CONDITIONER EFFECTIVENESS ON THE DRYING RATE OF HIGH ENERGY FORAGE SORGHUM

By

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SORGHUM

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Abstract: In the push to expand the production of biofuels, researchers are searching for new sources of cellulosic biomass to help supply the world's energy requirements. With new types of crops being used in this effort, new processing problems emerge. One problem that has been identified is how to swiftly process high energy forage sorghum from a standing crop to a stable biomass package for transport and storage. Current commercial processing uses mechanical conditioners to increase the rate at which water can escape the plant cells. However, this type of equipment has been optimized for forage production rather than bioenergy feedstocks. This research examines three mechanical conditioner designs to determine the unit's power requirements and drying rate changes when processing high energy forage sorghum. The three designs include a fluted roll, chisel impeller and "V" impeller. Results showed minimal power requirement difference between the three conditioners. The drying times for forage sorghum that was conditioned with the "V" impeller, chisel impeller and fluted roll conditioner was 43.2, 32.2, and 12.5 hours, respectively. This was a reduction in drying time of 30.2, 47.8, and 79.7% when compared to unconditioned material for chisel impeller, "V" impeller, and fluted roll conditioners.

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CHAPTER I

INTRODUCTION

To create enough biofuels to meet the Renewable Energy Initiative, much research is focused on various bioenergy feedstocks and on developing economical logistical systems for these feedstocks. The baseline biomass harvesting component of the logistical system consists of cutting the plant material, allowing the plant material to dry, and baling the plant material. Additional steps can be added to shorten the overall time needed to process the feedstocks including conditioning the material and/or moving the material to promote drying. The purpose of drying the material prior to baling is to reduce feedstock moisture content to a level low enough to prevent combustion due to microbial activity heating and to ensure a stable storage life. Current literature suggests that the moisture content of baled feedstocks be less than 20% moisture content wet basis. Field drying of feedstocks can be a major time consumer in the logistical system and is highly dependent on the type of feedstock and environmental conditions. Field drying rate relies on the feedstock initial moisture content and the rate at which the plant cells release moisture to the surrounding environment. Field drying rate can be enhanced by applying a feedstock conditioning step. Conditioning can be in the form of mechanical modification or applying chemical additives to the feedstock prior to baling pneumatically drying the material pre-or post-baling.

One necessary step to consider is using the most effective equipment to harvest the biomass in a timely manner prior to storage. Current forage machinery designed to process feedstock for animal consumption is being used to process the bioenergy feedstocks with fair results. Potentially, this machinery could be optimized to process larger quantities of biomass per acre. One point of optimization is determining the type of mechanical conditioner that increases the drying rate while minimizing the amount of additional power needed to run the conditioning system. The focus of this research was to determine effectiveness and energy usage of three different mechanical conditioning systems. The effectiveness of the conditioning units was determined by the change in drying rates as determined by thin-layer drying.

1.1 Objectives

The objectives of the research were to:

1. Evaluate three mechanical conditioner sections at varying mass flow rates and determine power usage, degree of visual conditioning, and feedstock drying rate differences for high energy forage sorghum.
2. Develop a high energy forage sorghum thin-layer drying rate model as a function of mass flow rate and conditioning to aid in the decision-making about biomass harvest at a single temperature and relative humidity.

CHAPTER II

REVIEW OF LITERATURE

The literature review covers the following topics: mechanical conditioning systems, drying rate models, and forage sorghum plant characteristics.

2.1 Mechanical Conditioning Systems

Mechanical systems for conditioning forage products have made several advances since first being introduced in the 1950s. The purpose of mechanical conditioners are to lessen a plant's resistance to moisture movement from the plant cells to the ambient air. Most mechanical systems discussed in the literature have focused on roller-type, impeller-type, and/or choppers-type conditioning. Choppers were not examined closely. Choppers are generally used in the production of silage-type material. The chopper produces small pieces of material that are stored in bags, piles, or silos. This material generally has higher moisture levels than is commonly accepted when baling forages.

For grass hay systems, conditioners have been used for several decades. These systems started as rollers to compress, crush, and crimp the grass stems. The designs varied with construction materials such as steel and rubber, along with the roller configuration. Bruhn (1955) studied several different factors involved in forage crushing, ranging from environmental conditions to mechanical inputs. Bruhn suggests multiple passes through a set of crushing rolls was advantageous. Results from the study showed that two sets of rollers with a speed ratio of 0.8 between the first and second set of rollers lessened drying time by an hour, as opposed to running two sets of rollers at the same speed.

Fairbanks and Thierstein (1966) evaluated the conditioning of alfalfa in Kansas using:

- a crusher with one smooth steel roll and a spiral-groove rubber roll
- a crimper with corrugated steel rolls
- a 12-ft trail behind a twin-rotor, rotary mower which cut, lacerated and windrowed the hay all in one operation
- a 12-ft self-propelled windrower with a crimper-crusher conditioning attachment

The most effective conditioners for increasing the drying rate in three different cuttings of alfalfa were the crushing conditioner followed by the crimper. The windrowers were not as effective as the crimping or crushing conditioner units in increasing material drying rate in a field setting due to the amount of material lying in the swath. The drying rate results for the windrowers were close to the mower and rake system without conditioning. This research found that environmental conditions and location of the harvest had a large influence on drying rate. Fairbanks and Thierstein determined that the economics of using windrowing machines reduced overall harvest costs as compared to the conditioning units because cutting and combining the material into a swath in one pass, rather than using an additional operation of raking the material together for baling.

Barrington and Bruhn (1970) studied a sorghum-sudangrass and an alfalfa brome grass crop to determine if there were any relative effects and relationships between conditioning treatments. The research determined that the conditioning needed to achieve an acceptable moisture content for the sorghum-sudangrass crop was different from the alfalfa brome grass. In order to have a drying rate of hours instead of days, the sorghum-sudangrass stalk must be shredded through its entire length and laid open to expose the pith (the portion of the plant with a high percentage of total moisture). Even with this extent of stalk conditioning, leaf drying rate was still higher than that for the stalk. The leaf material dried faster due to the evaporation rate from the surface. The hybrid sorghum-sudangrass stem had a low evaporation rate from the outer surface coupled with slow moisture movement internally through the stem. The exposed areas of the exposed stalk ends were not sufficient to increase drying rate enough to match the leaf evaporation rate. In alfalfa and other grass systems, the stems can simply be cracked to match the drying rate of the leaves. Barrington and Bruhn showed that the high roll-to-travel-speed ratio of 7 was able to increase the smooth or corrugated roll conditioning when compared to the lower ratios tested. The comparison of a flail conditioner to a crushing roller conditioner showed that the flail system produced drying rates similar to the crushing conditioner for the alfalfa brome grass. However, more leaf material and seeds were lost in the flail conditioning system. The flail conditioner chopped the large stem material into smaller pieces, increasing harvesting losses when compared to the crushing conditioner.

Mears and Roberts (1970) studied the effects of size and shape of stems on the drying rate of cut alfalfa. A sample of alfalfa stems were split longitudinally or left whole, then the rest of the foliage was removed and cut to different lengths. The experiment demonstrated that during drying the water moves most freely along the natural longitudinal ducts of the stem. Their studied confirmed the advantage of opening the alfalfa stem, exposing the greatest transverse cross-sectional area of the stem, to increase the drying rate. Opening the stems could be accomplished by crushing or crimping.

A laboratory test procedure was developed by Straub and Bruhn (1975) to simulate field conditioning. The test procedure employed a frame-based press that could provide a specific force and feed the material through at a consistent speed. The testing system also used a controlled drying chamber that maintained temperature and relative humidity. Based on the test stand setup, many comparisons could be made for different rolls and roll settings. The test procedure contained a control press that would only apply a set amount of pressure with a control set of smooth metal rolls for comparison. The drying chamber allowed comparisons at set conditions rather than the variable field conditions. The controlled drying chamber allowed for drying curves to be compared over several sets of tests.

Straub and Bruhn (1975) tested three sets of rolls with alfalfa cuttings. The sets were ribbed steel running against a solid ti-cord roll, two intermeshing ti-cord rolls, and a rubber-coated set of intermeshing rolls. The tests concluded that as the roll-to-roll pressure increased from 15 to30 lb/inch, rubber intermeshing rolls (both driven) had an increased drying rate and lower clipping losses over the control and other test rolls.

Klinner (1976) approached the conditioning question by outlining the criteria of treatment and design. The nine criteria are summarized as follows:

- Minimize fragmentation
- Limit damage to crop surface
- Apply severest treatment to the thick plant base and lessen toward the top of the plant
- Allow for crop density variances
- Adjustable for crop and conditions
- Low density swaths formation
- Crop inversion
- Crop stubble supports
- Functionally rugged and reliable

To meet the criteria, Klinner proposed a semi-rigidly mount Y-shaped steel conditioning flail, held at its base (Figure 1). A group of flails were arranged in a helical array with overlap between successive elements. This ensured that the entire crop was treated and prevented movement toward the center of the rotor. Crop conditioning occurred due to crop slip during acceleration around the rotor, causing surface abrasions and scuffs to the stem wall. The action of cutting the material caused the base to pass through the conditioner first, creating the most damage at the cut end rather than the top end of the plant. Klinner's results showed a power requirement of 2.6, 2.8, for a sickle bar mower with a steel roll conditioner or rubber roll conditioner, and 3.2 kW for a drum mower with the experimental flail rotor respectively, per meter width of the cut. The roll conditioners/sickle bar mower combinations had lower power requirements for conditioning, but the roll conditioners had more variability of the crop moisture at successive stages of drying for Italian ryegrass. The drying rate was increased by the experimental flail rotor over a simple sickle bar treatment by being 10% (w.b.) drier at a vapor pressure deficit of 250 mm.

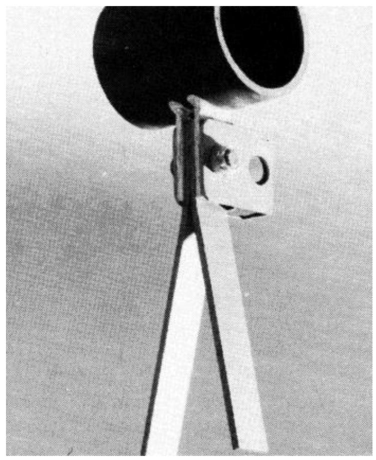


Figure 1. Experimental flail crop conditioning element described by Klinner (1976).

Chung and Verma (1982) tested four sets of roll conditioners with different pressures to determine the increase in drying rate. The rolls tested were intermeshing rubber, smooth cast iron, 8-bar crimper and 12-bar crimper. The rolls were evaluated at loads of 3.57 and 10.7 kg/cm of roll length. The roll loading did not have a statistically significant effect on the drying time between the two pressures tested. The intermeshing rubber and smooth cast iron rollers did produce better drying rates than the steel crimper rolls (8 or 12-bar crimper rolls). The steel crimper bars had a statistically significant increase in drying rate when compared to no conditioning, but the intermeshing rubber and smooth cast iron rolls reduced the total drying time to 20% moisture content by an average of 41% under good drying conditions. The steel crimper bars were able to reduce drying time by 26% under the same conditions.

Khalilian et al. (1982) investigated hard crushing and Orzan-G and Nutri-Binder use in alfalfa to increase drying rate and reduce the subsequent losses of material resulting from hard crushing. The hard crushing was accomplished by a pair of smooth steel rolls at pressures of 118, 137, and 157 N/linear cm of roll length. The experiment confirmed that hard crushing improves the drying rate, enough to cut, cure and bale alfalfa in one day. The Orzan-G binder was the most effective binder in terms of making a matted material with the lowest material losses.

For Coastal bermudagrass, the combinations of fluted steel upper rollers against two tire carcass rollers in a tandem roller mower conditioner offered increased digestibility and 2-4 hours faster drying time (Hellwig et al., 1983) over a conventional mower-conditioner with a fluted steel upper roller and a fluted tire carcass lower roll. The design had drawbacks in the increased loss of yield when compared to sickle bar mowers and no conditioning treatments.

Klinner and Hale (1984) evaluated plastic crop conditioning elements in various configurations (Figure 2 and Figure 3) to determine how well the designs performed for various forage crops. Twin rotors performed most favorably on Italian rye grass. One tufted and one full brush rotor had an increase in drying rate of 136% while a serrated/plain rib in a counter-rotating conditioner had an increase of 103%. The effects of conditioning on the drying rate were the greatest in the short period after conditioning but decreased as the final moisture content of the crop approached 30% w.b. Power requirements for the conditioners were different than the drying tests in terms of energy-related drying rate increase. The most efficient system was the twin intermeshing tufted brushes, which had a 18.1% increase in drying rate/kW input, while the configuration with the best drying rate increase (one tufted and one full brush rotor) had an energy rate increase of 10.0% in drying rate/kW input.

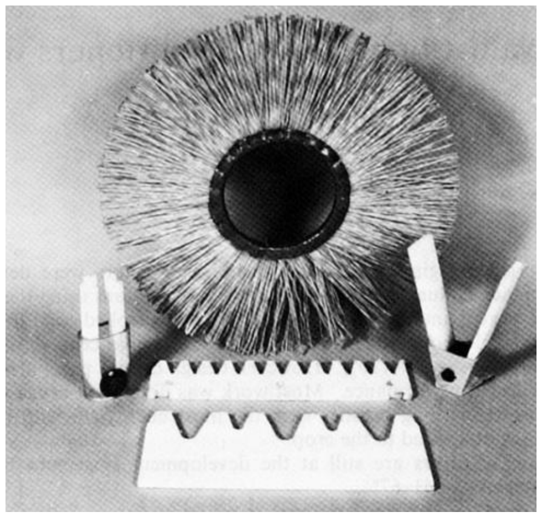


Figure 2. Plastic crop conditioning elements evaluated by Klinner and Hale (1984). Component description clockwise from center left: brush tuft, full brush, V-spoke, and profiled ribs.

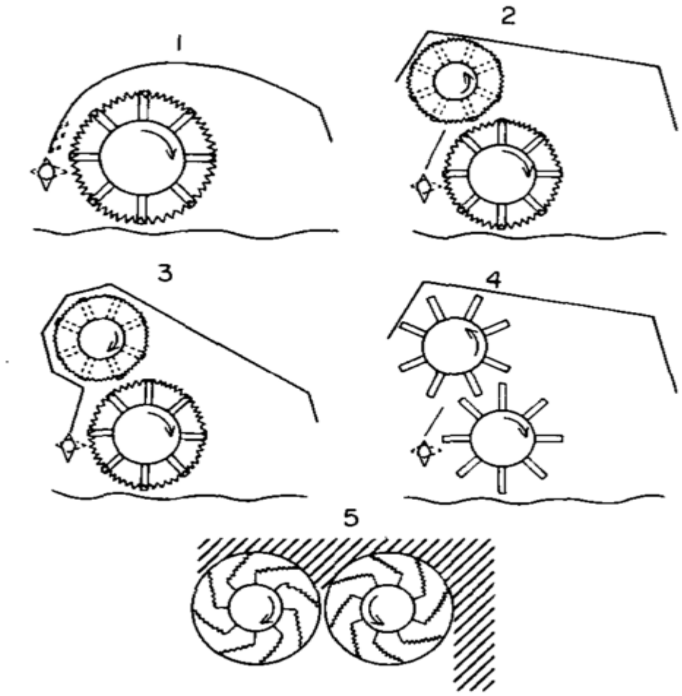


Figure 3. Rotor configurations for conditioning systems evaluated by Klinner and Hale (1984): 1) Single axis rotor; 2) Twin horizontal counter rotating rotors with speed differential; 3) Twin horizontal co-rotating rotors; 4) Twin horizontal counter-rotating intermeshing rotors; 5) Twin vertical counter-rotating rotors.

Chung and Verma (1986) studied four mechanical and two chemical conditioners, plus combinations of both types, on Italian ryegrass. The mechanical conditioners were:

- a flail conditioner made of rectangular blocks of rubber material for the flails
- rubber intermeshing rollers
- a brush conditioner that contained strips of nylon filaments impregnated with silicon carbide, mounted on steel rings that worked against a semi-circular housing containing similar brushes

- a crushing and brushing containing one smooth steel roll with an abrasive coating on one roll and 8 bars with brushes mounted between the bars on the other roll

The performance of the mechanical conditioning systems on the drying rate of Italian ryegrass demonstrated that the intermeshing rollers had the greatest change in drying time. The intermeshing rollers samples took 58.2 hours to dry to a 20% (w.b.) moisture content in 23°C and 58 % relative humidity conditions. The unconditioned control material had a drying time of 111.1 hours in the same conditions.

Rotz et al. (1987) studied the effects of mechanical and chemical conditioning on the drying, loss and quality of alfalfa. The mechanical conditioner, intermeshing rubber roller design, was found to increase the drying rate enough to save 2 days of field drying time on the first cutting of alfalfa. However, in subsequent cuttings, the benefit of the mechanical conditioning on the drying rate diminished primarily due to the changes in the structure of the stems after regrowth.

More recent studies have focused on impeller type variations from the typical roller system. Three impeller types were tested on alfalfa and grass hays at Iowa State University (Greenlees et al., 2000). The shapes were plastic "U"-shaped, steel "U"-shaped and the steel "Y"-shaped tines as various input conditions (Figure 4). A faster drying rate was achieved with higher rotor speeds in the impeller machines. The forage conditioned by the impeller machines dried more quickly than forage conditioned by the intermeshing roll machine (Greenlees et al., 2000); however, the leaf losses on alfalfa were significantly greater than with the intermeshing roller conditioner. A large error term excluded the statistical significance between mechanical conditioners; the impeller drying constants were nearly always numerically larger than those of the intermeshing rollers.

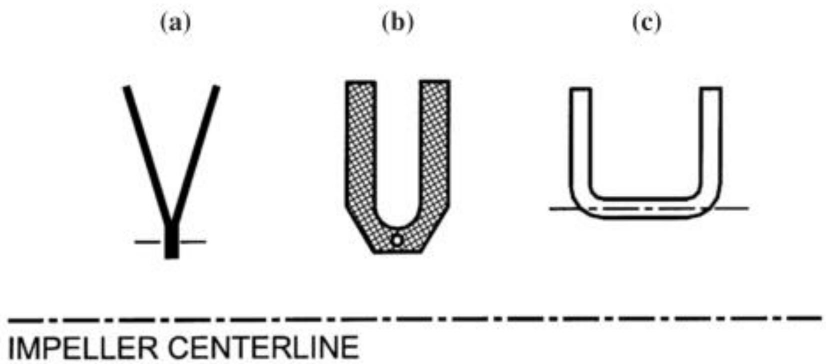


Figure 4. Impeller shapes discussed by Greenlees et al. (2000): (a) Steel "Y"-shaped from flat bar stock; (b) Molded plastic "U"-shaped; (c) Steel "U"-shaped from round bar stock.

Maceration is a subset of mechanical conditioning known as intensive forage conditioning where the plant material is shredded before being pressed into a mat. Some of the literature considers the mat-making a separate portion of the process. Alfalfa hay systems have also employed mechanical conditioners to improve drying rate of the final hay product. The systems have progressed to an intense type of conditioning, maceration, to surpass the drying rate limits found with simple conditioning. A crushing-impact maceration device has been tested on alfalfa. The results rotor speed, specific roll force, and feed rate to be critical factors that impact performance (Kraus et al., 1993). In terms of forage products, material is passed through or around rolls to shear the plant stems longitudinally and allow the liquid from the plant cells to be pressed out, under pressure, to reduce crop moisture. The format of the maceration devices experimented with until

2001 were described by Savoie (2001) and are shown in Figure 5.

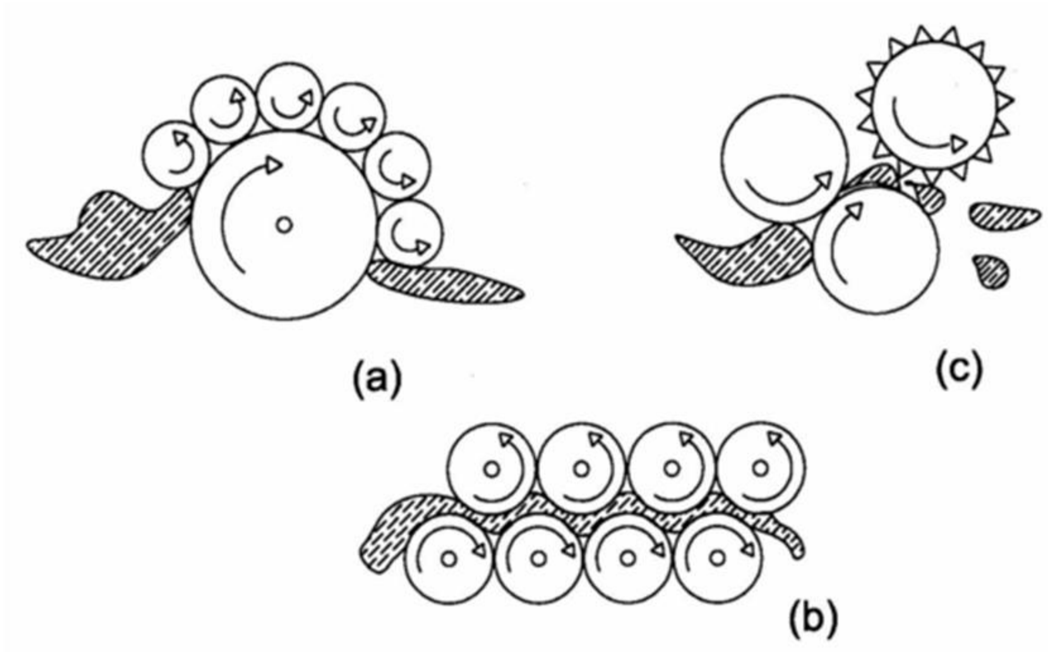


Figure 5. Common maceration forage conditioning roller configurations: (a) Peripheral roll; (b) Staggered roll; and (c) Crushing impact.

Maceration was approached as a method of handling forage to reduce losses of the leaves at low moistures and reduce damage from rain after cutting and during drying. Purdue University has worked on the development of a prototype machine that improves hay quality by increasing the drying rate to obtain a one day harvest routine on alfalfa (Krutz et al., 1979). The prototype produced a safe baling material in 2.25 hours while the control never reached below 30% moisture content the day of harvest. The maceration allowed a high ratio of evaporation compared to free water evaporation in the first hours of drying and the ratio changed as the material became drier.

Shinners et al. (1985) formed mats in a laboratory setting from macerated alfalfa to determine drying rate, tensile strength, weight loss due to flexing, and dry bulk density under varying machine conditions and configurations. They concluded that the procedures applied could produce a mat that can dry (to a moisture content of 20%.w.b.) under field conditions in as few as 4.5 hours.

Shinners et al. (1988) experimented with the design parameters of a peripheral macerator to determine the energy, capacity and degree of maceration by the variables of roll surface speed ratio, number of rolls, rotational speed of the cylinder and material moisture level. Results showed that increases in cylinder-to-roll speed ratios caused the energy requirement to increase asymptotically. Increasing roll count increases energy requirements; while material moisture levels were decreased from 79% (w.b.) to 50% (w.b.), the machine required more energy and capacity decreased. Material at 40% (w.b.) or less had decreasing energy requirements and greater capacity than at 50% (w.b.) due to the material being removed from the cylinder more easily.

In an evaluation of a new design of a crushing-impact forage macerator, Kraus et al. (1993) investigated the effects of impact rotor speed, crushing roll force, and feed rate. They found that feed rate and specific crushing roll force had the greatest effect on maceration. Increasing feed rate had a negative result on the degree of maceration. The degree of maceration was influenced more by the specific roll force than the impact rotor speed. The impact rotor speed had larger influences on the specific energy than the specific roll force. Reducing the number of elements from the previous nine roll peripheral macerator (Shinners et al., 1988) to this three roll crushing impact macerator has reduced the specific energy requirements with a much less complex machine system.

A study by Öztekin and Özcan (1997) in Turkey varied the mechanical method of maceration of alfalfa by having one main knurled roller carrying the material into contact with 6 knurled counter-rotating rollers (peripheral configuration) with rotational speed difference of 2.5:1. The results of the testing showed a drying time of 5 to 6 hours to reach 20% m.c.w.b. A similar study by Shinners et al. (1987) compared a seven-roll peripheral macerator to rubber intermeshing conditioner rollers for alfalfa. The study concluded that the macerated material could reach a moisture content of 20% w.b. in 2.6-6 hours while the intermeshing rubber roller material was unable to reach this level on the first day in field conditions.

Savoie et al. (1993) developed a large scale mat maker that contained a set of 8 macerating rolls (staggered configuration) that operate at a differential tip speed of 1.5:1 and performed evaluations on timothy and alfalfa and compared it to a rubber roll conditioner (New Holland, model 411) at normal operational speed of 8.0 km/h. The mats produced had a drying rate 61% and 137% greater than conventionally conditioned timothy and alfalfa, respectively. This provided an opportunity to bale the material within two days (based on field conditions in Quebec, Canada) compared to conventional mechanical conditioning requiring 3 to 4 days with additional handling for curing purposes.

Savoie et al. (1997) performed a two-year field study on the intensive forage conditioning of a timothy/alfalfa mix crop in Quebec, Canada. The intensive conditioner is comprised of three macerating steel rolls and the original lower rubber conditioning roll. The rolls are staggered slightly, increasing the contact area the material can touch. The intensive conditioning system required an average of 8.2 kW of PTO power more than conventional rubber conditioning. A compression system to produce a more mat-like form was proven to be unnecessary to improve drying rate or forage losses.

In a separate study at the Normandin Experimental Farm in Quebec, Canada, Savoie et al. (1999) determined the benefits of the three-roll system were a 28-38% drying rate increase over conventional conditioning in the first 4 hours of wilting. Savoie et al. (1999) did explain that the level of conditioning required by the forage will depend on the value of the forage and other economic inputs. Figure 6 and Figure 7 show the experimental roller design and configuration on the self-propelled windrower tested (Savoie et al., 1999).

Savoie et al. (1999) also tested a six-roll intensive forage conditioner in this experiment (staggered configuration); however, energy requirements were not reported. The design (Figure 8) had 2 conventional intermeshing rollers, followed by 4 finely grooved rolls (Figure 6). Researchers did report a 41-73% increase in drying rate for the first 4 hours of drying compared to a conventional system.

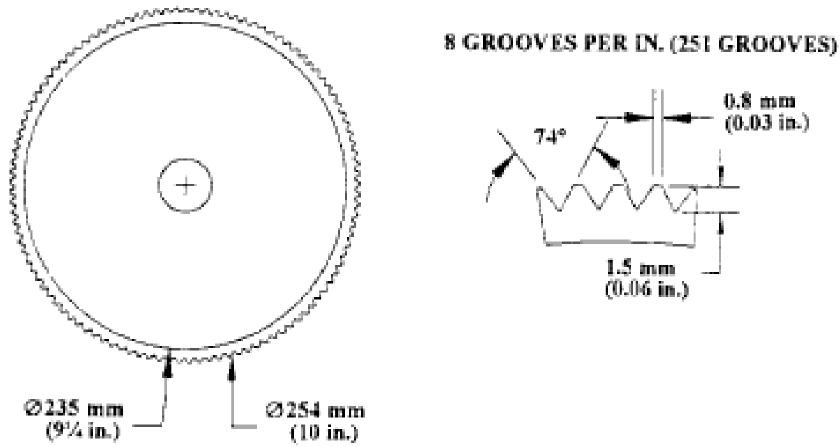


Figure 6. Savoie et al. (1999) experimental intensive forage conditioner roll design.

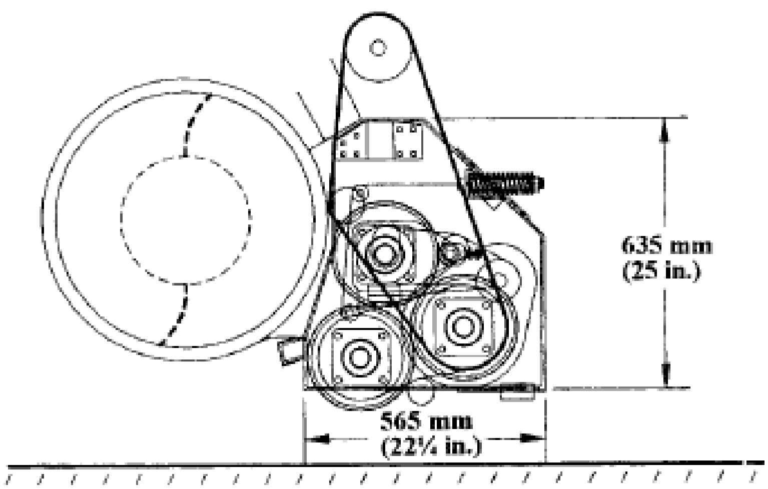


Figure 7. Savoie et al. (1999) three-roll intensive forage conditioning experimental design.

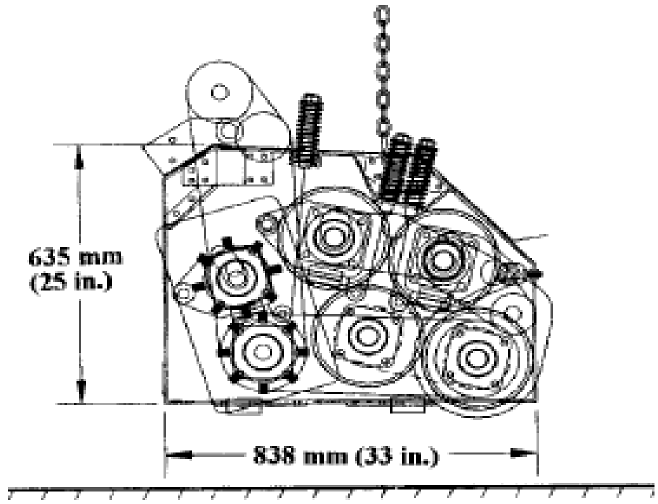


Figure 8. Savoie et al. (1999) six-roll intensive forage conditioning experimental design.

Some of the experiments with maceration applications reported specific energy of the equipment. Tremblay et al. (1994) determined an eight-roll staggered configuration macerator required 3.8 $(\mathrm{kW \cdot h})/(\mathrm{t\ DM})$, determined from 39 tests on timothy and alfalfa. In the study by Savoie et al. (1999), the energy required to operate the three-roll intensive forage conditioning system (staggered configuration) was in the order of 2.0 to 2.6 kW·h/t of dry matter on a self-propelled mower immediately behind the cutter bar. Larger capacity mowers may require 45 kW or more horsepower to operate a three-roll intensive forage conditioning system for a timothy hay crop than the smaller capacity mower converted for the experiment.

In a different inquiry about the effectiveness of maceration, Descôteaux and Savoie (2002) tested the effects of delaying maceration in different forages. Results showed that in slow-drying periods of overcast field conditions, a delay of maceration of 6 hours lowered final moisture levels more than a delay of maceration of 1 hour or the control treatment were able to lower the final moisture content. Laboratory tests did not confirm this result. By separating the maceration from the mowing process, the economic value of maceration is greatly reduced due to additional machinery and operational costs for performing the maceration.

In more recent work on the intensive conditioning, Shinners et al. (2006) examined seven-roller designs and a flail conditioner in the laboratory and in-field test to determine drying rate and leaf loss of alfalfa. They found that roll clearance between intermeshing urethane and intensive steel produced a higher drying rate constant than the impeller type conditioner in field tests in Utah for first and second cutting alfalfa. However, they also found that intermeshing urethane and intensive steel rollers produced statistically significant different drying rates from field tests in south-central Wisconsin.

2.2 Drying Rate Models

Researchers have used both field drying and laboratory drying studies to measure conditioner effectiveness on increasing drying rates of forages. The methods of field drying include measuring the environmental conditions at the sample locations, for example: Barrington and Bruhn (1970), Fairbanks and Thierstein (1966), and Klinner (1976). Laboratory techniques have focused on simulating field conditions or controlling certain environmental conditions to determine empirical models or time reductions that could be applied by producers to produce better quality hay products, for example; Straub and Bruhn (1975), Chung and Verma (1982), Khalilian et al. (1982), and Chung and Verma (1986). More recent work has been applied to thin-layer drying techniques to develop the moisture isotherms used to verify models, performance of drying equipment, and characterizing the drying rate of the product (Bonner, unpublished data, 2011. Idaho Falls, Idaho: Idaho National Labs).

2.2.1 Drying Theory

The drying process is the exchange of water between a material and its surroundings until the material reaches equilibrium with the properties of its environment, in terms of temperature and humidity. The factors that influence this equilibrium moisture content were ambient temperature, relative humidity, physical properties of the material and the previous moisture history of the material (Henderson et al., 1997).

2.2.2 Field Drying

Field drying differs from thin-layer drying with the addition of factors involving influences of the swath design, the effects of microclimates being created within the swath and area surrounding the swath, and high humidity or dew at night resulting in moisture gain by the crop. The parameters influencing field drying were discussed here, because in practicality, this is the final form in which biomass harvesting will occur. However, confirming field drying response would require several model iterations to develop and confirm.

In a study on altering the physical characteristics of alfalfa to increase the drying rate, Priepke and Bruhn (1970) discussed the drying curves that were produced by different treatments specifically designed to alter the physical characteristics of alfalfa. The drying curves were based on the fraction of water remaining in the material (dry basis moisture content) versus the time of drying, rather than moisture content versus time. The fraction of water was scaled logarithmically to emphasize the relationship of moisture loss to time from treatment. They identified three regions: first, exponential, and last. The first region was typically the first hour of drying time for their experiments, with the major influences being the initial plant characteristics, treatment, and drying conditions. The exponential region, which is usually the longest region in the experiments, fits the model:

$$\mathbf{W} = \mathbf{a}\mathbf{e}^{-\mathbf{bt}} \tag{1}$$

where the most important parameter is b, the drying rate constant. This region was also influenced by the drying conditions and the treatment. The third region was the slow drying period, which was influenced only by drying conditions and the treatment. In the third region, the plant was trying to reach equilibrium moisture, and for the tests conducted, the region started about 4 hours after cutting.

Rotz and Chen (1985) studied field drying rates and conditions for seven harvest years to determine the impact of different environmental factors on the drying rate of alfalfa in Michigan. Moisture content was predicted by Equation 2, but the development of the drying rate coefficient was expanded to accommodate more environmental conditions. The drying rate constant was determined from the following equation:

$$\mathrm{DR} = \frac{\mathrm{SI}\big(1 + 9.03(\mathrm{AR})\big) + 43.8(\mathrm{VPD})}{61.4(\mathrm{SM}) + \mathrm{SD}\big(1.82 - 0.83(\mathrm{DAY})\big)\big(1.68 + 24.8(\mathrm{AR})\big) + 2767} \tag{2}$$

where SI was solar insolation (W/m^2), AR was the application rate of any chemical conditioner (g of solution/g of dry-matter), VPD was the vapor pressure deficit (kPa), SM was the soil moisture content (% dry basis), SD was the swath density (g/m^2), and DAY was 1 for first day, 0 otherwise. Another equation:

$$\mathrm{DR} = \frac{\mathrm{SI}\big(1 + 9.03(\mathrm{AR})\big) + 5.42(\mathrm{VPD})}{66.4(\mathrm{SM}) + \mathrm{SD}\big(2.06 - 0.97(\mathrm{DAY})\big)\big(1.55 + 21.9(\mathrm{AR})\big) + 3037} \qquad (3)$$

was developed to use dry bulb temperature instead of vapor pressure deficit for easier use. Either model was most sensitive to solar intensity and swath density and was able to explain 75% of the variance in the drying rate of alfalfa within a moisture range of 80-20%.

In a recent article, Bartzanas et al. (2010) describe a model that they have worked on to predict field drying for biomass and the application of computational fluid dynamics (CFD) based modeling as a decision support model for biomass feedstock handling. The analytical model used an equivalent macro-porous medium approach and was validated from an existing Penman evaporation equation model with field conditions as inputs. The CFD approach modeled the biomass material as a macro-porous medium. The approach considered the drag effect of the air moving over the grass, and the mass and vapor transfer between the grass and the surrounding air. The CFD model simulated the process well for the area studied when compared to the analytical model with the same inputs, with the difference in the values estimated by the two models varying between 4 and 20% and a mean difference of 8%.

2.2.3 Thin-Layer Drying

Thin-layer drying is another method to characterize the drying of agricultural products. Thin-layer Drying of Grains and Crops (ASABE, 1998b) describes the conditions of the drying chamber and the material in a thin-layer method. Adhering to the standard allows for cross comparison of different data sets. Thin-layer drying eliminates much of the problem associated with airflow across and through the material because the material is to be at maximum three layers of particles.

The moisture is removed by the drier and higher temperature air. The model that describes the process is Page's equation (Thin-Layer Drying of Grains and Crops, ASAE S448),

$$MR = \frac{M - M_e}{M_i - M_e} = e^{-kt^n} \tag{4}$$

with coefficients of "k" and "n". The equation is similar to the one used by Priepke and Bruhn (1970). ASABE has published two standards that give the constants for several crops and grains, Thin-Layer Drying of Grains and Crops (ASAE S448) and Moisture Relationships of Plant-based Agricultural Products (ASAE D245.6). However, forage sorghum was not listed. The thin-layer drying model requires that the moisture content be described by a moisture ratio, eliminating the problems with moisture contents of samples not being equal at testing.

2.3 Plant Characteristics of High Energy Forage Sorghum

The type of sorghum grown for biofuels is dependent on the conversion process that will be implemented. For cellulosic bioethanol, plant material high in cellulose is desired. High energy forage (or high tonnage) sorghum is a warm-season annual grass which can produce large biomass yields per unit of land, and contains some of the largest amounts of cellulosic material. It is a subset of one of the six types of sorghums identified by Pederson and Rooney (2004), grouped by its intended end-use: sudangrass, forage sorghum, sorghum x sudangrass hybrid, grain sorghum for silage, sweet sorghum, and weeds.

Forage sorghum has thick primary stalks with no or few tillers; however, this is dependent on the hybrid traits (Figure 9). Genetic breeding is being used to develop the performance of the crop in relation to the carbon exchange rate over the desired production area, and specialized "energy sorghum" is becoming an available hybrid for production. The average plant height, stem diameter reported by Venuto and Kindiger (2008) was 2.3 meters and 1.4 centimeters, respectively, for 10 cultivars of hybrid forage sorghum harvested in August at El Reno, Oklahoma, over 2004-2006 growing seasons. The heights for the September harvest were slightly higher at 2.6 meters, but the stem diameter was lower at 1.3 cm.

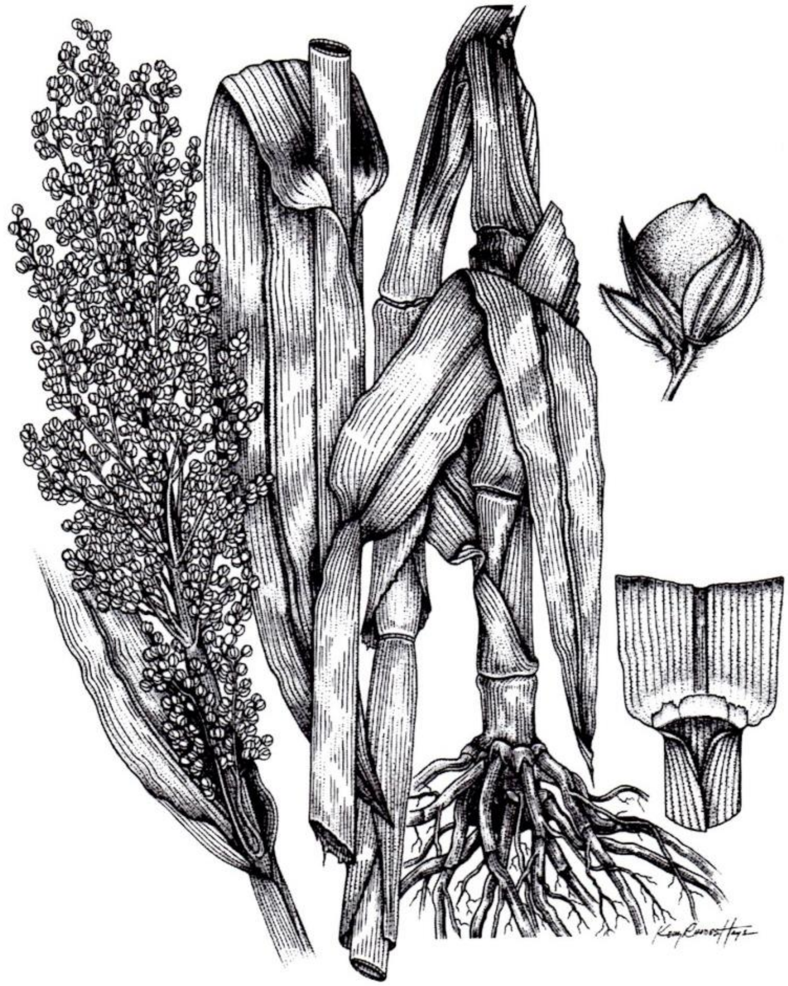


Figure 9. Sorghum plant structure illustration. Components description from left to right: inflorescence, leaf, stem, collar region (lower right), and caryopsis (upper right). (Pederson and Rooney, 2004)

CHAPTER III

METHODOLOGY

3.1 Description of Conditioner Test Units

Three types of mechanical conditioning units were evaluated in terms of power consumption and degree of conditioning. The units were manufactured by AGCO, Inc. (Hesston, KS) under the direction of Idaho National Laboratories (Idaho Falls, ID). The conditioning units included: fluted, “V”-impeller, and chisel impeller. The conditioner units were described in the following sections.

3.1.1 Fluted Roll Conditioning Unit

The fluted roll conditioner (Figure 10) consisted of four rolls working in pairs. Each pair operated at the same speed to keep the intermeshed timing correct. The in-feed roll pair had a faster speed than the out-feed rolls by 0.09 rpm because of inequalities in the sprocket configuration. The intermeshing point of the in-feed rollers sat 19.1 cm forward and 10.8 cm below the out-feed roller intermeshing point (Figure 11). The position of the bottom roll of each set was fixed while the top roll was allowed to move vertically. The top rolls of both pairs were set in front of the bottom rolls.

Figure 10. Fluted roll conditioner unit.

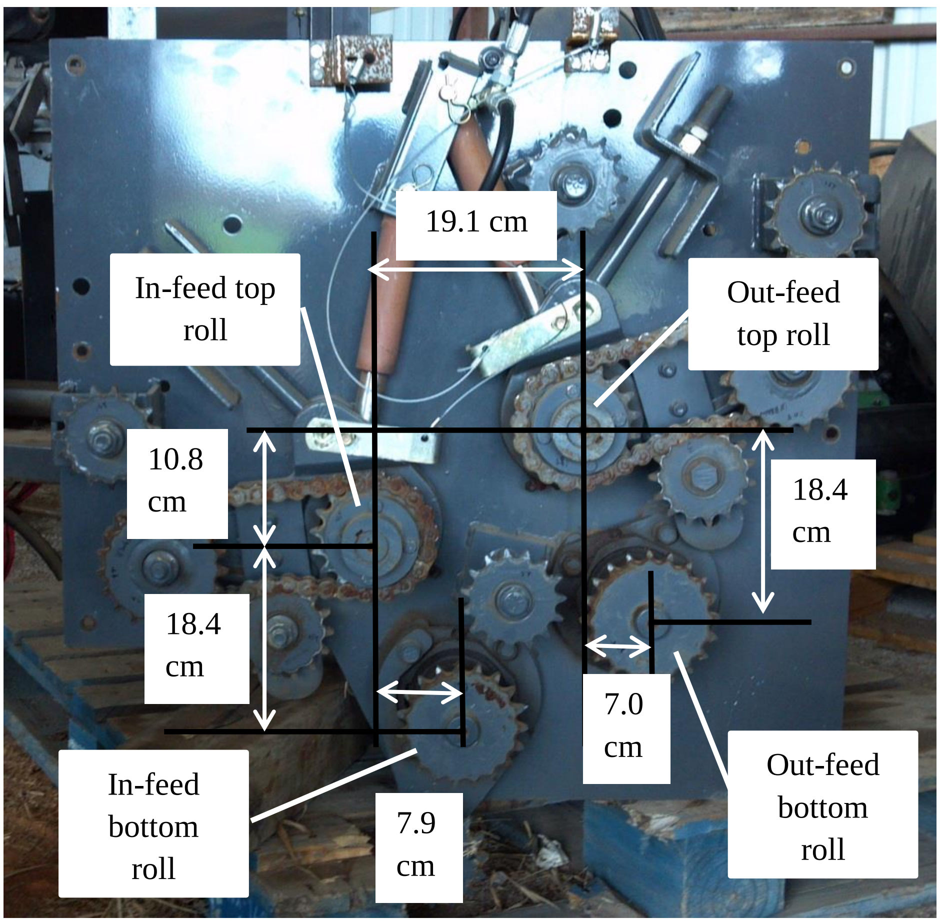


Figure 11. Fluted roll placement geometry in conditioner unit.

The type of conditioning was considered to be crimping, according to the definition described by Shinners et al. (2006). The diameter of each roll center was 14.4 cm, with the fluted attachment increasing the diameter to 19.5 cm (Figure 12). There were eight flutes per roll. The flutes tracked at an angle around the roll with a difference in the ends of approximately 6.7 cm.

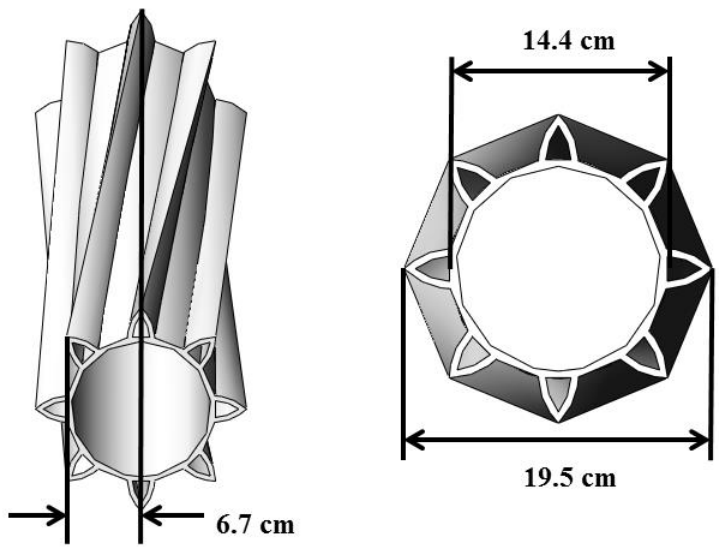


Figure 12. Fluted conditioner intermeshing rolls.

The top to bottom roll-to-roll minimum distance was set by the adjustment cams and adjustment rods, indicated by the arrows in Figure 13. The physical minimum roll-to-roll distance was 0.0 cm and the maximum was 6.4 cm. The working roll-to-roll distance was determined by running the unit at the desired roll speed and adjusting the distance to minimize the wear between the flutes and center roll, essentially providing a gap of zero between the rolls. Based on conversations with AGCO field engineers the front pair of rolls were set slightly wider than the rear rolls to provide some initial conditioning and then the final conditioning would be at the rear rolls. Setting the rolls in this configuration allowed the rear rolls to pull the material through the gap. The front rolls were set 0.6 cm wider than the rear rolls. The limitations of the equipment tested were the range of roll speed and the inability to change the speed between the first and second set of rolls. The design also restricted the sprocket size used.

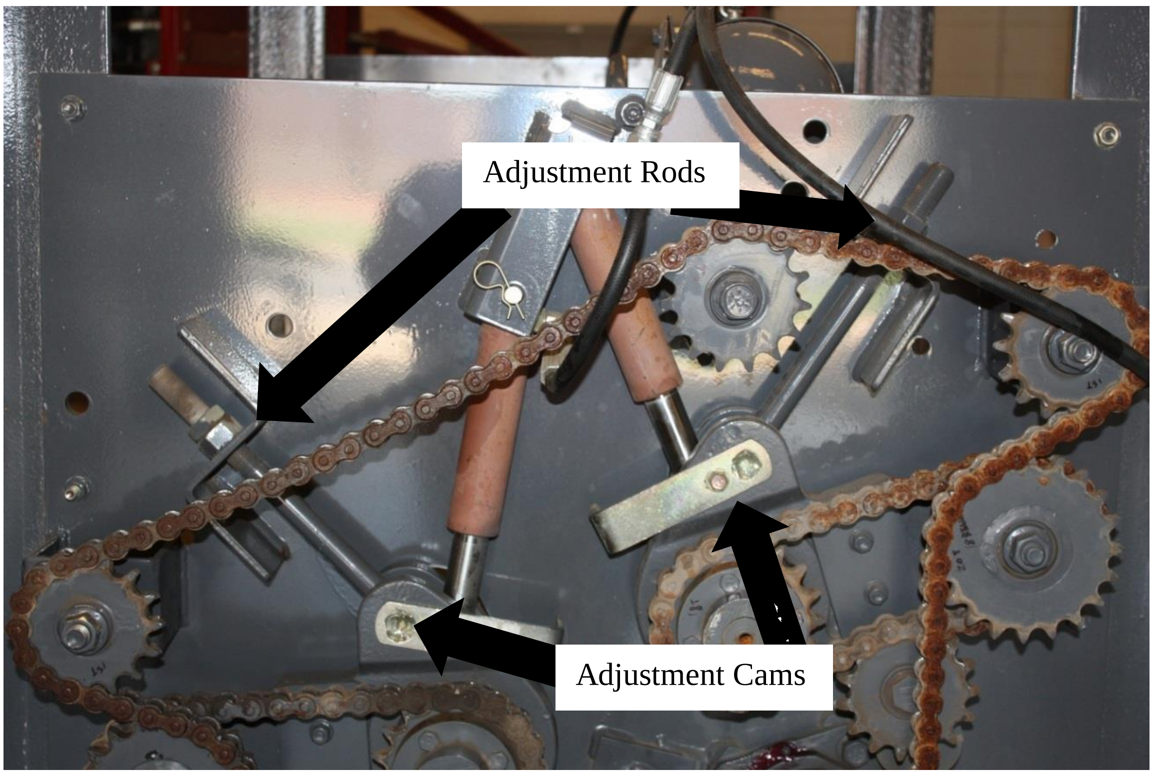


Figure 13. Location of the top to bottom roll-to-roll distance adjustment rods and cams for the fluted conditioner test unit.

The roll-to-roll distances and hydraulic accumulator pressure interacted to determine the amount of material conditioning that occurs as the material passes through the roller system. During the conditioning process, the rolls were able to move apart by overcoming the pressure in the hydraulic accumulator circuit identified in Figure 14 and Figure 15. The operating pressures were determined by the capacity of the hydraulic supply unit and conversations with AGCO field test engineers. The pressure of the hydraulic accumulator circuit was determined by priming the accumulator to the desired pressure. The range available from the circuit setup was 0-34,000 kPa. Typical operating ranges for high energy forage sorghum were between 6900 to 8300 kPa. For the fluted conditioner unit evaluation, three pressures were selected to bracket the recommended range: 3450, 6900, and 10,300 kPa.

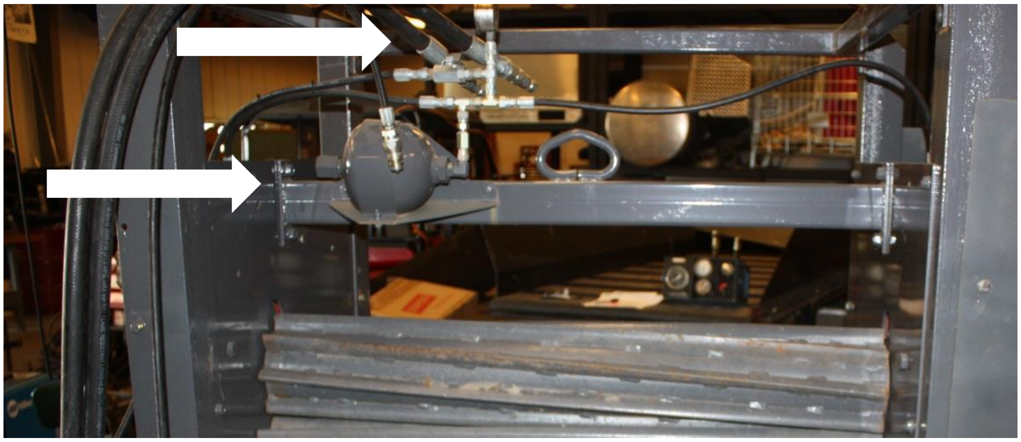


Figure 14. Accumulator and pressure gauge for the roll-to-roll pressure circuit on the fluted roller conditioner test unit.

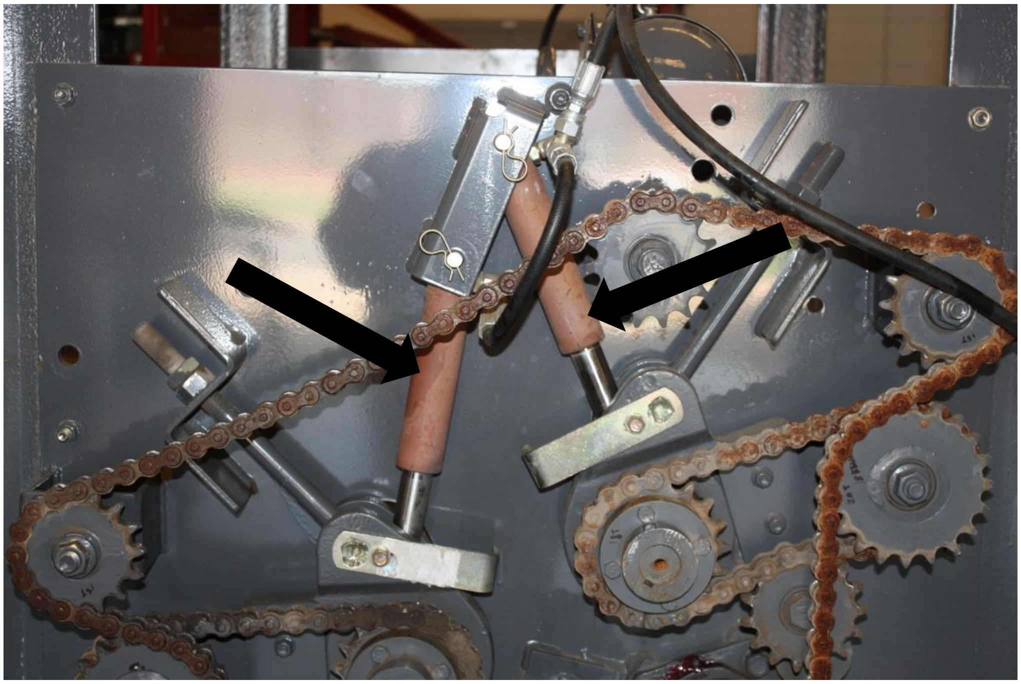


Figure 15. Roll cylinders in the accumulator circuit activated by the accumulator pressure.

3.1.2 Chisel Impellers

The chisel impellers, wide flat plates of metal that were bent and tapered to the connection point, were approximately 12.5 cm wide, with a thickness 1.0 cm. The chisel impellers (Figure 16) were arranged in four rows with four impellers in each row. The impellers were arranged to balance the rotor’s inertia during operation.

Figure 16. Picture of the chisel impeller conditioner test unit.

A metal shield was used to control the amount of interaction between the feedstock and the impellers (Figure 17). The design of the conditioning unit provided the opportunity to set the shield in various configurations and distance from the impellers. A limitation of the test was the hood gap control. The physical unit was limited on the amount of adjustment due to mounting hardware. For this study, the shield was placed in the two extreme positions: highest possible clearance and lowest possible clearance. Due to the geometry of the impellers, the largest gap from the extended chisel tip to shield was 5.7 cm and the smallest gap was 0.6 cm.

Figure 17. Material guidance shield for the impeller conditioners.

The hydraulic drive motor on the conditioner unit allowed a range of speeds to be obtained by changing the flow rate and/or pressure. The range available was from 0-1200 rpm. Two test speeds were determined from baseline testing, with the available hydraulic source influencing the range. The rotor shaft speed was set at 800 rpm or 1000 rpm, which represents a range covering the speed suggested by Deere & Company (2013). The speeds were higher than the speed used by Greenlees et al. (2000) in evaluating alfalfa and grass.

3.1.3 “V”-Impellers

The “V”-impeller conditioner was composed of 30 impellers, each containing two steel bars, 1.0 cm by 4.5 cm by 17.0 cm in length. The two steel bars were set at an angle to each other so that the inside opening of the “V” was 4.0 cm. Rotating about a point at the base of the bars (Figure 18), the bars were able to pivot approximately 160 degrees at their base. There were five rows of impellers with six impellers in each row. The impellers were set in a staggered pattern.

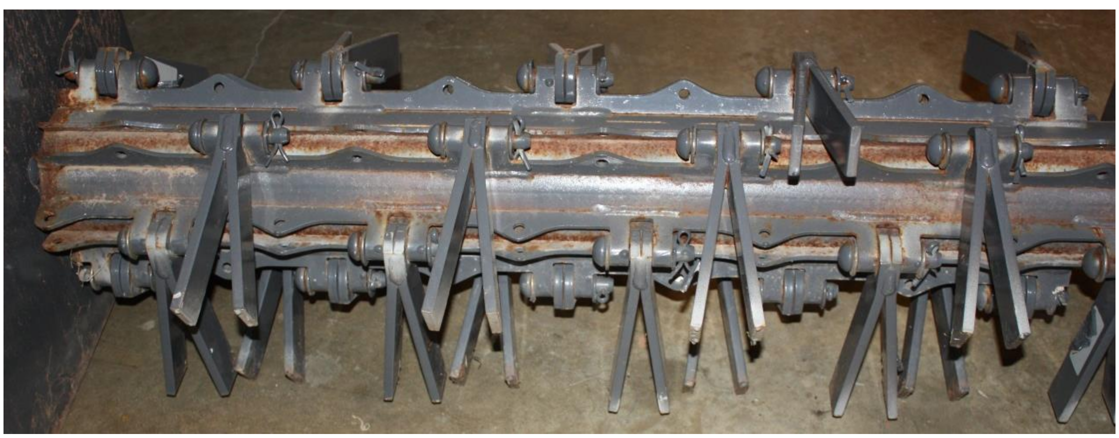


Figure 18. Picture of the “V”-impeller conditioner test unit.

As with the chisel impeller unit, a metal shield was used to control the amount of interaction between the feedstock and the impellers (Figure 17). Due to the geometry of the impellers, the measurements for the gaps were different than for the chisel impeller unit. The largest gap was 7.0 cm and the smallest gap was 1.9 cm. The speed of the rotor shaft was set at the same speeds as the chisel impeller.

3.2 Statistical Design

A completely randomized design was used for the fluted roller conditioner. There were six treatments composed of two feedstock feed rates and three roll-to-roll pressures. Three replicates of each treatment were completed. A split block design was used for the impeller tests. The tests were blocked by the impeller type and shield gap. There were eight treatments composed of two feedstock feed rates and two impeller speeds that were completely randomized. Three replicates of each treatment were completed.

3.3 Field Conditioner Power Requirements

The test conditioner units were remotely powered by a John Deere 7230R. The speed of the hydraulic motor output shaft on the conditioner units was measured by a rotary encoder (Figure 19). The rotary encoder was mounted at the hydraulic motor output shaft with a flexible coupler. The detailed drawing for the encoder mount was provided in Appendix A and the encoder specifications were provided in Appendix B. The rotary encoder signal was logged as a counter at 10 Hz with National Instruments Signal Express (Austin, TX) software and USB-6212 data acquisition unit.

Figure 19. Motor encoder on drive sprocket powering the rollers and rotors.

The test units were set up to be powered hydraulically; therefore, power was calculated based on the flow rate and pressure differential across the drive motor. Power was calculated using the following equation:

$$\mathbf{P} = \frac{\Delta\mathbf{p} \times \mathbf{Q}}{\mathbf{60}} \qquad (\mathbf{5})$$

where p is pressure in MPa, Q is flowrate in l/min and P is power in kW (Goering et al., 2003). To determine the conditioner power consumption, the conditioner hydraulic system was connected in line with a flow meter and two pressure transducers. The flow meter was connected to a rigid hydraulic line to provide the necessary configuration for maintaining accuracy as described by the installation procedure provided by Blancett, Inc, (Racine, WI). The flow was not restricted by the hydraulic fittings, eliminating any need for compensation in the power calculations. Detailed sensor specifications and a detailed schematic of the hydraulic sensor setup were provided in Appendix B. One pressure transducer was mounted with the hydraulic flow meter in the inflow line. The second transducer was mounted in the return line of the circuit on an aluminum housing rigidly connected in the flow line. The sensors were monitored and recorded at 10 Hz with National Instruments Signal Express software and USB-6212 data acquisition unit. System configurations for the logging software were listed in Appendix B. The selected sampling rate provided approximately 50 data points per test run. The flow meter and pressure sensor data were used in calculating the power consumption of the test unit for each treatment. The electronic system schematic was detailed in Appendix B.

The initial accumulation circuit pressure between rolls was monitored with a pressure transducer during the test. The signal was logged at 1,000 Hz with National Instruments Signal Express software and USB-6212 data acquisition unit. A dial gauge was used to set the pressure on the fluted roller tests (Figure 20).

Figure 20. Roll-to-roll pressure transducer and readout gauge for the fluted conditioner.

The minimum distance between the rolls was set at 2.5 cm for the front rolls and 3.2 cm for the rear rolls. The spacing was set as indicated by the AGCO field engineers. The distance was monitored during testing to determine if the roll-to-roll pressure was exceeded as the material was fed through the rollers. The measurements were made with a rotary potentiometer and pulley system (Figure 21) to translate the linear motion into a rotary motion, creating a voltage change across the potentiometer. The rotary potentiometer specifications were listed in Appendix B.

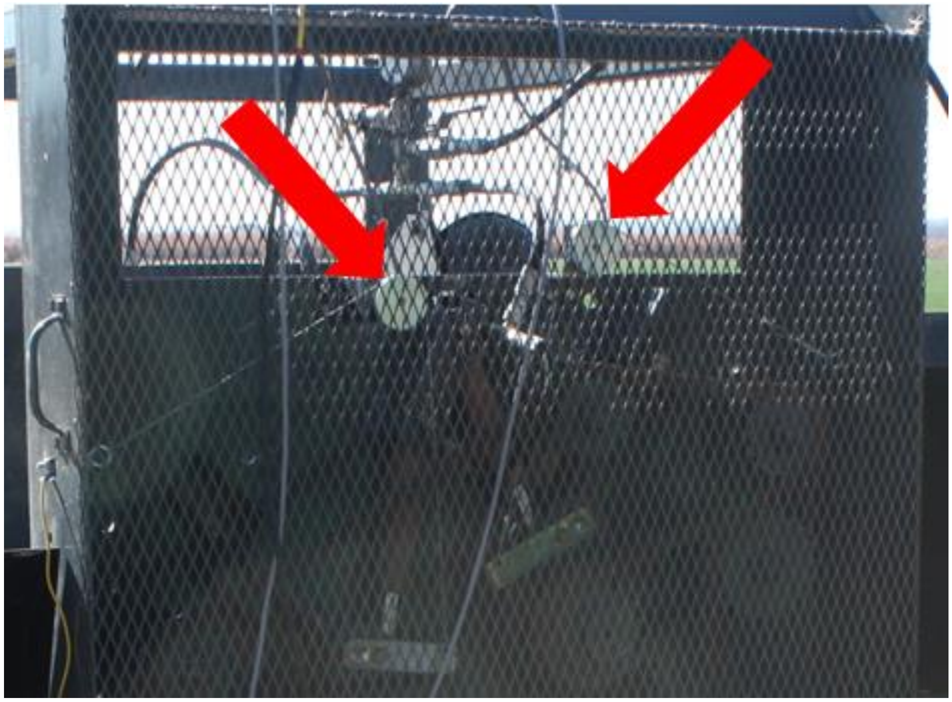


Figure 21. Potentiometer sensor arrangement that monitors roller movement for the fluted conditioner.

3.3 Data Extraction and Analysis for Power and Specific Energy Requirements

The data collected using Signal Express was stored in National Instruments TDM format. To convert this data from a TDM format to Excel format the TDM Excel Add-In and TDM Excel Add-In COM-API provided by National Instruments was used. The add-ins were coupled with VBA scripts to extract the data from the Signal Express Log Files. The VBA scripts were provided in Appendix C.

The Signal Express log files from the conditioner tests required a four-step process to combine and calculate power usage. The files were extracted with the .tdms extraction add-in resulting in three separate Excel workbooks. The first step was to combine the three sepearate workbooks using the "power test.xltm" template file, found in the "Scripts" folder, with sheets called "Ctr0", "Ctr1", and "Voltage". The second step was to modify the data with the conditioner power calculation script. The third step was to run the conditioner power averaging script to determine the average power for each test. The averages were typically based on the time period of 2-6 seconds of the test. The average eliminated the startup and shut down effects on the pressures in the hydraulic system. The fourth and final step of the process was to extract the power averages from each test and put test averages into a common file through the conditioner power evaluation summary script.

The specific energy was based on the conditioner power requirement for processing the feedstock and the dry matter content of the processed sample. The dry matter feed rate (t DM/h·m) was determined from the dry basis moisture content of the dry sample (MC_D) and the mass of the wet material in tons (G_W) using the following equation:

$$\text{Dry Matter Feed Rate} = \frac{100 \times G_W}{(100 + MC_D)} \tag{6}$$

The specific energy (kW·h/t DM) was found using the following equation:

$$SE = \frac{P}{\text{Dry Matter Feed Rate}} \tag{7}$$

with power (P) in kW/m and dry matter feed rate in t dm/h·m.

3.4 Test Material

The forage sorghum used for all the tests came from a plot at the South Central Research Station in Chickasha, Oklahoma. The high energy forage sorghum (Blade ES5200) was planted on 3 May 2012 with a planting density of 52,000 seeds/acre. The plot was fertilized with 220 lb/acre of 46-0-0 on 15 May 2012. Weather data for the growing season was provided in Table 1.

Table 1. Monthly temperature and rainfall for the test material growing period.

	Temperature(°C)		
	Max	Min	Rainfall (in)
May	85	61	5.92
June	92	67	2.81
July	100	73	1.89
August	97	69	1.68
September	89	61	4.62
October	73	48	0.54
November	69	37	0.86
December[a]	62	34	0.00

[a]weather conditions for the time period of the conditioner unit power testing

The material was at full maturity and post-senescence with the first killing frost occurring October 28, 2012.The conditioning were started on 19 November and continued through December 11, 2012. The material was cut with a machete or shears, approximately 5 cm above the ground or above any brace roots. Care was taken not to deform the stalk bottoms before the test was performed.

3.4.1 Material Characterization

To determine the physical characteristics of the material processed by the conditioner units, ten plant samples were gathered from each material harvest and kept for plant characteristic measurements. The measurements included total plant height including the leaves and inflorescence, if present, number of leaves, number of nodes and the presence of roots. Using a digital caliper, diameters of the stalk were measured at the cut end of the plant and then at every node. To account for irregular cross sections, two diameter measurements were taken: one orthogonal to the other at each location. The average of these two readings was used as the location diameter. The plane used for each diameter remained constant for each plant, and the leaves were removed at the collar, so that the incidence of a leaf collar would not influence the diameter measurement. The length of the internodal region was measured to the nearest 5 mm. The plant was also weighed on a scale (including leaves) to determine mass. The measurements were used to describe the plant shape distribution and variance among the tests.

A separate group of 50 plants were measured for the mass fraction of the leaves to describe the variance in the amount of leaf matter in the tests. The plants were weighed then stripped of leaves and reweighed. The weigh scale had a precision of 0.02 kg.

3.4.2 Material Setup

The material cut from the field was loaded on a conveyor and fed through each test unit. The material was laid on the conveyor in a manner to not introduce all the thickness of the material at once. The material was laid as evenly as possible across the width of the conveyor (Figure 22). The cut end of the material entered the conditioning unit first to simulate the infield process of the discs cutting the material and feeding the material into the conditioner. The feed rate was determined by the following equation:

$$\text{feed rate} = \frac{\text{mass} \times \text{speed} \times 3.6}{\text{length of infeed}} \tag{8}$$

where feed rate is tons (metric)/hour·meter, mass is in kilograms, speed is in m/s, and length of in-feed in meters. The tests performed required either 18.1 kg or 27.2 kg to produce feed rates of 8.9 t/h·m or 13.3 t/h·m. The feed rate was limited by the conveyor speed and the amount of material the conveyor could hold without belt slippage. The material needed for each test was weighed using a dial scale measuring to the nearest 0.09 kg. The material was then transferred to the feed conveyor.

Figure 22. Forage sorghum arranged on the in-feed conveyor for a conditioner test run.

3.4.3 Conditioned Material Moisture Content

For each test, a sample was collected to determine moisture content. The sample was randomly selected from the material on the out-feed and placed into a preweighed paper bag and weighed with a scale with 0.01 g precision (model ML802E, Mettler Toledo, Switzerland)). The sample was oven-dried according to ASABE S358.3 (ASABE, 2012) at 55 °C for 72 h. The dry basis moisture content was calculated using the following equation:

$$\mathrm{MC} = \frac{\mathrm{M_W} - \mathrm{M_D}}{\mathrm{M_D}} \tag{9}$$

where MC is the dry basis moisture content, M_W is the wet weight of the sample and M_D is the dry weight of the sample. The moisture content was used to determine the dry matter flow rates for each test.

3.5 Conditioning Level Grading

After conditioning, five plant stalks were randomly recovered for the visual grading. Pictures of each stalk were taken for a visual grading record. Conditioner quantification was based on the following scale (example pictures are in Appendix D):

Level 0- No damage

Level 1- No permanent distortion of stem shape; cracks apparent in lower section but not past nodes; when held from root end plant, will bend at 1 location

Level 2- general shape of stem remains; cracks that extend across 1 node; when held from root end, plant will bend at 2 locations

Level 3- root end significantly deformed (non-circular shape); severe deformation at root; cracks extend beyond 2-3 nodes with 1-2 cracks extending past ½ of plant length; cross breaking of exposed pith

Level 4- Stem distorted at root end; multiple cracks extending beyond ½ of length; pieces of stem nearly separated from rest of plant stem; damage visible at upper end of plant, when held from root end plant will bend at 3-4 locations

Level 5- Stem distorted at root end; cracks running nearly ¾ of the length in multiple locations; sections of the stems completely missing; when held from root end, plant will bend at more than 5 locations; bruising on leaves

3.6 Drying Rate Determination

For the drying rate evaluation, large forced air dryers were used with a data acquisition system that would record individual tray weights, and temperature and relative humidity inside and outside the dryer. The dryers available for use in this experiment were recirculating dryers with a temperature range of 0-500°F. A test was performed to determine temperature stability of the systems, and the lowest temperature where stability (±5°C over a 12 hour period) occurred was 60°C. Absolute humidity could not be adjusted during the test, but was monitored to determine if there was an influence from this factor. The forced air dryers had air from a duct in the lower rear of the dryer and an outlet on the upper surface but were not centered. To ensure the even flow of air over the trays in the dryer, a shroud was built to direct the airflow over the drying trays (Figure 23). The air passed over the tray through a rectangular opening found under each drying tray location. The opening was smaller than the drying tray itself by 2.54 cm in both directions. The top of the shroud had a cover that allowed air to pass along the outer edges, which allowed for less turbulence and evenness of air flow. The drying tray setup was tested for approaching airflow velocity across two trays in each dryer. Results of the airflow tests were within the specifications of Thin-Layer Drying of Grains and Crops (ASAE S448) of velocities of at least 0.3 m/s. The airflow results were provided in Table 2. Detailed drawings of the shroud were provided in Appendix A.

Figure 23. Picture of the thin-layer drying chambers.

Table 2. Approaching air velocities for different positions under the drying trays.

	West Dryer		East Dryer	
	Front Left Tray (m/s)	Front Right Tray (m/s)	Front Left Tray (m/s)	Front Right Tray (m/s)
Point 1	0.35	0.35	0.35	0.32
Point 2	0.34	0.36	0.37	0.36
Point 3	0.33	0.32	0.33	0.37

The drying trays (Figure 24) were lightweight metal trays (50.8 cm x 81.3 cm x 10 cm) with a metal mesh of 16 x 18 openings per inch. The trays were reinforced along the top edge for rigidity. Metal chain connected to the tray corners was used to suspend the tray from the load cell with an “s” hook.

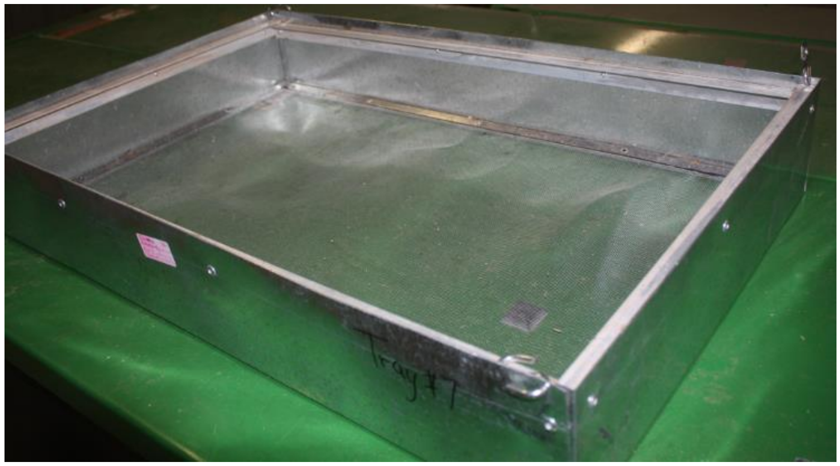


Figure 24. Picture of a thin-layer drying tray.

The data acquisition system recorded the mass of each tray every 15 minutes (with the forced air shut off) to the nearest 0.08 gram for at least 48 hours. Load cell specifications and data acquisition system schematics were provided in Appendix B.

3.6.1 Test Procedure

One sample of at least 4.25 kg was collected at least 0.2 m from the conveyor sides and the start and end of the material stream after conditioning. The material was picked up from the conveyor as whole stalks if possible so that the material had stalk and leaf sections. With the time required to complete a set of drying tests, all of the material was treated using the same storage procedure to minimize variance over the time required to complete all the drying tests. After conditioning, the material was rapidly frozen to -15°C in a vacuum sealed plastic bag and then transferred to a cold storage area and maintained at a temperature of 0°C. In most cases, the material was longer than the vacuum bag, so the stalks were bent to fit into the bag. The bags were slightly smaller than the size of the drying tray, so the material was able to fit into the drying tray without further manipulation. The material was also wrapped in a layer of plastic to protect the bag from puncturing and to provide an additional barrier to moisture transfer.

Prior to conducting the thin-layer drying tests, the sample was once again taken to -15°C in the smaller freezers for a period of at least two days so the material would all start out frozen (less moisture loss during handling). A sample was placed into a drying tray and that tray was labeled. The material was spread evenly onto the tray to allow for even air movement and drying. The tray was placed into the dryer, suspended from a single load cell. Samples were randomly placed into the drying locations to randomize the effects of the any airflow variances from influencing all of the replications of a single treatment. The drying chamber was sealed to make sure the air was forced across the tray. The data acquisition system recorded the weight of each tray automatically every 15 minutes with the heater and fan off. The sample weights were monitored until all samples had weight changes of less than 1.5 % over a 24 hour period of time and the moisture ratio (MR) was less than 0.05 (according to Thin-layer Drying of Grains and Crops, ASAE S448).

3.6.2 Dryer Data Extraction and Analysis

The dryer data extraction was aided by the use of the TDM Excel Add-In for Microsoft Excel Download and TDM Excel Add-In COM-API provided by National Instruments. The add-ins were coupled with VBA scripts to extract the data from the Signal Express Log Files.

Each set of samples for the drying studies had log files saved to a common folder on the computer for that specific dryer. The common folder (example: west_dryer_set_1) can be copied to another computer for data processing. Because the data log files from both the east and west dryers could have the same name, the log names were modified to avoid a loss of data. A macro enabled Excel template file was created with embedded scripts. The data extraction template file for the corresponding dryer was placed in the same folder as the log files so that the script could access the *.tdms files. The average data from each log entry was extracted and added to a common Excel file.

The analysis was a multi-step process that used nonlinear regression to fit the data from each sample to the thin-layer drying model (Eqn. 4). Moisture equilibrium was found by first determining moisture content at each time interval of the drying test for each sample in a dry basis format. Dry basis moisture content was determined in accordance to ASABE 358.3 and resulted in a graph similar to Figure 25. The next step was to determine the difference of the moisture content from one interval to the next. The moisture equilibrium was calculated by averaging the moisture content when the moisture content was at a steady level (this would be in equilibrium with the dryer conditions) or when the difference was <1.5%. The moisture ratio, a method that normalizes the moisture content of the samples to 1.0, was calculated using Equation 4. An example of a moisture ratio graph was shown in Figure 26. The moisture ratio information was then used to extract the coefficients for the drying model, Eqn. 4, with SPSS's nonlinear regression analysis. The resulting "k" and "n" coefficients were used to generate a model as shown in Figure 26. The "k" and "n" coefficients for each sample were used to determine the predicted dry-down times for the treatment analysis of variance.

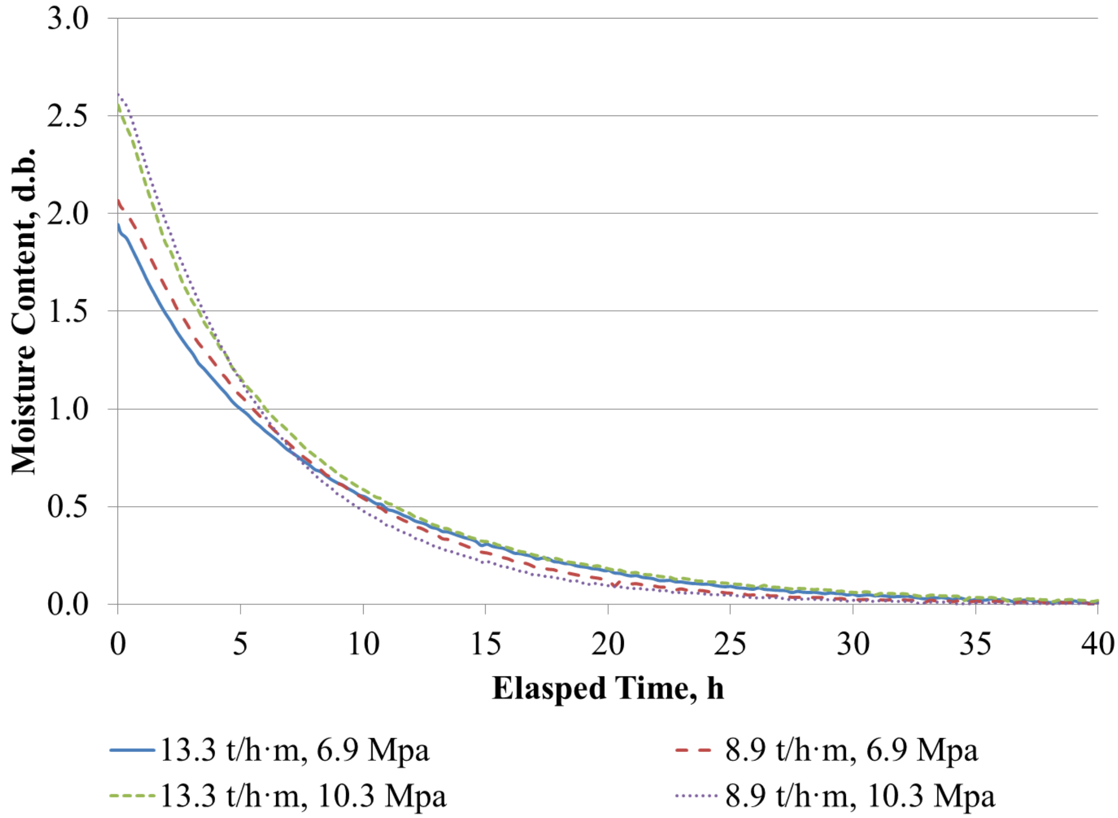


Figure 25. Non-normalized drying curve for fluted conditioner treatments.

The predicted times to dry to 0.1 and 0.2 moisture ratio were used in the univariate analysis of variances. The moisture ratios of 0.1 and 0.2 were chosen as points of comparison because they span the moisture content that Bonner and Kenney (2013) indicate as a safe storage level (approximately 17%).

After examining the statistical models for the predicted equations, a general overall model was developed from a new set of “k” and “n” coefficients, which were determined by using nonlinear regression with all of the experimental data for each treatment that should be included in that model.

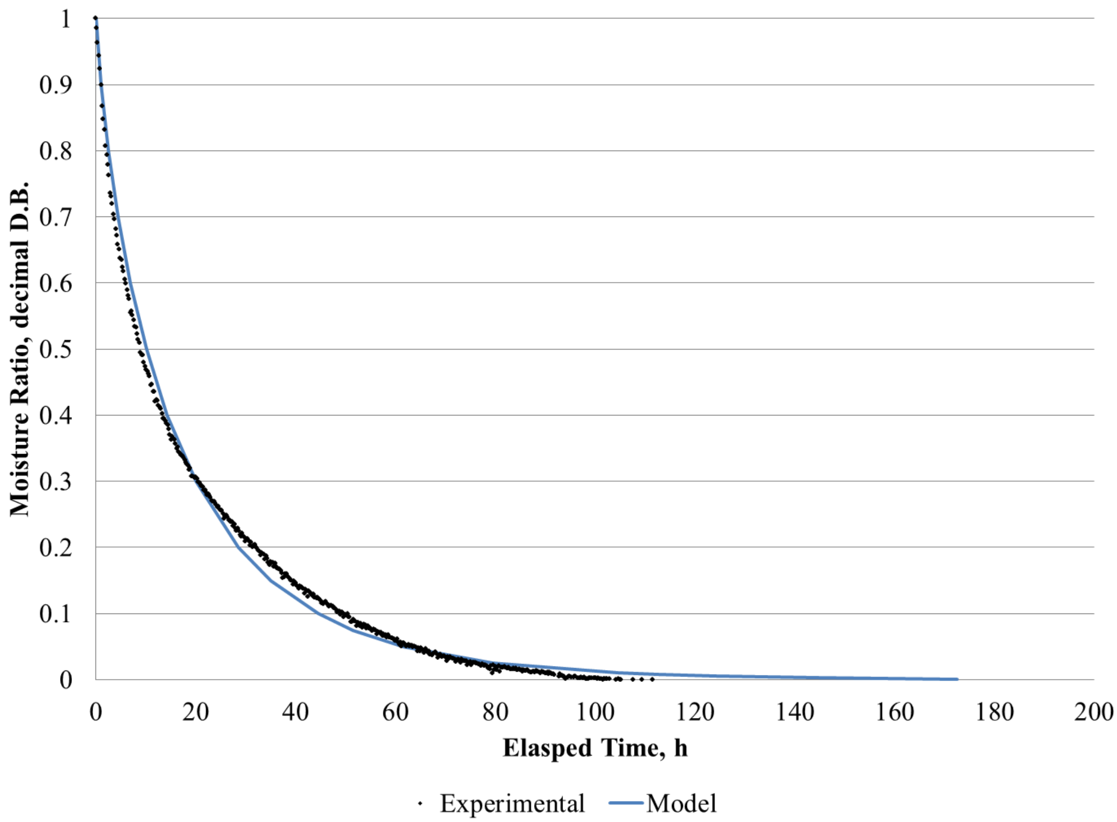


Figure 26. Normalized drying curve and model for a conditioner test.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Forage Sorghum Pre-conditioning Plant Characteristics

The plant material was harvested in lots. A total of 13 lots were harvested for the study. The harvesting lot procedure was tested for variances to determine if the plant material was similar between lots. Table 3 shows the plant characterizations of the material by lot used in the fluted conditioner tests. The analyses of variance indicate that the material was not significantly different between the lots in terms of plant height, plant weight or stalk diameter. Table 4 shows the plant characterizations for the lots used in the impeller conditioner tests. The lots were not vary statistically different in terms of plant weight or stalk diameter. Plant height was significantly different among the lots. Lot 5 was different from 6, 8, 9 and 10. Lot 6 was different from 7, 11, 12, and 13. There were no significant differences between lots 7 through 13. Harvest lots 5 and 6 were used in the chisel impeller tests with a shield gap of 0.6 cm. Of all the plant characteristics evaluated, plant height should have minimal impacts on the conditioner tests. No statistical analyses were conducted to determine if plant height impacted the conditioner tests because of how the treatments were distributed within harvest lot. The conditioner treatments within harvest lot were provided in Appendix F. The average heights of material for all of the conditioner units were similar to those reported by Venuto and

Kindiger (2008) in August and September harvests; however, stage of maturity was different with the test material at a mature stage compared to anthesis and late milk stages.

Table 3. Forage sorghum height, weight, and diameter for the harvested material for the lots used in the fluted conditioner unit evaluations.

Harvest lot	Date and time	Plant Height (cm)		Plant Weight (g)		Stalk Diameter (mm)	
		Average[b]	SD[a]	Average[b]	SD[a]	Average[b]	SD[a]
1	11/27 8:30	195	44	367	189	20.89	5.11
2	11/27 10:30	200	41	339	175	20.77	5.93
3	11/27 16:00	212	30	351	180	19.50	5.01
4	11/28 8:30	200	43	398	232	21.53	5.32
Average Fluted Material		202	39	364	189	20.65	5.39
F		0.33		0.17		0.35	
P-Value		0.81		0.92		0.79	

[a] Standard deviation.
[b]No significant differences between harvest lots.

Table 4. Forage sorghum height, weight, and diameter for the harvested material for the lots used in the impeller conditioner unit evaluations.

Harvest lot	Date and time	Plant Height (cm)		Plant Weight (g)		Stalk Diameter (mm)	
		Average[c]	SD[a]	Average[b]	SD[a]	Average[b]	SD[a]
5	11/29 9:30	261c	16	484	153	21.32	4.49
6	11/29 13:30	215a	33	388	172	20.74	4.49
7	11/29 14:30	246b,c	27	438	159	20.39	4.22
8	11/30 10:30	228a,b	21	450	167	19.41	6.23
9	11/30 13:30	231a,b	23	296	164	17.30	4.59
10	12/6 9:00	234a,b	34	390	112	20.67	3.62
11	12/6 13:00	249b,c	27	425	169	21.05	4.00
12	12/11 13:00	253b,c	17	538	100	22.28	3.98
13	12/11 15:30	251b,c	23	432	175	20.58	4.51

Table 4. Forage sorghum height, weight, and diameter for the harvested material for the lots used in the impeller conditioner unit evaluations, cont'd.

Harvest lot	Date and time	Plant Height (cm)		Plant Weight (g)		Stalk Diameter (mm)	
		Average[b]	SD[a]	Average[b]	SD[a]	Average[b]	SD[a]
Average Impeller Material		241	28	427	161	20.18	3.60
F		3.44		1.90		2.175	
P-Value		<0.01		0.07		0.06	

[a] Standard deviation.
[b] No significant differences between harvest lots.
[c] Letters appearing next to the data indicate the statistically similar groups at the 0.05 level.

Moisture content of the forage sorghum used for each conditioner evaluation test was measured and the results by treatment were provided in Appendix E. There were no significant differences in moisture content based on univariate analysis of variance. The leaf portion of the forage sorghum was determined to be a small fraction of the overall plant mass (results were provided in Appendix E). Because the leaf fraction was relatively small compared to stalk mass, no separation of the stalk and leaf material was done prior to the drying studies.

4.2 Visual Conditioning Quantification

The average visual rating for all fluted roller tests was 3 on a scale of 0-5 with a standard deviation of 1. A visual condition level of 3 means the root end was significantly deformed and does not maintain a circular shape; cracks in the stem extend beyond 2-3 nodes with 1-2 cracks extending past ½ of plant length; and cross breaking of exposed pith is present. This level of conditioning was adequate, but not as aggressive as planned.

The average visual rating for the chisel unit was 2 for the shield gap of 0.6 cm except for the 13.3 t/h and 800 rpm rotor speed treatment, which had a rating of 1. A rating of 2 on the visual conditioning quantification means that the general shape of the stem remains circular; there were cracks that extend across one node; and when held from root end, the plant bent at maximum at two locations. The average rating for the 5.7 shield gap was 1; lower than the smaller shield gap. A visual rating of 1 means that there were no distortion of stem shape; cracks were apparent in lower section but do not extend past the node; and when held from root end the plant bent at one location. The feed rate and impeller speed had no significant effect on visual rating. The chisel unit had a higher visual conditioning rating with the smaller impeller-to-shield gap than the larger gap.

The average visual rating for the “V” conditioner unit was 2 for all treatments except for the 8.9 t/h·m feed rate, 800 rpm, 1.9 cm shield gap treatment, which had a rating of 1. Comparing the degree of visual conditioning across all units, the fluted roller unit produced higher visual conditioning than the other conditioning units.

4.3 Field Conditioner Power Requirements

The fluted impeller conditioner did not show a well-defined trend when looking at the average power (Table 5). The interaction of feed rate and roll-to-roll pressure was significant with a P-value of 0.04. The primary effects of feed rate and roll-to-roll pressure were more significant than their interaction. The analysis showed that feed rate and pressure influence the power needed for processing the material. As roll-to-roll pressure increases, the power required decreases. The data also showed that increasing feed rate lowered the required power. The feed rate results indicate that the feed rate must be increased to completely evaluate the fluted conditioner. These tests were limited by the feedstock load that could be handled by the in-feed and out-feed conveyors. The design of these conveyors should be improved for future studies.

Specific energy was examined for the fluted roller unit and the results were provided in Table 5. There were no significant effects due to the interaction of feed rate and roll-to-roll pressure. Both roll-to-roll pressure and feed rate effects were significant. The feed rate appeared to explain more of the variability than the roll-to-roll pressure. Although the statistical analysis showed significance in the factors, the actual values do not differ by large amounts with the standard deviations allowing each treatment to overlap the next treatment in the 8.9 t/h·m feed rate for specific energy. The fluted conditioner had an average power consumption of 2.4 kW/m and a standard deviation of 0.4 kW/m for a feedrate of 8.9 t/h·m. The average power consumption for 13.3 t/h·m was 1.7 kW/m with a standard deviation of 0.6 kW/m. Power consumption and specific energy data were provided in Appendix F.

Table 5. Fluted conditioner unit power and specific energy requirements for processing forage sorghum.

Feed Rate, t/h·m	Pressure, kPa	Power Consumption[a], kW/m		Specific Energy, kW·h/t DM[b]	
		Average	SD[c]	Average	SD[c]
8.9	3450	3.1	0.2	1.1	0.1
8.9	6900	2.6	0.3	1.0	0.1
8.9	10300	2.8	0.5	1.0	0.3
13.3	3450	2.8	0.4	0.7	0.1
13.3	6900	1.5[d]	0.3[d]	0.4[d]	0.1[d]
13.3	10300	2.5	0.2	0.6	0.1
Feed Rate	F	12.15		38.60	
	P-Value	<0.01		<0.01	
Pressure	F	11.19		4.13	
	P-Value	<0.01		0.04	
Feed Rate*Pressure	F	4.48		1.60	
	P-Value	0.04		0.24	

[a] Additional power above baseline requirements
[b] Dry Matter
[c] Standard Deviation
[d] Based on 2 replications, error with logging created one rep without power data

The impeller conditioner units were analyzed together. The power and specific energy results were provided in Table 6. As expected, the results showed that the required power to process the forage sorghum increases with increasing speed. The average power for the impeller conditioners units at 800 rpm was 4.5kW/m with a standard deviation of 1.0 kW/m. The average power for impeller conditioners at 1000 rpm was 5.5 kW/m with a standard deviation of 1.1 kW/m. The trend was supported by the univariate analysis of variance. The power required for processing showed the "V" type impeller had higher requirements than the chisel at all instances except for the 8.9 t/h·m, 1000 rpm and 5.7cm gap treatment but the trend was not statistically significant at the 0.05 level. The type, gap between the impellers, and the shield were not different in the power required to process forage sorghum. The conditioners had an average power consumption of 5.0 kW/m and a standard deviation of 1.2 kW/m.

The specific energy for the impeller type conditioner was influenced by the feed rate and the speed (results in Table 6). The trend identified was that increasing feed rates decreased specific energy. The average specific energy was 1.9 kW·h/t DM with a standard deviation of 0.5 kW·h/t DM and 1.2 kW·h/t DM with a standard deviation of 0.4 kW·h/t DM for feed rates of 8.9 t/h·m and 13.3 t/h·m, respectively. The trend for the speed factor was the opposite; increasing speed increased specific energy. The speed trend was expected from the trend established with the power results and supported by the univariate analysis of variance. The average specific energy for the impeller conditioners were 1.3 kW·h/t DM and a standard deviation of 0.4 kW·h/t DM and 1.8 kW·h/t DM with a standard deviation of 0.5 kW·h/t DM for 800 and 1000 rpm, respectively. There were no differences in the required specific energy to process forage sorghum between shield gap and type of conditioner. The conditioners had an average specific energy of 1.5 kW·h/t DM and a standard deviation of 0.5 kW·h/t DM.

Table 6. Impeller conditioner unit power and specific energy requirements for processing forage sorghum.

Unit	Shield Gap, cm	Feed Rate, t/h·m	Impeller Speed, rpm	Power Consumption[a], kW/m Average	Power Consumption[a], kW/m SD[c]	Specific Energy[a], kW·h/t DM[b] Average	Specific Energy[a], kW·h/t DM[b] SD[c]
Chisel	0.6	8.9	800	4.8	0.1	1.9	0.2
	0.6	8.9	1000	5.3	0.1	2.1	0.2
	0.6	13.3	800	4.9	0.3	1.3	0.1
	0.6	13.3	1000	5.4	0.4	1.5	0.3
	5.7	8.9	800	5.4	0.8	1.8	0.5
	5.7	8.9	1000	6.1	0.4	2.5	0.1
	5.7	13.3	800	3.8	2.4	0.8	0.6
	5.7	13.3	1000	4.9	0.2	1.2	0.7
"V"	1.9	8.9	800	5.0	0.2	1.6	0.2
	1.9	8.9	1000	6.4	0.7	2.5	0.5
	1.9	13.3	800	5.0	0.1	1.1	0.1
	1.9	13.3	1000	6.1	1.0	1.4	0.2
	7.0	8.9	800	5.4[d]	0.1[d]	1.5[d]	0.4[d]
	7.0	8.9	1000	6.6	0.9	2.1	0.7
	7.0	13.3	800	5.2	0.0	1.2	0.3
	7.0	13.3	1000	6.6	0.2	1.7	0.2
	Type		F	2.02		0.07	
			P-Value	0.16		0.80	
	Gap		F	0.04		0.84	
			P-Value	0.84		0.37	
	Feed Rate		F	0.21		22.74	
			P-Value	0.65		<0.01	
	Speed		F	11.03		16.41	
			P-Value	<0.01		<0.01	

[a] Additional power above baseline requirements
[b] Dry Matter
[c] Standard Deviation
[d] Based on 2 replications, error with logging created one rep without power data

The power requirements of all of the conditioner models were greater than the rotary power requirements identified in ASABE (1998a) for mower-conditioner units, which reported requirements of 4.5-8 kW/m, with the power required to cut the material included. The baseline power measured for the units tested were 5.9 kW/m for fluted rolls, 5.8 kW/m for the chisel impeller, and 5.7 kW/m for the “V” impeller. The specific energy requirements are similar to results Tremblay et al. (1994) determined for an eight roll staggered configuration macerator required in timothy and alfalfa plots.

4.4 Drying Rates

The thin-layer drying test configuration including starting and ending times were provided in Appendix G. The dryer temperature and absolute humidity for the thin-layer drying studies were shown in Table 7 (with additional details about the samples in each drying set in Appendix G). The dryers did maintain the temperature specified in the methodology except for the west dryer on drying set 4. The west dryer’s temperature sensor had a loose ground wire during this test, which could explain the larger variance. The absolute humidity, an uncontrollable factor in the dryer systems, remained relatively steady during the drying tests with a variance of 0.07% and 0.04% for the west and east dryers, respectively.

The conditioned forage sorghum sample weight data was used to calculate moisture content according to ASABE S358.3 on a dry basis. The moisture content was plotted against elapsed time to determine if the general shape of the curve fit Page’s equation (Eqn. 1) for agricultural crops (Figure 25). The drying rate curves for all conditioned forage sorghum samples followed the general shape of Page’s equation.

The average equilibrium moisture levels for the different treatments in the fluted conditioner thin-layer studies were presented in Table 8, with detailed results in

Appendix H. The moisture equilibrium values were checked for significance against the factors of the treatments. The fluted conditioner unit sample's moisture equilibriums were not influenced by the factors at the 0.05 level. The moisture equilibriums for the impeller conditioner units, shown in Table 9, were not influenced by the factors at the 0.05 level. Detailed results were provided in Appendix H.

Table 7. Average temperature and absolute humidity maintained inside the dryers for the thin-layer drying studies.

Dryer Set	West Dryer				East Dryer			
	Temperature, °C		Absolute Humidity, %		Temperature, °C		Absolute Humidity, %	
	Average	SD[a]	Average	SD[a]	Average	SD[a]	Average	SD[a]
1	58.3	2.6	1.9	0.4	62.6	3.0	2.6	0.4
2	58.4	1.7	1.8	0.5	62.3	2.1	2.3	0.5
3	57.7	2.1	2.0	0.5	61.7	2.2	2.2	0.5
4	50.1	5.4	1.5	0.7	61.8	2.1	2.5	0.6
5	57.4	2.6	2.0	0.4	61.5	1.4	2.3	0.4
6	58.2	1.7	2.0	0.3	62.1	1.7	2.2	0.3
7	57.1	1.6	2.4	0.3	61.1	1.8	2.7	0.3
8	57.4	2.3	2.2	0.3	61.4	2.5	2.5	0.3
9	56.9	1.8	2.2	0.6	61.5	2.0	2.6	0.6

[a]Standard Deviation

Table 8. Average moisture equilibrium for the fluted conditioner treatments.

Feed rate, t/h·m	Pressure, kPa	Moisture Equilibrium, % d.b.	
		Average	Standard Deviation
8.9	3450	0.97	0.15
8.9	6900	1.20	0.10
8.9	10300	0.90	0.36
13.3	3450	1.27	0.40
13.3	6900	1.57	1.34
13.3	10300	0.87	0.21
Feed Rate	F	0.63	
	P-Value	0.44	
Pressure	F	1.17	
	P-Value	0.34	

Table 9. Average moisture equilibrium for the impeller conditioner treatments.

Type	Shield Gap, cm	Feed rate, t/h·m	Impeller Speed, rpm	Moisture Equilibrium, % d.b. Average	Standard Deviation
Chisel	0.6	8.9	800	2.00	0.62
	0.6	8.9	1000	1.70	0.44
	0.6	13.3	800	1.77	0.40
	0.6	13.3	1000	1.70	0.10
	5.7	8.9	800	1.80	0.52
	5.7	8.9	1000	1.57	0.15
	5.7	13.3	800	1.83	0.42
	5.7	13.3	1000	1.63	0.38
"V"	1.9	8.9	800	1.93	0.61
	1.9	8.9	1000	1.47	0.31
	1.9	13.3	800	1.40	0.26
	1.9	13.3	1000	1.67	0.64
	7.0	8.9	800	1.77	0.57
	7.0	8.9	1000	1.40	0.35
	7.0	13.3	800	1.63	0.42
	7.0	13.3	1000	1.27	0.21
	Type		F	2.63	
			P-Value	0.11	
	Gap		F	0.66	
			P-Value	0.42	
	Feed Rate		F	0.66	
			P-Value	0.42	
	Speed		F	3.68	
			P-Value	0.06	

Based on the univariate analysis of variance of drying time required to achieve a moisture ratio of 0.2, there were no significant differences between the treatments for the fluted conditioner. The same results were found for the drying time to achieve a moisture ratio of 0.1. The average drying time to achieve a moisture ratio of 0.2 was 11.4 hours with a standard deviation of 1.9 hours. The average drying time to achieve a moisture ratio of 0.1 was 16.3 hours with a standard deviation of 2.7 hours. The average drying rate coefficients by treatment for the fluted conditioner were provided in Table 10. Graphical representations of the drying rate models by treatment for the fluted conditioner are shown in Figure 27. Detailed drying rate results for the fluted conditioner tests were provided in Appendix H.

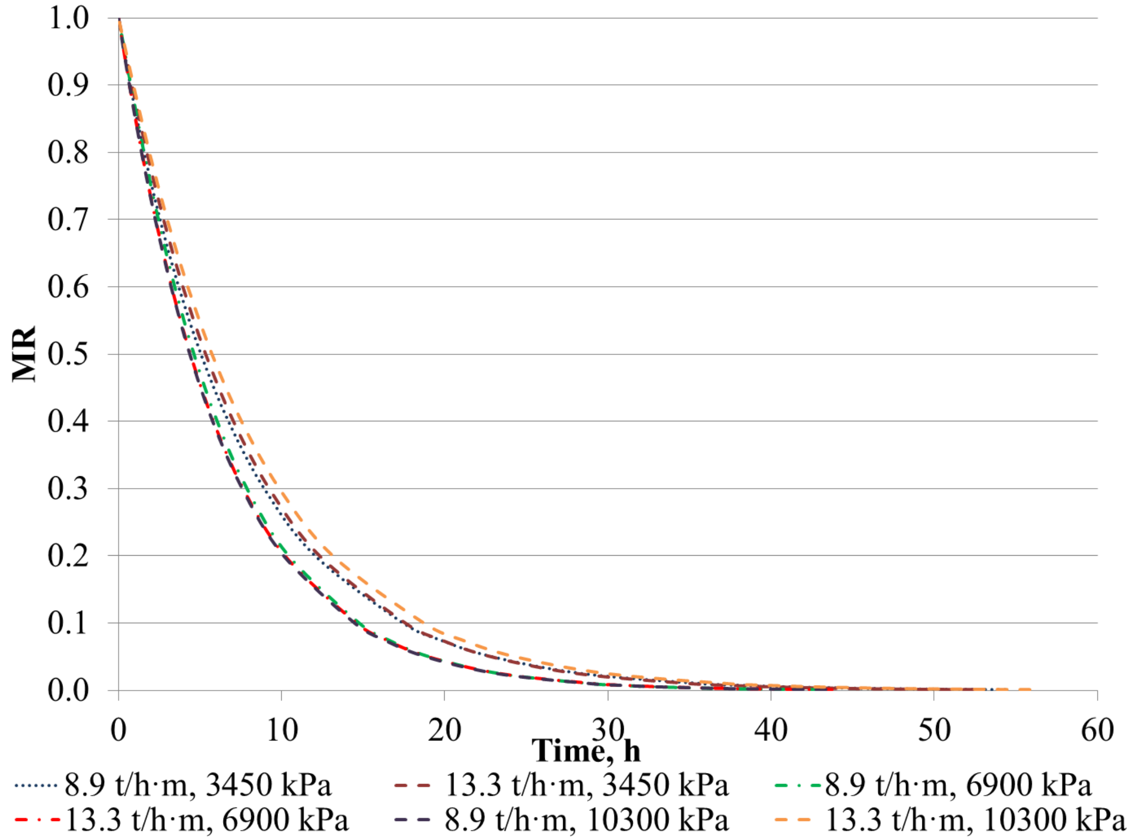


Figure 27. Graphical representation of the fluted conditioning unit thin-layer drying rate models.

Table 10. Average drying rate coefficients for the fluted conditioner treatments.

Feed Rate, t/h·m	Pressure, kPa	K		N		R^2
		Value	Standard Error	Value	Standard Error	
8.9	3450	0.146	0.002	0.965	0.005	0.995
8.9	6900	0.144	0.003	1.028	0.009	0.990
8.9	10300	0.160	0.004	0.998	0.011	0.983
13.3	3450	0.127	0.001	1.013	0.004	0.997
13.3	6900	0.181	0.006	0.929	0.017	0.961
13.3	10300	0.129	0.003	0.993	0.010	0.983

Based on the univariate analysis of variance of drying times required to achieve a moisture ratio of 0.2, there were no significant differences between the treatments for the chisel conditioner. The same results were found for the drying time to achieve a moisture ratio of 0.1. The average drying time to achieve a moisture ratio of 0.2 was 38.4 hours with a standard deviation of 5.4 hours. The average drying time to achieve a moisture ratio of 0.1 was 59.8 hours with a standard deviation of 9.3 hours. The average drying rate coefficients by treatment, determined by nonlinear regression of the data, for the chisel conditioner were provided in Table 11. Graphical representations of the drying rate models by treatment for the chisel conditioner are shown in Figure 28. Detailed drying rate results for the chisel conditioner tests were provided in Appendix H.

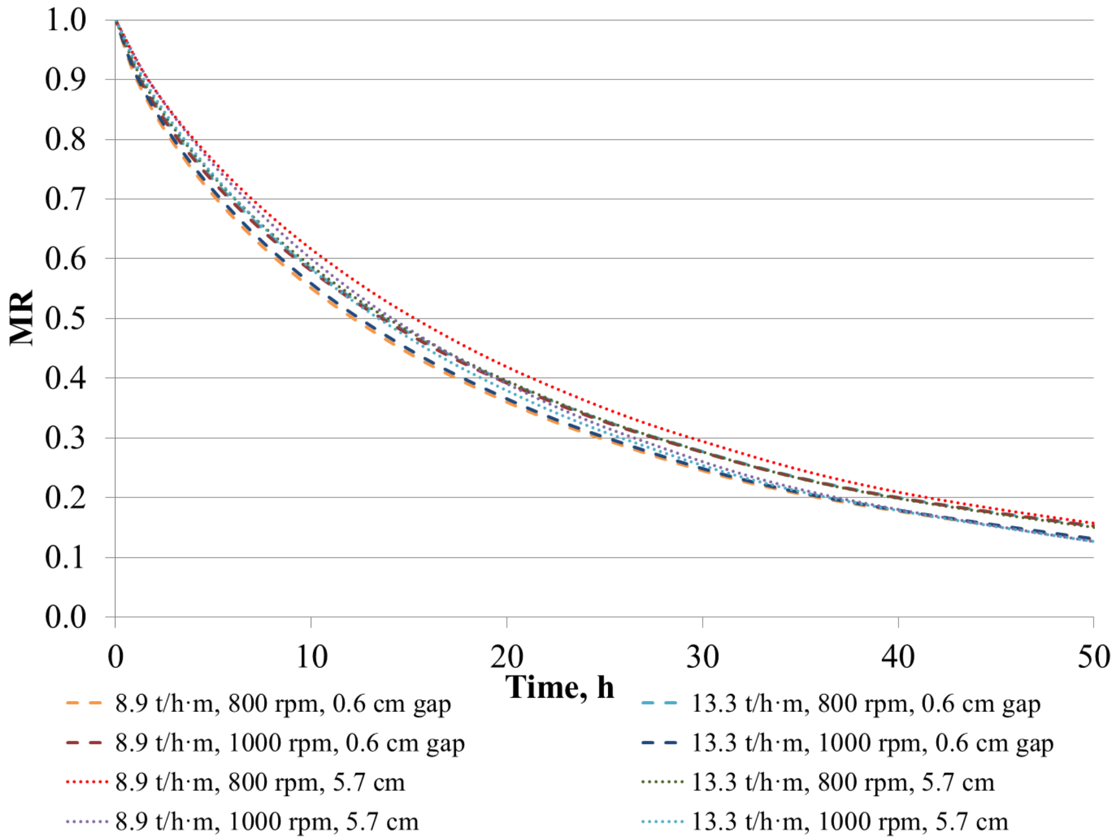


Figure 28. Graphical representation of the chisel conditioning unit thin-layer drying rate models.

Table 11. Average drying rate coefficients for the chisel conditioner treatments.

Shield Gap, cm	Feed Rate, t/h·m	Impeller Speed, rpm	K Value	K Standard Error	N Value	N Standard Error	R^2
0.6	8.9	800	0.101	0.001	0.773	0.003	0.990
0.6	8.9	1000	0.096	0.002	0.776	0.005	0.968
0.6	13.3	800	0.091	0.001	0.778	0.004	0.981
0.6	13.3	1000	0.096	0.001	0.785	0.003	0.991
5.7	8.9	800	0.069	0.001	0.845	0.003	0.991
5.7	8.9	1000	0.068	0.001	0.877	0.004	0.991
5.7	13.3	800	0.091	0.002	0.780	0.007	0.953
5.7	13.3	1000	0.080	0.001	0.837	0.005	0.984

Based on the univariate analysis of variance of drying times required to achieve a moisture ratio of 0.2, there were no significant differences between the treatments for the "V" conditioner. The same results were found for the drying time to achieve a moisture ratio of 0.1. The average drying time to achieve a moisture ratio of 0.2 was 28.8 hours with a standard deviation of 5.3 hours. The average drying time to achieve a moisture ratio of 0.1 was 44.4 hours with a standard deviation of 8.9 hours. The average drying rate coefficients by treatment, determined by nonlinear regression of the data, for the "V" conditioner were provided in Table 12. Graphical representations of the drying rate models by treatment for the "V" conditioner are shown in Figure 29. Detailed drying rate results for the "V" conditioner tests were provided in Appendix H.

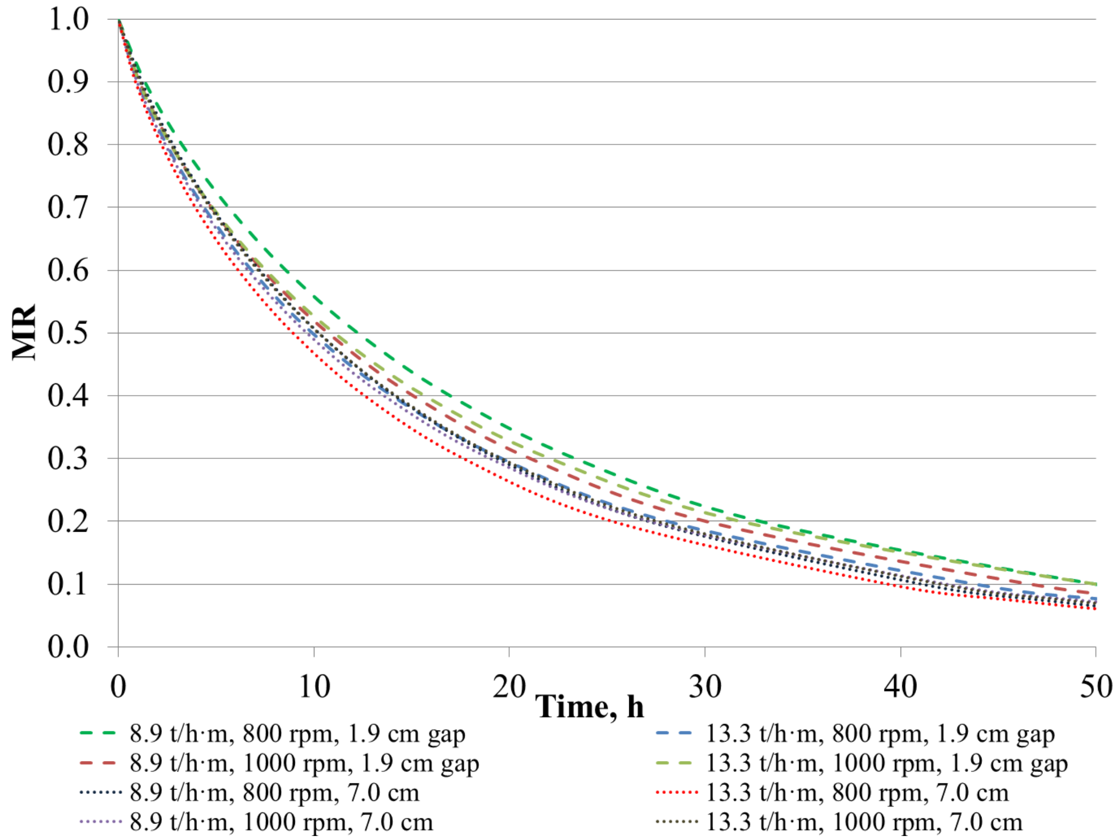


Figure 29. Graphical representation of the “V” conditioning unit thin-layer drying rate models.

Table 12. Average drying rate coefficients for the "V" conditioner treatments.

Shield Gap, cm	Feed rate, t/h·m	Impeller Speed, rpm	K Average	K Standard Error	N Average	N Standard Error	R^2
1.9	8.9	800	0.087	0.002	0.836	0.006	0.975
1.9	8.9	1000	0.104	0.002	0.805	0.006	0.970
1.9	13.3	800	0.112	0.002	0.801	0.005	0.984
1.9	13.3	1000	0.107	0.002	0.786	0.006	0.970
7.0	8.9	800	0.906	0.001	0.853	0.005	0.987
7.0	8.9	1000	0.112	0.002	0.806	0.004	0.986
7.0	13.3	800	0.129	0.003	0.783	0.008	0.959
7.0	13.3	1000	0.101	0.002	0.837	0.006	0.977

Because there were no significant differences in the treatment effects laid out for the three conditioning units, the data for a specific conditioner was combined to develop an overall model for each conditioner unit. The control model had a general model developed from three samples that were collected to represent the unconditioned material. The overall models were shown in Figure 30 and the drying rate coefficients were provided in Table 13.

The fluted conditioner model had the most drastic change in drying times when compared to the control. At a moisture ratio of 0.17, the drying time was reduced by 79.7%. The material processed by the fluted conditioner took about 12.5 hours to dry to a moisture ratio of 0.17, whereas the control took 61.7 hours. The two impeller conditioners were less influential in reducing the drying time to reach 0.17 moisture ratios. The “V” and chisel impellers had a drying time of 32.2 hours and 43.1 hours, respectively. The “V” had a drying time reduction of 47.8% over the control. The chisel had a drying time reduction of 30.2% over the control.

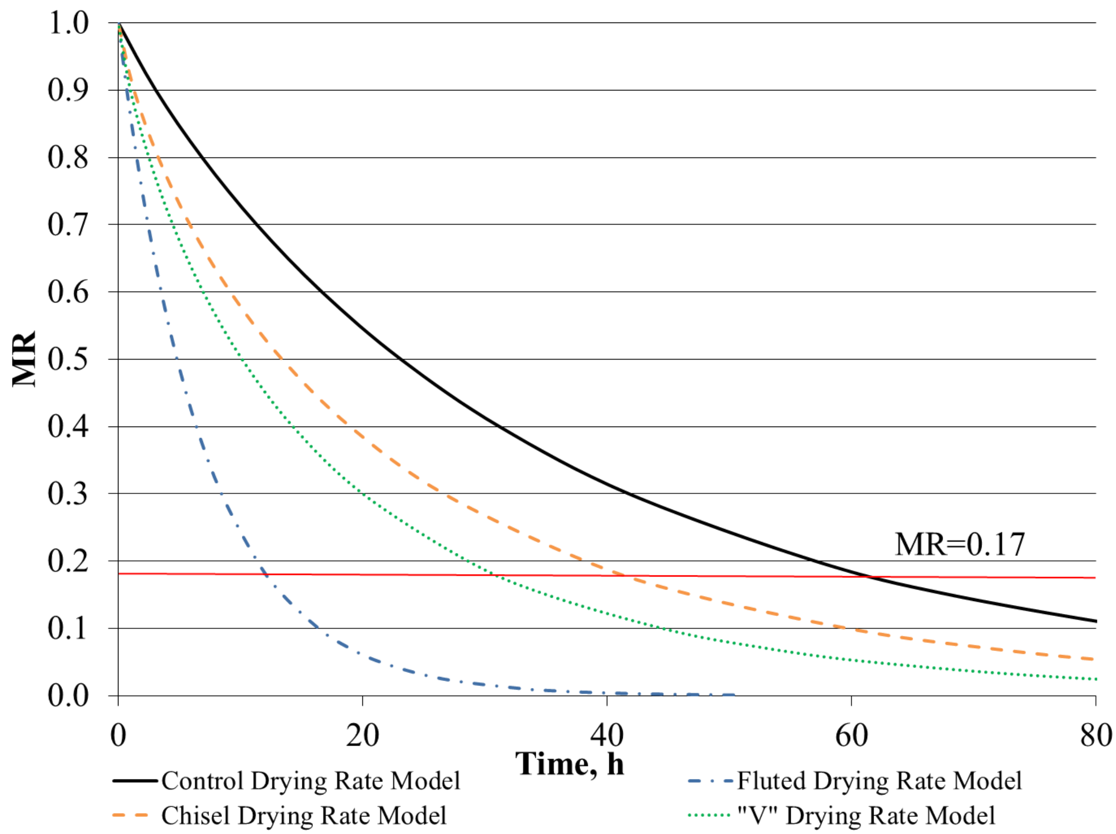


Figure 30. Average thin-layer drying rate models for the evaluated conditioners and non-conditioned material.

Table 13. Drying rate coefficients for the evaluated conditioners and non-conditioned material.

Model	K	Standard Error	N	Standard Error	R^2
Control	0.037	0.001	0.933	0.008	0.959
Fluted	0.149	0.002	0.979	0.004	0.980
Chisel	0.086	0.001	0.804	0.002	0.978
“V”	0.106	0.001	0.811	0.002	0.971

With consideration of all of the components tested on the conditioning units, the fluted conditioner was the most effective at reducing drying rate and consumed the least power. The impeller conditioning test units may perform better at test conditions beyond those that were achieved with the current testing setup. The impeller conditioning units were better than the non-conditioned control material in drying rate performance. The visual grading results were in agreement with drying rate results. However, all conditioner test units need to be tested at higher loading conditions to anticipate future field yields. The primary limitation of these tests was the inability to achieve higher feed rates due to the limitations of the in-feed and out-feed conveyors the largest feed rate evaluation in this study was 84% of current commercial equipment.

CHAPTER V

CONCLUSIONS

The power required to condition forage sorghum using a fluted roll conditioner unit was 1.5-3.1 kW/h·m above the baseline power. The power for the chisel unit was 3.8-6.1 kW/h·m above the baseline power. The power for the “V” conditioner unit was 5.0-6.6 kW/h·m above the baseline power. The differences in the power requirements indicate that the fluted roll conditioner unit would be the most economical to operate.

The thin-layer drying studies indicated that the fluted roller conditioner would provide an opportunity for faster drying by opening and crimping the stalk material. The degree of conditioning differed among units. The impeller units produced more bruising-type effects and the fluted produced crushing-type effects.

The unconditioned material had a drying time of >60 hours to reach a moisture content of 17% d.b. The “V” impeller conditioner unit was able to reduce the drying time by 47.8% when compared to the unconditioned material. The chisel conditioner unit was able to reduce drying time by 30.2% when compared to the unconditioned material. The fluted conditioner was able to produce material that had 17% d.b. moisture content in 12.5 hours and reduced the drying time 79.7% reduction over the unconditioned material. In consideration of all the results, the fluted roll conditioner unit increased the drying rate to the greatest degree at the lowest power requirements.

CHAPTER VI

FUTURE WORK

The conclusions from this research provided insight into the direction of the future work. These insights fall into four areas: power source, conveyor system, drying system, and timeframe.

In the current study, the hydraulic power supply from the John Deere 7320 R limited the actual operating range of some of the mechanical conditioner operating parameters. The impeller conditioners would slow when the conveyor system was engaged. The fluted rollers were also limited; but since only one speed was tested the extent was not as apparent. It is recommended that future research consider the use of a hydraulic power pack. The power pack should supply at least 40 gallons per minute at 3000 psi. The flow meter may need to change if the power pack is much larger.

During the power testing, observations were made that the conveyor system was inadequate for the feed rates that would match conditions found in Central Oklahoma given average growing conditions. The conveyor system lacked the ability to move field-type yields into any unit. The belt was relying on the friction of the drive roller to advance the belt. Overload on the belt system proved to be at approximately 45 kg of material over the top surface. Originally, the load on the system was going to be closer to 100 kg, but the feed rate was adjusted to a much lower number to accommodate the conveyor limitations. With such a light load of material, this could contribute to the findings of insignificant differences over the range of parameters tested.

The drying system works well in some points for determining the drying rate; however, there are some areas that could benefit from adjustment. The program controlling the fan on the dryers could be changed to a programmable type-controller to allow for adherence to the thin-layer protocol specified in S448 (ASABE, 1998b). Also, to meet the standard more precisely, the ability to have the dryer at temperature before the test begins would be necessary. The drying shroud could have some adjustments to allow for easier access to the trays, perhaps windows, allowing researchers to check during the study to see if the tray is touching the deck. The drying tray suspension should be improved to aid in easier leveling of the tray when loading.

Testing needs to be repeated in the same time frame to be able to compare yearly crop effects as well as an earlier crop maturity when the plant is in an active growth stage (with even higher plant moistures and different plant structures to determine power requirements and how drying rate is affected).

REFERENCES

ASABE Standards. 1998a. D497.4: Agricultural machinery management data. St. Joseph, Mich.: ASABE.

ASABE Standards. 1998b. S448: Thin-layer drying of grains and crops. St. Joseph, Mich: ASABE.

ASABE Standards. 2012. S358.3: Moisture measurement — forages. St. Joseph, Mich: ASABE.

Barrington, G. P., and H. D. Bruhn. 1970. Effect of mechanical forage-harvesting devices on field-curing rates and relative harvesting losses. *Trans. ASAE* 13(6):874-0878.

Bartzanas, T., A. A. Sapounas, O. Green, D. D. Bochtis, and C. G. Sorensen. 2010. A numerical modelling approach for biomass field drying [electronic resource]. *Biosystems Eng.* 106(4):458-469.

Bonner, I. J., and K. L. Kenney. 2013. Moisture sorption characteristics and modeling of energy sorghum (*sorghm bicolor* (l.) moench). *J. of Stored Products Res.* 52(2013):128-136.

Bruhn, H. D. 1955. Status of hay crusher development. *Agri. Eng.* 36(3):165-170.

Chung, M. T. M., and L. R. Verma. 1982. Mechanical conditioning of ryegrass forage. *Trans. ASAE* 25(4):893-0896.

Chung, M. T. M., and L. R. Verma. 1986. Mechanical and chemical conditioning in the laboratory to accelerate drying of ryegrass forage. *Trans. ASAE* 29(2):361-365.

Deere & Company. 2013. Changing impeller rotor speed (impeller conditioner). Moline, IL: Deere & Company. Available at: http://manuals.deere.com/omview/OMFH310745_19/OUO6085,00008A0_19_20080929.html. Accessed 9 April 2013.

Descôteaux, S., and P. Savoie. 2002. Intensive forage conditioning applied after mowing: Prototype development and drying experiments. *Canadian Biosystems Eng.* 44(2):15-21.

Fairbanks, G. E., and G. E. Thierstein. 1966. Performance of hay-conditioning machines. *Trans. ASAE* 9(2):182-0184.

Goering, C. E., M. L. Stone, D. W. Smith, and T. P.K. 2003. Hydraulic systems. In *Off-road vehicle engineering principles*, 255-302. St. Joseph, Mich.: ASAE.

Greenlees, W. J., H. M. Hanna, K. J. Shinners, S. J. Marley, and T. B. Bailey. 2000. A comparison of four mower conditioners on drying rate and leaf loss in alfalfa and grass. *Applied Eng. in Agric.* 16(1):1-6.

Hellwig, R. E., T. J. Scarnato, and W. G. Monson. 1983. Roll design for a tandem roll mower-conditioner. *Trans. ASAE* 26:713-715.

Henderson, S. M., R. L. Perry, and J. H. Young. 1997. *Principles of process engineering*. 4th ed. American Society of Agricultural Engineers, St. Joseph, Mich.

Khalilian, A., D. Batchelder, and G. McLaughlin. 1982. Forage drying using hard crushing and binders. *Trans. ASAE* 25(5):1225-1228.

Klinner, W. E. 1976. A mowing and crop conditioning system for temperate climates. *Trans. ASAE* 19(2):237-241.

Klinner, W. E., and O. D. Hale. 1984. Design evaluation of crop conditioners with plastic elements. *J. Agri. Eng. Res.* 30(0):255-263.

Kraus, T. J., K. J. Shinners, and R. G. Koegel. 1993. Evaluation of a crushing-impact forage macerator. *Trans. ASAE* 36:1541-1545.

Krutz, G. W., D. A. Holt, and D. Miller. 1979. For fast field drying of forage crops. *Agri. Eng.* 60(8):16-17.

Mears, D. R., and W. J. Roberts. 1970. Methods of accelerating forage drying. *Trans. ASAE* 13(4):531-533.

Öztekin, S., and M. T. Özcan. 1997. Application of the maceration technique for drying forage in turkey. *J. Agri. Eng. Res.* 66(1):79-84.

Pederson, J. F., and W. L. Rooney. 2004. Sorghums. In *Agronomy*. L. E. Moser, B. L. Burson, and L. E. Sollenberger, eds. Madison, Wisc.: American Society of Agronomy, Inc.

Priepke, E. H., and H. D. Bruhn. 1970. Altering physical characteristics of alfalfa to increase the drying rate. *Trans. ASAE* 13(6):827-0831.

Rotz, C. A., and Y. Chen. 1985. Alfalfa drying model for the field environment. *Trans. ASAE* 28(5):1686-1691.

Rotz, C. A., S. M. Abrams, and R. J. Davis. 1987. Alfalfa drying, loss and quality as influenced by mechanical and chemical conditioning. *Trans. ASAE* 30(3):630-0635.

Savoie, P., M. Binet, G. Choiniere, D. Tremblay, A. Amyot, and R. Theriault. 1993. Development and evaluation of a large-scale forage mat maker. *Trans. ASAE* 36(2):285-291.

Savoie, P., N. Asselin, J. Lajoie, and D. Tremblay. 1997. Evaluation of intensive forage conditioning with a modified disk mower. *Applied Eng. in Agric.* 13(6):709-714.

Savoie, P., D. Tremblay, S. P. Lemay, M. Roberge, and J. Lajoie. 1999. Intensive forage conditioning applied to a self-propelled mower. *Applied Eng. in Agric.* 15(2):107-115.

Savoie, P. 2001. Intensive mechanical conditioning of forages: A reveiw. *Canadian Biosystems Eng.* 43:2.1-2.12.

Shinners, K. J., G. P. Barrington, R. J. Straub, and R. G. Koegel. 1985. Forming mats from macerated alfalfa to increase drying rates. *Trans. ASAE* 28(2):374-377.

Shinners, K. J., R. G. Koegel, and R. J. Straub. 1987. Drying rates of macerated alfalfa mats. *Trans. ASAE* 30(4):909-912.

Shinners, K. J., R. G. Koegel, and R. J. Straub. 1988. Design considerations and performance on a forage maceration device. *Applied Eng. in Agric.* 4(1):13-18.

Shinners, K. J., J. M. Wuest, J. E. Cudoc, and M. E. Herzmann. 2006. Intensive conditioning of alfalfa: Drying rate and leaf loss. ASABE Paper No. 061051. St. Joseph, Mich. : ASABE.

Straub, R. J., and H. D. Bruhn. 1975. Evaluation of roll design in hay conditioning. *Trans. ASAE* 18(2):217-0220.

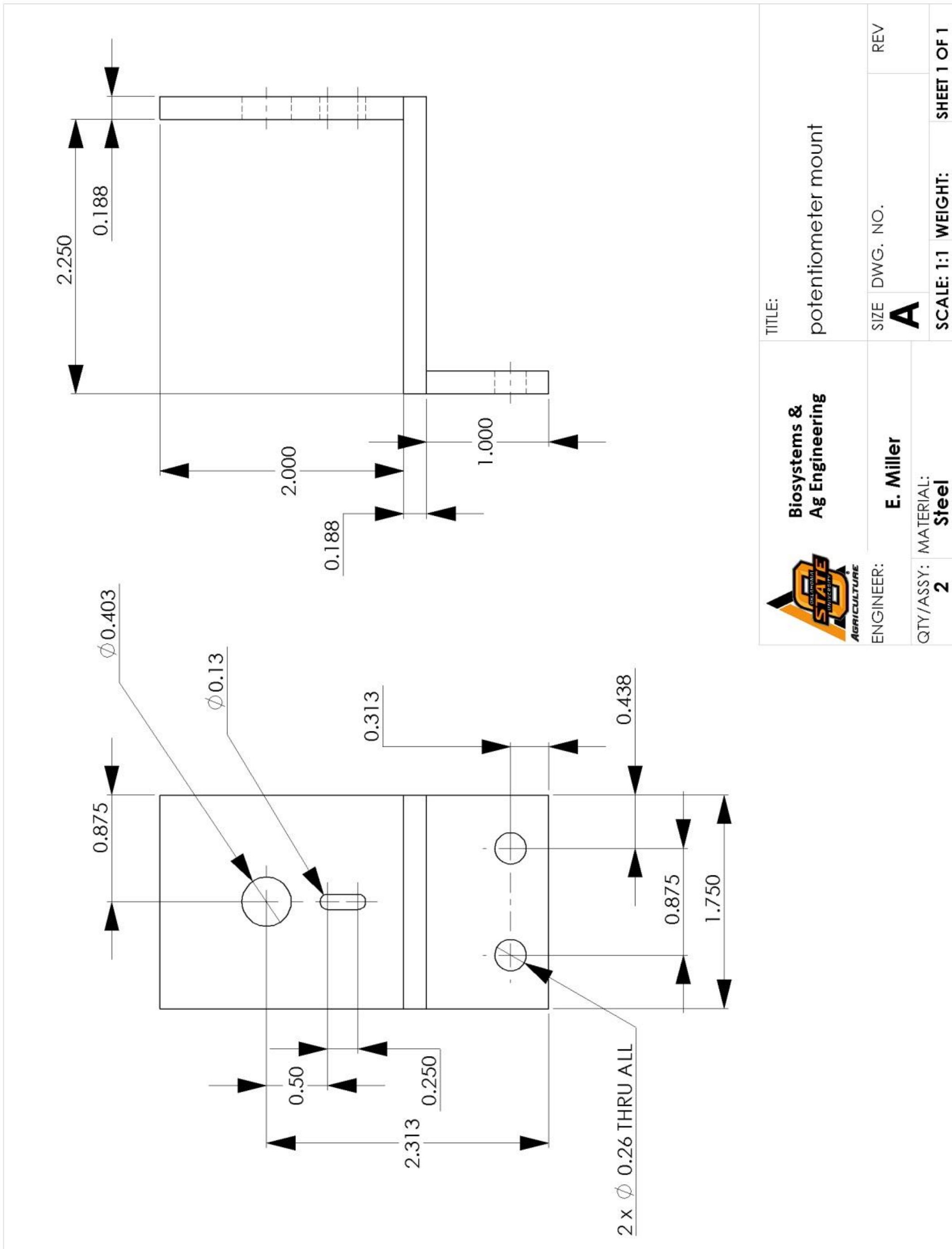
Tremblay, D., P. Savoie, and M. Drouin. 1994. Power requirements to macerate fresh forage and chop wilted mats. *Trans. ASAE* 37:1037-1042.

Venuto, B., and B. Kindiger. 2008. Forage and biomass feedstock production from hybrid forage sorghum and sorghum-sudangrass hybrids [electronic resource]. *Grassland science* 54(4):189-196.

APPENDICES

APPENDIX A: Mechanical Drawings

Mechanical drawings for the test conditioner sensor mounts, drying chambers, and drying trays were provided in Appendix A. The drying chambers were designed to be used in the drying ovens at the South Central Research Station in Chickasha, Oklahoma. The drying chambers were designed to regulate the airflow across the drying trays. The drying trays were suspended from eyebolts by chains over the openings in the bottom panel of the drying chamber.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potentiometer mount
Biosystems & Ag Engineering
ENGINEER: E. Miller
QTY/ASSY: 2
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DWG. NO.
REV
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WEIGHT:
SHEET 1 OF 1
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∅0.13
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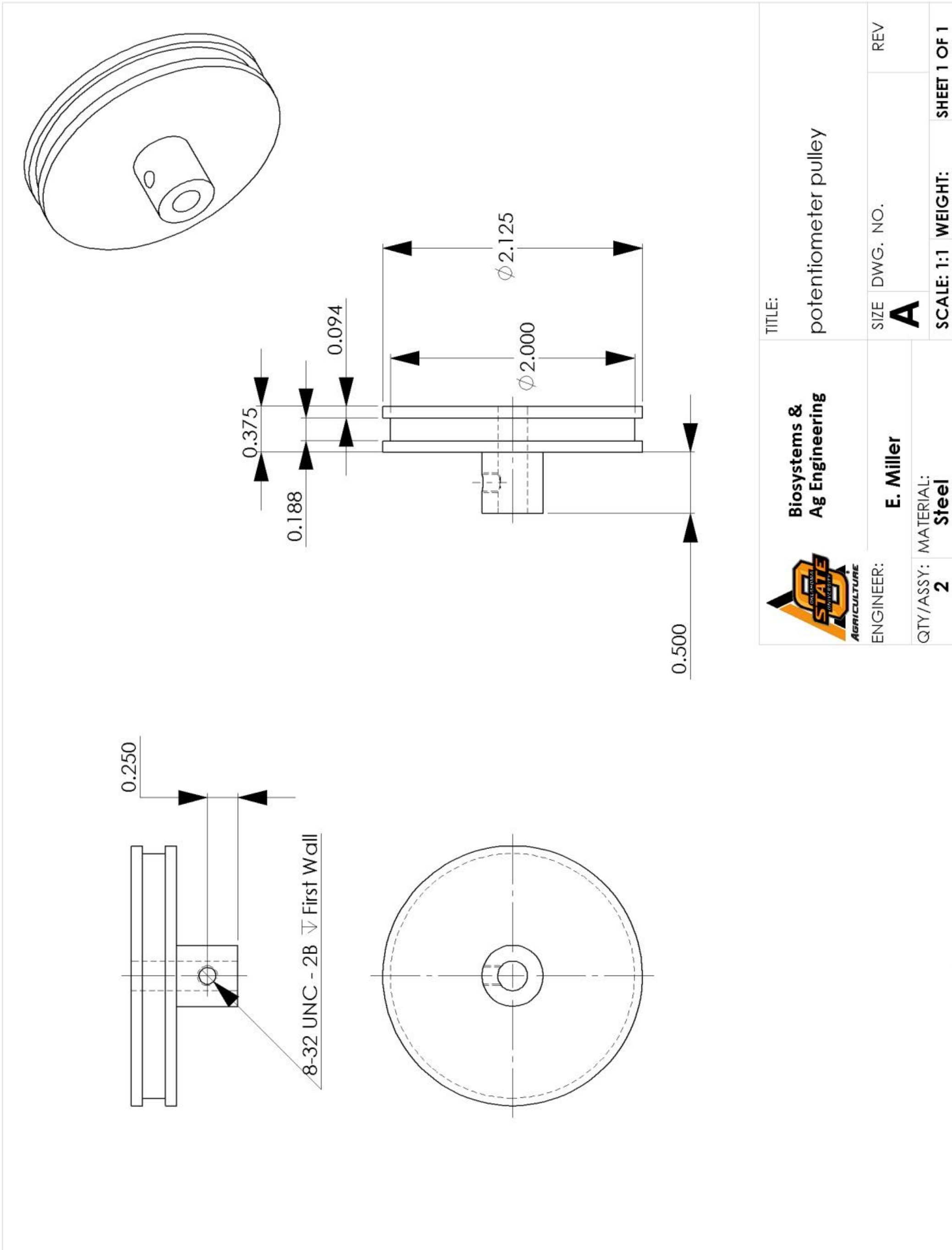

0.375
0.094
0.188
Ø2.125
Ø2.000
0.500
0.250
8-32 UNC - 2B ⊽ First Wall
Biosystems &
Ag Engineering
AGRICULTURE
ENGINEER:
E. Miller
QTY/ASSY:
2
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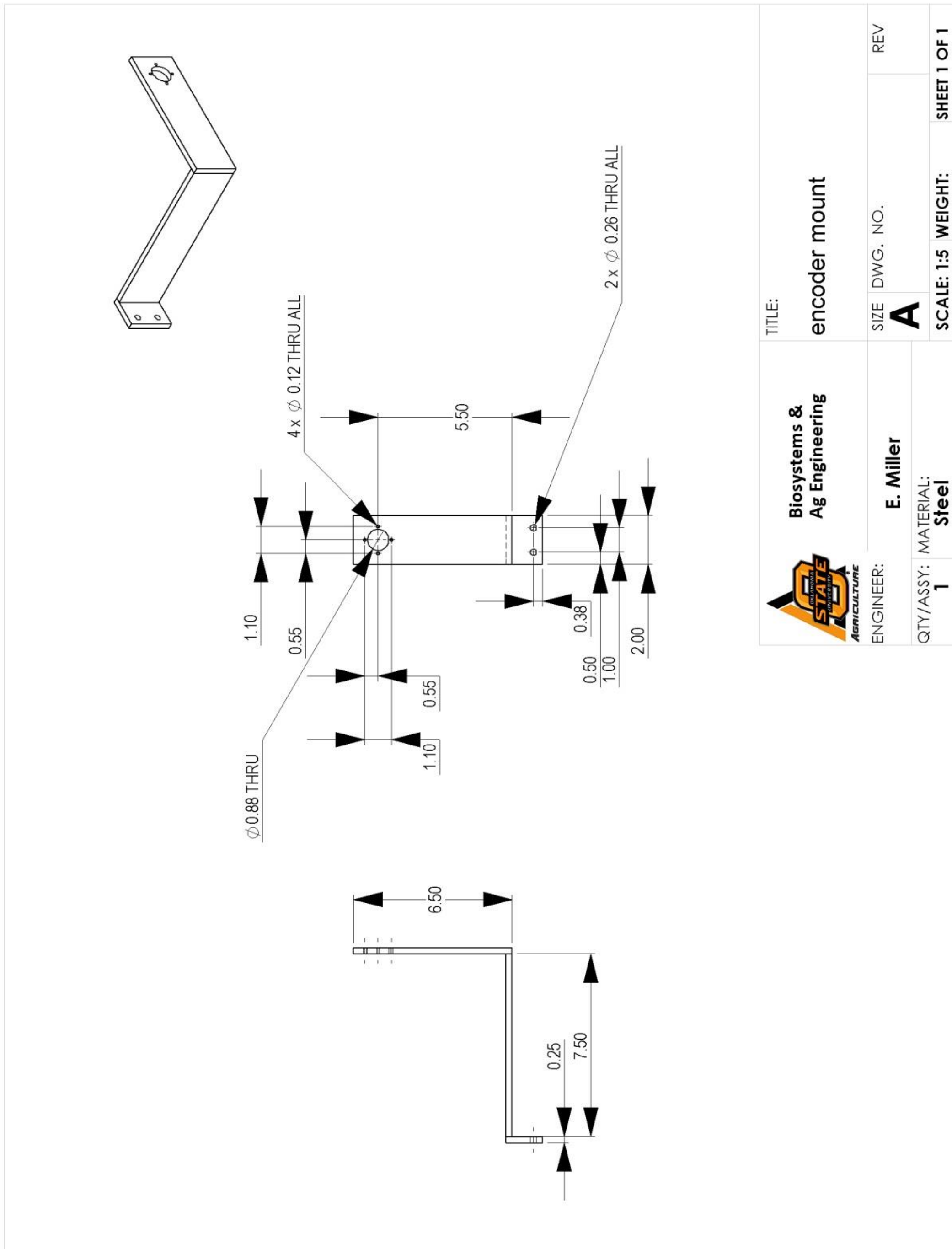
TITLE:
potentiometer pulley
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



4 x ∅ 0.12 THRU ALL
2 x ∅ 0.26 THRU ALL
5.50
1.10
0.55
0.55
1.10
∅0.88 THRU
0.38
0.50
1.00
2.00
6.50
0.25
7.50
TITLE:
encoder mount
Biosystems &
Ag Engineering
AGRICULTURE
ENGINEER:
E. Miller
SIZE
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DWG. NO.
REV
QTY/ASSY:
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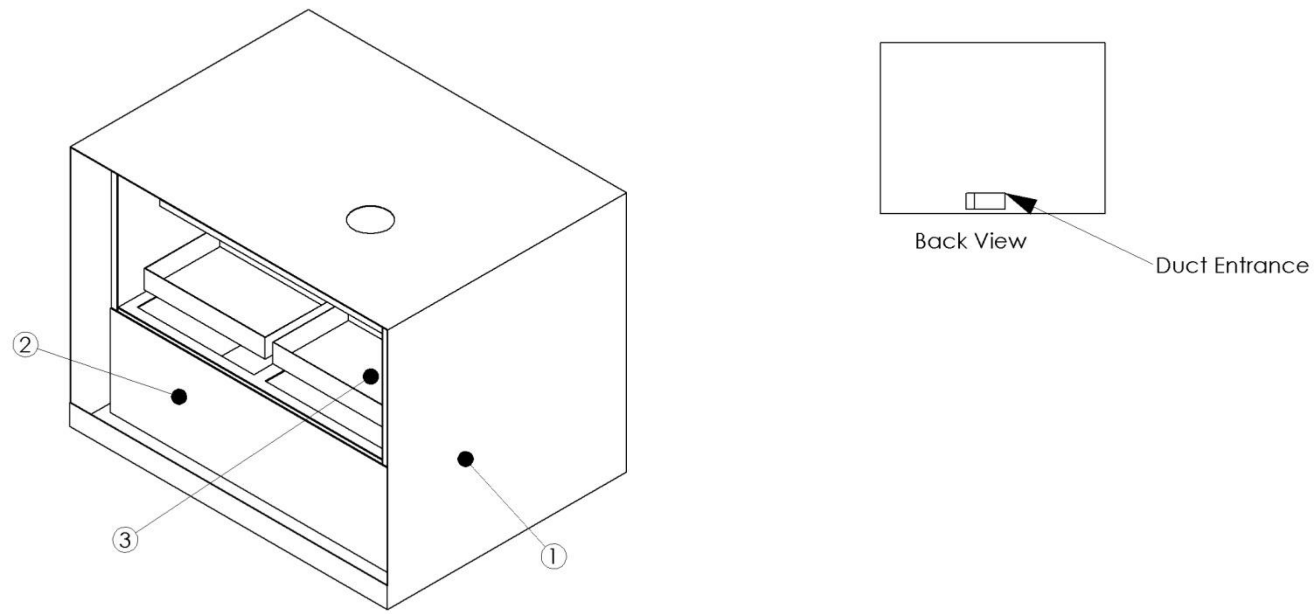
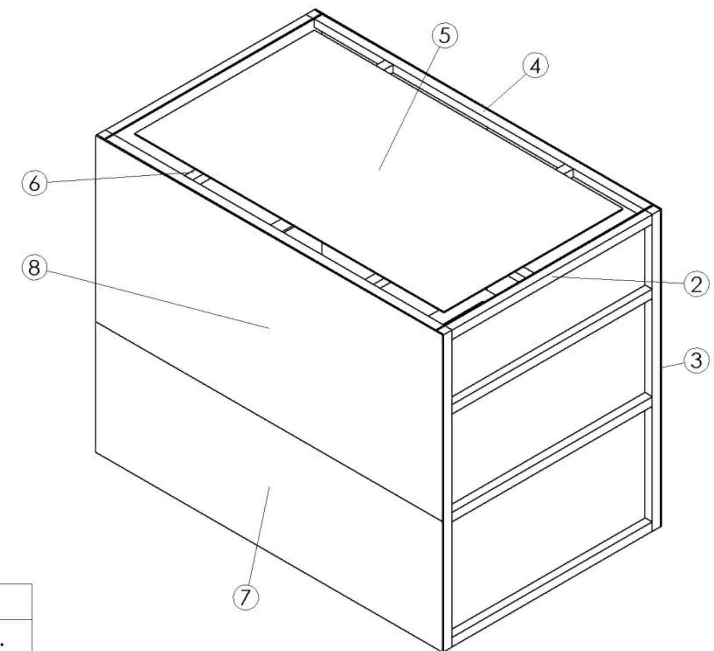
MATERIAL:
Steel
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1



ITEM NO.	Description	QTY.
1	chick dryers	1
2	Cabinet	1
3	tray	4
4	Duct	1

Biosystems & Ag Engineering		TITLE: Chickasha Dryer Layout	
ENGINEER: E. Miller		SIZE A	DWG. NO. / REV
QTY/ASSY: 2	MATERIAL:	SCALE: 1:25 WEIGHT:	SHEET 1 OF 7



BOM Table			
ITEM NO.	PART NUMBER	Material	QTY.
1	Bottom Panel	See Sheet 5	1
2	Side Panel	See Sheet 6	2
3	plywood back	1/4" plywood 36-3/4" X 58-1/4"	2
4	spanner	1-1/2"X1-3/4" X70"	6
5	top	1/4" 65-1/2" plywood, 38" x	1
6	side support	1-1/2" x 1-3/4" x 42-1/2"	2
7	bottom front	1/4" plywood, 24" x 73-1/2"	1
8	top front	1/4" plywood, 34-1/4' x 73-1/2"	1

Biosystems & Ag Engineering

TITLE: Cabinet

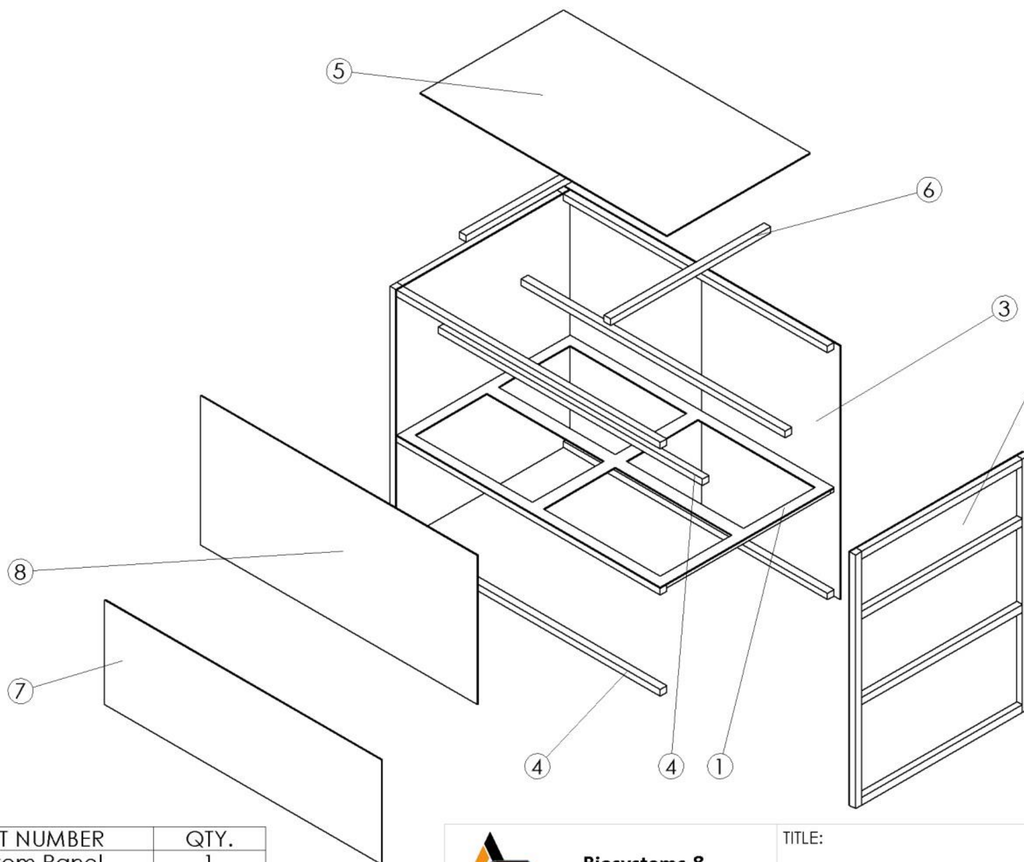
ENGINEER: E. Miller

QTY/ASSY: 2 | MATERIAL: Listed

SIZE A | DWG. NO. | REV

SCALE: 1:20 | WEIGHT: | SHEET 2 OF 7

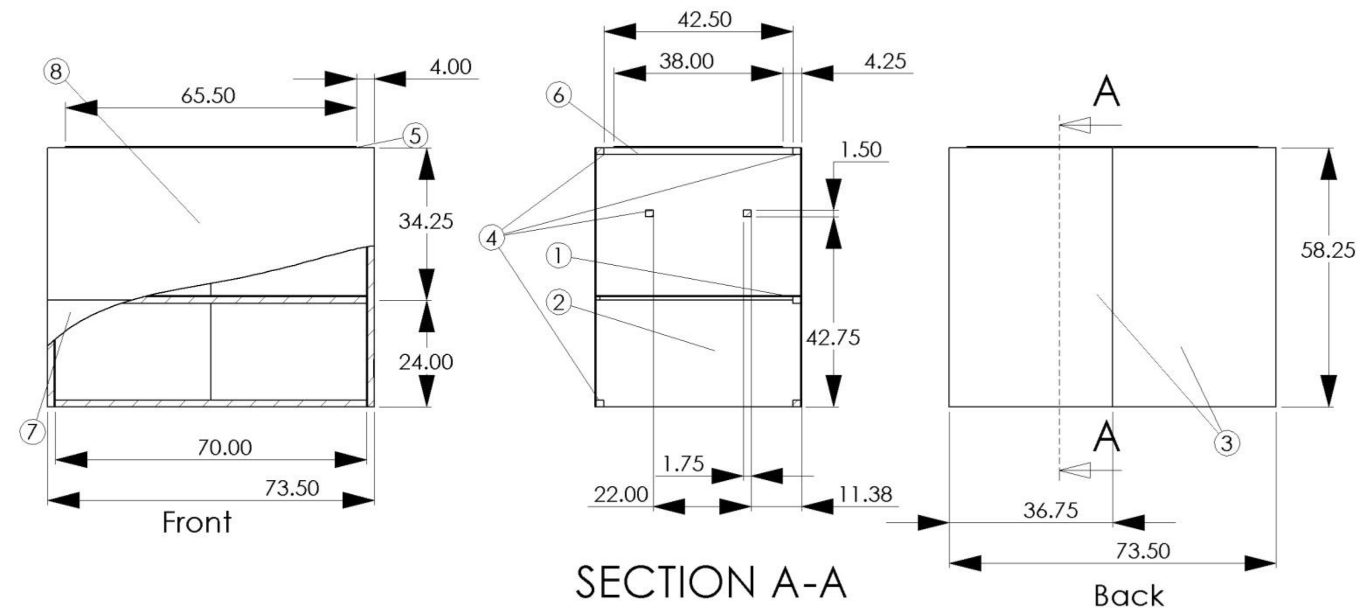
5 4 3 2 1



ITEM NO.	PART NUMBER	QTY.
1	Bottom Panel	1
2	Side Panel	2
3	plywood back	2
4	spanner	6
5	top	1
6	side support	2
7	bottom front	1
8	top front	1

Biosystems & Ag Engineering		TITLE: Cabinet		
ENGINEER: E. Miller		SIZE A	DWG. NO.	REV
QTY/ASSY: X	MATERIAL:	SCALE: 1:50	WEIGHT:	SHEET 3 OF 7

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Bottom Panel	SeeSheet 5	1
2	Side Panel	See Sheet 6	2
3	plywood back	1/4" plywood, 36-3/4" x 58-1/4"	2
4	spanner	1-1/2" x 1-3/4" x 70"	6
5	top	1/4" plywood, 38" x 65-1/2"	1
6	side support	1-1/2" x 1-3/4" x 42-1/2"	2
7	bottom front	1/4" plywood, 24" x 73-1/2"	1
8	top front	1/4" plywood, 34-1/4" x 73-1/2"	1

Biosystems & Ag Engineering

TITLE: Cabinet

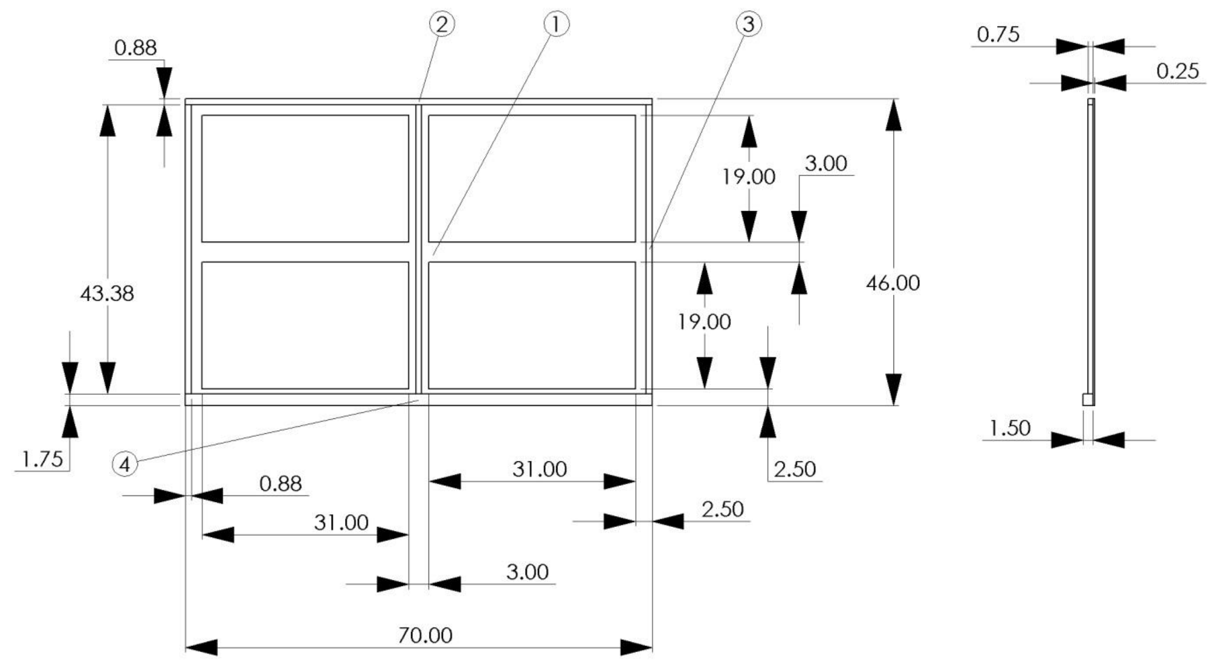
ENGINEER: **E. Miller**

QTY/ASSY: **X** MATERIAL:

SIZE **A** DWG. NO. REV

SCALE: 1:30 WEIGHT: **SHEET 4 OF 7**

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Bottom	1/4" Plywood	1
2	long tack strip	3/4" x 7/8" X 70"	1
3	short tack strip	3/4" x 7/8" x 43-3/8"	3
4	spanner	1-1/2" x 1-3/4" x 70"	1

Biosystems & Ag Engineering

ENGINEER: E. Miller

QTY/ASSY: 2

MATERIAL: Listed

TITLE: Bottom Panel

SIZE A

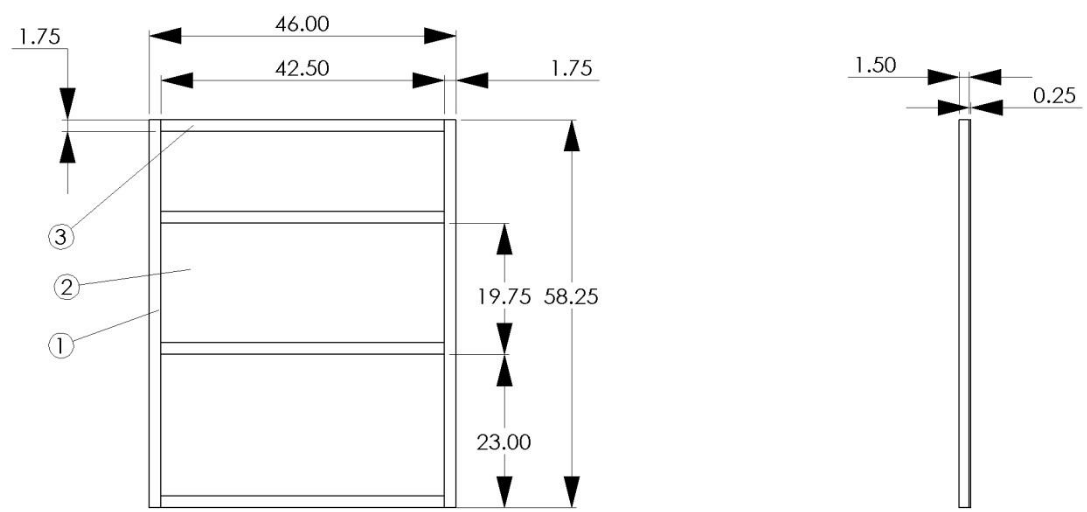
DWG. NO.

REV

SCALE: 1:20 WEIGHT:

SHEET 5 OF 7

5 4 3 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	front beam	1-1/2" x 1-3/4" x 58-1/4"	2
2	tray area side	1/4 plywood, 46" x 58-1/4"	1
3	side support	1-1/2"X 1-3/4" X 42-1/2"	4

Biosystems & Ag Engineering

TITLE: Side Panel

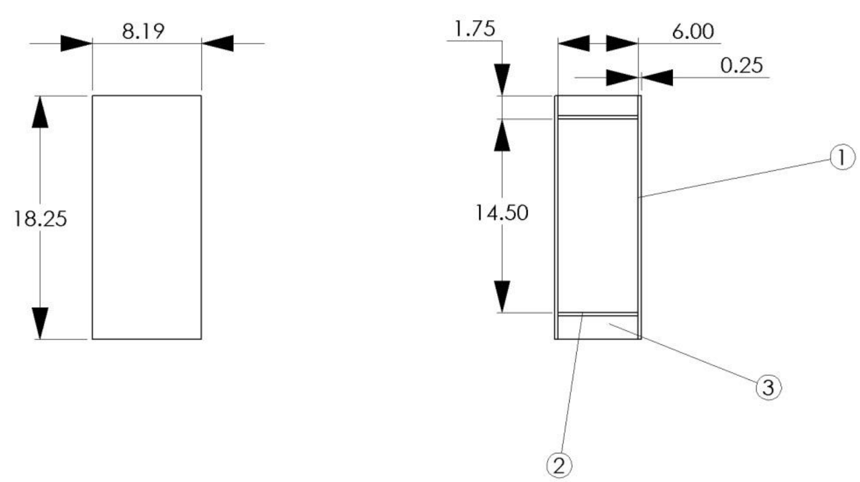
ENGINEER: **E. Miller**

QTY/ASSY: **4** MATERIAL: **Listed**

SIZE **A** DWG. NO. REV

SCALE: 1:20 WEIGHT: SHEET 6 OF 7

5 4 3 2 1



ITEM NO.	PART NUMBER	Material	QTY.
1	Duct Top	1/4 plywood, 8-3/16 x 18-1/4	2
2	Duct side	1/4 plywood, 6 x 8-3/16	2
3	duct trim 1	1-1/2 x 1-3/4 x6	4

Biosystems & Ag Engineering

TITLE: Duct

ENGINEER: E. Miller

QTY/ASSY: 2

MATERIAL: Listed

SIZE A

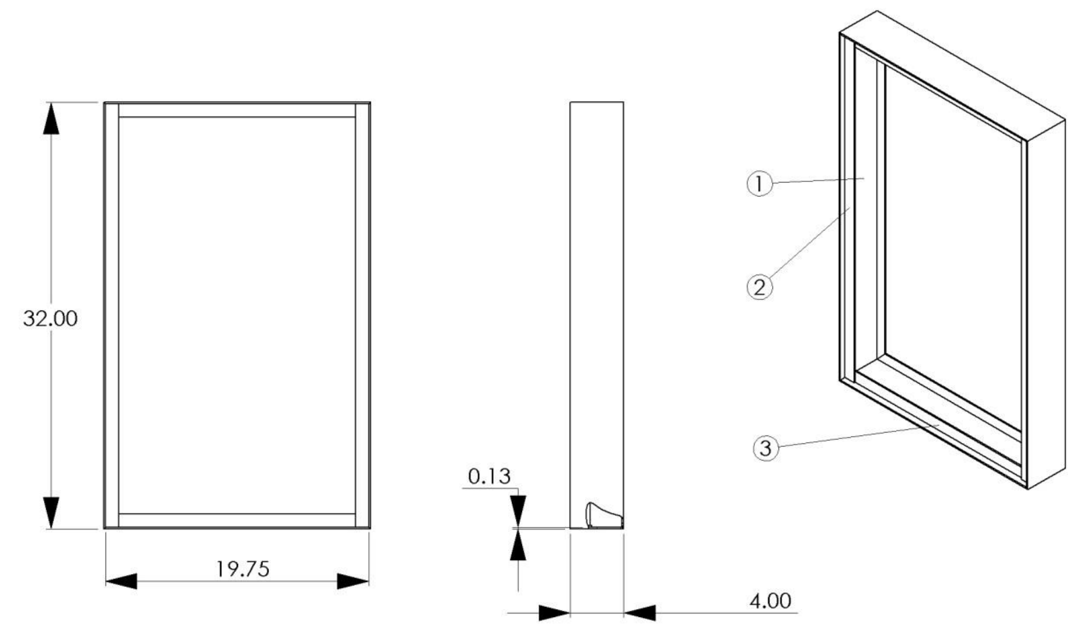
DWG. NO.

REV

SCALE: 1:10 WEIGHT:

SHEET 7 OF 7

5 4 3 2 1



ITEM	PART NAME	DESCRIPTION	QTY.
1	tray edge	al flashing	4
2	support long side	al, 1/8 x 1 x 1 x 31-3/4	2
3	support short side	al, 1/8 x 1 x 1x 19-1/2	2
4	Mesh (not shown)	metal, 16 x18 openings/inch	

Biosystems & Ag Engineering

TITLE: tray

ENGINEER: **E. Miller**

QTY/ASSY: **8** MATERIAL: **Listed**

SIZE **A** DWG. NO. REV

SCALE: 1:10 **WEIGHT:** **SHEET 1 OF 1**

5 4 3 2 1

APPENDIX B: Electronic Measurement and Data Logging Systems

Electronic measurement and data collection systems for the conditioner evaluation and thin-layer drying systems were provided in Appendix B. The wiring diagrams were provided to illustrate how sensors were connected to the National Instruments data acquisition (DAQ) hardware. National Instruments Signal Express 2012 software was used to monitor and record the data collected from the DAQ system. Screen shots from Signal Express were provided to illustrate the software settings selected for the conditioner unit evaluation and thin-layer drying studies.

APPENDIX B.1. Sensor Information

- Pressure Transducer, Ashcroft (Stratford, CT), T27M0242EW5000#GXCY
    - Accuracy 0.25% of Span
    - Thermal Effects 1% of Total Error Band
- Potentiometer, Honeywell (Morristown, NJ), RV4NAYSD503A
    - Linearity ± 5%
- Encoder, Dynapar (Gurnee, IL), E10020000302
    - Accuracy ± 5.4°
- Flowmeter, Blanchett (Racine, WI), B111-110
    - Accuracy ± 1% of reading
    - Repeatability ± 0.1%
- Load Cell, 25 lb, Omega (Sunbury, OH), LC101
    - Accuracy ± 0.03% FSO
    - Linearity ± 0.03% FSO
    - Hysteresis ± 0.02% FSO
    - Repeatability ± 0.01% FSO
- Differential pressure transmitter, 0.25"w. c., Dwyer (Michigan City, IN), DM-2002
    - Accuracy ± 1% FS at 70°F
    - Stability ± 1% FS/yr
    - Thermal Effect ± 0.055% FS/°F
- Temperature, Measurement Specialties (Hampton, VA), HTM 2500
    - Accuracy ± 3%
- Relative Humidity, Measurement Specialties (Hampton, VA), HTM 2500
    - Accuracy ±3%
    - Hysteresis ± 1.5

Load Cell Calibration

Table 14. Load cell equation coefficient values based on calibration tests performed at Oklahoma State University.

Date	Load Cell	Slope	Y-intercept	R^2
February 1, 2013	1	3.7729	0.0449	1.0000
February 1, 2013	2	3.8065	0.0846	0.9998
February 1, 2013	3	3.8095	0.1541	0.9995
February 1, 2013	5	3.7669	0.0629	1.0000
February 1, 2013	6	3.7847	0.0831	0.9999
February 1, 2013	7	3.7577	0.0779	0.9999
February 1, 2013	8	3.7803	0.1262	0.9876
April 20, 2013	9	3.7530	0.0465	0.9999

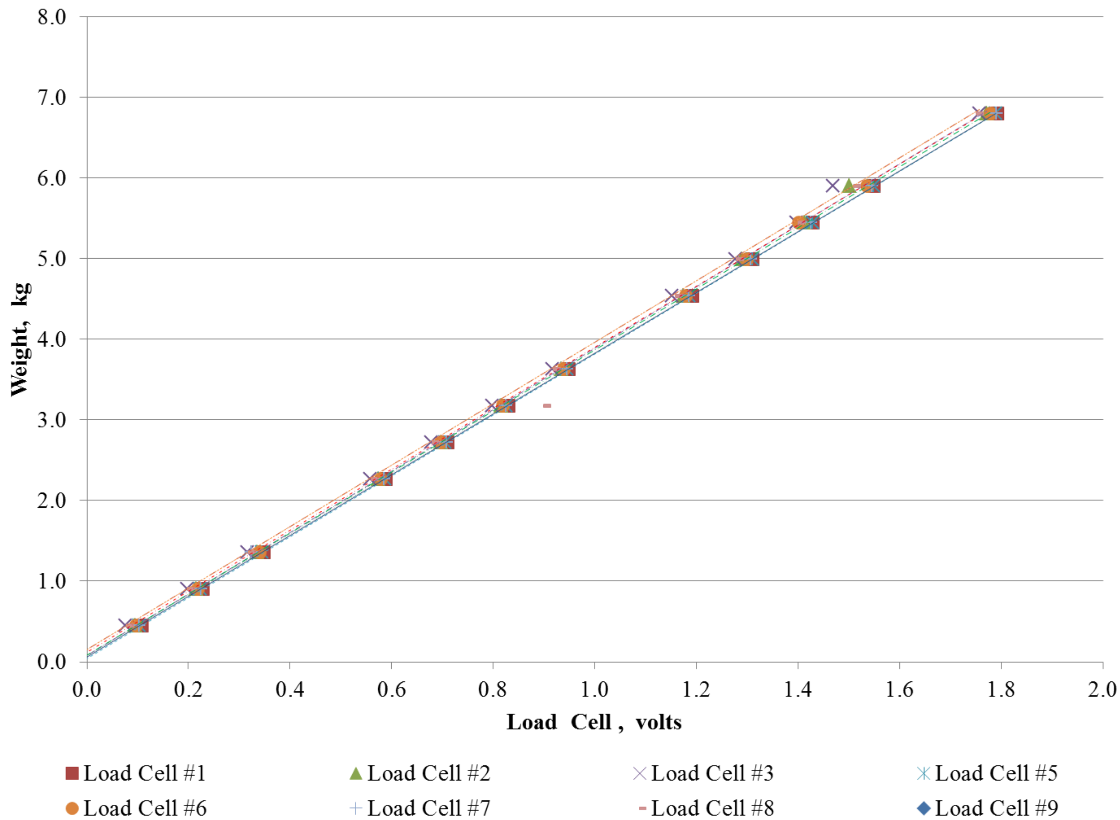


Figure 31. Calibration relationships for the load cells used in the thin-layer drying studies.

APPENDIX B.2. Field Conditioner Power Test Data Acquisition Schematic and Software Settings

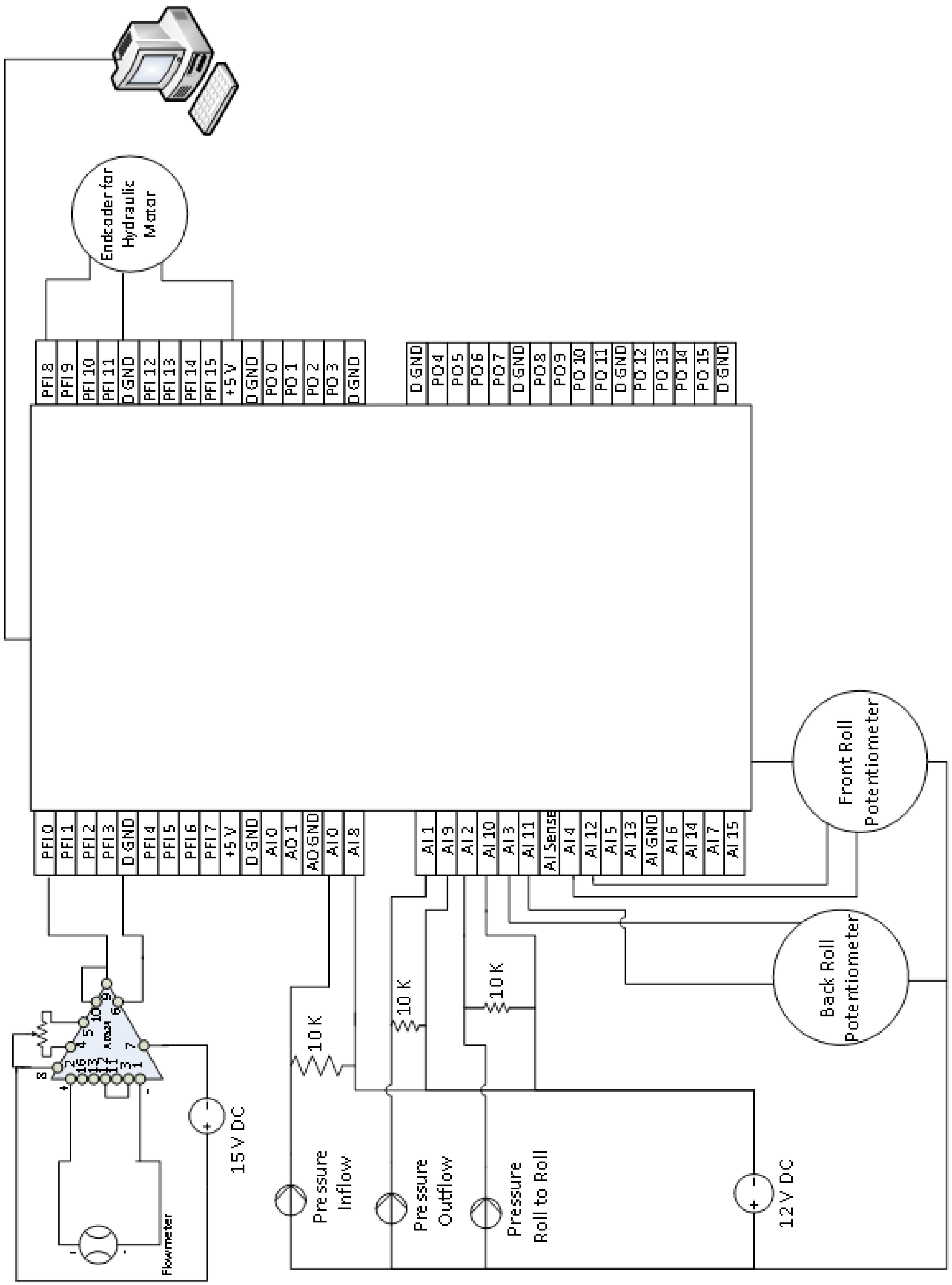


Figure 32. Field conditioner power test data acquisition schematic.

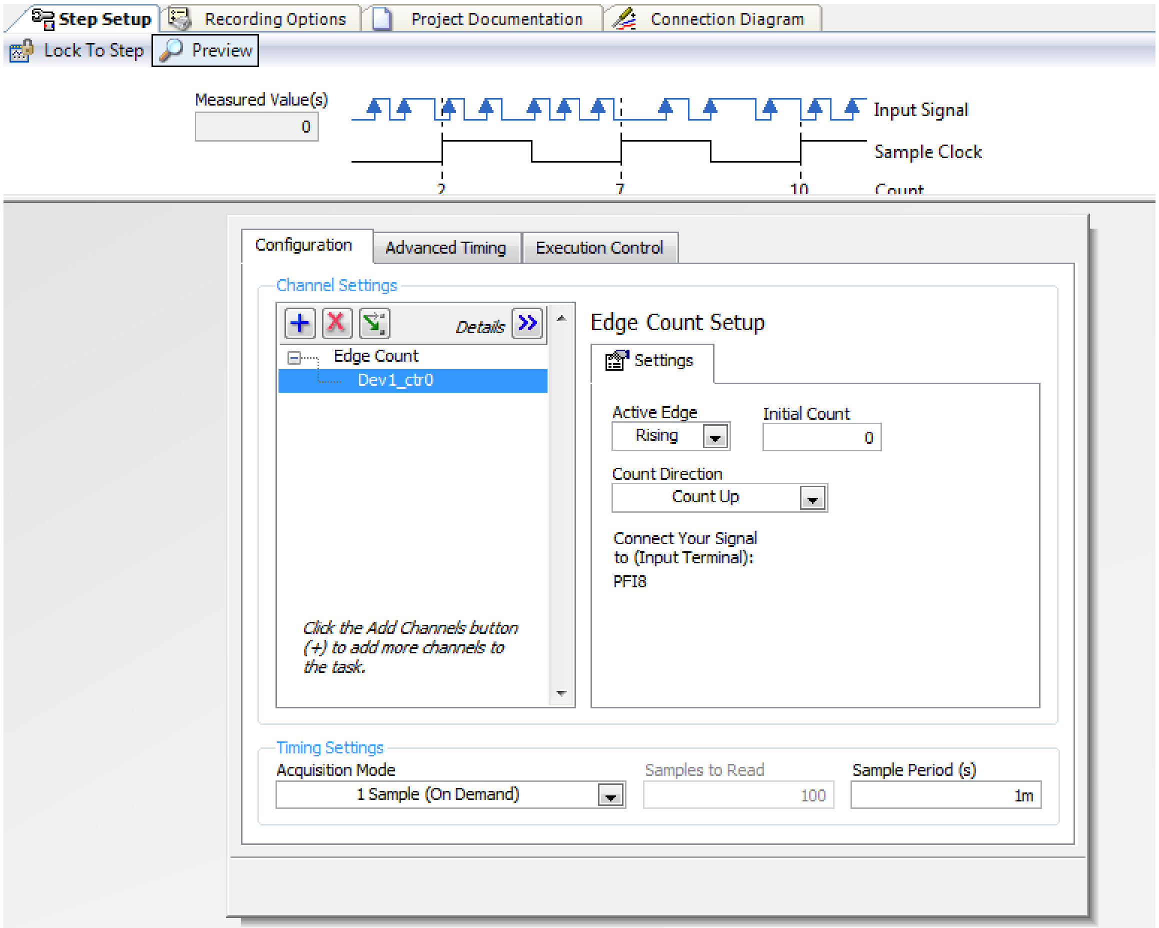


Figure 33. National Instruments Signal Express software system settings used to record the encoder on the field conditioner's hydraulic motor speed.

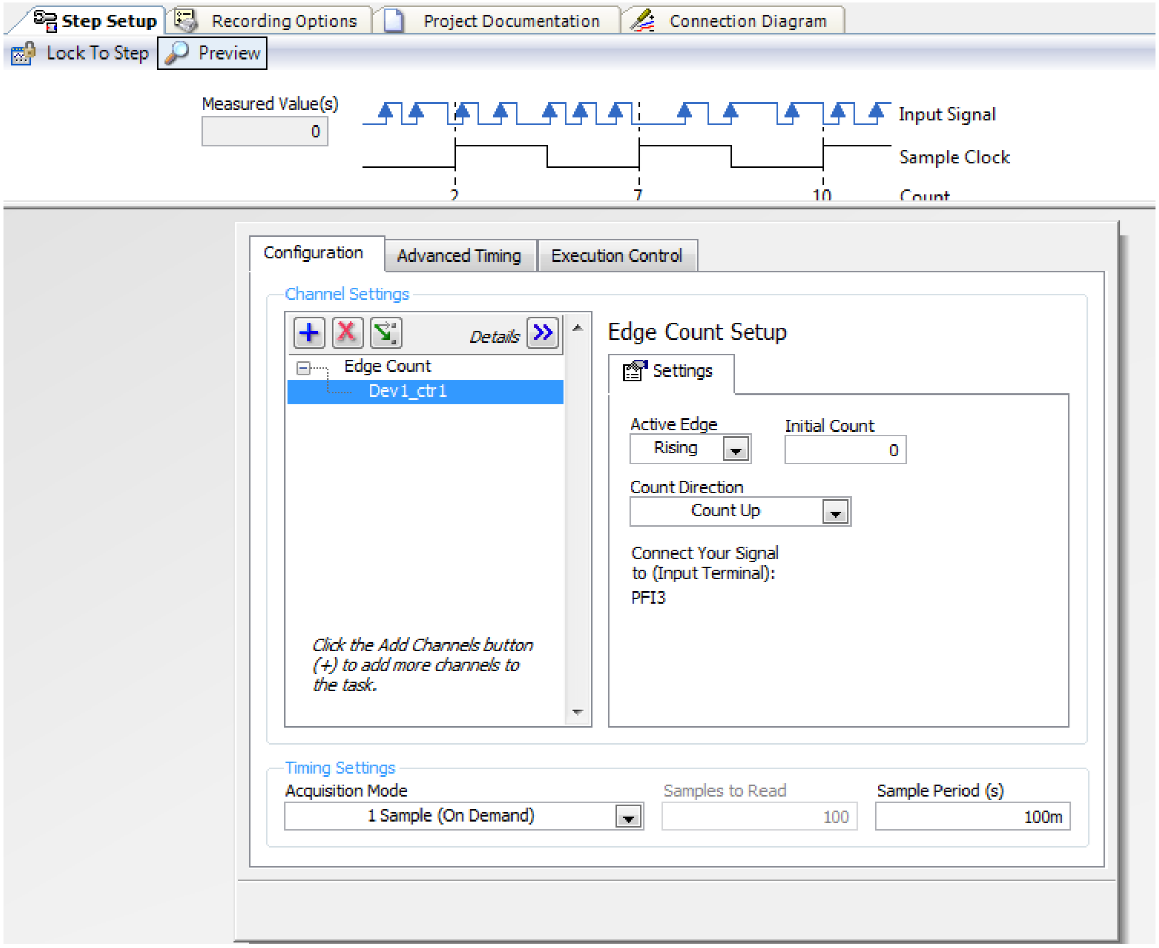


Figure 34. National Instruments Signal Express software system settings used to record the flowmeter counts that were used in calculating hydraulic flow on the field conditioner's driving motor.

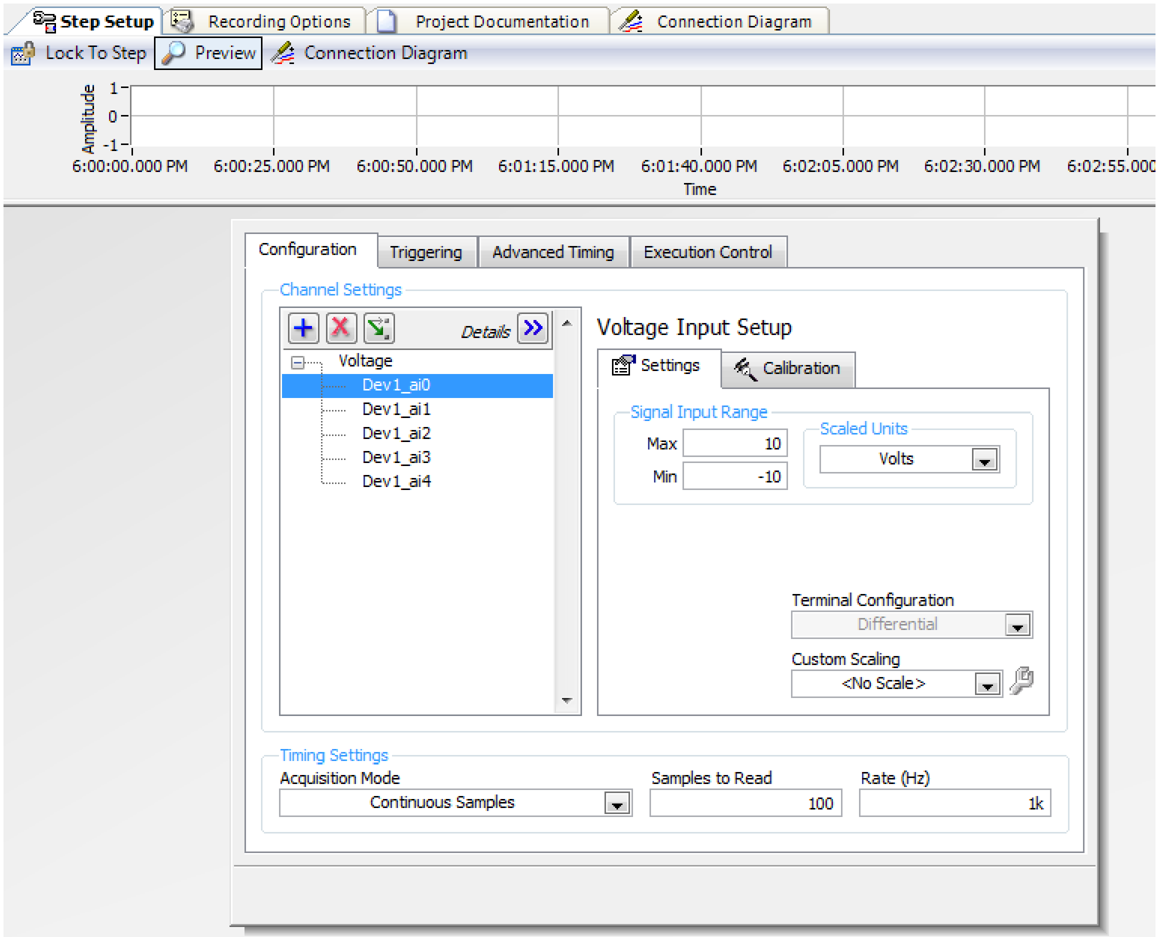


Figure 35. National Instruments Signal Express software system settings used to record the voltage generated by the hydraulic pressure transducers and roll-to-roll movement potentiometers on the field conditioner unit.

APPENDIX B.3. East Dryer Data Acquisition Schematic and Software Settings

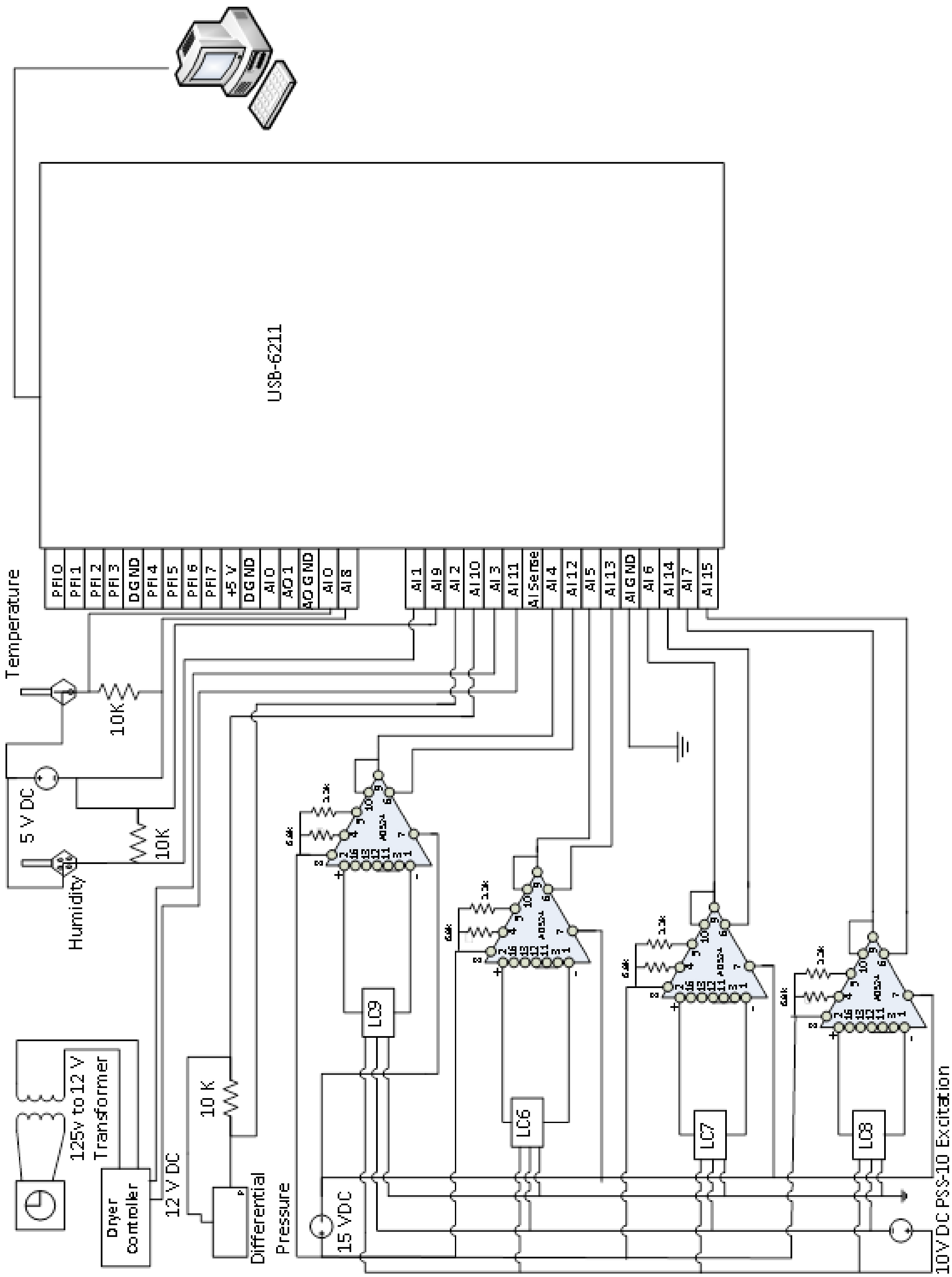


Figure 36. East dryer data acquisition schematic.

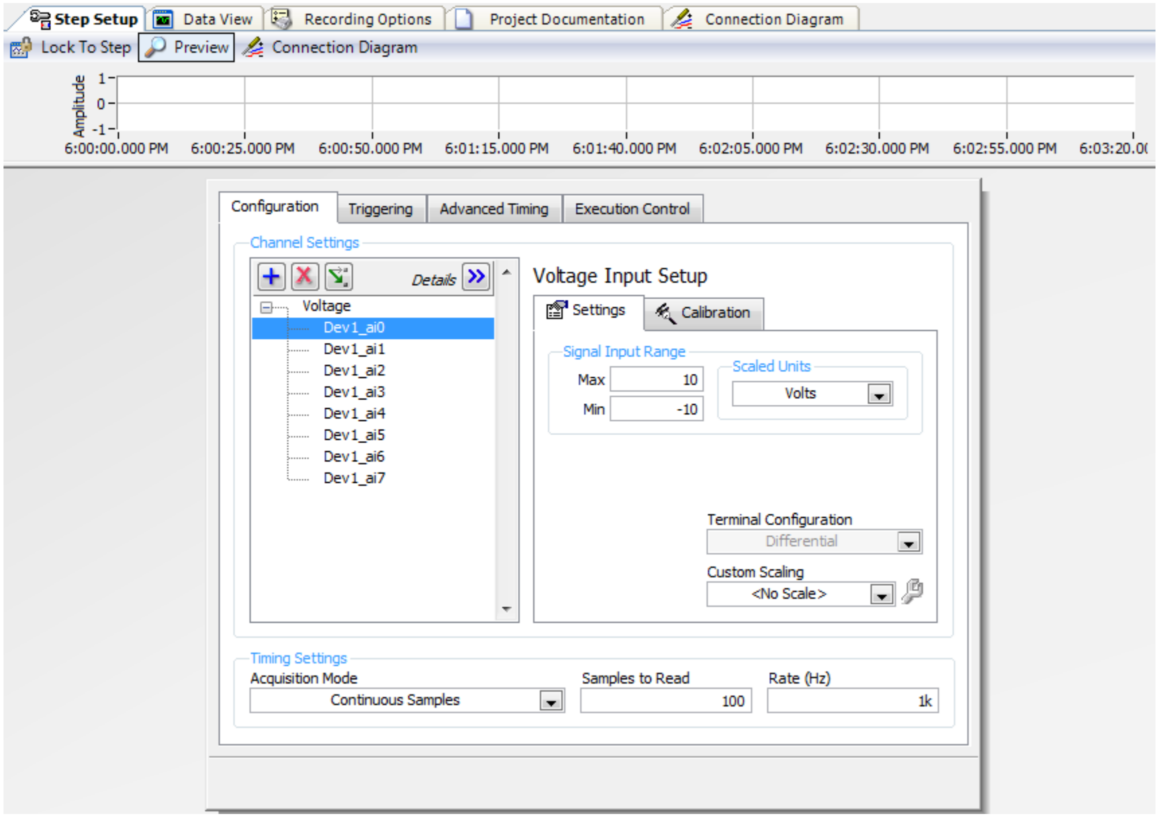


Figure 37. National Instruments Signal Express software system settings used to record the voltage outputs for the load cells, temperature, relative humidity and pressure differential for the east and west dryers.

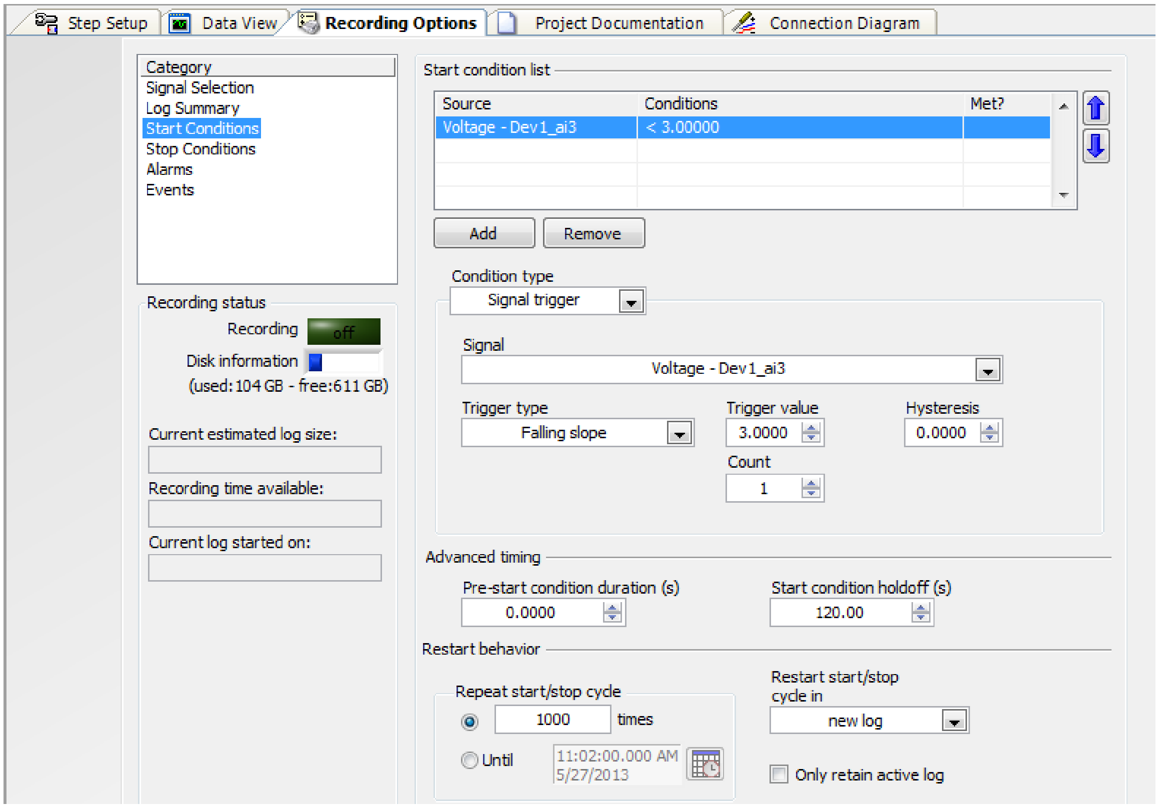


Figure 38. National Instruments Signal Express software system settings used to create voltage signal logs for the thin-layer drying studies on the east dryer.

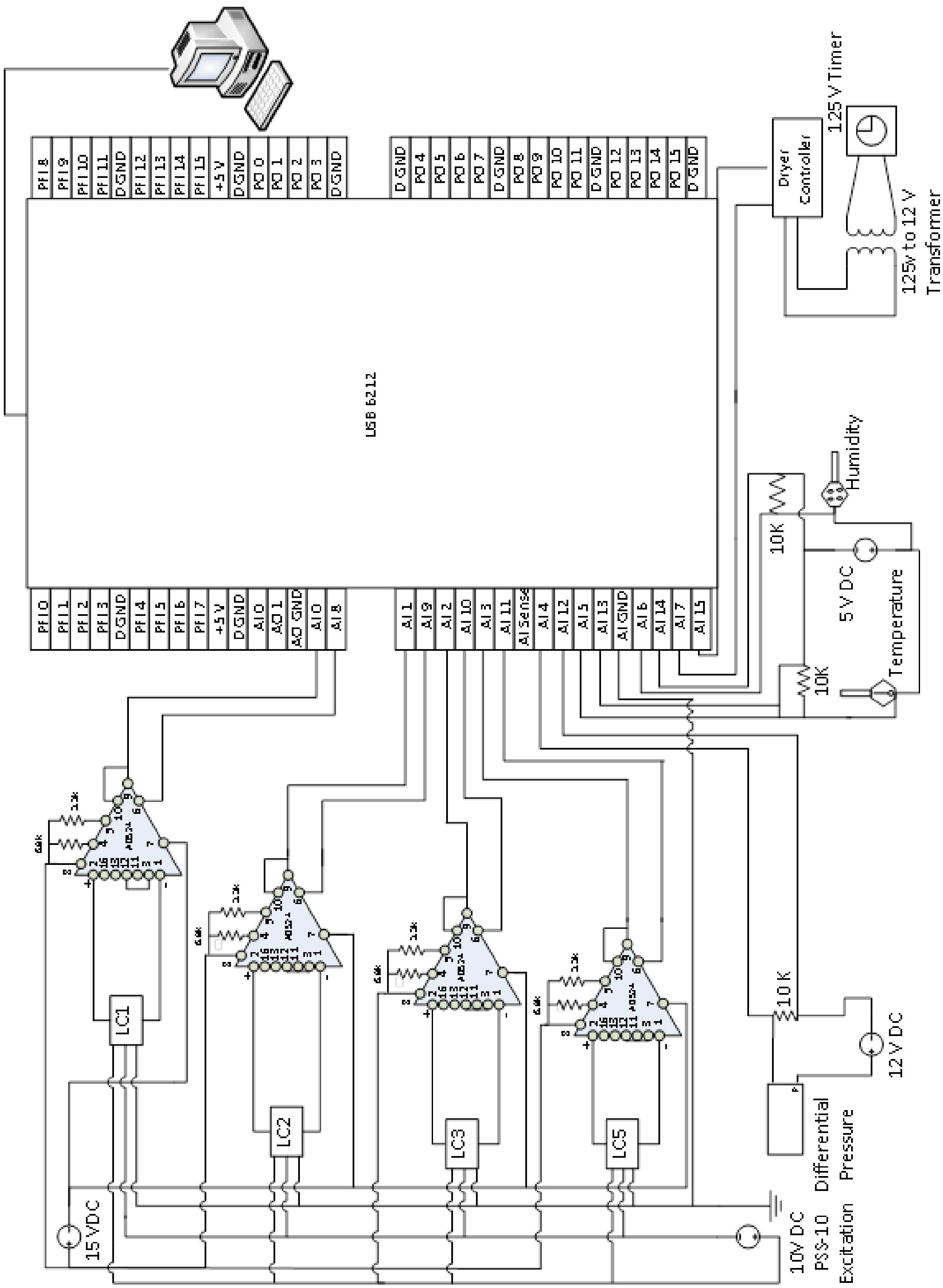


Figure 39. West dryer data acquisition schematic.

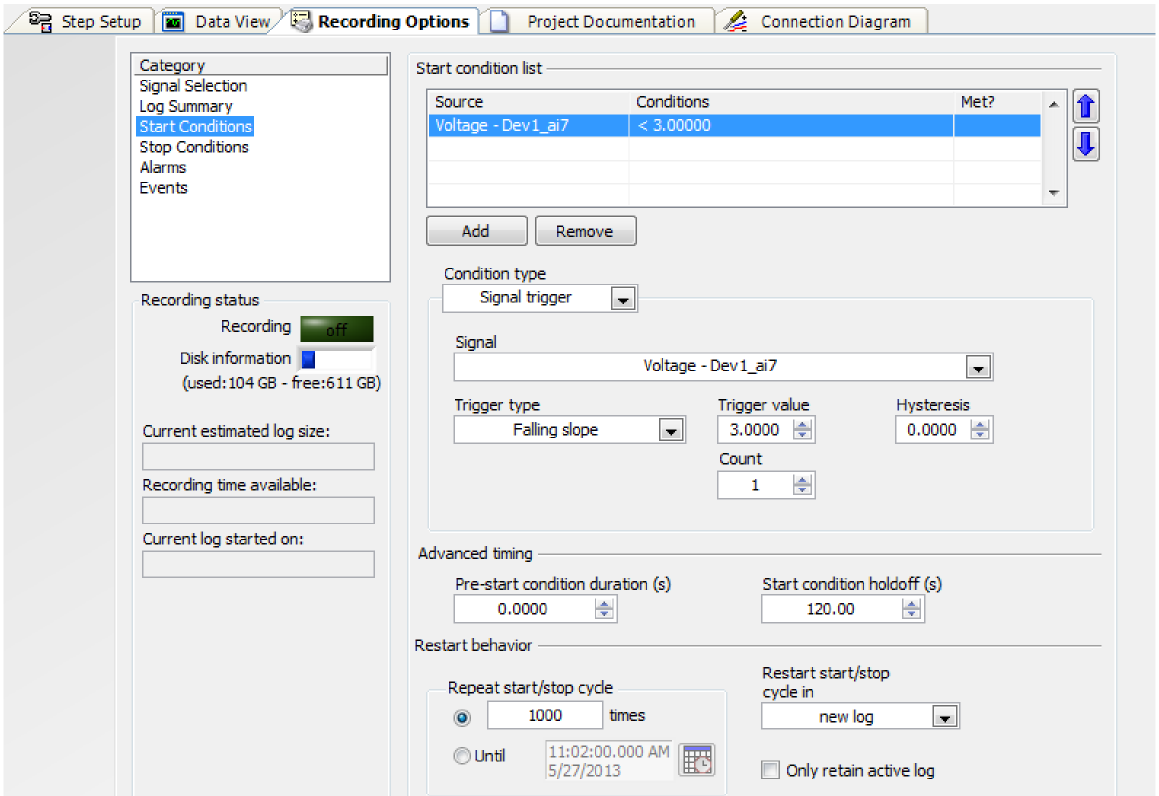


Figure 40. National Instruments Signal Express software system settings used to create the logs of the voltage signals for the thin-layer drying studies on the west dryer.

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APPENDIX C: Microsoft Excel Scripts for Extracting and Processing Signal Express Data Log Files

The National Instruments Signal Express data extraction was aided by the use of the TDM Excel Add-In for Microsoft Excel Download and TDM Excel Add-In COM-API provided by National Instruments. The link to download the add-ins was found at http://zone.ni.com/devzone/cda/epd/p/id/2944. The add-ins were coupled with VBA scripts to extract the data from the Signal Express Log Files. The add-ins must be installed before using the VBA scripts.

Each set of samples for the drying studies had log files saved to a common folder on the computer for that specific dryer. The common folder (example: west_dryer_set_1) was copied to another computer for data processing. Because the data log files from both the east and west dryers could have the same name, the folder name indicated the dryer to avoid a loss of data. A macro-enabled Excel template file was created with embedded scripts. The data extraction template file for the corresponding dryer was placed in the same folder as the log files so the script could access the *.tdms files. The script produced an average value for each set of logs, which were created at 15 minute intervals. The script then placed the average data from each log entry into the Excel file the script was embedded in, creating a summary file for the entire data run of each set of samples.

The Signal Express log files from the conditioner tests required a four-step process to combine and calculate the power usage. The files were extracted with the .tdms extraction add-in resulting in three separate Excel workbooks. The first step was to combine the three sepearate workbooks using the "power test.xltm" template file, found in the "Scripts" folder, with sheets called "Ctr0", "Ctr1", and "Voltage". The second step was to modify the data with the conditioner power calculation script. The third step was to run the conditioner power averaging script to determine the average power of each test. The averages were typically based on the time period of 2-6 seconds of the test. The average eliminated the startup and shut down effects on the pressures in the hydraulic system. The fourth and final step of the process was to extract the power averages of each test to a common file through the conditioner power evaluation summary script for comparison.

APPENDIX C.1. East Dryer Data Extraction and Processing Script

```
Sub Macro1()

   Call RecursiveFolders(ThisWorkbook.Path)

End Sub

Sub RecursiveFolders(ByVal MyPath As String)
   Dim FileSys As Object
   Dim objFolder As Object
   Dim objSubFolder As Object
   Dim objFile As Object
   Dim wkbOpen As Workbook
   Dim Excel, TdmAddIn
   Dim objExcel
   Dim objWorkBook
   Dim lastRow As Long
   Dim nextrow As Long
   Dim wBook As Workbook
   Dim wSheet As Worksheet
   Dim mSheet As Worksheet

   Set FileSys = CreateObject("Scripting.FileSystemObject")
   Set objFolder = FileSys.GetFolder(MyPath)
   nextrow = 3

   Application.ScreenUpdating = False

   For Each objSubFolder In objFolder.SubFolders

         TdmsFilePath = objSubFolder & "\Voltage.TDMS"
         On Error Resume Next
         Set Excel = CreateObject("Excel.Application")
                  Set TdmAddIn = Excel.COMAddIns.Item("ExcelTDM.TdmAddin")
                  Excel.Visible = True
         Excel.DisplayAlerts = False
         Call TdmAddIn.Object.ImportFile(TdmsFilePath, True)
         Call Excel.ActiveWindow.Activate
         On Error GoTo 0

         Set wBook = Excel.Activeworkbook
         Set mSheet = wBook.Sheets("Voltage (root)")
         Set wSheet = wBook.Sheets(2)
```

```
lastRow = wSheet.Range("A" & wSheet.Rows.Count).End(xlUp).Row
wSheet.Range("J1").Formula = "=AVERAGE(b2:b" & lastRow & ")"
wSheet.Range("k1").Formula = "=AVERAGE(c2:c" & lastRow & ")"
wSheet.Range("l1").Formula = "=AVERAGE(d2:d" & lastRow & ")"
wSheet.Range("m1").Formula = "=AVERAGE(e2:e" & lastRow & ")"
wSheet.Range("n2:n" & lastRow).Formula = "=IF(F2-0.52347<=0,"""",F2-
        0.52347)"
wSheet.Range("o2:o" & lastRow).Formula = "=IF(g2-0.55080<=0,"""",g2-
        0.55080)"
wSheet.Range("p2:p" & lastRow).Formula = "=IF(h2-0.58065<=0,"""",h2-
        0.58065)"
wSheet.Range("q2:q" & lastRow).Formula = "=IF(i2-0.51461<=0,"""",i2-
        0.51461)"
wSheet.Range("n1").Formula = "=AVERAGE(n2:n" & lastRow & ")"
wSheet.Range("o1").Formula = "=AVERAGE(o2:o" & lastRow & ")"
wSheet.Range("p1").Formula = "=AVERAGE(p2:p" & lastRow & ")"
wSheet.Range("q1").Formula = "=AVERAGE(q2:q" & lastRow & ")"
wSheet.Range("r2:r" & lastRow).Formula = "=IF(b2-
        $J$1*0.9<=0,"""",IF(b2>($J$1*1.1),"""",b2))"
wSheet.Range("s2:s" & lastRow).Formula = "=IF(c2-
        $k$1*0.9<=0,"""",IF(c2>($k$1*1.1),"""",c2))"
wSheet.Range("t2:t" & lastRow).Formula = "=IF(d2-
        $l$1*0.9<=0,"""",IF(d2>($l$1*1.1),"""",d2))"
wSheet.Range("u2:u" & lastRow).Formula = "=IF(e2-
        $m$1*0.9<=0,"""",IF(e2>($m$1*1.1),"""",e2))"
wSheet.Range("v2:v" & lastRow).Formula = "=IF(n2="""","""",IF(n2-
        $n$1*0.9<=0,"""",IF(n2>($n$1*1.1),"""",n2)))"
wSheet.Range("w2:w" & lastRow).Formula = "=IF(o2="""","""",IF(o2-
        $o$1*0.9<=0,"""",IF(o2>($o$1*1.1),"""",o2)))"
wSheet.Range("x2:x" & lastRow).Formula = "=IF(p2="""","""",IF(p2-
        $p$1*0.9<=0,"""",IF(p2>($p$1*1.1),"""",p2)))"
wSheet.Range("y2:y" & lastRow).Formula = "=IF(q2="""","""",IF(q2-
        $q$1*0.9<=0,"""",IF(q2>($q$1*1.1),"""",q2)))"
wSheet.Range("r1").Formula = "=AVERAGE(r2:r" & lastRow & ")"
wSheet.Range("s1").Formula = "=AVERAGE(s2:s" & lastRow & ")"
wSheet.Range("t1").Formula = "=AVERAGE(t2:t" & lastRow & ")"
wSheet.Range("u1").Formula = "=AVERAGE(u2:u" & lastRow & ")"
wSheet.Range("v1").Formula = "=AVERAGE(v2:v" & lastRow & ")"
wSheet.Range("w1").Formula = "=AVERAGE(w2:w" & lastRow & ")"
wSheet.Range("x1").Formula = "=AVERAGE(x2:x" & lastRow & ")"
wSheet.Range("y1").Formula = "=AVERAGE(y2:y" & lastRow & ")"

mSheet.Range("A21").Formula = "Average Data to Merge into Master Data File"
mSheet.Range("A22").Formula = "=D4"
mSheet.Range("A23").Formula = "=D5"
mSheet.Range("B22").Formula = wSheet.Range("B1")
```

```
        mSheet.Range("c22").Formula = wSheet.Range("c1")
        mSheet.Range("d22").Formula = wSheet.Range("d1")
        mSheet.Range("e22").Formula = wSheet.Range("e1")
        mSheet.Range("f22").Formula = wSheet.Range("f1")
        mSheet.Range("g22").Formula = wSheet.Range("g1")
        mSheet.Range("h22").Formula = wSheet.Range("h1")
        mSheet.Range("i22").Formula = wSheet.Range("i1")
        mSheet.Range("b23").Formula = wSheet.Range("r1")
        mSheet.Range("c23").Formula = wSheet.Range("s1")
        mSheet.Range("d23").Formula = wSheet.Range("t1")
        mSheet.Range("e23").Formula = wSheet.Range("u1")
        mSheet.Range("f23").Formula = wSheet.Range("v1")
        mSheet.Range("g23").Formula = wSheet.Range("w1")
        mSheet.Range("h23").Formula = wSheet.Range("x1")
        mSheet.Range("i23").Formula = wSheet.Range("y1")

        ActiveSheet.Range("A" & nextrow) = mSheet.Range("a23")
        ActiveSheet.Range("b" & nextrow) = mSheet.Range("b23")
        ActiveSheet.Range("c" & nextrow) = mSheet.Range("c23")
        ActiveSheet.Range("d" & nextrow) = mSheet.Range("d23")
        ActiveSheet.Range("e" & nextrow) = mSheet.Range("e23")
        ActiveSheet.Range("f" & nextrow) = mSheet.Range("f23")
        ActiveSheet.Range("g" & nextrow) = mSheet.Range("g23")
        ActiveSheet.Range("h" & nextrow) = mSheet.Range("h23")
        ActiveSheet.Range("i" & nextrow) = mSheet.Range("i23")


        nextrow = nextrow + 1

        Excel.Activeworkbook.SaveAs Filename:=objSubFolder & "\Voltage.xlsx"
        Excel.Activeworkbook.Close savechanges:=False
        Excel.Application.Quit
      Call RecursiveFolders(objSubFolder.Path)
   Next
   Application.ScreenUpdating = True
End Sub
```

APPENDIX C.2. West Dryer Data Extraction and Processing Script

```
Sub Macro1()
        Call RecursiveFolders(ThisWorkbook.Path)
End Sub

Sub RecursiveFolders(ByVal MyPath As String)
    Dim FileSys As Object
    Dim objFolder As Object
    Dim objSubFolder As Object
    Dim objFile As Object
    Dim wkbOpen As Workbook
    Dim Excel, TdmAddIn
    Dim objExcel
    Dim objWorkBook
    Dim lastRow As Long
    Dim nextrow As Long
    Dim wBook As Workbook
    Dim wSheet As Worksheet
    Dim mSheet As Worksheet

    Set FileSys = CreateObject("Scripting.FileSystemObject")
    Set objFolder = FileSys.GetFolder(MyPath)
    nextrow = 3

    Application.ScreenUpdating = False

    For Each objSubFolder In objFolder.SubFolders

            TdmsFilePath = objSubFolder & "\Voltage.TDMS"
            On Error Resume Next
            Set Excel = CreateObject("Excel.Application")
            Set TdmAddIn = Excel.COMAddIns.Item("ExcelTDM.TdmAddin")
            Excel.Visible = True
            Excel.DisplayAlerts = False
            Call TdmAddIn.Object.ImportFile(TdmsFilePath, True)
            Call Excel.ActiveWindow.Activate
            On Error GoTo 0

            Set wBook = Excel.Activeworkbook
            Set mSheet = wBook.Sheets("Voltage (root)")
            Set wSheet = wBook.Sheets(2)

            lastRow = wSheet.Range("A" & wSheet.Rows.Count).End(xlUp).Row
```

```
wSheet.Range("j2:j" & lastRow).Formula = "=IF(b2-0.50938<=0,"""",b2-
        0.50938)"
wSheet.Range("k2:k" & lastRow).Formula = "=IF(c2-0.47389<=0,"""",c2-
        0.47389)"
wSheet.Range("l2:l" & lastRow).Formula = "=IF(d2-0.47803<=0,"""",d2-
        0.47803)"
wSheet.Range("m2:m" & lastRow).Formula = "=IF(e2-0.50600<=0,"""",e2-
        0.50600)"
wSheet.Range("n1").Formula = "=AVERAGE(f2:f" & lastRow & ")"
wSheet.Range("o1").Formula = "=AVERAGE(g2:g" & lastRow & ")"
wSheet.Range("p1").Formula = "=AVERAGE(h2:h" & lastRow & ")"
wSheet.Range("q1").Formula = "=AVERAGE(i2:i" & lastRow & ")"
wSheet.Range("j1").Formula = "=AVERAGE(j2:j" & lastRow & ")"
wSheet.Range("k1").Formula = "=AVERAGE(k2:k" & lastRow & ")"
wSheet.Range("l1").Formula = "=AVERAGE(l2:l" & lastRow & ")"
wSheet.Range("m1").Formula = "=AVERAGE(m2:m" & lastRow & ")"
wSheet.Range("r2:r" & lastRow).Formula = "=IF(j2="""","""",IF(j2-
        $j$1*0.9<=0,"""",IF(j2>($j$1*1.1),"""",j2)))"
wSheet.Range("s2:s" & lastRow).Formula = "=IF(k2="""","""",IF(k2-
        $k$1*0.9<=0,"""",IF(k2>($k$1*1.1),"""",k2)))"
wSheet.Range("t2:t" & lastRow).Formula = "=IF(l2="""","""",IF(l2-
        $l$1*0.9<=0,"""",IF(l2>($l$1*1.1),"""",l2)))"
wSheet.Range("u2:u" & lastRow).Formula = "=IF(m2="""","""",IF(m2-
        $m$1*0.9<=0,"""",IF(m2>($m$1*1.1),"""",m2)))"
wSheet.Range("v2:v" & lastRow).Formula = "=IF(f2-
        $n$1*0.9<=0,"""",IF(f2>($n$1*1.1),"""",f2))"
wSheet.Range("w2:w" & lastRow).Formula = "=IF(g2-
        $o$1*0.9<=0,"""",IF(g2>($o$1*1.1),"""",g2))"
wSheet.Range("x2:x" & lastRow).Formula = "=IF(h2-
        $p$1*0.9<=0,"""",IF(h2>($p$1*1.1),"""",h2))"
wSheet.Range("y2:y" & lastRow).Formula = "=IF(i2-
        $q$1*0.9<=0,"""",IF(i2>($q$1*1.1),"""",i2))"
wSheet.Range("r1").Formula = "=AVERAGE(r2:r" & lastRow & ")"
wSheet.Range("s1").Formula = "=AVERAGE(s2:s" & lastRow & ")"
wSheet.Range("t1").Formula = "=AVERAGE(t2:t" & lastRow & ")"
wSheet.Range("u1").Formula = "=AVERAGE(u2:u" & lastRow & ")"
wSheet.Range("v1").Formula = "=AVERAGE(v2:v" & lastRow & ")"
wSheet.Range("w1").Formula = "=AVERAGE(w2:w" & lastRow & ")"
wSheet.Range("x1").Formula = "=AVERAGE(x2:x" & lastRow & ")"
wSheet.Range("y1").Formula = "=AVERAGE(y2:y" & lastRow & ")"

mSheet.Range("A21").Formula = "Average Data to Merge into Master Data File"
mSheet.Range("A22").Formula = "=D4"
mSheet.Range("A23").Formula = "=D5"
mSheet.Range("B22").Formula = wSheet.Range("B1")
mSheet.Range("c22").Formula = wSheet.Range("c1")
```

```
            mSheet.Range("d22").Formula = wSheet.Range("d1")
            mSheet.Range("e22").Formula = wSheet.Range("e1")
            mSheet.Range("f22").Formula = wSheet.Range("f1")
            mSheet.Range("g22").Formula = wSheet.Range("g1")
            mSheet.Range("h22").Formula = wSheet.Range("h1")
            mSheet.Range("i22").Formula = wSheet.Range("i1")
            mSheet.Range("b23").Formula = wSheet.Range("r1")
            mSheet.Range("c23").Formula = wSheet.Range("s1")
            mSheet.Range("d23").Formula = wSheet.Range("t1")
            mSheet.Range("e23").Formula = wSheet.Range("u1")
            mSheet.Range("f23").Formula = wSheet.Range("v1")
            mSheet.Range("g23").Formula = wSheet.Range("w1")
            mSheet.Range("h23").Formula = wSheet.Range("x1")
            mSheet.Range("i23").Formula = wSheet.Range("y1")

            ActiveSheet.Range("A" & nextrow) = mSheet.Range("a23")
            ActiveSheet.Range("b" & nextrow) = mSheet.Range("b23")
            ActiveSheet.Range("c" & nextrow) = mSheet.Range("c23")
            ActiveSheet.Range("d" & nextrow) = mSheet.Range("d23")
            ActiveSheet.Range("e" & nextrow) = mSheet.Range("e23")
            ActiveSheet.Range("f" & nextrow) = mSheet.Range("f23")
            ActiveSheet.Range("g" & nextrow) = mSheet.Range("g23")
            ActiveSheet.Range("h" & nextrow) = mSheet.Range("h23")
            ActiveSheet.Range("i" & nextrow) = mSheet.Range("i23")

            nextrow = nextrow + 1

            Excel.Activeworkbook.SaveAs Filename:=objSubFolder & "\Voltage.xlsx"
            Excel.Activeworkbook.Close savechanges:=False
            Excel.Application.Quit
        Call RecursiveFolders(objSubFolder.Path)
    Next
    Application.ScreenUpdating = True
End Sub
```

APPENDIX C.3. Conditioner Power Calculation Script

```
Sub button1_click()
  Dim app As New Excel.Application
  Dim wBook As Workbook
  Dim wSheet As Worksheet
  Dim strExtension As String
  Dim strPath As String
  Dim lastRow As Long
  Dim lastRow1 As Long
  Dim Count1 As Long
  Dim Count2 As Long
  Dim Count3 As Long
  Dim Count4 As Long
  Dim Count5 As Long
  Dim filename As String

  app.Visible = False
  Application.DisplayAlerts = False
  Me.Range("A2:A" & Me.Rows.Count).ClearContents
  strPath = ThisWorkbook.Path & "\..\"
  ChDir strPath
  strExtension = Dir(strPath & "Filter Summaries\*.xlsm")
  Do While strExtension <> ""
    Application.ScreenUpdating = False

      Set wBook = Workbooks.Open(strPath & "Filter Summaries\" & strExtension)
      Set wSheet = wBook.Sheets("Voltage")
      app.DisplayAlerts = False
            lastRow1 = wSheet.Range("A" & wSheet.Rows.Count).End(xlUp).Row
            Count1 = 1
            Count2 = 0
            Count3 = 10
            Count4 = 2
            wSheet.Range("h2:h" & lastRow1).Formula = "=(b2-c2)"
            wSheet.Range("i2:i" & lastRow1).Formula = "=h2/10000"
            wSheet.Range("j2:j" & lastRow1).Formula = "=(i2*312500)-1250"
            wSheet.Range("k2:k" & lastRow1).Formula = "=j2*.0069"
            Count5 = lastRow1 / 100

            Do While Count1 <> Count5
            wSheet.Range("l" & Count4).Formula = "=AVERAGE(k" & Count2 & "2:K" &
                      Count3 & "1)"
            Count2 = Count2 + 10
            Count3 = Count3 + 10
            Count1 = Count1 + 1
```

```
        Count4 = Count4 + 1

        Loop
    Set wSheet = wBook.Sheets("Ctr0")
      app.DisplayAlerts = False
        lastRow1 = wSheet.Range("A" & wSheet.Rows.Count).End(xlUp).Row
        Count1 = 1
        Count2 = 0
        Count3 = 10
        Count4 = 2
        wSheet.Range("b2").Formula = 0
        wSheet.Range("b3:b" & lastRow1).Formula = "=(b2+.1)"
        wSheet.Range("c2").Formula = a2
        wSheet.Range("c3:c" & lastRow1).Formula = "=(a3-a2)"
        wSheet.Range("d2:d" & lastRow1).Formula = "=(c2/.1)"
        wSheet.Range("e2:e" & lastRow1).Formula = "=(D2*(1/200)*60)"
        wSheet.Range("f2:f" & lastRow1).Formula = "=E2*(36/19)"
      Set wSheet = wBook.Sheets("Ctr1")
      app.DisplayAlerts = False
        lastRow1 = wSheet.Range("A" & wSheet.Rows.Count).End(xlUp).Row
        Count1 = 1
        Count2 = 0
        Count3 = 10
        Count4 = 2
        wSheet.Range("b2").Formula = 0
        wSheet.Range("b3:b" & lastRow1).Formula = "=(b2+.1)"
        wSheet.Range("c2").Formula = a2
        wSheet.Range("c3:c" & lastRow1).Formula = "=(a3-a2)"
        wSheet.Range("d2:d" & lastRow1).Formula = "=(c2/.1)"
        wSheet.Range("e2:e" & lastRow1).Formula = "=(D2*60)"
        wSheet.Range("f2:f" & lastRow1).Formula = "=E2/958.571"
        wSheet.Range("g2:g" & lastRow1).Formula = "=F2*3.79"
    wBook.Close True
    Set wSheet = Nothing
    Set wBook = Nothing
    lastRow = Me.Range("A" & Me.Rows.Count).End(xlUp).Row
    Me.Range("A" & lastRow).Offset(1, 0).Value = strExtension
   strExtension = Dir
   Application.ScreenUpdating = True
  Loop

  Application.DisplayAlerts = True
  app.DisplayAlerts = True
  app.Quit
End Sub
```

APPENDIX C.4. Conditioner Power Averaging Script

```
Sub button1_click()
  Dim app As New Excel.Application

  Dim wBook As Workbook
  Dim wSheet As Worksheet
  Dim strExtension As String
  Dim strPath As String
  Dim lastRow As Long
  Dim lastRow1 As Long
  Dim Count1 As Long
  Dim Count2 As Long
  Dim Count3 As Long
  Dim Count4 As Long
  Dim Count5 As Long
  Dim filename As String

  app.Visible = False
  Application.DisplayAlerts = False
  Me.Range("A2:A" & Me.Rows.Count).ClearContents
  strPath = ThisWorkbook.Path & "\..\"
  ChDir strPath
  strExtension = Dir(strPath & "Filter Summaries\*.xlsm")

  Do While strExtension <> ""
    Application.ScreenUpdating = False
    Application.DisplayAlerts = False

     Set wBook = Workbooks.Open(strPath & "Filter Summaries\" & strExtension)
    Set wSheet = wBook.Sheets("Voltage")
    app.DisplayAlerts = False
        wSheet.Range("m2").Formula = "=AVERAGE(L22:L61)"
        wSheet.Range("n2").Formula = "=STDEV.S(L22:L61)"
     Set wSheet = wBook.Sheets("Ctr1")
        wSheet.Range("h2").Formula = "=AVERAGE(G22:G61)"
        wSheet.Range("i2").Formula = "=STDEV.S(G22:G61)"
     Set wSheet = wBook.Sheets("Ctr0")
        wSheet.Range("g2").Formula = "=AVERAGE(F22:F61)"
        wSheet.Range("h2").Formula = "=STDEV.S(F22:F61)"
     Set wSheet = wBook.Sheets("Power Calculation")
        wSheet.Range("c2").Formula = "=AVERAGE(B22:B61)"
        wSheet.Range("d2").Formula = "=STDEV.S(B22:B61)"
        app.DisplayAlerts = False
      wBook.Close True
```

```
    Set wSheet = Nothing
    Set wBook = Nothing
    lastRow = Me.Range("A" & Me.Rows.Count).End(xlUp).Row
    Me.Range("A" & lastRow).Offset(1, 0).Value = strExtension
   strExtension = Dir
   Application.ScreenUpdating = True
  Loop

  Application.DisplayAlerts = True
  app.DisplayAlerts = True
  app.Quit
End Sub
```

APPENDIX C.5. Conditioner Power Evaluation Summary Script

```
Sub button1_click()
  Dim app As New Excel.Application

  Dim wBook As Workbook
  Dim mBook As Workbook
  Dim wSheet As Worksheet
  Dim mSheet As Worksheet
  Dim strExtension As String
  Dim strPath As String
  Dim nextrow As Long
  Dim lastRow As Long
  Dim lastRow1 As Long
  Dim Count1 As Long
  Dim Count2 As Long
  Dim Count3 As Long
  Dim Count4 As Long
  Dim Count5 As Long
  Dim filename As String

  app.Visible = False
  Application.DisplayAlerts = False
  strPath = ThisWorkbook.Path & "\..\"
  Set mBook = Excel.ActiveWorkbook
  Set mSheet = mBook.Sheets("Sheet1")
  nextrow = 3
  mSheet.Range("A3:J300") = ""
  ChDir strPath
  strExtension = Dir(strPath & "Filter Summaries\*.xlsm")
  Do While strExtension <> ""
    Application.ScreenUpdating = False
    Application.DisplayAlerts = False

  Set wBook = Workbooks.Open(strPath & "Filter Summaries\" & strExtension)
          mSheet.Range("A" & nextrow) = strExtension

          Set wSheet = wBook.Sheets("Voltage")
          mSheet.Range("b" & nextrow) = wSheet.Range("m2")
          mSheet.Range("c" & nextrow) = wSheet.Range("n2")

          Set wSheet = wBook.Sheets("Ctr0")
          mSheet.Range("d" & nextrow) = wSheet.Range("g2")
          mSheet.Range("e" & nextrow) = wSheet.Range("h2")

          Set wSheet = wBook.Sheets("Ctr1")
```

```
        mSheet.Range("f" & nextrow) = wSheet.Range("h2")
        mSheet.Range("g" & nextrow) = wSheet.Range("i2")

        Set wSheet = wBook.Sheets("Power Calculation")
        mSheet.Range("h" & nextrow) = wSheet.Range("c2")
        mSheet.Range("i" & nextrow) = wSheet.Range("d2")

     mSheet.Range("A" & nextrow) = strExtension
     nextrow = nextrow + 1
       app.DisplayAlerts = False
     wBook.Close False
     Set wSheet = Nothing
     Set wBook = Nothing
     'lastRow = Me.Range("A" & Me.Rows.Count).End(xlUp).Row
   strExtension = Dir
   Application.ScreenUpdating = True
  Loop

  Application.DisplayAlerts = True
  app.DisplayAlerts = True
  app.Quit
End Sub
```

APPENDIX D: Visual Grading Conditioning Level Criteria

Visual grading conditioning level criteria were provided in Appendix C. The visual grading criteria were subjective. Pictures and written criteria were used in the classification process to give the grader visual and written descriptions corresponding to conditioning levels ranging from 0 to 5. The following were the written criteria:

Level 0- No damage

Level 1- No permanent distortion of stem shape; cracks apparent in lower section but not past nodes; when held from root end plant will bend at 1 location

Level 2- general shape of stem remains; cracks that extend across 1 node; when held from root end plant will bend at 2 locations

Level 3- root end significantly deformed (non-circular shape); severe deformation at root; cracks extend beyond 2-3 nodes with 1-2 cracks extending past ½ of plant length; cross breaking of exposed pith

Level 4- Stem distorted at root end; multiple cracks extending beyond ½ of length; pieces of stem nearly separated from rest of plant stem; damage visible at upper end of plant; when held from root end plant will bend at 3-4 locations

Level 5- Stem distorted at root end; cracks running nearly ¾ of the length in multiple locations; sections of the stems completely missing; when held from root end plant will bend at more than 5 locations; bruising on leaves

Figure 41. Visual grading conditioning level 0.

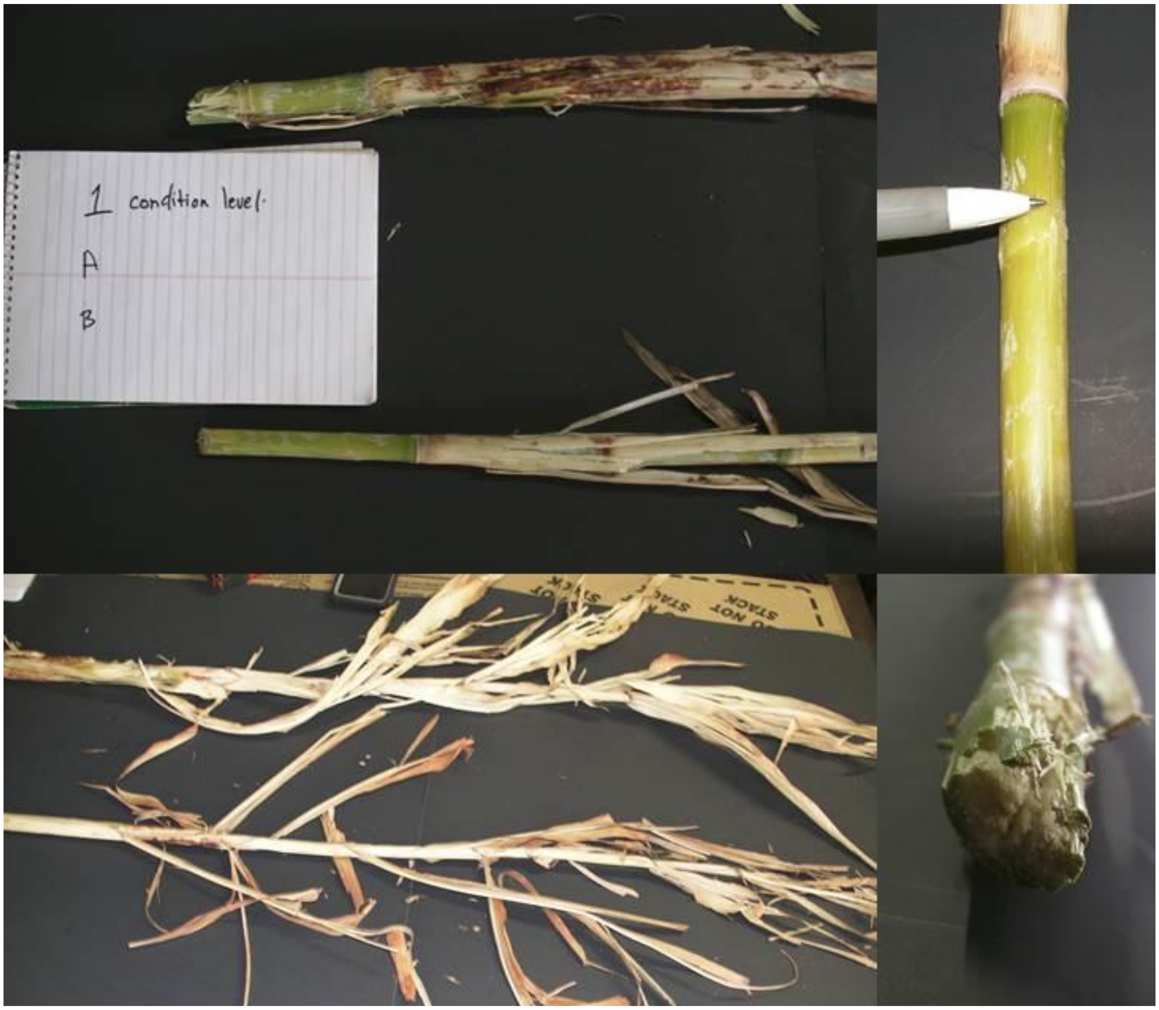

Figure 42. Visual grading conditioning level 1.

Figure 43. Visual grading conditioning level 2.

Figure 44. Visual grading conditioning level 3.

Figure 45. Visual grading conditioning level 4.

Figure 46. Visual grading conditioning level 5.

APPENDIX E: Characteristics of the High Energy Forage Sorghum Used for the Conditioner Evaluations.

Plant characteristic measurements from the forage sorghum used during the field conditioner evaluations were provided in Appendix E. These measurements were used to determine the variability of the test material prior to conditioning. The material was harvested in lots to have the material ready to perform the conditioning tests in a short time span. The goal was to perform the conditioner test using similar forage sorghum. Ten subsamples from each harvest lot were collected and evaluated for weight, height, and stalk diameter. Weight and height measurements were completed within four hours of cutting. The stalk diameter measurements were performed at a later date (2-3 weeks) due to the time needed to conduct these measurements. Water losses during this time period were assumed to have little to no effect on the stalk node diameters.

The diameter measurements were performed at the nodes rather than the center of the internode. The node diameter, chosen to represent the stalk diameter, would be larger than the diameter of the center internode, but would extend a short distance away from the node line. This method results in an over-estimate on the stalk volume rather than an underestimate.

The moisture content of the material was determined for each individual conditioner test. The samples were taken after the power test. The sample was weighed and dried according to ASABE S358.3 (ASABE, 2012) at 55 °C for 72 h. The dry basis moisture content was calculated as:

$$MC = \frac{M_W - M_D}{M_D}, \tag{8}$$

where MC was the dry basis moisture content, M_W was the gross wet weight of the sample, and M_D was the gross dry weight of the sample. The dry basis moisture content was used to determine the dry matter flow rates for each test sample.

Table 15. Forage sorghum height, weight, and stalk diameter characterization and statistical analysis by harvest lot used in the fluted conditioner tests.

Harvest lot	Date and time	Plant Height (cm)		Plant Weight (g)		Stalk Diameter (mm)	
		Average[b]	SD[a]	Average[b]	SD[a]	Average[b]	SD[a]
1	11/27 8:30	195	44	367	189	20.89	5.11
2	11/27 10:30	200	41	339	175	20.77	5.93
3	11/27 16:00	212	30	351	180	19.50	5.01
4	11/28 8:30	200	43	398	232	21.53	5.32
Average Fluted Material		202	39	364	189	20.65	5.39
F-Value		0.33		0.17		0.35	
P-Value		0.81		0.92		0.79	

[a] Standard deviation.
[b] No significant differences between harvest lots.

Table 16. Forage sorghum height, weight, and stalk diameter characterization and statistical analysis by harvest lot used in the impeller conditioner tests.

Harvest lot	Date and time	Plant Height (cm)		Plant Weight (g)		Stalk Diameter (mm)	
		Average[c]	SD[a]	Average[b]	SD[a]	Average[b]	SD[a]
5	11/29 9:30	261c	16	484	153	21.32	4.49
6	11/29 13:30	215a	33	388	172	20.74	4.49
7	11/29 14:30	246b,c	27	438	159	20.39	4.22
8	11/30 10:30	228a,b	21	450	167	19.41	6.23
9	11/30 13:30	231a,b	23	296	164	17.30	4.59
10	12/6 9:00	234a,b	34	390	112	20.67	3.62
11	12/6 13:00	249b,c	27	425	169	21.05	4.00
12	12/11 13:00	253b,c	17	538	100	22.28	3.98
13	12/11 15:30	251b,c	23	432	175	20.58	4.51
Average Impeller Material		241	28	427	161	20.18	3.60
F-Value		3.44		1.90		2.175	
P-Value		<0.01		0.07		0.06	

[a] Standard deviation.
[b] No significant differences between harvest lots.
[c]Letters appearing next to the data indicate the statistically similar groups at the 0.05 level.

Table 17. Forage sorghum height, weight, diameter, moisture content characterization, and statistical analysis of the material used in the fluted conditioner tests.

Feed Rate, t/h·m	Roll-to-roll Pressure, kPa	Harvest Lot	Moisture Content,% d.b.[a]
8.9	3450	1	210
8.9	3450	3	242
8.9	3450	4	192
8.9	6900	1	212
8.9	6900	2	214
8.9	6900	4	286
8.9	10300	2	237
8.9	10300	3	231
8.9	10300	4	174
13.3	3450	2	203
13.3	3450	3	273
13.3	3450	4	187
13.3	6900	2	154
13.3	6900	3	269
13.3	6900	4	309
13.3	10300	1	160
13.3	10300	3	220
13.3	10300	4	318
Feed Rate	F-Value		0.19
	P-Value		0.67
Pressure	F-Value		0.32
	P-Value		0.73

[a] No significant differences between treatments.

Table 18. Forage sorghum stalk diameter and moisture content characterization by treatment for material used in the impeller conditioner test units evaluation.

Type[a]	Gap, cm	Feed Rate, t/h·m	Speed, rpm	Harvest Lot	Moisture Content, % d. b.
Chisel a	0.6	8.9	800	5	228
	0.6	8.9	800	5	282
	0.6	8.9	800	6	229
	0.6	8.9	1000	5	215
	0.6	8.9	1000	5	278
	0.6	8.9	1000	7	279
	0.6	13.3	800	5	256
	0.6	13.3	800	5	223
	0.6	13.3	800	6	278
	0.6	13.3	1000	5	309
	0.6	13.3	1000	6	167
	0.6	13.3	1000	7	312
	5.7	8.9	800	7	127
	5.7	8.9	800	8	219
	5.7	8.9	800	9	231
	5.7	8.9	1000	7	248
	5.7	8.9	1000	8	281
	5.7	8.9	1000	9	261
	5.7	13.3	800	7	233
	5.7	13.3	800	8	164
	5.7	13.3	800	8	256
	5.7	13.3	1000	7	273
	5.7	13.3	1000	8	201
	5.7	13.3	1000	9	227
“V” b	1.9	8.9	800	10	231
	1.9	8.9	800	10	203
	1.9	8.9	800	10	152
	1.9	8.9	1000	10	304
	1.9	8.9	1000	10	203
	1.9	8.9	1000	10	229
	1.9	13.3	800	10	213
	1.9	13.3	800	11	168
	1.9	13.3	800	11	222
	1.9	13.3	1000	10	204
	1.9	13.3	1000	10	217
	1.9	13.3	1000	11	235
	7.0	8.9	800	12	191
	7.0	8.9	800	13	266

Table 18. Forage sorghum stalk diameter and moisture content characterization by treatment for material used in the impeller conditioner test units evaluation, cont'd.

Type	Gap, cm	Feed Rate, t/h·m	Speed, rpm	Harvest Lot	Moisture Content, % d. b. [a]
	7.0	8.9	800	13	98
	7.0	8.9	1000	12	228
	7.0	8.9	1000	12	192
	7.0	8.9	1000	13	103
	7.0	13.3	800	12	176
	7.0	13.3	800	13	289
	7.0	13.3	800	13	194
	7.0	13.3	1000	12	227
	7.0	13.3	1000	13	267
	7.0	13.3	1000	13	217
		Type		F	5.56
				P-Value	0.02
		Gap		F	2.18
				P-Value	0.15
		Feed Rate		F	0.62
				P-Value	0.44
		Speed		F	2.98
				P-Value	0.09

[a] Letters appearing next to the test parameter indicate the statistically similar groups at the 0.05 level.

Table 19. Forage sorghum leaf fraction results for the conditioner evaluation study.

Sample No.	# of leaves	Weight with leaves, g	Weight of Leaf Portion, g	Stalk to Leaf ratio
1	5	260	20	12:1
2	8	460	20	22:1
3	4	120	<20	xxx[a]
4	0	220	<20	xxx[a]
5	3	400	<20	xxx[a]
6	5	520	20	25:1
7	8	200	20	9:1
8	4	420	<20	xxx[a]
9	5	200	20	9:1
10	6	420	20	20:1
11	4	340	<20	xxx[a]
12	1	460	<20	xxx[a]
13	2	240	<20	xxx[a]
14	3	540	<20	xxx[a]
15	2	380	20	18:1
16	6	280	20	13:1
17	8	460	40	11:1
18	3	480	<20	xxx[a]
19	8	460	20	22:1
20	5	540	<20	xxx[a]
21	2	460	<20	xxx[a]
22	3	380	<20	xxx[a]
23	2	440	<20	xxx[a]
24	12	400	20	19:1
25	6	420	20	20:1
26	4	540	20	26:1
27	8	240	40	5:1
28	5	500	20	24:1
29	7	380	40	9:1
30	1	220	<20	xxx[a]
31	3	210	30	6:1
32	3	320	20	15:1
33	7	600	40	14:1
34	5	510	30	16:1
35	3	140	<20	xxx[a]
36	2	320	<20	xxx[a]
37	6	640	20	31:1
38	2	380	20	18:1

Table 19. Forage sorghum leaf fraction results for the conditioner evaluation study, cont'd

Sample No.	# of leaves	Weight with leaves, g	Weight of Leaf Portion, g	Stalk to Leaf ratio
39	3	740	<20	xxx[a]
40	7	480	20	23:1
41	9	260	40	6:1
42	5	500	20	24:1
43	6	260	20	12:1
44	3	180	<20	xxx[a]
45	6	420	<20	xxx[a]
46	4	540	20	26:1
47	8	520	20	25:1
48	6	260	20	12:1
49	6	460	20	22:1
50	4	520	<20	xxx[a]

[a]Scale resolution=20 grams, so no stalk to leaf ratios were calculated

APPENDIX F: Conditioner Evaluation Power and Specific Energy Data

Conditioner evaluation data that were used in calculating power usage were provided in Appendix F. The data includes average and standard deviations for the 10 and 1000 Hz data. The differential pressure across the drive motor for the conditioner units were measured to provide the pressure portion of the hydraulic power equation. The motor speed was measured at the motor shaft driving the conditioner unit. The motor speed was adjusted by the speed ratio of the conditioner chain drive system for the final speed used in the power calculation. The fluid flow rate entering the hydraulic motor that powers the conditioning unit was measured to provide the flow rate portion of the hydraulic power calculation.

Table 20. Average and standard deviation differential pressure, roller speed, and flow rate values for the fluted conditioner evaluation test runs.

Feed Rate, t/h·m	Roll-to-roll Pressure, kPa	Differential Pressure, MPa		Roller Speed, rpm		Flowrate, l/min	
		Average	SD[a]	Average	SD[a]	Average	SD[a]
8.9	3450	-8.75	0.05	761	170	68.0	18.3
8.9	3450	-8.73	0.05	778	77	65.5	6.8
8.9	3450	-8.73	0.04	796	70	64.9	7.9
8.9	6900	-8.71	0.05	*[b]	*[b]	62.7	16.9
8.9	6900	-8.72	0.05	783	74	64.8	9.4
8.9	6900	-8.78	0.05	707	113	60.5	8.3
8.9	10300	-8.71	0.05	790	264	66.5	25.9
8.9	10300	-8.71	0.05	774	58	66.2	6.7
8.9	10300	-8.76	0.06	708	154	59.3	10.0
13.3	3450	-8.76	0.06	729	425	66.5	33.9
13.3	3450	-8.75	0.08	686	186	61.0	10.9
13.3	3450	-8.76	0.05	761	92	64.3	8.9
13.3	6900	*[c]	*[c]	*[c]	*[c]	*[c]	*[c]
13.3	6900	-8.80	0.06	555	215	52.4	15.7
13.3	6900	-8.79	0.05	633	141	55.5	9.4
13.3	10300	-8.79	0.04	723	84	63.3	7.5
13.3	10300	-8.74	0.07	716	160	61.4	10.4
13.3	10300	-8.79	0.05	727	95	60.7	8.3

[a]Standard deviation

[b]Missing data on the hydraulic motor encoder

[c] Missing data due to logging error

Table 21. Average and standard deviation differential pressure, impeller speed, and flow rate values for the chisel conditioner evaluation test runs.

Shield gap, cm	Feed Rate, t/h·m	Impeller speed, rpm	Differential Pressure, MPa		Impeller Speed, rpm		Flowrate, l/min	
			Average	SD[a]	Average	SD[a]	Average	SD[a]
0.6	8.9	800	-8.69	0.02	980	32	78.5	8.6
0.6	8.9	800	-8.67	0.03	1010	39	78.0	6.1
0.6	8.9	800	-8.66	0.01	1004	112	77.9	10.3
0.6	8.9	1000	-8.67	0.03	1056	53	82.3	5.9
0.6	8.9	1000	-8.67	0.03	1051	36	82.6	6.4
0.6	8.9	1000	-8.66	0.00	1054	32	81.8	6.7
0.6	13.3	800	-8.66	0.02	1014	44	81.5	6.0
0.6	13.3	800	-8.67	0.04	1004	60	79.2	6.5
0.6	13.3	800	-8.70	0.05	968	86	76.4	7.3
0.6	13.3	1000	-8.68	0.03	1050	50	80.5	6.3
0.6	13.3	1000	-8.66	0.02	1110	100	86.3	8.3
0.6	13.3	1000	-8.67	0.03	1094	243	82.7	19.5
5.7	8.9	800	-8.66	0.00	1018	34	80.2	7.1
5.7	8.9	800	-8.66	0.01	1021	34	79.2	8.7
5.7	8.9	800	-8.62	0.00	527	119	89.7	17.6
5.7	8.9	1000	-8.67	0.03	1123	265	91.2	48.2
5.7	8.9	1000	-8.67	0.03	1145	120	87.2	9.9
5.7	8.9	1000	-8.67	0.02	1121	121	85.6	10.7
5.7	13.3	1000	-8.70	0.03	979	81	77.0	10.4
5.7	13.3	1000	-8.65	0.01	1015	41	88.7	37.9
5.7	13.3	1000	-8.63	0.00	423	105	47.0	7.1
5.7	13.3	800	-8.66	0.00	1060	26	81.5	6.5
5.7	13.3	800	-8.63	0.01	662	134	59.1	9.2
5.7	13.3	800	-8.67	0.00	1270	60	96.7	7.7

[a]Standard deviation

Table 22. Average and standard deviation differential pressure, impeller speed, and flow rate values for the "V" conditioner evaluation test runs.

Shield gap, cm	Feed Rate, t/h·m	Impeller speed, rpm	Differential Pressure, Mpa		Impeller Speed, rpm		Flowrate, l/min	
			Average	SD[a]	Average	SD[a]	Average	SD[a]
1.9	8.9	800	-8.66	0.02	1011	27	77.1	7.8
1.9	8.9	800	-8.65	0.01	1018	16	79.5	7.6
1.9	8.9	800	-8.67	0.04	1003	45	80.1	6.9
1.9	8.9	1000	-8.65	0.01	1268	20	92.5	5.5
1.9	8.9	1000	-8.65	0.00	1274	7	91.9	6.2
1.9	8.9	1000	-8.67	0.03	1081	43	83.3	8.0
1.9	13.3	800	-8.67	0.04	991	40	79.8	7.1
1.9	13.3	800	-8.67	0.03	1008	62	78.6	6.7
1.9	13.3	800	-8.68	0.03	995	44	78.4	6.9
1.9	13.3	1000	-8.65	0.00	1279	5	94.4	6.2
1.9	13.3	1000	-8.69	0.03	1033	46	78.6	5.8
1.9	13.3	1000	-8.65	0.03	1157	127	87.4	9.6
7.0	8.9	800	-8.64	0.00	1010	7	81.9	6.8
7.0	8.9	800	*[b]	*[b]	*[b]	*[b]	*[b]	*[b]
7.0	8.9	800	-8.64	0.00	1034	42	82.4	7.4
7.0	8.9	1000	-8.66	0.01	1288	63	98.5	5.8
7.0	8.9	1000	-8.65	0.02	1135	87	88.4	7.7
7.0	8.9	1000	-8.65	0.01	1086	39	85.8	7.2
7.0	13.3	800	-8.64	0.00	993	40	80.0	7.0
7.0	13.3	800	-8.67	0.03	1013	45	81.2	6.6
7.0	13.3	800	-8.66	0.02	996	37	79.7	6.8
7.0	13.3	1000	-8.65	0.01	1267	40	95.0	6.6
7.0	13.3	1000	-8.65	0.02	1194	96	92.3	8.5
7.0	13.3	1000	-8.66	0.02	1100	79	86.5	8.7

[a] Standard deviation
[b] Missing data due to logging error

Table 23. Average and standard deviation power consumption and specific energy values for the fluted conditioner evaluation test runs.

Feed Rate, t/h·m	Roll-to Roll Pressure, kPa	Power Consumption, kW/m Average	Power Consumption, kW/m SD[a]	Specific Energy, kW·h/t DM[b]
8.9	3450	3.36	2.51	1.17
8.9	3450	2.99	0.91	1.15
8.9	3450	2.90	1.05	0.95
8.9	6900	2.59	2.28	0.91
8.9	6900	2.88	1.26	1.02
8.9	6900	2.35	1.10	1.02
8.9	10300	3.09	3.49	1.17
8.9	10300	3.07	0.89	1.14
8.9	10300	2.17	1.33	0.67
13.3	3450	3.16	4.62	0.72
13.3	3450	2.39	1.44	0.67
13.3	3450	2.86	1.19	0.62
13.3	6900	*[c]	*[c]	*[c]
13.3	6900	1.26	2.14	0.35
13.3	6900	1.67	1.26	0.51
13.3	10300	2.74	1.02	0.54
13.3	10300	2.44	1.37	0.59
13.3	10300	2.39	1.11	0.75
Feed Rate	F-Value	12.15		38.60
	P-Value	<0.01		<0.01
Pressure	F-Value	11.19		4.13
	P-Value	<0.01		0.04
Feedrate*Pressure	F-Value	4.48		1.60
	P-Value	0.04		0.24

[a] Standard deviation

[b]Dry matter

[c]Missing data due to logging error

Table 24. Average and standard deviation power consumption and specific energy values for the impeller conditioner evaluation test runs.

Type	Shield gap, cm	Feed rate, t/h·m	Impeller speed, rpm	Power Consumption, kW/m		Specific Energy, kW·h/t DM[b]
				Average	SD[a]	
Chisel	0.6	8.9	800	10.6	1.2	3.9
	0.6	8.9	800	10.5	0.9	4.5
	0.6	8.9	800	10.5	1.5	3.9
	0.6	8.9	1000	11.1	0.8	3.9
	0.6	8.9	1000	11.2	0.9	4.7
	0.6	8.9	1000	11.0	1.0	4.7
	0.6	13.3	800	11.0	0.9	2.9
	0.6	13.3	800	10.7	0.9	2.6
	0.6	13.3	800	10.4	1.0	2.9
	0.6	13.3	1000	10.9	0.9	3.3
	0.6	13.3	1000	11.6	1.2	2.3
	0.6	13.3	1000	11.2	2.8	3.5
	5.7	8.9	800	10.8	1.0	2.8
	5.7	8.9	800	10.7	1.2	3.8
	5.7	8.9	800	12.0	2.5	4.5
	5.7	8.9	1000	12.3	6.9	4.8
	5.7	8.9	1000	11.8	1.4	5.0
	5.7	8.9	1000	11.6	1.5	4.7
	5.7	13.3	1000	10.4	1.5	2.6
	5.7	13.3	1000	12.0	5.4	2.4
	5.7	13.3	1000	6.3	1.0	1.7
	5.7	13.3	800	11.0	0.9	3.1
	5.7	13.3	800	7.9	1.3	1.8
	5.7	13.3	800	13.1	1.1	3.2
“V”	1.9	8.9	800	10.4	1.1	3.9
	1.9	8.9	800	10.7	1.1	3.6
	1.9	8.9	800	10.8	1.0	3.1
	1.9	8.9	1000	12.5	0.8	5.7
	1.9	8.9	1000	12.4	0.9	4.2
	1.9	8.9	1000	11.3	1.1	4.2
	1.9	13.3	800	10.8	1.0	2.5
	1.9	13.3	800	10.6	0.9	2.1
	1.9	13.3	800	10.6	1.0	2.6
	1.9	13.3	1000	12.7	0.9	2.9
	1.9	13.3	1000	10.6	0.8	2.5
	1.9	13.3	1000	11.8	1.4	3.0
	7.0	8.9	800	11.0	1.0	3.6

Table 24. Average and standard deviation power consumption and specific energy values for the impeller conditioner evaluation test runs, cont'd.

Type	Shield gap, cm	Feed rate, t/h·m	Impeller speed, rpm	Power Consumption, kW/m		Specific Energy, kW·h/t DM[b]
				Average	SD[a]	
"V"	7.0	8.9	800	*[c]	*[c]	*[c]
	7.0	8.9	800	11.1	1.1	2.5
	7.0	8.9	1000	13.3	0.8	4.9
	7.0	8.9	1000	11.9	1.1	3.9
	7.0	8.9	1000	11.6	1.0	2.6
	7.0	13.3	800	10.8	1.0	2.2
	7.0	13.3	800	11.0	0.9	3.2
	7.0	13.3	800	10.8	1.0	2.4
	7.0	13.3	1000	12.8	1.0	3.1
	7.0	13.3	1000	12.4	1.2	3.4
	7.0	13.3	1000	11.7	1.2	2.8
	Type		F	2.02		0.07
			P-Value	0.16		0.80
	Gap		F	0.04		0.84
			P-Value	0.84		0.37
	Feed Rate		F	0.21		22.74
			P-Value	0.65		<0.01
	Speed		F	11.03		16.41
			P-Value	<0.01		<0.01

[a] Standard deviation

[b]Dry matter

[c]Missing data due to logging error

APPENDIX G: Organization of the Thin-Layer Drying Tests

Information related to the thin-layer drying rate tests were provided in Appendix G. The drying set, dryer ID, start time and stop time for each conditioner treatment were provided in Tables 41-44. Graphs of the dryer and ambient temperature and absolute humidity for each drying set were provided to verify the relatively constant dryer conditions in comparison to ambient data.

Table 25. Fluted roller conditioner thin-layer drying test configurations with starting and ending times.

Feed Rate, t/h	Roll-to-Roll Pressure, kPa	Drying Set	Dryer ID	Start Time	Stop Time
8.9	3450	2	West	2/26/2013 17:26	3/3/2013 9:51
8.9	3450	3	East	3/3/2013 12:51	3/8/2013 7:46
8.9	3450	4	East	3/8/2013 10:20	3/14/2013 10:10
8.9	6900	2	West	2/26/2013 17:26	3/3/2013 9:51
8.9	6900	2	East	2/26/2013 17:23	3/3/2013 9:07
8.9	6900	3	West	3/3/2013 12:54	3/8/2013 7:49
8.9	10300	2	East	2/26/2013 17:23	3/3/2013 9:07
8.9	10300	3	West	3/3/2013 12:54	3/8/2013 7:49
8.9	10300	3	East	3/3/2013 12:51	3/8/2013 7:46
13.3	3450	2	East	2/26/2013 17:23	3/3/2013 9:07
13.3	3450	3	East	3/3/2013 12:51	3/8/2013 7:46
13.3	3450	4	East	3/8/2013 10:20	3/14/2013 10:10
13.3	6900	2	West	2/26/2013 17:26	3/3/2013 9:51
13.3	6900	2	East	2/26/2013 17:23	3/3/2013 9:07
13.3	6900	3	West	3/3/2013 12:54	3/8/2013 7:49
13.3	10300	2	West	2/26/2013 17:26	3/3/2013 9:51
13.3	10300	3	West	3/3/2013 12:51	3/8/2013 7:49
13.3	10300	4	East	3/8/2013 10:20	3/14/2013 10:10

Table 26. Chisel impeller conditioner thin-layer drying test configurations with starting and ending times.

Shield Gap, cm	Feed Rate, t/h·m	Impeller Speed, rpm	Drying Set	Dryer ID	Start Time	Stop Time
0.6	8.9	800	4	East	3/8/2013 10:20	3/14/2013 10:10
0.6	8.9	800	4	West	3/8/2013 10:24	3/14/2013 10:14
0.6	8.9	800	5	East	3/14/2013 13:24	3/21/2013 15:34
0.6	8.9	1000	4	West	3/8/2013 10:24	3/14/2013 10:14
0.6	8.9	1000	5	West	3/14/2013 12:05	3/21/2013 14:38
0.6	8.9	1000	5	East	3/14/2013 13:24	3/21/2013 15:34
0.6	13.3	800	4	West	3/8/2013 10:24	3/14/2013 10:14
0.6	13.3	800	5	West	3/14/2013 12:05	3/21/2013 14:38
0.6	13.3	800	5	East	3/14/2013 13:24	3/21/2013 15:34
0.6	13.3	1000	5	West	3/14/2013 12:05	3/21/2013 14:38
0.6	13.3	1000	5	East	3/14/2013 13:24	3/21/2013 15:34
0.6	13.3	1000	6	West	3/21/2013 16:08	3/27/2013 10:59
5.7	8.9	800	6	West	3/21/2013 16:08	3/27/2013 10:59
5.7	8.9	800	6	East	3/21/2013 5:04	3/27/2013 11:55
5.7	8.9	800	7	West	3/27/2013 12:52	4/2/2013 8:21
5.7	8.9	1000	6	West	3/21/2013 16:08	3/27/2013 10:59
5.7	8.9	1000	6	East	3/21/2013 5:04	3/27/2013 11:55
5.7	8.9	1000	7	East	3/27/2013 13:48	3/27/2013 9:02
5.7	13.3	800	6	East	3/21/2013 5:04	3/27/2013 11:55
5.7	13.3	800	7	West	3/27/2013 12:52	4/2/2013 8:21
5.7	13.3	800	7	East	3/27/2013 13:48	3/27/2013 9:02
5.7	13.3	1000	6	West	3/21/2013 16:08	3/27/2013 10:59
5.7	13.3	1000	6	East	3/21/2013 5:04	3/27/2013 11:55
5.7	13.3	1000	7	East	3/27/2013 13:48	3/27/2013 9:02

Table 27. "V" impeller conditioner thin-layer drying test configurations with starting and ending times.

Shield Gap, cm	Feed Rate, t/h·m	Impeller Speed, rpm	Drying Set	Dryer ID	Start Time	Stop Time
1.9	8.9	800	7	East	3/27/2013 13:48	3/27/2013 9:02
1.9	8.9	800	8	West	4/2/2013 12:42	4/8/2013 7:30
1.9	8.9	800	1	East	2/20/2013 16:47	2/26/2013 14:22
1.9	8.9	1000	7	West	3/27/2013 12:52	4/2/2013 8:21
1.9	8.9	1000	8	West	4/2/2013 12:42	4/8/2013 7:30
1.9	8.9	1000	9	East	4/8/2013 12:12	4/14/2013 9:39
1.9	13.3	800	1	West	2/20/2013 16:50	2/26/2013 11:43
1.9	13.3	800	8	West	4/2/2013 12:42	4/8/2013 7:30
1.9	13.3	800	8	East	4/2/2013 13:37	4/8/2013 8:26
1.9	13.3	1000	7	West	3/27/2013 12:52	4/2/2013 8:21
1.9	13.3	1000	8	West	4/2/2013 12:42	4/8/2013 7:30
1.9	13.3	1000	8	East	4/2/2013 13:37	4/8/2013 8:26
7.0	8.9	800	1	East	2/20/2013 16:47	2/26/2013 14:22
7.0	8.9	800	1	West	2/20/2013 16:50	2/26/2013 11:43
7.0	8.9	800	1	West	2/20/2013 16:50	2/26/2013 11:43
7.0	8.9	1000	9	West	4/8/2013 11:17	4/14/2013 8:43
7.0	8.9	1000	8	East	4/2/2013 13:37	4/8/2013 8:26
7.0	8.9	1000	9	East	4/8/2013 12:12	4/14/2013 9:39
7.0	13.3	800	9	East	4/8/2013 12:12	4/14/2013 9:39
7.0	13.3	800	1	East	2/20/2013 16:47	2/26/2013 14:22
7.0	13.3	800	1	West	2/20/2013 16:50	2/26/2013 11:43
7.0	13.3	1000	8	East	4/2/2013 13:37	4/8/2013 8:26
7.0	13.3	1000	9	West	4/8/2013 11:17	4/14/2013 8:43
7.0	13.3	1000	9	East	4/8/2013 12:12	4/14/2013 9:39

Table 28. Control material thin-layer drying test configurations with starting and ending times.

Sample No.	Drying Set	Dryer ID	Start Time	Stop Time
C1	3	East	3/3/2013 12:51	3/8/2013 7:46
C2	4	West	3/8/2013 10:24	3/14/2013 10:14
C3	5	West	3/14/2013 12:05	3/21/2013 14:38

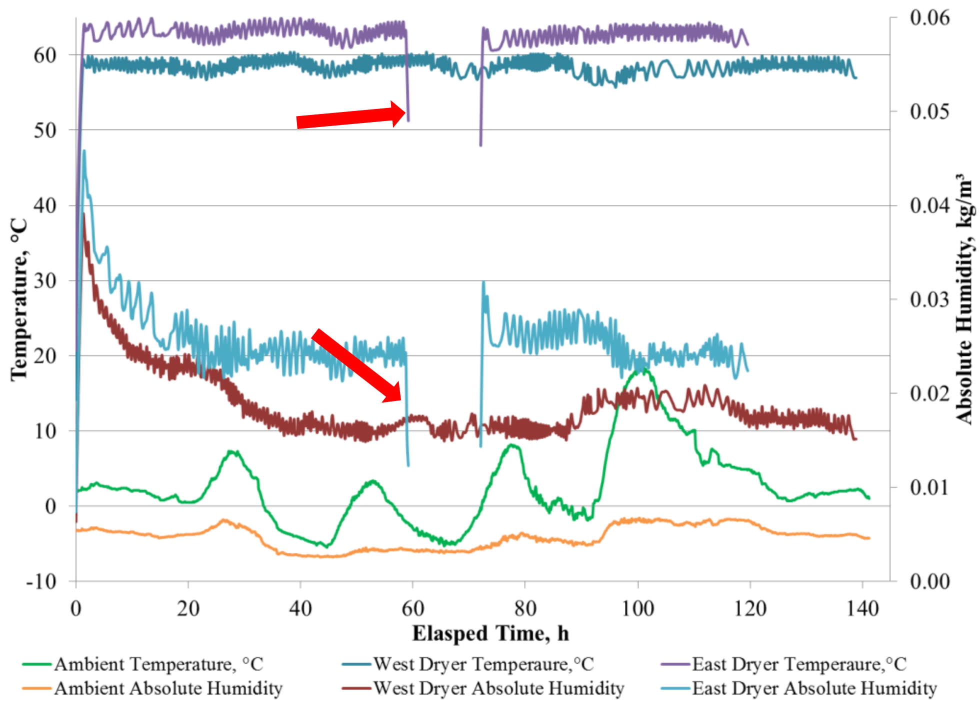

Figure 47. Dryer and ambient temperature and absolute humidity data recorded during drying set one.

*Arrows denote a 12 hour breakdown on the East Dryer

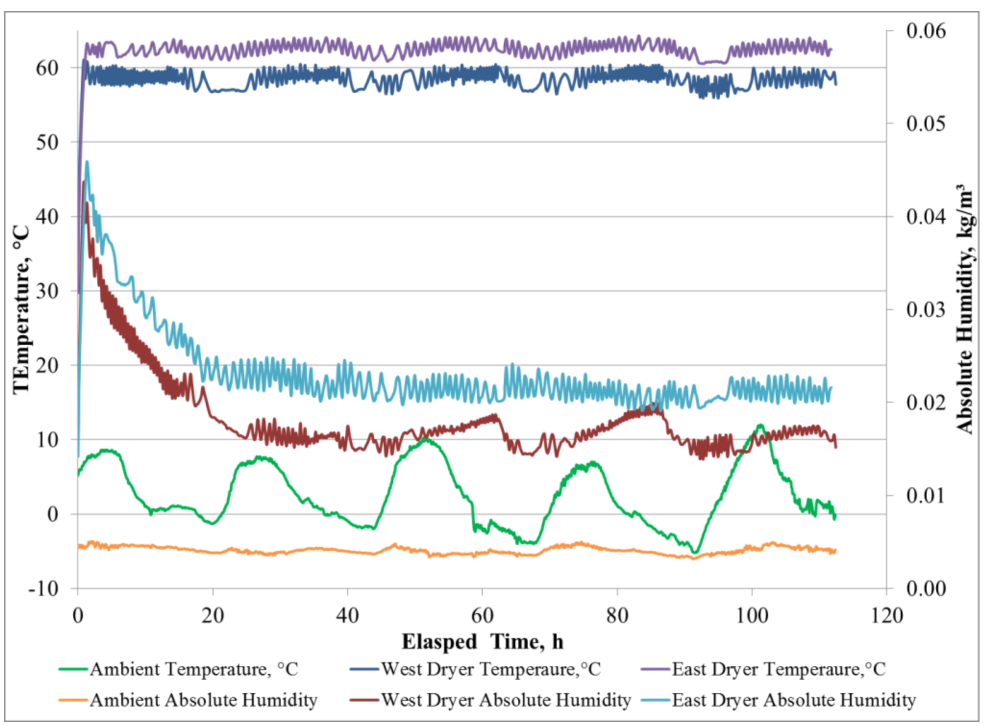

Figure 48. Dryer and ambient temperature and absolute humidity data recorded during drying set two.

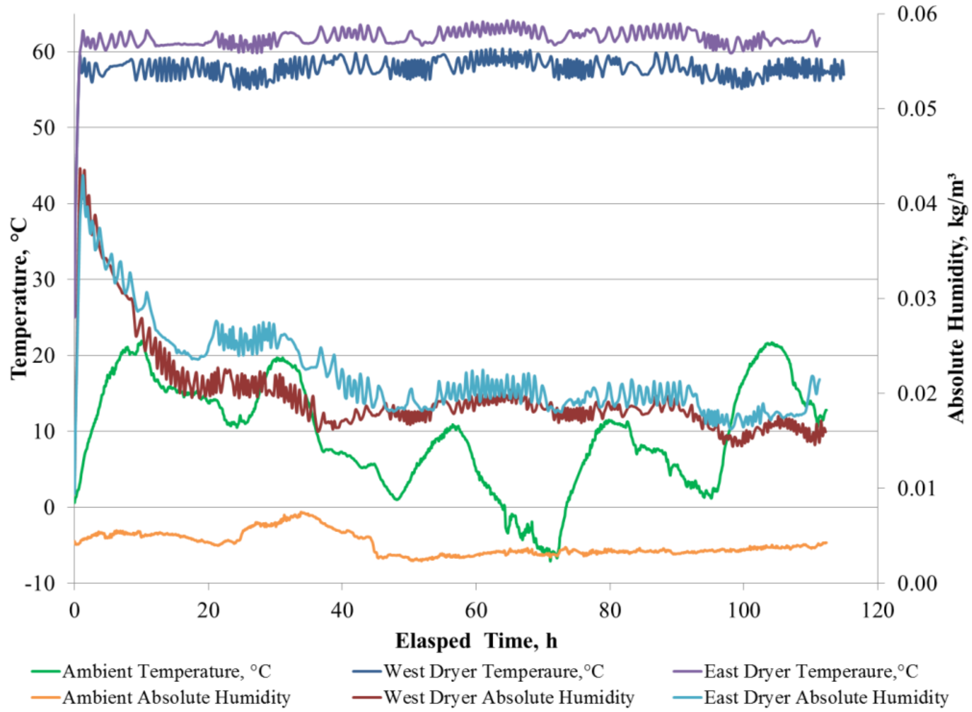

Figure 49. Dryer and ambient temperature and absolute humidity data recorded during drying set three.

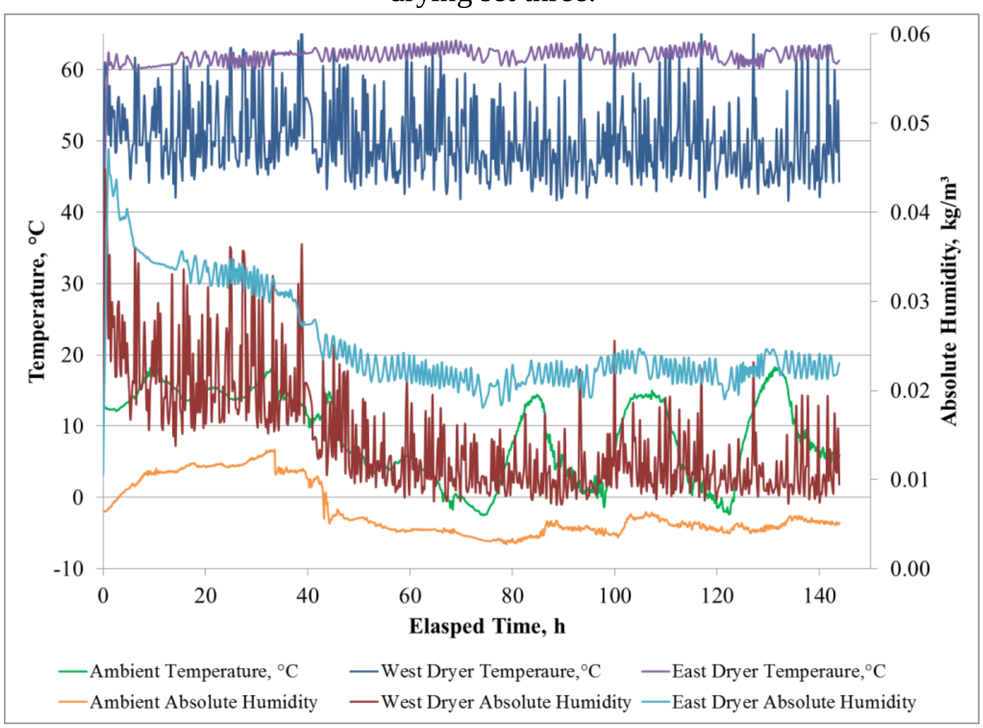

Figure 50. Dryer and ambient temperature and absolute humidity data recorded during drying set four.

* The large variance with the West Dryer temperature sensor was due to a loose temperature sensor ground wire in the circuit.

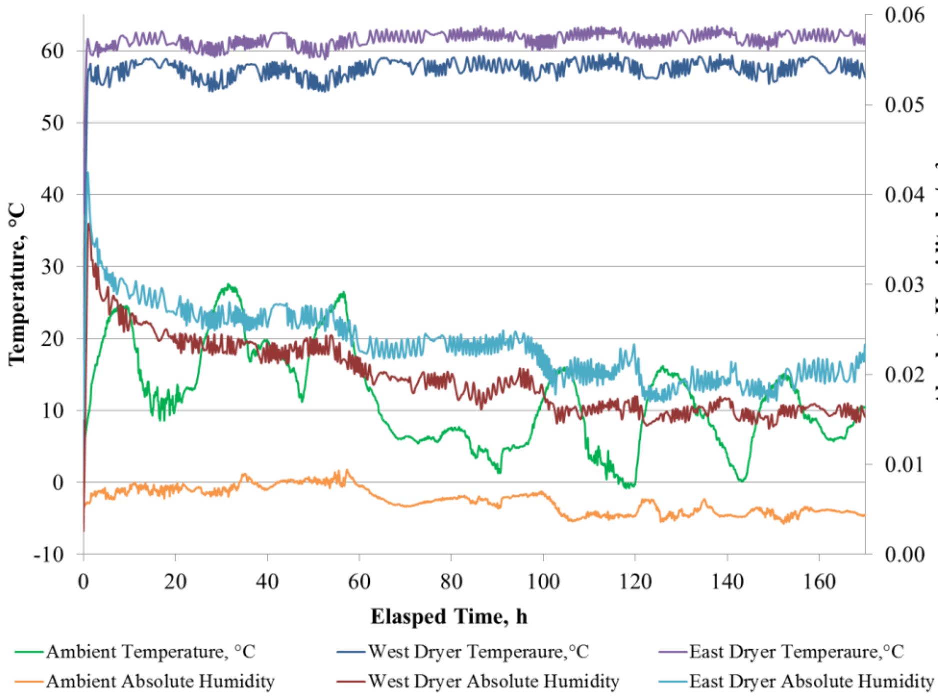

Figure 51. Dryer and ambient temperature and absolute humidity data recorded during drying set five.

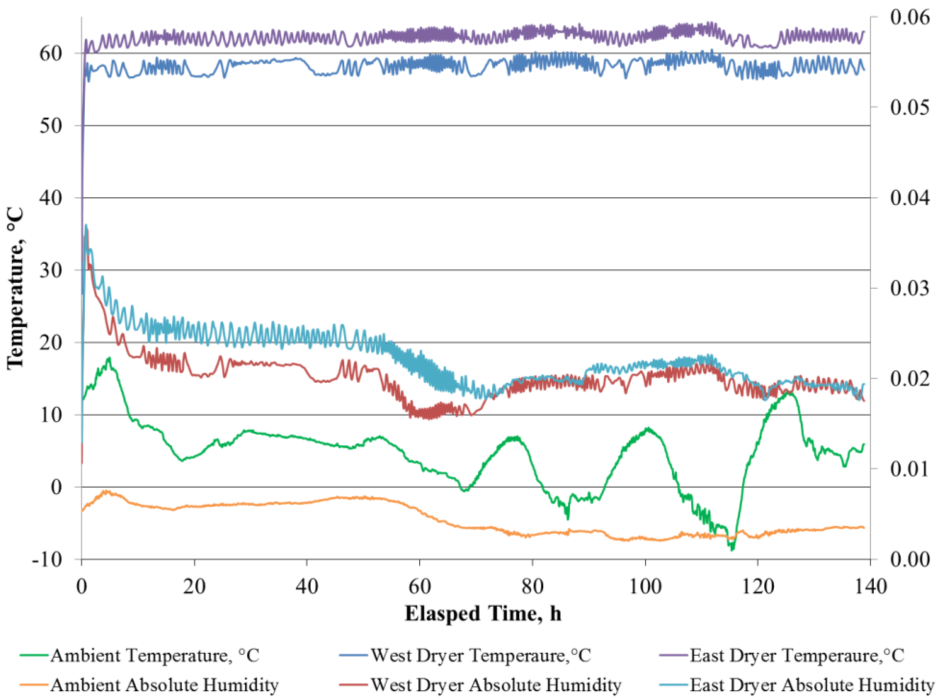

Figure 52. Dryer and ambient temperature and absolute humidity data recorded during drying set six.

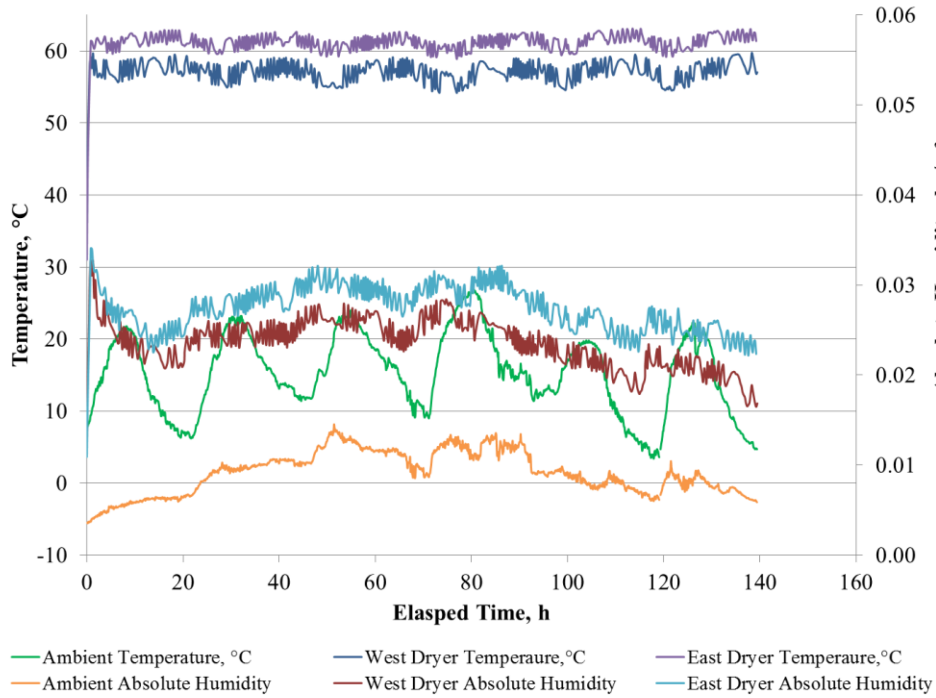

Figure 53. Dryer and ambient temperature and absolute humidity data recorded during drying set seven.

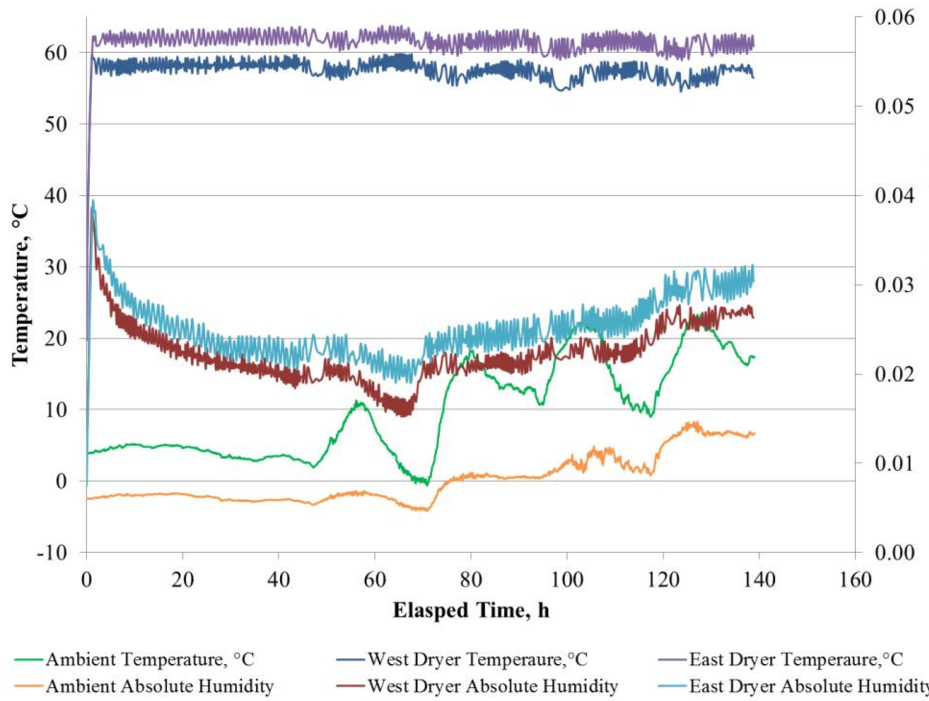

Figure 54. Dryer and ambient temperature and absolute humidity data recorded during drying set eight.

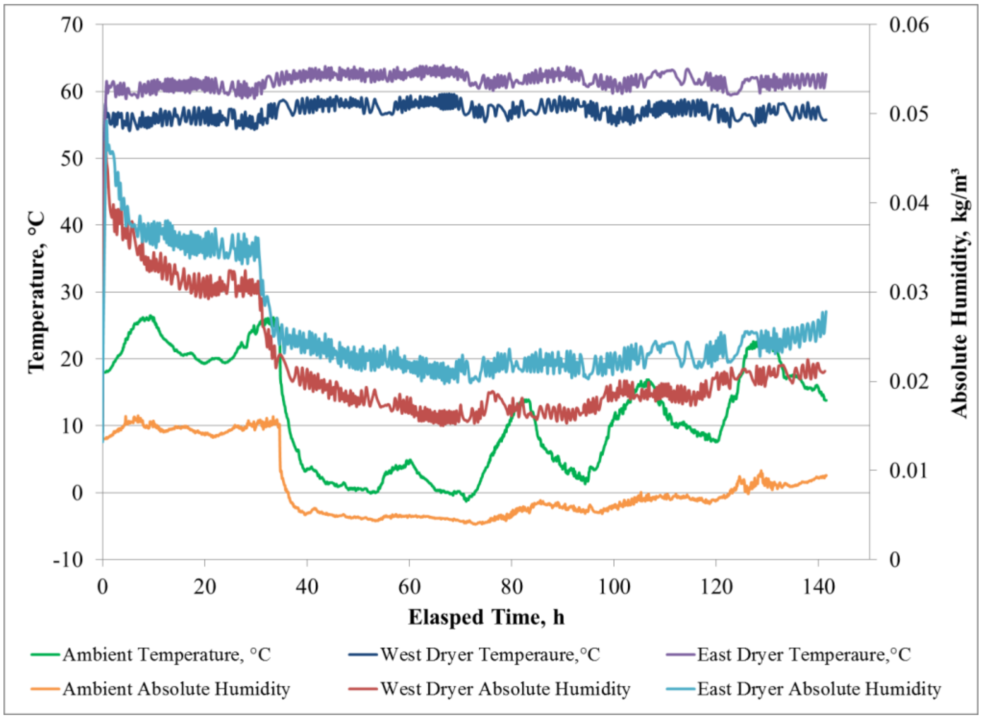

Figure 55. Dryer and ambient temperature and absolute humidity data recorded during drying set nine.

APPENDIX H: Thin-Layer Drying Rate Coefficients

Moisture equilibrium, drying rates, and drying rate coefficients for the fluted, chisel, and "V" impeller conditioner treatments were provided in Appendix H. The moisture equilibrium values were used for the respective drying rate determination for each sample. The drying rate coefficients were determined using nonlinear regression analysis on the experimental data. The drying rate coefficients were reported with the standard error value according to ASABE S448.

Table 29. Moisture equilibrium levels for the fluted conditioner thin-layer drying tests at a drying temperature at 60°C and 0.02 kg/m^3 absolute humidity.

Feed Rate, t/h·m	Roll-to-Roll Pressure, kPa	Moisture Equilibrium, % d.b.
8.9	3450	0.80
8.9	3450	1.10
8.9	3450	1.00
8.9	6900	1.10
8.9	6900	1.30
8.9	6900	1.20
8.9	10300	0.60
8.9	10300	1.30
8.9	10300	0.80
13.3	3450	1.70
13.3	3450	0.90
13.3	3450	1.20
13.3	6900	0.60
13.3	6900	3.10
13.3	6900	1.00
13.3	10300	0.80
13.3	10300	1.10
13.3	10300	0.70
Feed Rate	F-Value	0.66
	P-Value	0.44
Pressure	F-Value	1.17
	P-Value	0.34

Table 30. Moisture equilibrium levels for the impeller conditioner thin-layer drying tests at a drying temperature at 60°C and 0.02 kg/m^3 absolute humidity.

Type	Shield Gap, cm	Feed Rate, t/h·m	Impeller Speed, rpm	Moisture Equilibrium, % d.b.
Chisel	0.6	8.9	800	1.50
	0.6	8.9	800	1.80
	0.6	8.9	800	2.70
	0.6	8.9	1000	2.20
	0.6	8.9	1000	1.50
	0.6	8.9	1000	1.40
	0.6	13.3	800	2.00
	0.6	13.3	800	2.00
	0.6	13.3	800	1.30
	0.6	13.3	1000	1.70
	0.6	13.3	1000	1.60
	0.6	13.3	1000	1.80
	5.7	8.9	800	2.10
	5.7	8.9	800	1.20
	5.7	8.9	800	2.10
	5.7	8.9	1000	1.70
	5.7	8.9	1000	1.60
	5.7	8.9	1000	1.40
	5.7	13.3	800	1.70
	5.7	13.3	800	2.30
	5.7	13.3	800	1.50
	5.7	13.3	1000	1.90
	5.7	13.3	1000	1.20
	5.7	13.3	1000	1.80
“V”	1.9	8.9	800	1.40
	1.9	8.9	800	1.80
	1.9	8.9	800	2.60
	1.9	8.9	1000	1.80
	1.9	8.9	1000	1.20
	1.9	8.9	1000	1.40
	1.9	13.3	800	1.60
	1.9	13.3	800	1.50
	1.9	13.3	800	1.10
	1.9	13.3	1000	2.40
	1.9	13.3	1000	1.20
	1.9	13.3	1000	1.40
	7.0	8.9	800	2.40
	7.0	8.9	800	1.60
	7.0	8.9	800	1.30

Table 30. Moisture equilibrium levels for the impeller conditioner thin-layer drying tests at a drying temperature at 60°C and 0.02 kg/m^3 absolute humidity, cont'd.

Type	Shield Gap, cm	Feed Rate, t/h·m	Impeller Speed, rpm	Moisture Equilibrium, % d.b.
	7.0	8.9	1000	1.80
	7.0	8.9	1000	1.20
	7.0	8.9	1000	1.20
	7.0	13.3	800	1.30
	7.0	13.3	800	2.10
	7.0	13.3	800	1.50
	7.0	13.3	1000	1.20
	7.0	13.3	1000	1.50
	7.0	13.3	1000	1.10
	Type	F	2.63	
		P-Value	0.11	
	Gap	F	0.66	
		P-Value	0.42	
	Feed Rate	F	0.66	
		P-Value	0.42	
	Speed	F	3.68	
		P-Value	0.06	

Table 31. Thin-layer drying rate coefficients for the fluted conditioner treatments at a drying temperature of 60°C and 0.02 kg/m^3 absolute humidity.

Feed Rate, t/h	Roll-to-roll Pressure, kPa	K	Standard Error	N	Standard Error	R^2
8.9	3450	0.153	0.002	0.928	0.006	0.998
8.9	3450	0.122	0.001	1.017	0.004	0.999
8.9	3450	0.161	0.001	0.964	0.002	1.000
8.9	6900	0.203	0.002	0.923	0.004	0.999
8.9	6900	0.118	0.001	1.122	0.003	1.000
8.9	6900	0.119	0.001	1.063	0.003	1.000
8.9	10300	0.191	0.001	0.973	0.004	0.999
8.9	10300	0.146	0.001	1.068	0.004	0.999
8.9	10300	0.142	0.005	0.978	0.014	0.989
13.3	3450	0.112	0.002	1.061	0.006	0.999
13.3	3450	0.147	0.001	0.974	0.002	1.000
13.3	3450	0.127	0.001	0.991	0.003	0.999
13.3	6900	0.148	0.001	0.997	0.002	1.000
13.3	6900	0.191	0.004	1.093	0.012	0.998
13.3	6900	0.140	0.001	0.963	0.002	1.000
13.3	10300	0.140	0.001	0.975	0.002	1.000
13.3	10300	0.179	0.001	0.914	0.003	0.999
13.3	10300	0.079	0.001	1.128	0.004	1.000

Table 32. Thin-layer drying rate coefficients for the chisel conditioner treatments at a drying temperature of 60°C and 0.02 kg/m^3 absolute humidity.

Shield Height, cm	Feed Rate, t/h·m	Impeller Speed, rpm	K	Standard Error	N	Standard Error	R^2
0.6	8.9	800	0.111	0.002	0.764	0.005	0.992
0.6	8.9	800	0.097	0.002	0.767	0.004	0.993
0.6	8.9	800	0.093	0.001	0.796	0.003	0.997
0.6	8.9	1000	0.092	0.001	0.754	0.004	0.993
0.6	8.9	1000	0.080	0.001	0.787	0.004	0.993
0.6	8.9	1000	0.100	0.001	0.816	0.003	0.997
0.6	13.3	800	0.087	0.002	0.767	0.005	0.989
0.6	13.3	800	0.097	0.001	0.751	0.003	0.995
0.6	13.3	800	0.078	0.001	0.864	0.005	0.995
0.6	13.3	1000	0.109	0.001	0.745	0.003	0.995
0.6	13.3	1000	0.102	0.001	0.786	0.004	0.995
0.6	13.3	1000	0.077	0.001	0.833	0.004	0.995
5.7	8.9	800	0.075	0.001	0.809	0.005	0.993
5.7	8.9	800	0.059	0.001	0.904	0.006	0.993
5.7	8.9	800	0.074	0.001	0.826	0.004	0.995
5.7	8.9	1000	0.086	0.002	0.821	0.005	0.993
5.7	8.9	1000	0.060	0.001	0.895	0.004	0.996
5.7	8.9	1000	0.060	0.001	0.919	0.006	0.993
5.7	13.3	800	0.094	0.002	0.836	0.005	0.994
5.7	13.3	800	0.088	0.002	0.740	0.005	0.988
5.7	13.3	800	0.069	0.001	0.861	0.004	0.996
5.7	13.3	1000	0.071	0.001	0.828	0.004	0.996
5.7	13.3	1000	0.077	0.001	0.869	0.005	0.995
5.7	13.3	1000	0.085	0.001	0.841	0.002	0.999

Table 33. Thin-layer drying rate coefficients for the "V" conditioner treatments at a drying temperature of 60°C and 0.02 kg/m^3 absolute humidity.

Shield Height, cm	Feed Rate, t/h·m	Impeller Speed, rpm	K	Standard Error	N	Standard Error	R^2
1.9	8.9	800	0.062	0.001	0.897	0.004	0.997
1.9	8.9	800	0.092	0.001	0.807	0.003	0.996
1.9	8.9	800	0.098	0.002	0.858	0.007	0.991
1.9	8.9	1000	0.101	0.001	0.769	0.004	0.996
1.9	8.9	1000	0.113	0.001	0.845	0.004	0.997
1.9	8.9	1000	0.086	0.001	0.858	0.005	0.995
1.9	13.3	800	0.129	0.001	0.745	0.003	0.996
1.9	13.3	800	0.101	0.001	0.804	0.004	0.995
1.9	13.3	800	0.092	0.001	0.908	0.005	0.997
1.9	13.3	1000	0.106	0.001	0.734	0.003	0.997
1.9	13.3	1000	0.103	0.002	0.827	0.005	0.995
1.9	13.3	1000	0.093	0.001	0.865	0.004	0.998
7.0	8.9	800	0.072	0.002	0.983	0.008	0.994
7.0	8.9	800	0.116	0.001	0.799	0.003	0.998
7.0	8.9	800	0.089	0.001	0.844	0.004	0.997
7.0	8.9	1000	0.120	0.001	0.756	0.004	0.996
7.0	8.9	1000	0.104	0.001	0.873	0.003	0.998
7.0	8.9	1000	0.103	0.002	0.829	0.005	0.995
7.0	13.3	800	0.096	0.001	0.861	0.004	0.998
7.0	13.3	800	0.154	0.002	0.810	0.006	0.995
7.0	13.3	800	0.114	0.002	0.769	0.004	0.995
7.0	13.3	1000	0.102	0.001	0.882	0.002	0.999
7.0	13.3	1000	0.094	0.001	0.808	0.004	0.995
7.0	13.3	1000	0.091	0.002	0.879	0.005	0.996

Table 34. Analysis of variance for predicted drying times to achieve a moisture ratio level of 0.10 for the fluted conditioner.

Parameter	Degrees of Freedom	F-Value	P-Value
Model	4	174.68	<0.01
Feed Rate	1	1.30	0.27
Pressure	2	1.85	0.19

Table 35. Analysis of variance for predicted drying times to achieve a moisture ratio level of 0.20 for the fluted conditioner.

Parameter	Degrees of Freedom	F-Value	P-Value
Model	4	163.92	<0.01
Feed Rate	1	1.31	0.27
Pressure	2	1.55	0.25

Table 36. Analysis of variance for predicted drying times to achieve a moisture ratio level of 0.10 for the chisel conditioner.

Model with interactions			
Parameter	Degrees of Freedom	F-Value	P-Value
Model	5	227.22	<0.01
Gap	1	0.05	0.82
Feed Rate	1	0.00	0.96
Speed	1	0.83	0.37

Table 37. Analysis of variance for predicted drying times to achieve a moisture ratio level of 0.20 for the chisel conditioner.

Parameter	Degrees of Freedom	F	P-Value
Model	5	276.42	<0.01
Gap	1	0.06	0.80
Feed Rate	1	0.04	0.85
Speed	1	0.70	0.41

Table 38. Analysis of variance for predicted drying times to achieve a moisture ratio level of 0.10 for the “V” conditioner.

Parameter	Degrees of Freedom	F-Value	P-Value
Model	5	145.71	<0.01
Gap	1	3.01	0.10
Feed Rate	1	0.21	0.65
Speed	1	0.11	0.75

Table 39. Analysis of variance for predicted drying times to achieve a moisture ratio level of 0.20 for the “V” conditioner.

Parameter	Degrees of Freedom	F-Value	P-Value
Model	5	177.73	<0.01
Gap	1	3.27	0.09
Feed Rate	1	0.15	0.70
Speed	1	0.27	0.61

VITA

Elizabeth Arlene Miller

Candidate for the Degree of

Master of Science

Thesis: CONDITIONER EFFECTIVENESS ON THE DRYING RATE OF HIGH ENERGY FORAGE SORGHUM

Major Field: Biosystems & Agricultural Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Biosystems & Agricultural Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2013.

Completed the requirements for the Bachelor of Science in Biosystems & Agricultural Engineering at Oklahoma State University, Stillwater, Oklahoma in 2002.

Experience:

July 2010-Present
Research Engineer, Biosystems & Agricultural Engineering Department
Oklahoma State University, Stillwater, Oklahoma

June 2002-July 2010
Project Engineer-Mechanical Design of Mattress Manufacturing Equipment
Leggett & Platt, Inc., Carthage, Missouri

Professional Memberships:

National Society of Professional Engineers
Oklahoma Society of Professional Engineers
American Society of Agricultural and Biological Engineers
Gamma Sigma Delta
Alpha Epsilon
Tau Beta Pi