	6.90	6.80	6.40	5.88
Ave						30.60			6.64			5.38
Middle DE				14.00	9.80	30.00	8.40	7.80	7.14	9.00	8.40	6.67
2				12.00	8.40	30.00	8.40	7.80	7.14	9.80	9.20	6.12
3				13.00	9.00	30.77	8.60	8.00	6.98	7.40	6.80	8.11
Ave						30.26			7.09			6.97
Middle Back				9.20	6.40	30.43	7.20	7.00	2.78	10.40	9.60	7.69
2				8.00	5.60	30.00	6.80	6.40	5.88	11.00	10.20	7.27
3				9.60	6.40	33.33	8.60	8.20	4.65	9.60	9.00	6.25
Ave						31.26			4.44			7.07
Back				16.20	10.60	34.57	5.00	4.80	4.00	10.20	9.40	7.84
2				10.80	7.60	29.63	9.80	9.20	6.12	10.00	9.20	8.00
3				10.80	7.60	29.63	7.40	7.00	5.41	7.80	7.20	7.69
Ave						31.28			5.18			7.85
MC GRAND AVERAGE (%)						30.85			5.84			6.82
MC CALCULATION BASED ON WEIGHT LOSS (%)									6.67			6.08

HEATING SPECIFICATIONS (24 HOURS)		
INPUT HEAT ENERGY, Btu [kJ]	2.28E+07	2.34E+07
INPUT ELECTRIC ENERGY Btu [kJ]	2.50E+06	2.64E+06
INPUT HEAT ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	1.63E+04	3.69E+04
INPUT ELECTRICAL ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	1.79E+03	4.17E+03
TOTAL INPUT ENERGY Btu/lb [kJ/kg]	1.81E+04	4.10E+04

Test Number : 11/10/2009

Drying Start Date and Time	11/10/2009	6:30 PM
Drying End Date and Time	11/12/2009	9:30 AM
Drying Material	Corn Stover	
Corn Hybrid	Dekalb 111 day corn	
Harvest Location	Kent Berns Dairy East Field	
Date Harvested	11/7/2009	
Harvesting Machine Model	John Deere 9860 Combine	

NOTE:				
1.Full load stover				
2. Gas flow conversion	1000/1.08	ft^3/hr		
3. Heating value of natural ga	1028	Btu/ft^3		
4. Electrical energy conversic	3412.3	Btu/kwh		
5. Btu to kJ conversion	1.05506	kJ/Btu		
6. Trailer Length	45	ft	14	m
7. Trailer width	8	ft	2	m

DATA COLLECTION

PARAMETER	At Zero			INITIAL			12 hr			24 hr			39 hr		
WEIGHT, lbs [kg]	13070.0		5940.9	13070.0		5940.9	10940.0		4972.7	10510.0		4777.3	10550.0		4795.5
WATER WEIGHT REMOVED, lbs [kg]	0		0.0	0		0.0	2130.0		968.2	2560.0		1163.6	2520.0		1145.5
RELATIVE HUMIDITY (%)	46.22			46.22			94.2			56.5			56.5		
GAS FLOW (hr)	39														
NATURAL GAS CONSUMPTION (ft^3)	22160.66														
CUMULATIVE ELECTRICITY CONSUMPTION (kWh)	0			0			345			625			1118		
STATIC PRESSURE, in.H2O [kPa]	0		0	1.9		0.473	1.9		0.473	1.9		0.473	1.9		0.473
TRAILER TEMPERATURE POINTS (F)/(°C)	T1	55.0	12.8	T1	54.0	12.2	T1	67.0	19.4	T1	87.0	30.6	T1	76.0	24.4
	T2	48.0	8.9	T2	50.0	10.0	T2	64.0	17.8	T2	83.0	28.3	T2	73.0	22.8
	T4	55.0	12.8	T4	53.0	11.7	T4	65.0	18.3	T4	85.0	29.4	T4	73.0	22.8
	T3	51.0	10.6	T3	52.0	11.1	T3	62.0	16.7	T3	82.0	27.8	T3	71.0	21.7
	T4	52.0	11.1	T4	52.0	11.1	T4	63.0	17.2	T4	84.0	28.9	T4	72.0	22.2
	T5	47.0	8.3	T5	51.0	10.6	T5	58.0	14.4	T5	80.0	26.7	T5	69.0	20.6
		51.3	10.7		52.0	11.1		63.2	17.3		83.5	28.6		72.3	22.4
AMBIENT TEMPERATURE, F [°C]	51.3		12.8	51.3		10.7	35.4		1.9	50.0		10.0	41.5		5.3
INLET PLENUM TEMP, F [°C]	48.6		9.2	63.5		17.5	50.0		10.0	70.4		21.3	60.5		15.8
MIDDLE PLENUM TEMP, F [°C]	50.0		10.0	73.0		22.8	60.0		15.6	80.0		26.7	69.0		20.6
NATURAL GAS PRESSURE, psi [kPa]	4.0		27.6	4.0		27.6	4.0		27.6	4.0		27.6	4.0		27.6
STOVER DEPTH, ft [m]	6.7		2.0	6.7		2.0	6.3		1.9	6.2		1.9	6.1		1.9
VOLUME ft^3 [m^3]	2399.90		56.89	2399.90		56.89	2279.09		54.03	2219.11		52.61	2189.12		51.90
BULK DENSITY, lb/ft^3 [kg/m^3]	5.45		104.42	5.45		104.42	4.80		92.04	4.74		90.81	4.82		92.40
Moisture Content (%)	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%
Dryer End				7.60	6.20	18.42	10.00	9.00	10.00	7.80	7.40	5.13	11.00	10.40	5.45
2				14.40	9.00	37.50	10.80	9.80	9.26	7.80	7.40	5.13	9.20	8.80	4.35
3				14.20	10.60	25.35	9.60	8.40	12.50	6.80	6.40	5.88	11.40	10.80	5.26
Ave						27.09			10.59			5.38			5.02
Middle DE				7.00	5.60	20.00	6.40	5.60	12.50	9.00	8.40	6.67	10.00	9.20	8.00
2				11.80	8.20	30.51	6.20	5.40	12.90	9.80	9.20	6.12	15.60	14.60	6.41
3				10.80	8.00	25.93	15.20	12.80	15.79	7.40	6.80	8.11	17.20	16.00	6.97
Ave						25.48			13.73			6.97			7.13
Middle Back				11.20	8.40	25.00	7.40	6.40	13.51	10.40	9.60	7.69	7.20	6.80	5.56
2				7.20	5.60	22.22	17.80	15.40	13.48	11.00	10.20	7.27	15.40	14.00	9.09
3				8.40	6.80	19.05	8.20	7.20	12.19	9.60	9.00	6.25	17.80	16.60	6.74
Ave						22.09			13.06			7.07			7.13
Back				9.40	6.80	27.66	6.20	5.40	12.90	10.20	9.40	7.84	7.00	6.60	5.71
2				6.00	4.80	20.00	16.60	14.20	14.46	10.00	9.20	8.00	8.40	8.00	4.76
3				18.40	13.80	25.00	14.80	13.00	12.16	7.80	7.20	7.69	13.00	12.20	6.15
Ave						24.22			13.17			7.85			5.54
MC GRAND AVERAGE (%)						24.72			12.64			6.82			6.20
MC CALCULATION BASED ON WEIGHT LOSS (%)									10.06			6.38			6.74

HEATING SPECIFICATIONS (24 HOURS)

INPUT HEAT ENERGY, Btu [kJ]	2.28E+07	2.34E+07
INPUT ELECTRIC ENERGY Btu [kJ]	2.13E+06	2.25E+06
INPUT HEAT ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	9.04E+03	2.01E+04
INPUT ELECTRICAL ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	8.33E+02	1.93E+03
TOTAL INPUT ENERGY Btu/lb [kJ/kg]	9.87E+03	2.20E+04

Test Number : 12/2/2009

Drying Start Date and Time	12/2/2009	10:30 AM	NOTE:			
Drying End Date and Time	12/3/2009	9:30 AM	1. Half load stover			
Drying Material	Corn Stover		2. Gas flow conversion	1000/1.08	ft^3/hr	
Corn Hybrid	Crow's 116 day corn		3. Heating value of natural ga	1028	Btu/ft^3	
Harvest Location	Kent Berns Dairy South Silage		4. Electrical energy conversio	3412.3	Btu/kwh	
Date Harvested	11/18/2009		5. Btu to kJ conversion	1.05506	kJ/Btu	
Harvesting Machine Model	John Deere 9860 Combine		6. Trailer Length	45	ft	14 m
			7. Trailer width	8	ft	2 m

DATA COLLECTION															
PARAMETER	At Zero			INITIAL			6 hr			12 hr			23 hr		
WEIGHT, lbs [kg]	4630.0	2104.5		4630.0	2104.5		4433.0	2015.0		4294.0	1951.8		4250.0	1931.8	
WATER WEIGHT REMOVED, lbs [kg]	0	0.0		0	0.0		197.0	89.5		336.0	152.7		380.0	172.7	
RELATIVE HUMIDITY (%)	87.1			87.1			83.7			76.2			88.5		
GAS FLOW (hr)	23														
NATURAL GAS CONSUMPTION (ft^3)	21237.30														
CUMULATIVE ELECTRICITY CONSUMPTION (kWh)	0			0			175			336			748		
STATIC PRESSURE, in.H2O [kPa]	0	0		1.1	0.274		1.1	0.274		1.1	0.274		1.1	0.274	
TRAILER TEMPERATURE POINTS (F)/(°C)	T1	55.0	12.8	T1	55.0	12.8	T1	50.0	10.0	T1	53.0	11.7	T1	46.0	7.8
	T2	51.0	10.6	T2	51.0	10.6	T2	44.0	6.7	T2	47.0	8.3	T2	38.0	3.3
	T4	52.0	11.1	T4	52.0	11.1	T4	48.0	8.9	T4	55.0	12.8	T4	48.0	8.9
	T3	48.0	8.9	T3	48.0	8.9	T3	47.0	8.3	T3	50.0	10.0	T3	41.0	5.0
	T4	48.0	8.9	T4	48.0	8.9	T4	53.0	11.7	T4	50.0	10.0	T4	43.0	6.1
	T5	50.0	10.0	T5	50.0	10.0	T5	43.0	6.1	T5	46.0	7.8	T5	42.0	5.6
		50.7	10.4		50.7	10.4		47.5	8.6		50.2	10.1		43.0	6.1
AMBIENT TEMPERATURE, F [°C]	31.5	12.8		31.5	-0.3		31.4	-0.4		27.1	-2.7		24.2	-4.3	
INLET PLENUM TEMP, F [°C]	32.0	0.0		42.4	5.8		49.3	9.6		40.8	4.9		41.0	5.0	
MIDDLE PLENUM TEMP, F [°C]	36.8	2.7		50.0	10.0		51.0	10.6		48.0	8.9		45.0	7.2	
NATURAL GAS PRESSURE, psi [kPa]	4.0	27.6		4.0	27.6		4.0	27.6		4.0	27.6		4.0	27.6	
STOVER DEPTH, ft [m]	3.7	1.1		3.7	1.1		3.2	1.0		3.1	0.9		3.1	0.9	
VOLUME ft^3 [m^3]	1319.47	31.28		1319.47	31.28		1139.54	27.01		1109.56	26.30		1109.56	26.30	
BULK DENSITY, lb/ft^3 [kg/m^3]	3.51	67.28		3.51	67.28		3.89	74.59		3.87	74.20		3.83	73.44	
Moisture Content (%)	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%
Dryer End				34.80	30.50	12.36	33.80	29.60	12.43	32.90	30.10	8.51	34.20	32.10	6.14
2				33.50	28.90	13.73	32.90	28.70	12.77	33.10	30.10	9.06	33.80	31.80	5.92
3				33.10	28.30	14.50	33.10	29.10	12.08	34.00	30.90	9.12	33.70	31.40	6.82
Ave						13.53			12.42			8.90			6.29
Middle DE				33.60	29.70	11.61	31.20	27.30	12.50	32.70	29.80	8.87	33.90	31.80	6.19
2				32.10	27.50	14.33	33.40	29.20	12.57	33.60	30.40	9.52	33.50	31.50	5.97
3				33.10	28.10	15.11	32.10	28.10	12.46	33.10	30.20	8.76	33.70	31.40	6.82
Ave						13.68			12.51			9.05			6.33
Middle Back				32.70	27.80	14.98	32.80	28.50	13.11	32.90	29.40	10.64	33.80	31.70	6.21
2				32.10	27.80	13.40	33.10	28.80	12.99	33.20	29.90	9.93	33.40	31.30	6.28
3				31.20	26.90	13.78	33.50	29.00	13.43	33.80	30.80	8.87	34.00	31.70	6.76
Ave						14.05			13.18			9.81			6.42
Back				33.80	28.80	14.79	32.60	28.00	14.11	34.10	30.80	9.67	34.10	31.90	6.45
2				31.10	26.70	14.14	33.70	29.30	13.05	34.20	31.20	8.77	34.20	32.10	6.14
3				33.10	27.90	15.71	34.10	29.30	14.07	33.90	30.50	10.03	33.80	31.40	7.10
Ave						14.88			13.74			9.49			6.56
MC GRAND AVERAGE (%)						14.04			12.96			9.31			6.40
MC CALCULATION BASED ON WEIGHT LOSS (%)									10.22			7.31			6.35

HEATING SPECIFICATIONS		
INPUT HEAT ENERGY, Btu [kJ]	2.18E+07	2.24E+07
INPUT ELECTRIC ENERGY Btu [kJ]	2.55E+06	2.69E+06
INPUT HEAT ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	5.75E+04	1.30E+05
INPUT ELECTRICAL ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	6.72E+03	1.56E+04
TOTAL INPUT ENERGY Btu/lb [kJ/kg]	6.42E+04	1.45E+05

Test Number : 11/17/2009

Drying Start Date and Time	11/17/2009	6:15 AM
Drying End Date and Time	11/19/2009	6:15 PM
Drying Material	Corn Cobs	
Corn Hybrid	Dekalb 111 day corn	
Harvest Location	ISU Research Farm	
Date Harvested	11/17/2009	
Harvesting Machine Model	John Deere 9860 Combine	

NOTE:				
1. Full load cobs				
2. Gas flow conversion	1000/1.08	ft^3/hr		
3. Heating value of natural ga	1028	Btu/ft^3		
4. Electrical energy conversio	3412.3	Btu/kwh		
5. Btu to kJ conversion	1.05506	kJ/Btu		
6. Trailer Length	45	ft	14	m
7. Trailer width	8	ft	2	m

DATA COLLECTION															
PARAMETER	At Zero			INITIAL			12 hr			24 hr			36 hr		
WEIGHT, lbs [kg]	22520.0		10236.4	22520.0		10236.4	19550.0		8886.4	19080.0		8672.7	19040.0		8654.5
WATER WEIGHT REMOVED, lbs [kg]	0		0.0	0		0.0	2970.0		1350.0	3440.0		1563.6	3480.0		1581.8
RELATIVE HUMIDITY (%)	74.9			74.9			42.3			84.6			100		
GAS FLOW (hr)	36														
NATURAL GAS CONSUMPTION (ft^3)	22160.66														
CUMULATIVE ELECTRICITY CONSUMPTION (kWh)	0			0			332			705			844		
STATIC PRESSURE, in.H2O [kPa]	0		0	2		0.498	1.9		0.473	1.7		0.423	1.8		0.448
TRAILER TEMPERATURE POINTS (F)/(°C)	T1	40.0	4.4	T1	41.0	5.0	T1	77.0	25.0	T1	63.0	17.2	T1	70.0	21.1
	T2	37.0	2.8	T2	45.0	7.2	T2	64.0	17.8	T2	59.0	15.0	T2	70.0	21.1
	T4	39.0	3.9	T4	41.0	5.0	T4	76.0	24.4	T4	61.0	16.1	T4	69.0	20.6
	T3	40.0	4.4	T3	45.0	7.2	T3	69.0	20.6	T3	61.0	16.1	T3	70.0	21.1
	T4	40.0	4.4	T4	43.0	6.1	T4	70.0	21.1	T4	61.0	16.1	T4	69.0	20.6
	T5	38.0	3.3	T5	44.0	6.7	T5	63.0	17.2	T5	59.0	15.0	T5	72.0	22.2
		39.0	3.9		43.2	6.2		69.8	21.0		60.7	15.9		70.0	21.1
AMBIENT TEMPERATURE, F [°C]	36.2		4.4	36.2		2.3	46.2		7.9	38.4		3.6	41.2		5.1
INLET PLENUM TEMP, F [°C]	38.5		3.6	52.8		11.6	58.4		14.7	56.4		13.6	64.0		17.8
MIDDLE PLENUM TEMP, F [°C]	37.0		2.8	60.0		15.6	65.0		18.3	55.0		12.8	63.0		17.2
NATURAL GAS PRESSURE, psi [kPa]	4.0		27.6	4.0		27.6	4.0		27.6	4.0		27.6	4.0		27.6
STOVER DEPTH, ft [m]	6.8		2.1	6.8		2.1	6.4		2.0	6.2		1.9	6.2		1.9
VOLUME ft^3 [m^3]	2459.02		58.30	2459.02		58.30	2309.08		54.74	2249.10		53.32	2249.10		53.32
BULK DENSITY, lb/ft^3 [kg/m^3]	9.16		175.60	9.16		175.60	8.47		162.34	8.48		162.66	8.47		162.32
Moisture Content (%)	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%
Dryer End				44.80	35.40	20.98	33.80	28.80	14.79	34.40	31.40	8.72	31.60	30.00	5.06
2				37.00	29.60	20.00	40.80	34.40	15.69	33.60	29.80	11.31	35.40	32.40	8.47
3				31.60	25.00	20.89	41.40	35.40	14.49	37.40	35.00	6.42	33.00	29.00	12.12
Ave						20.62			14.99			8.82			8.55
Middle DE				33.20	25.60	22.89	31.80	26.60	16.35	38.00	34.20	10.00	25.60	23.40	8.59
2				32.60	25.40	22.09	36.80	30.60	16.85	33.80	30.40	10.06	36.00	33.00	8.33
3				33.00	25.60	22.42	35.00	28.60	18.29	38.80	35.00	9.79	34.00	31.00	8.82
Ave						22.47			17.16			9.95			8.58
Middle Back				35.20	27.60	21.59	36.40	32.00	12.09	33.40	30.40	8.98	31.80	28.80	9.43
2				37.60	29.40	21.81	37.00	32.40	12.43	42.00	38.20	9.05	35.20	32.00	9.09
3				37.20	28.60	23.11	33.20	29.00	12.65	25.00	22.80	8.80	40.40	37.20	7.92
Ave						22.17			12.39			8.94			8.81
Back				30.00	22.80	24.00	34.60	29.20	15.61	33.40	30.40	8.98	23.40	21.00	10.26
2				27.80	21.20	23.74	32.80	26.20	20.12	32.20	29.20	9.32	31.40	28.60	8.92
3				35.40	27.00	23.72	32.60	29.40	9.82	32.40	29.60	8.64	35.00	32.00	8.57
Ave						23.82			15.18			8.98			9.25
MC GRAND AVERAGE (%)						22.27			14.93			9.17			8.80
MC CALCULATION BASED ON WEIGHT LOSS (%)									10.46			8.26			8.06

HEATING SPECIFICATIONS (24 HOURS)		
INPUT HEAT ENERGY, Btu [kJ]	2.28E+07	2.34E+07
INPUT ELECTRIC ENERGY Btu [kJ]	2.41E+06	2.54E+06
INPUT HEAT ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	6.62E+03	1.49E+04
INPUT ELECTRICAL ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	6.91E+02	1.62E+03
TOTAL INPUT ENERGY Btu/lb [kJ/kg]	7.31E+03	1.66E+04

Test Number : 9/23/2009

Drying Start Date and Time	9/23/2009	
Drying End Date and Time	9/28/2009	
Drying Material	Eucalyptus	
Harvest Location		
Date Harvested		
Harvesting Machine Model		

PARAMETER	At Zero			INITIAL			2 hr			8.5 hr			29 hr			38.5 hr		
WEIGHT, lbs [kg]	24500.0	11136.4		24500.0	11136.4		22500.0	10227.3		19600.0	8909.1		13200.0	6000.0		12170.0	5531.8	
WATER WEIGHT REMOVED, lbs [kg]	0	0.0		0	0.0		2000.0	909.1		4900.0	2227.3		11300.0	5136.4		12330.0	5604.5	
RELATIVE HUMIDITY (%)																		
GAS FLOW (hr)	38.5																	
NATURAL GAS CONSUMPTION (ft^3)	26777.47																	
CUMULATIVE ELECTRICITY CONSUMPTION (kWh)																		
STATIC PRESSURE, in.H2O [kPa]																		
TRAILER TEMPERATURE POINTS (F)/(°C)	T1			T1			T1			T1			T1			T1		
	T2			T2			T2			T2			T2			T2		
	T4			T4			T4			T4			T4			T4		
	T3			T3			T3			T3			T3			T3		
	T4			T4			T4			T4			T4			T4		
	T5			T5			T5			T5			T5			T5		
AMBIENT TEMPERATURE, F [°C]																		
INLET PLENNUM TEMP, F [°C]																		
MIDDLE PLENNUM TEMP, F [°C]																		
NATURAL GAS PRESSURE, psi [kPa]																		
DRYER TEMP, F [°C]																		
STOVER DEPTH, ft [m]																		
Moisture Content (%)	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%
Dryer End																		
2																		
3																		
Ave						55.62												
Middle DE																		
2																		
3																		
Ave						54.09												
Middle Back																		
2																		
3																		
Ave						56.32												
Back																		
2																		
3																		
Ave						55.72												
MC GRAND AVERAGE (%)						55.44												
MC CALCULATION BASED ON WEIGHT LOSS (%)									51.48			44.30			17.29			10.29

HEATING SPECIFICATIONS		
INPUT HEAT ENERGY, Btu [kJ]	2.82E+07	2.68E+07
INPUT HEAT ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	2369.69	5496

Test Number : 10/7/2009

Drying Start Date and Time	10/7/2009	
Drying End Date and Time	10/13/2009	
Drying Material	Eucalyptus	
Harvest Location		
Date Harvested		
Harvesting Machine Model		

PARAMETER	At Zero			INITIAL			9.9hr			19.4hr			22.7hr			29.3		
WEIGHT, lbs [kg]	17920.0	8145.5		17920.0	8145.5		14650.0	6659.1		12400.0	5636.4		11760.0	5345.5		10800.0	4909.1	
WATER WEIGHT REMOVED, lbs [kg]	0	0.0		0	0.0		3270.0	1486.4		5520.0	2509.1		6160.0	2800.0		7120.0	3236.4	
RELATIVE HUMIDITY (%)																		
GAS FLOW (hr)	29.3																	
NATURAL GAS CONSUMPTION (ft^3)	27054.48																	
CUMULATIVE ELECTRICITY CONSUMPTION (kWh)																		
STATIC PRESSURE, in.H2O [kPa]																		
TRAILER TEMPERATURE POINTS (F)/(°C)	T1			T1			T1			T1			T1			T1		
	T2			T2			T2			T2			T2			T2		
	T4			T4			T4			T4			T4			T4		
	T3			T3			T3			T3			T3			T3		
	T4			T4			T4			T4			T4			T4		
	T5			T5			T5			T5			T5			T5		
AMBIENT TEMPERATURE, F [°C]																		
INLET PLENNUM TEMP, F [°C]																		
MIDDLE PLENNUM TEMP, F [°C]																		
NATURAL GAS PRESSURE, psi [kPa]																		
DRYER TEMP, F [°C]																		
STOVER DEPTH, ft [m]																		
Moisture Content (%)	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%	Wet g	Dry g	%
Dryer End				30.00	15.20	49.33										30.00	25.40	15.33
2				30.00	15.20	49.33										30.00	25.00	16.67
3				30.00	15.40	48.67										30.00	21.80	27.33
Ave						49.11												19.78
Middle DE				30.00	15.00	50.00										30.00	23.20	22.67
2				30.00	15.40	48.67										30.00	23.80	20.67
3				30.00	16.20	46.00										30.00	24.80	17.33
Ave						48.22												20.22
Back				30.00	14.40	52.00										30.00	27.60	8.00
2				30.00	13.20	56.00										30.00	27.60	8.00
3				30.00	13.40	55.33										30.00	27.60	8.00
Ave						54.44												8.00
MC GRAND AVERAGE (%)						50.59												16.00
MC CALCULATION BASED ON WATER WEIGHT LOSS (%)									39.56			28.59			24.71			18.02

HEATING SPECIFICATIONS		
INPUT HEAT ENERGY, kJ [Btu]	2.85E+07	2.71E+07
INPUT HEAT ENERGY PER UNIT MASS, Btu/lb [kJ/kg]	3799.79	8812

Cost calculations

Test Number : 11/1/2009

COST CALCULATIONS	24 HOURS	
TOTAL NATURAL GAS COST (@ , $0.0013/ft^3)	$136.51	
TOTAL ELECTRICITY COST (@ $0.10/kwh), $	$31.67	
TOTAL COST	$168.18	
Weight Dry Matter lb DM [kg DM]	3744.05	1701.84
COST per weight dry matter, $/ 2200 lb DM [$/tonne DM]	$98.82	
COST per weight dry matter per % point, $/ 2200 lb DM/% [$/ tonne DM/%]	$4.09	

Test Number : 11/17/2009

COST CALCULATIONS	24 HOURS	
TOTAL NATURAL GAS COST (@ , $0.0013/ft^3)	$136.51	
TOTAL ELECTRICITY COST (@ $0.10/kwh), $	$30.46	
TOTAL COST	$166.97	
Weight Dry Matter lb DM [kg DM]	17504.80	7956.73
COST per weight dry matter, $/ 2200 lb DM [$/tonne DM]	$20.98	
COST per weight dry matter per % point, $/ 2200 lb DM/% [$/ tonne DM/%]	$1.50	

Test Number : 11/10/2009

COST CALCULATIONS	24 HOURS	
TOTAL NATURAL GAS COST (@ , $0.0013/ft^3)	$136.51	
TOTAL ELECTRICITY COST (@ $0.10/kwh), $	$27.00	
TOTAL COST	$163.51	
Weight Dry Matter lb DM [kg DM]	9801.79	4455.36
COST per weight dry matter, $/ 2200 lb DM [$/tonne DM]	$36.70	
COST per weight dry matter per % point, $/ 2200 lb DM/% [$/ tonne DM/%]	$2.00	

Test Number : 12/2/2009

COST CALCULATIONS		
TOTAL NATURAL GAS COST (@ , $0.0013/ft^3)	$130.82	
TOTAL ELECTRICITY COST (@ $0.10/kwh), $	$32.31	
TOTAL COST	$163.14	
Weight Dry Matter lb DM [kg DM]	3980.13	1809.15
COST per weight dry matter, $/ 2200 lb DM [$/tonne DM]	$90.17	
COST per weight dry matter per % point, $/ 2200 lb DM/% [$/ tonne DM/%]	$11.73	

Industrial natural gas price (http://www.eia.doe.gov/dnav/ng/hist/n3035ia3m.htm)

Nov-09	$6.16	/1000ft3
	$0.0062	/ft3

Electrical rate for industrial application, Alliant Iowa

(https://www.alliantenergy.com/Community/EconomicDevelopment/AbouttheMidwest/BusinessClimate/ElectricIndustrialRatesCentsperkWh/index.htm)

4.32	cents/kWh
$0.043	/kWh

Bulk density raw data

Test Number : 11/1/2009	INITIAL	24 hr	49.42 hr
WEIGHT, lbs [kg]	2445.5	1812.0	1800.6
STOVER DEPTH 1 [m]	1.12	0.99	0.94
STOVER DEPTH 2 [m]	1.31	1.08	1.06
STOVER DEPTH 3 [m]	1.08	0.91	0.89
STOVER DEPTH 4 [m]	1.22	1.11	1.08
VOLUME 1 [m^3]	36.75	32.57	30.90
VOLUME 2 [m^3]	43.07	35.51	34.85
VOLUME 3 [m^3]	35.51	29.92	29.26
VOLUME 4 [m^3]	40.11	36.50	35.51
BULK DENSITY, 1 [kg/m^3]	66.55	55.63	58.27
BULK DENSITY, 2 [kg/m^3]	56.77	51.03	51.66
BULK DENSITY, 3 [kg/m^3]	68.87	60.56	61.53
BULK DENSITY, 4 [kg/m^3]	60.96	49.65	50.71
Average Bulk Density	**63.29**	**54.22**	**55.54**
Std Dev	**5.46**	**4.94**	**5.22**

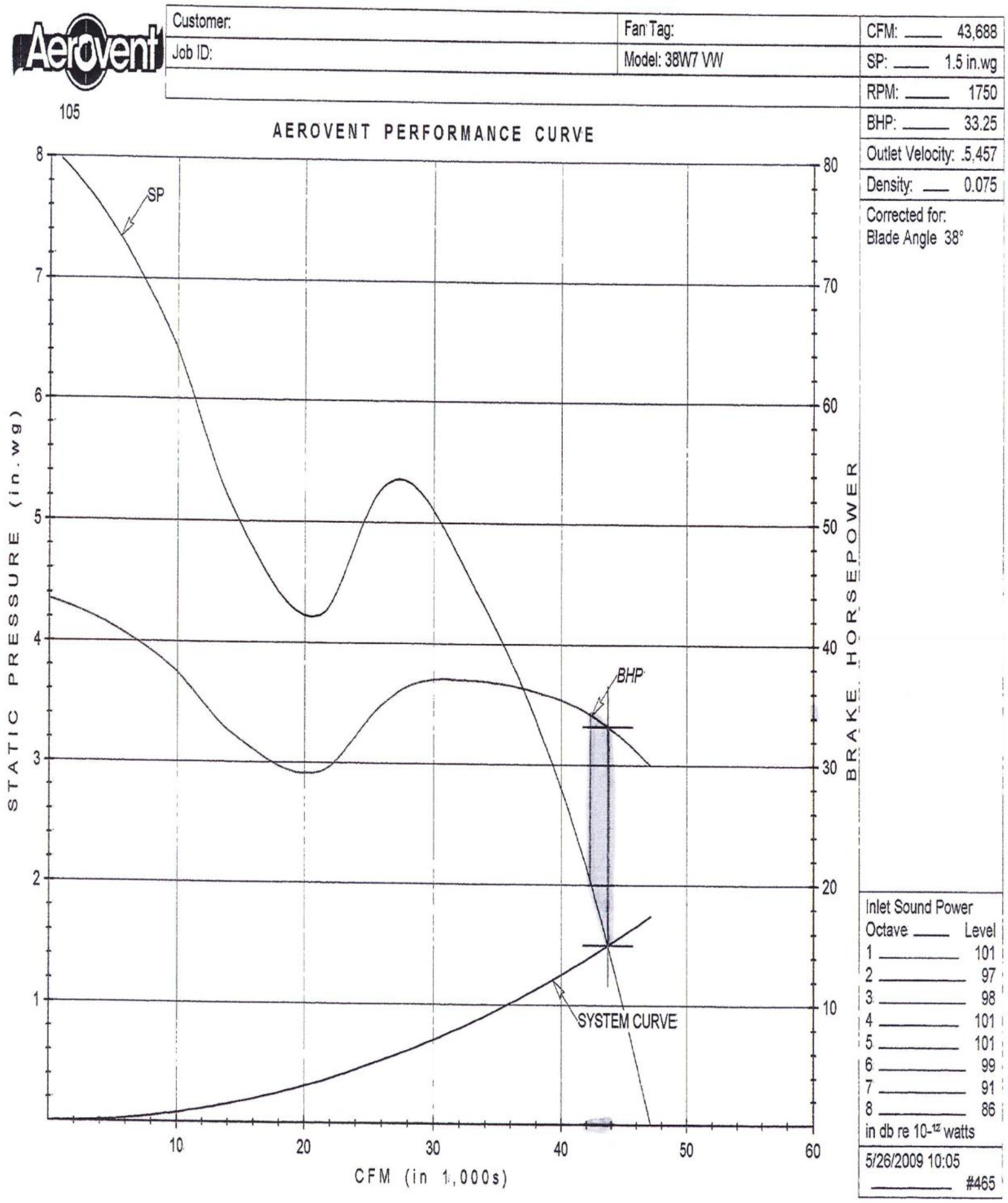
Test Number : 12/2/2009	INITIAL	6 hr	12 hr	23 hr
WEIGHT, lbs [kg]	2104.5	2015.0	1951.8	1931.8
STOVER DEPTH, in [m]	1.1	1.1	1.0	1.0
STOVER DEPTH, in [m]	1.16	1.12	1.08	1.08
STOVER DEPTH, in [m]	1.08	1.07	1.01	1
STOVER DEPTH, in [m]	1.06	1.05	1.05	1.05
VOLUME ft^3 [m^3]	36.73	34.52	33.54	33.21
VOLUME ft^3 [m^3]	38.14	36.83	35.51	35.51
VOLUME ft^3 [m^3]	35.51	35.18	33.21	32.88
VOLUME ft^3 [m^3]	34.85	34.52	34.52	34.52
BULK DENSITY, lb/ft^3 [kg/m^3]	57.29	58.37	58.20	58.17
BULK DENSITY, lb/ft^3 [kg/m^3]	55.18	54.72	54.96	54.40
BULK DENSITY, lb/ft^3 [kg/m^3]	59.27	57.27	58.77	58.75
BULK DENSITY, lb/ft^3 [kg/m^3]	60.38	58.37	56.54	55.96
Average Bulk Density	**58.03**	**57.18**	**57.12**	**56.82**
Std Dev	**2.29**	**1.72**	**1.72**	**2.01**

Test Number : 11/10/2009	INITIAL	12 hr	24 hr	39 hr
WEIGHT, lbs [kg]	5940.9	4972.7	4777.3	4795.5
STOVER DEPTH 1 [m]	2.0	1.9	1.9	1.9
STOVER DEPTH 2 [m]	2.2	2.14	2.11	2.11
STOVER DEPTH 3 [m]	2.05	1.89	1.84	1.83
STOVER DEPTH 4 [m]	1.92	1.84	1.84	1.82
VOLUME 1 [m^3]	66.81	63.45	61.78	60.94
VOLUME 2 [m^3]	72.34	70.36	69.38	69.38
VOLUME 3 [m^3]	67.40	62.14	60.50	60.17
VOLUME 4 [m^3]	63.13	60.50	60.50	59.84
BULK DENSITY, 1 [kg/m^3]	88.92	78.38	77.33	78.69
BULK DENSITY, 2 [kg/m^3]	82.13	70.67	68.86	69.12
BULK DENSITY, 3 [kg/m^3]	88.14	80.02	78.96	79.70
BULK DENSITY, 4 [kg/m^3]	94.11	82.19	78.96	80.14
Average Bulk Density	**88.32**	**77.82**	**76.03**	**76.91**
Std Dev	**4.91**	**5.01**	**4.84**	**5.23**

Test Number : 11/17/2009	INITIAL	12 hr	24 hr	36 hr
WEIGHT, lbs [kg]	10236.4	8886.4	8672.7	8654.5
STOVER DEPTH 1 [m]	2.1	2.0	1.9	1.9
STOVER DEPTH 2 [m]	2.1	2.05	2.05	2.05
STOVER DEPTH 3 [m]	2.05	1.99	1.95	1.95
STOVER DEPTH 4 [m]	2.17	2.08	2.05	2.05
VOLUME 1 [m^3]	68.46	64.28	62.61	62.61
VOLUME 2 [m^3]	69.05	67.40	67.40	67.40
VOLUME 3 [m^3]	67.40	65.43	64.12	64.12
VOLUME 4 [m^3]	71.35	68.39	67.40	67.40
BULK DENSITY, 1 [kg/m^3]	149.53	138.24	138.52	138.23
BULK DENSITY, 2 [kg/m^3]	148.25	131.84	128.67	128.40
BULK DENSITY, 3 [kg/m^3]	151.87	135.81	135.27	134.98
BULK DENSITY, 4 [kg/m^3]	143.47	129.94	128.67	128.40
Average Bulk Density	**148.28**	**133.96**	**132.78**	**132.50**
Std Dev	**3.54**	**3.76**	**4.93**	**4.92**

APPENDIX C. FAN CURVE

Fan Curve for Blueline 3830 (Cook Industrial Electric Co. Inc. Cordele, Georgia)



Calculation For Airflow in Table 3 and Data Points for Figure 6

	Static pressure, kPa	Static pressure, in water (1 kPa = 4.014 in water)	Airflow (cfm) x1000	Airflow m3/min (1 CFM = 0.0283 m3/min)
11/1/2009	0.23	0.92	45.5	1.3
	0.12	0.48	46	1.3
	0.12	0.48	46	1.3
11/10/2009	0.47	1.89	44.7	1.3
	0.47	1.89	44.7	1.3
	0.47	1.89	44.7	1.3
	0.47	1.89	44.7	1.3
12/2/2009	0.27	1.08	45	1.3
	0.27	1.08	45	1.3
	0.27	1.08	45	1.3
	0.27	1.08	45	1.3
11/17/2009	0.5	2.01	42.1	1.2
	0.47	1.89	44.7	1.3
	0.42	1.69	42.7	1.2
	0.45	1.81	44.9	1.3

APPENDIX D: DATA FOR AVERAGE MASS FRACTION CALCULATIONS

Half Load Stover 11/1/2009

Composition	Weight 1	Fractions (%)	Weight 2	Fractions (%)	Weight 3	Fractions (%)	Average Weight Fraction (%)
Cobs	13.8	29.9	5.6	14.6	27.2	39.4	28.0
Stalk/husk	16	34.6	10.6	27.6	9.6	13.9	25.4
Leaves	13.8	29.9	20.6	53.6	29.4	42.6	42.0
Other	2.6	5.6	1.6	4.2	2.8	4.1	4.6
Total	46.2	100	38.4	100	69	100	

Full Load Stover 11/10/2009

Composition	Weight 1	Fractions (%)	Weight 2	Fractions (%)	Weight 3	Fractions (%)	Average Weight Fraction (%)
Cobs	42	48.1	12.6	20.7	22.8	31.0	33.3
Stalk/husk	24.6	28.1	26.2	43.1	27.4	37.2	36.2
Leaves	19.8	22.7	21.8	35.9	22.8	31.0	29.8
Other	1	1.1	0.2	0.3	0.6	0.8	0.8
Total	87.4	100	60.8	100	73.6	100	

Half Load Stover 12/2/2009

Composition	Weight 1	Fractions (%)	Weight 2	Fractions (%)	Weight 3	Fractions (%)	Average Weight Fraction (%)
Cobs	15	24.8	3.8	8.6	6.4	13.1	15.5
Stalk/husk	27.8	46.0	14.4	32.6	11.6	23.7	34.1
Leaves	17.4	28.8	25.6	57.9	30.8	63.0	49.9
Other	0.2	0.3	0.4	0.9	0.1	0.2	0.5
Total	60.4	100	44.2	100	48.9	100	

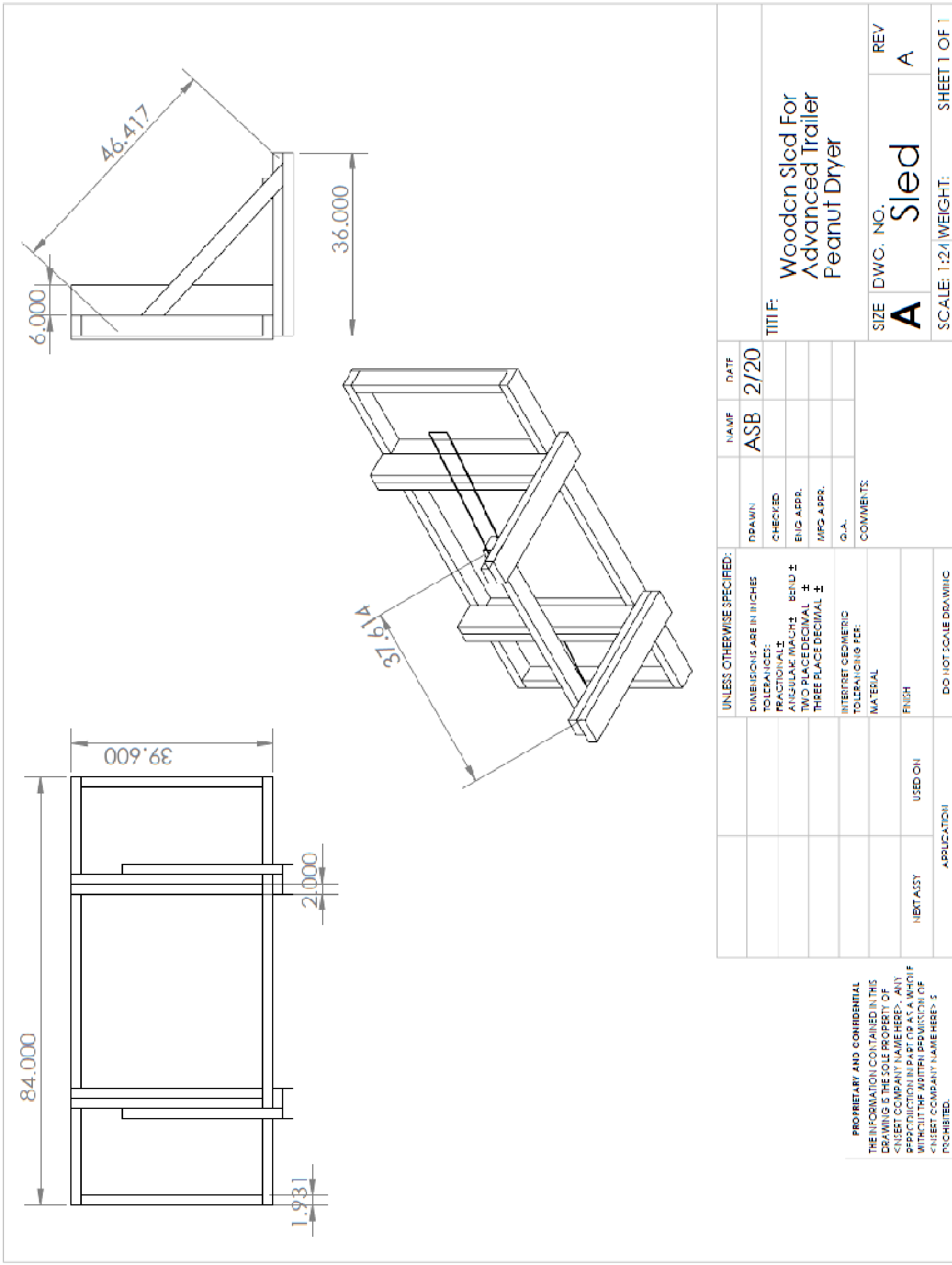
Full Load Cobs 11/17/2009

Composition	Weight 1	Fractions (%)	Weight 2	Fractions (%)	Weight 3	Fractions (%)	Average Weight Fraction (%)
Cobs	301.8	95.5	240	93.7	237.6	96.6	95.3
Stalk/husk	10.2	3.2	6.8	2.7	6.6	2.7	2.9
Leaves	2.4	0.8	2	0.8	1.6	0.7	0.7
Other	1.6	0.5	7.4	2.9	0.2	0.1	1.2
Total	316	100	256.2	100	246	100	

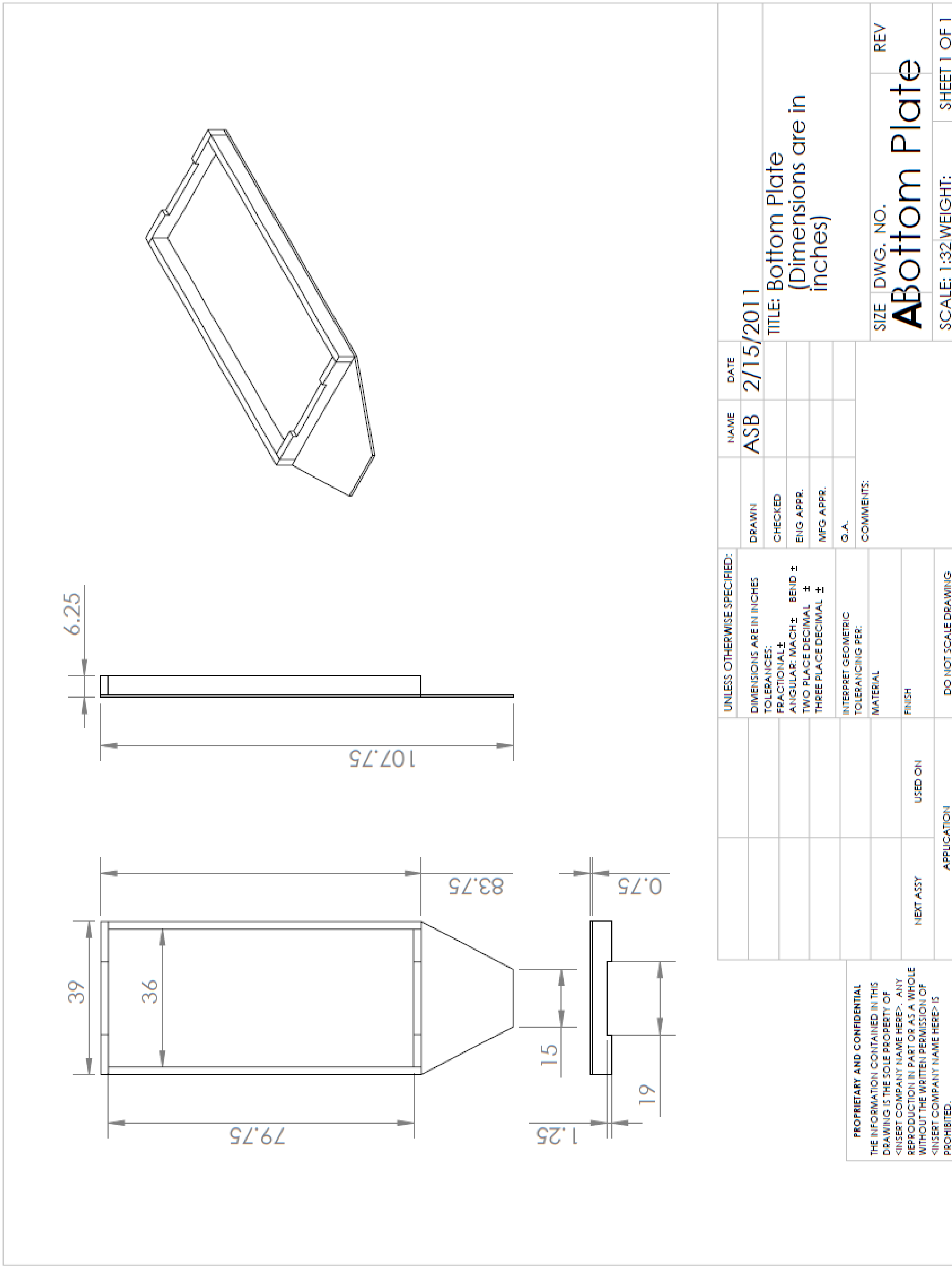
Eucalyptus 10/7

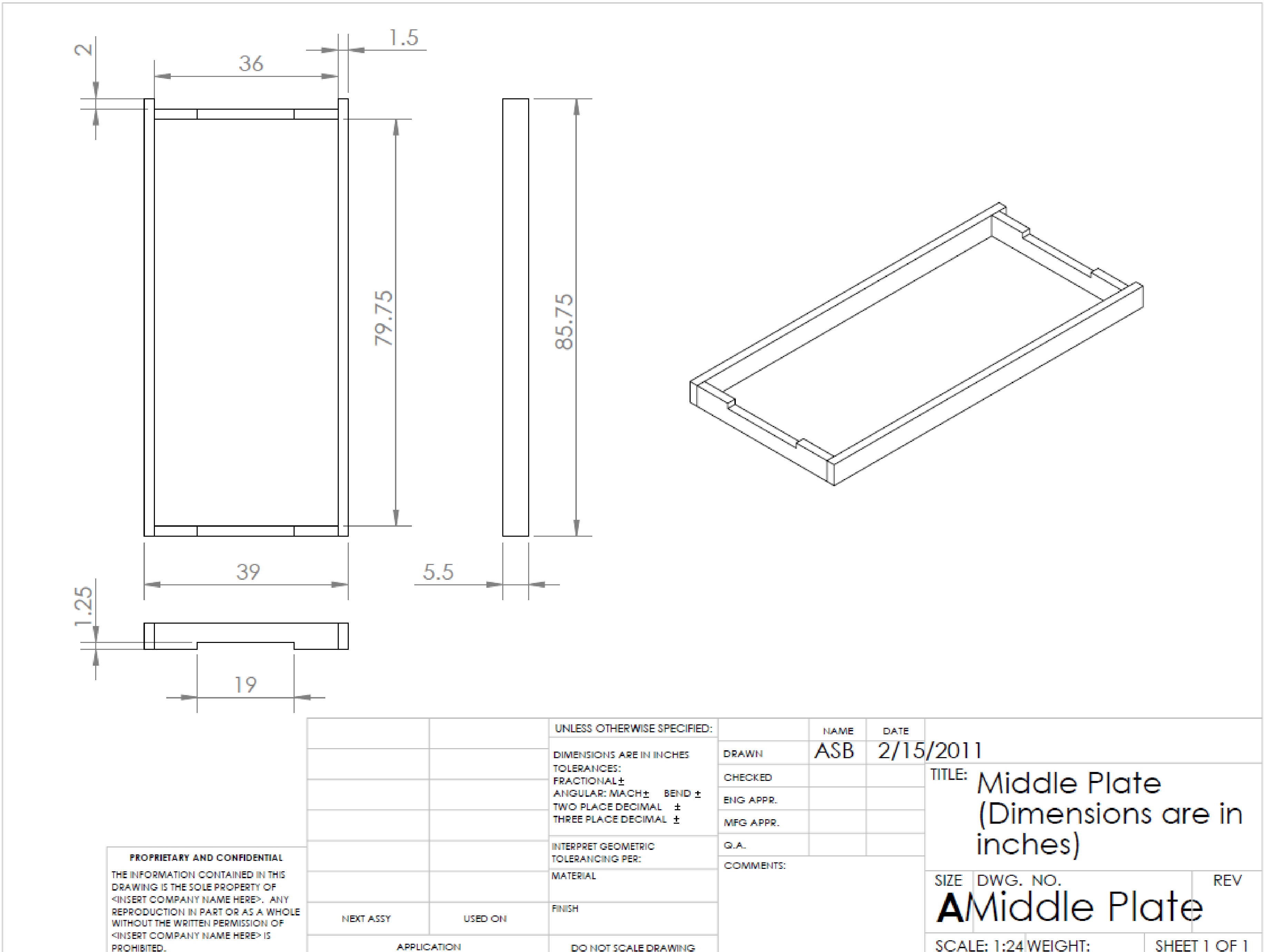
Composition	Weight 1	Fractions (%)	Weight 2	Fractions (%)	Weight 3	Fractions (%)	Average Weight Fraction (%)
Chips	38	83.7	33	85.9	25.6	88.9	86.2
Other	7.4	16.3	5.4	14.1	3.2	11.1	13.8
Total	45.4	100.0	38.4	100.0	28.8	100.0	

APPENDIX E: WOODEN SLED TECHNICAL DRAWING

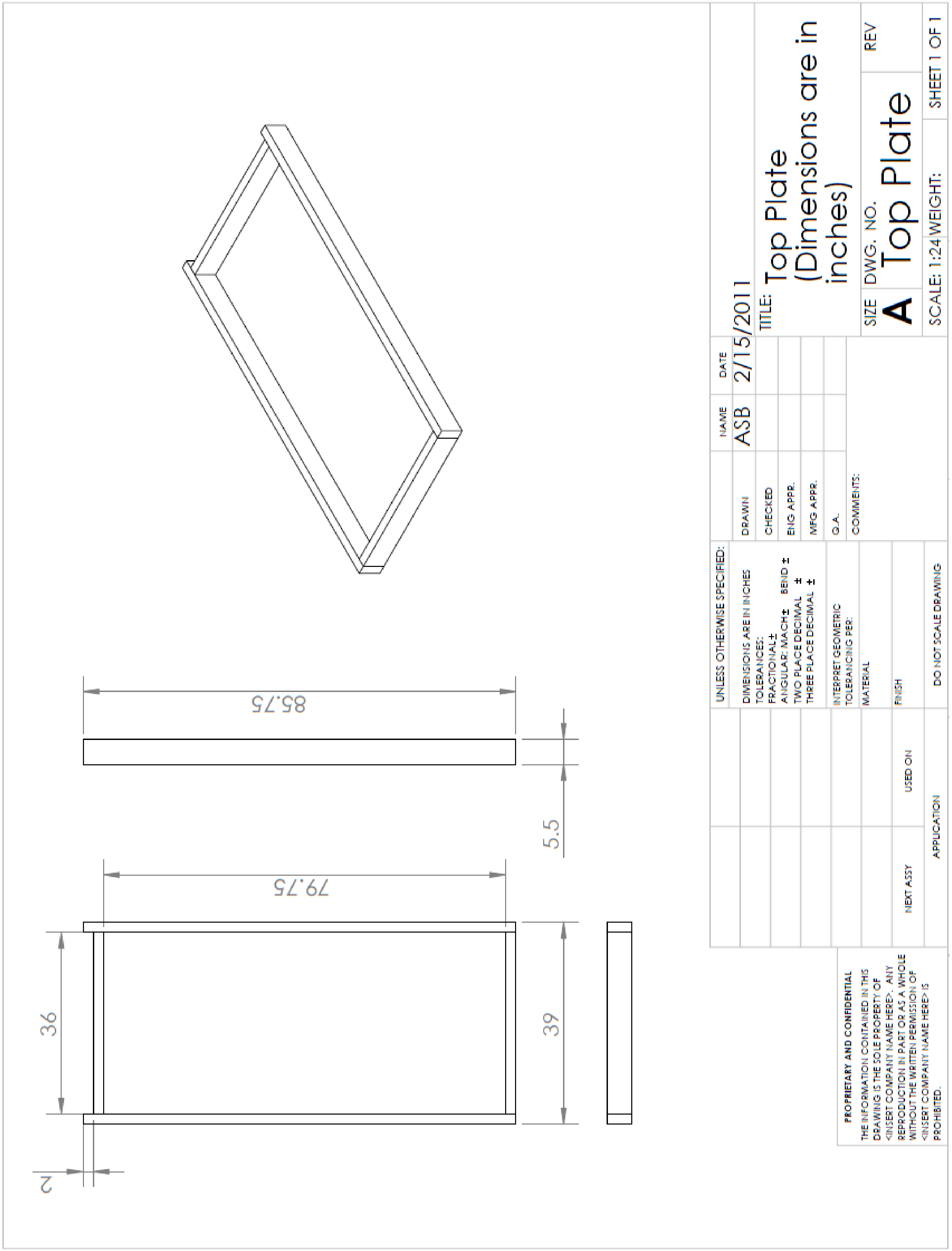


APPENDIX F. TECHNICAL DRAWINGS FOR THE TEST APPARATUS.





2
36
1.5
79.75
85.75
39
5.5
1.25
19
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ASB
2/15/2011
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Middle Plate (Dimensions are in inches)
SIZE
A
DWG. NO.
Middle Plate
REV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.


85.75
79.75
5.5
36
39
2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
ASB
2/15/2011
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE: Top Plate (Dimensions are in inches)
SIZE
A
DWG. NO.
Top Plate
REV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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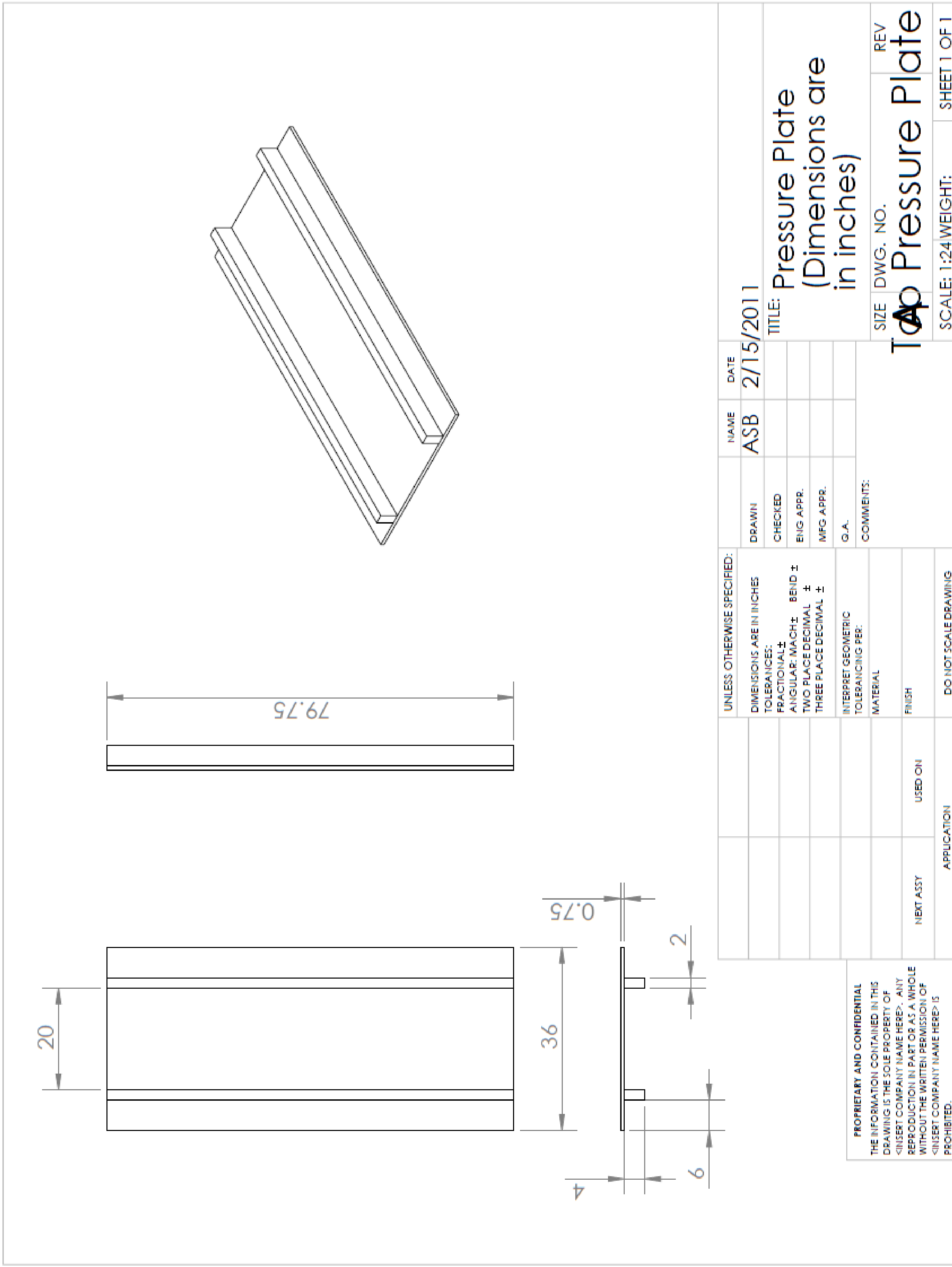
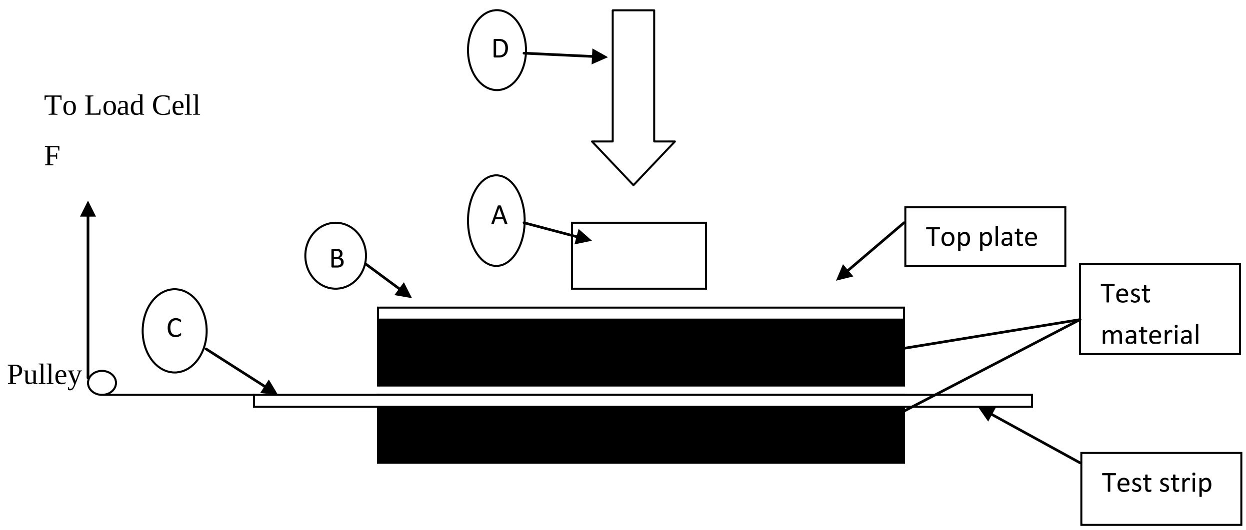


79.75
20
36
0.75
2
6
4
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NAME
DATE
DRAWN
ASB
2/15/2011
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Pressure Plate (Dimensions are in inches)
SIZE
A
DWG. NO.
Top Pressure Plate
REV
SCALE: 1:24
WEIGHT:
SHEET 1 OF 1

APPENDIX G. CALCULATION OF ADDITIONAL WEIGHT ON TOP PLATE.

It is assumed that weight or force acting on the bottom material is not the same as the top test material. Hence an average value of the top and bottom weight must be calculated. The cross section of the weight acting on the test strip can be seen below.

A. Additional weight = W
B. Top plate weight = 28kg
C. Test strip weight = T
D. Equivalent weight of 1.5 m depth of material, W= 132 kg



Weight acting on top side = A + B

Weight acting on bottom side = A +B +C

Equivalent weight of material, W = (A + B)/2 + (A+B+C)/2

Therefore, additional weight, A = (2W - 2B – C)/2

Data and calculation of additional weights for each test strips:

Test strip		Weight, kg	Additional weight added, kg	
HDPE	h	6.45	**101.0**	
UHMW	u	6.3	**101.1**	
GS	g	20.9	**93.8**	
MS	m	12.35	**98.1**	
SS	s	18.07	**95.2**	
OAK	o	5.17	**101.7**	
PINE	p	8.62	**99.9**	
Weight of top plate		t	28	kg
Bulk Density MOG		b	46.4	kg/m3
Total area of box		a	1.9	m2
Height of material		hi	1.5	m
Equivalent weight of M.O.G. at 1.5 m height.				
	=	46.4 x 1.9 x 1.5		
	=	w	132	kg

APPENDIX H. TEST DATASHEET FOR APPARATUS TRIAL RUN.

Date	9/22/10
Material	M.O.G.
Date Harvest	10/2/10
Harvest Location	Bruner Farm
Hybrid Type	Dekalb DKC 52-59 VT3
Combine	John Deere 9570 STS

Moisture Content(% Wet basis)

	Before	After	Container	MC %
1	41.03	40.06	33.52	14.83
2	38.99	38.06	33.77	21.68
3	45.01	43.7	35.96	16.93
			Ave	17.81

Test	OAK			PINE			Mild Steel		
	Bulk Density kg/m3	Coefficient of Friction		Bulk Density kg/m3	Coefficient of Friction		Bulk Density kg/m3	Coefficient of Friction	
		Static	Dynamic		Static	Dynamic		Static	Dynamic
1	42.61	0.466	0.196	52.55	0.388	0.241	53.12	0.398	0.247
2	53.68	0.419	0.182	51.53	0.412	0.209	54.61	0.387	0.231
3	60.36	0.422	0.248	54.74	0.432	0.221	51.23	0.422	0.28
Ave	52.22	0.44	0.21	52.94	0.41	0.22	52.99	0.40	0.25
Std Dev	8.96	0.03	0.03	1.64	0.02	0.02	1.69	0.02	0.02

Test	Stainless Steel			Galvanized Steel			HDPE		
	Bulk Density	Coefficient of Friction		Bulk Density	Coefficient of Friction		Bulk Density	Coefficient of Friction	
		Static	Dynamic		Static	Dynamic		Static	Dynamic
1	58.45	0.421	0.321	51.65	0.841	0.411	52.12	0.211	0.153
2	48.80	0.319	0.281	54.57	0.531	0.281	56.31	0.245	0.167
3	55.76	0.367	0.338	56.31	0.611	0.322	57.21	0.231	0.149
Ave	54.34	0.37	0.31	54.18	0.66	0.34	55.21	0.23	0.16
Std Dev	4.98	0.05	0.03	2.35	0.16	0.07	2.72	0.02	0.01

APPENDIX I. ANOVA TABLE FOR STATIC COEFFICIENT OF FRICTION AND DYNAMIC COEFFICIENT OF FRICTION TESTS.

ANOVA Table for Static Coefficient of Friction

The ANOVA Procedure

Dependent Variable: scof

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.29258028	0.05851606	11.73	0.0003
Error	12	0.05984400	0.00498700		
Corrected Total	17	0.35242428			

R-Square	Coeff Var	Root MSE	scof Mean
0.830193	17.12430	0.070619	0.412389

Source	DF	Anova SS	Mean Square	F Value	Pr > F
strip	5	0.29258028	0.05851606	11.73	0.0003

ANOVA Table for Dynamic Coefficient of Friction

The ANOVA Procedure

Dependent Variable: dcof

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.06878578	0.01375716	11.07	0.0004
Error	12	0.01491533	0.00124294		
Corrected Total	17	0.08370111			

R-Square	Coeff Var	Root MSE	dcof Mean
0.821802	14.17145	0.035255	0.248778

Source	DF	Anova SS	Mean Square	F Value	Pr > F
strip	5	0.06878578	0.01375716	11.07	0.0004

ACKNOWLEDGEMENTS

My warmest appreciation to Dr Carl Bern for the unending support and guidance. It was a great honor working with an expert in this field and the knowledge you have imparted has greatly inspired me. Thank you to Dr Thomas Brumm, Dr Brian Steward and Dr Lawrence Johnson for your support and guidance as well. Thank you also to Jeff Askey for all the support, dedication and your friendship. Thank you to Andy Suby, Manager of BioCentury Research Farm all the help and support.

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