EFFECTS OF A HYDRAULIC PRESSURE SYSTEM AND GROOVED ROLLERS ON AN IN-FIELD SWEET SORGHUM PRESS

By

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EFFECTS OF A HYDRAULIC PRESSURE SYSTEM AND GROOVED ROLLERS ON AN IN-FIELD SWEET SORGHUM PRESS

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Dedicated to the memory of my grandfathers…

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NOMENCLATURE

D	Mean diameter (m, mm)
e	Roll gap (mm)
E10	Blend of 10% ethanol and 90% gasoline
kg	Kilogram
L	Roller length (mm)
MPa	Megapascal
M_s	Weight basis moisture content of stalks (%)
m_j	Mass of juice from a single repetition (kg)
mm	Millimeters
m_s	Mass of stalks from a single repetition (kg)
n_M	Maximum rotational speed (RPM)
OSU	Oklahoma State University
P	System hydraulic pressure (MPa)
P2	Hydraulic pressure applied to the second roller (MPa)
P3	Hydraulic pressure applied to the third roller (MPa)
r	Mean roller radius (mm)
Roll gap	Minimum vertical distance between two roller surfaces (mm)
RPM	Rotations per minute

PP2	Projected pressure of the second roller (MPa)
PP3	Projected pressure of the third roller (MPa)
t	Thickness of incoming layer of stalks (mm)
V_M	Maximum tangential velocity (meters per minute)
α	Statistical significance level (%)
β	Projected width of roller in contact with stalks
η	Pressing Efficiency (%)
ρ	Radius of hydraulic cylinder (mm)

CHAPTER I

STATEMENT OF THE PROBLEM

There is a clear and present need for renewable energy sources. The Renewable Fuel Standard states that 36 billion gallons (136.3 billion liters) of the annual liquid fuels used in the United States must come from renewable sources by 2022, with 21 billion gallons (79.5 billion liters) being derived from sources other than corn starch (US Government, 2007). The United States and the European Union have both committed themselves to increasing renewable and sustainable energy sources (US Government, 2007; European Commission, 2008). Examples of renewable and sustainable energy sources include solar power, windmills, hydroelectric dams, and biofuels. Biofuels have been of particular interest in recent years, especially given that worldwide oil demand was greater than the available supply in 2006 and 2007 (EIA, 2009). It is unlikely that a single source of biofuels will completely replace petroleum, but a diversified portfolio of biofuel sources can offset the need for petroleum.

One of the most common forms of biofuel is ethanol, which can be blended with gasoline. The most common mixture of ethanol and gasoline, E10, is composed of 90% gasoline and 10% ethanol. This mixture has been approved by every US auto maker for every make and model using a gasoline engine (Growth Energy, 2009). With a modified engine, pure ethanol can perform better than pure gasoline (RFA, 2009). There have been cars in Brazil capable of using 100% ethanol fuel since 1979 (Best Cars, 2000).

A tropical climate, abundant sugar cane, and progressive government policies have made ethanol a part of Brazil’s fuel infrastructure for the past thirty years (Rohter, 2006). The Brazilian model has been studied for possible use in the US with corn replacing sugar cane. This has caused considerable concern over the use of a food crop as a fuel source. Many people worry that this will raise food costs and that the US does not produce enough corn to meet its fuel needs. This has led many US researchers to explore alternative sources of ethanol feedstocks, such as soybeans (Barret, 2007), sweet and grain sorghum (Michaels, 2007; Welch, 2007; Wilmoth, 2007), and switchgrass (Micheals, 2007; Willmoth, 2007).

Recently, much work has been done at Oklahoma State University (OSU) regarding the production of ethanol from sweet sorghum. Sweet sorghum is an attractive biofuel feedstock because it can be grown on land which would not support corn production. Mr. Lee McClune (President, Sorganol® Production Co. Inc, Knoxville, IA, www.sorganol.com) devised a process for the production of ethanol from sweet sorghum (Kundiyana, 2006). This process involves harvesting juice from sweet sorghum stalks in the field, fermenting the juice on-site, and distilling the fermented juice into fuel grade ethanol (Kundiyana, 2006). In-field juice extraction and on-site fermentation are used in McClune’s process to prevent the degradation of the juice. The in-field juice extraction is carried out with McClune’s (2008a) patented sweet sorghum harvester.

McClune also provided OSU researchers with a small sorghum press for experiments involving in-field pressing of sweet sorghum. As seen in Figure 1.1, this press was composed of six smooth surfaced rollers arranged in pairs. The bottom three rollers were fixed in place while the vertical positions of the top three rollers were adjusted using long threaded rods attached to the bearing housings on each end of the rollers' central shafts.

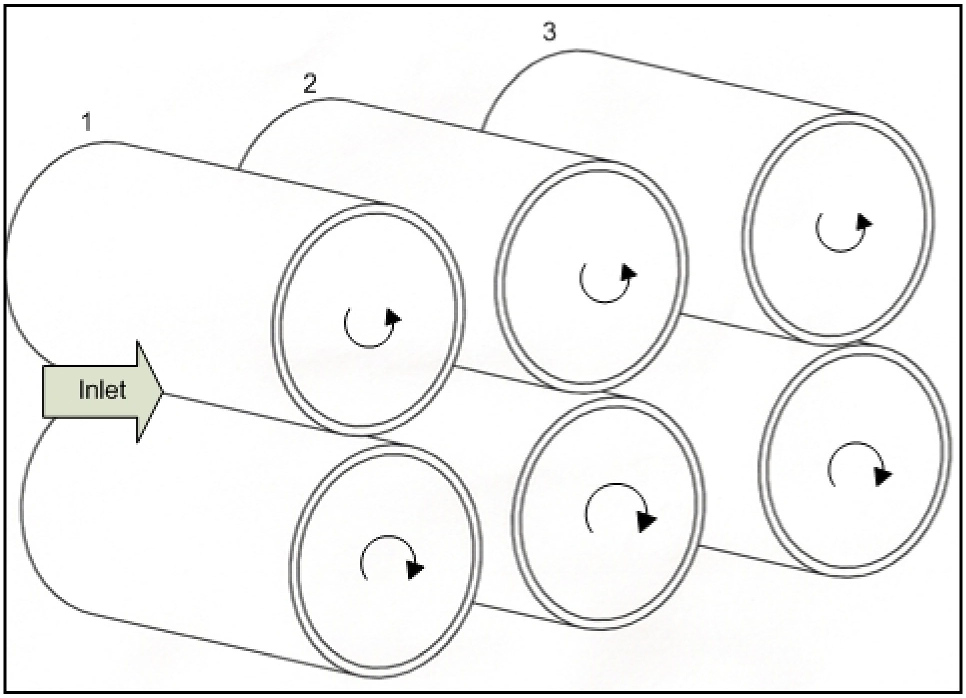

Figure 1.1: Configuration of original rollers

This design was capable of extracting juice from sweet sorghum stalks, but it had a number of problems, with the most significant being that the machine often became plugged with crushed stalks. These plugs would then have to be manually cleared, causing downtime. Additionally, the smooth rollers failed to grip incoming stalks from time to time unless the stalks were manually forced into the first roll gap. Another problem was the relatively high moisture content of the crushed stalks, or bagasse, exiting the press. The bagasse being noticeably wet led to speculations that pressing efficiency could be improved.

1.1 Research Objectives

Given the shortcomings of the press, the primary goals of this research were to redesign components of the in-field sweet sorghum press in order to address the issues of throughput and low pressing efficiency. These goals were further broken down into the following specific objectives:

1. Redesign the rollers for better grip on sweet sorghum stalks
2. Redesign rollers for better juicing efficiency
3. Design a system to allow rollers to move vertically to prevent plugging
4. Compare the efficiencies of the redesigned and original rollers

CHAPTER II

REVIEW OF LITERATURE

Sweet sorghum has long been known to be an excellent source of sugar (NAS, 1882), which can easily be fermented and distilled into fuel grade ethanol (Cardno, 2008; Neale, 2008; Sabater, 2008; Zenk, 2008). The primary factor keeping sweet sorghum from competing with corn as a fuel crop is the lack of an established production method (Neale, 2008; Robinson, 2007). Mechanically harvesting sweet sorghum requires a either a specialized harvester capable of extracting the sugary juice from the stalks in the field (McClune, 2008a) or a modified sugar cane harvester and a large nearby pressing facility (Hugot, 1986). The juice must be quickly moved to a fermenter to prevent degradation of the sugars in the juice.

The centralized pressing facility model has a juicing efficiency which ranges from 70 to over 90% (Hugot, 1986; Monroe et al, 1984) but would be prohibitively expensive to put in place, and it would require either a high degree of cooperation between growers or a large investment from an independent pressing company. The in-field juice extraction model has a lower juicing efficiency of 30 to 50%, but it would allow the initial cost to be easily spread among several independent growers. However, there is no commercially available machinery capable of pressing sweet sorghum juice in the field (Neale, 2008; Robinson, 2007; Zenk, 2008).

2.1 Patent Search

Due to similarities between sweet sorghum and sugar cane, improvements in the OSU in-field sweet sorghum press were the result of evaluating sugar milling technology. A patent search was conducted both to evaluate the state of sugar milling technology and to ensure that no existing patents would be infringed.

2.1.1 US Pat. 5273512: Mill Feeder Roll

This roller design employed a semi-smooth outer shell, a series of juice channels beneath this shell, and removable slotted inserts which cap the holes in the outer shell, leading to the juice channels (Ducasse, 1993). Ducasse (1993) designed this roller to be paired with another roller of similar design in order to "force feed" a standard sugar mill. At the core of the roller was a shaft surrounded by a tube. This pipe had a series of ribs radiating out from it, with plates connecting the flanges. These plates formed the semi-smooth roller surface. Rectangular holes were cut into these flanges for the removable slotted inserts. The inserts capped a series of small tubes which led to the pipes used for juice channels. When sugar cane passed between the two rollers, juice was forced through the slotted inserts into the juice channels (Ducasse, 1993), which helped prevent the juice from absorbing back into the mat of incoming sugar canes. The two rollers were designed such that one would have protruding flanges while the other would have recessed flanges, allowing the two rollers to be loosely meshed and aided in feeding.

2.1.2 US Pat. 3969802: Mill Roll

Bouvet (1976) claimed to have improved upon the basic grooved mill roller by including a system of channels under the surface of the roller and holes in the surface leading to these channels. This was designed to decrease the reabsorption of juice into the mat of canes being pressed. This roller's grooves had roughened walls to prevent slippage of material passing through the press (Bouvet, 1976). Bouvet (1976) further claimed that increasing the size of the juice channels toward the edges of the roller would further decrease reabsorption, and that making the holes in the outer shell increase in diameter as they approached the juice channels would decrease plugging of the holes.

2.1.3 US Pat. 4391026: Mill Roll

Casey and Ducasse's (1983) claims were similar to those of Bouvet (1976). Their design featured V-shaped grooves, juice channels, and a series of holes leading to the juice channels (Casey and Ducasse, 1983). The goal was once again to decrease reabsorption of juice in to the cane mat. This roller's juice channels did not change in cross section, and were described as circular channels running parallel to the axis of the roller. This design also differs from that of US Patent No. 369802 (Bouvet, 1976) in that it includes removable inserts placed into the surface of the roller at the top of the holes leading to the inner juice channels. These inserts can be replaced without removing the roller from the mill, thus reducing down time if they become damaged (Casey and Ducasse, 1983).

2.1.4 US Pat. 4546698: Mill Roll with Increased Juice Flow Capacity

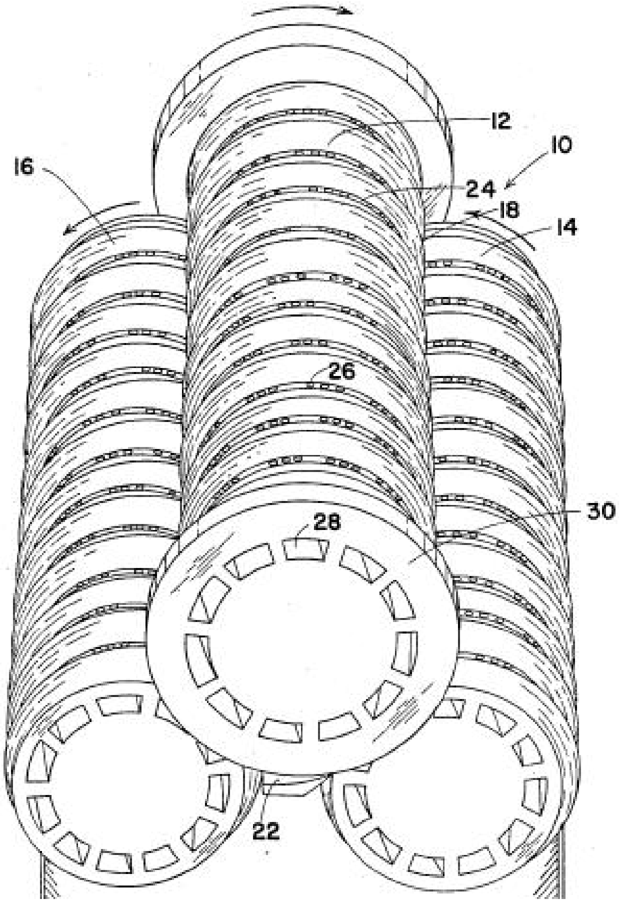

Figure 2.1: Drawing of mill rollers with V grooving and subsurface juice channels (Bouvet, 1985)

Bouvet (1985) designed a mill roller with a series of juice channels beneath a grooved roller surface with a series of holes in the surface leading to the channels, as seen in Figure 2.1. This roller primarily differed from previous designs (Casey and Ducasse, 1983; Bouvet, 1976) in that the juice channels were in a spiral configuration with regard to the axis of the roller. This allowed multiple juice channels to be present in the roll gap of the press at the same time (Bouvet, 1985) in an effort to prevent reabsorption.

2.1.5 US Pat. 4989305: Sugar Cane Mill Roller

Pole and Dhavlikar (1991) outlined the design of a mill roller with a series of juice channels beneath the surface of a grooved roller. This design featured holes in the outer surface drilled at multiple angles leading into juice channels below the roller surface. This design further included a vacuum system which connected to the juice channel present in the roll gap through a novel end plate configuration (Pole and Dhavlikar, 1991). All of these improvements to the standard grooved roller were designed to reduce juice reabsorption by providing multiple juice pathways and increasing juice velocity in the channels.

2.1.6 US Pat. 4407111: Infield Mobile Syrup Extractor

Brune and Schmidt (1983) designed an in-field press composed of a two roller crusher and a three roller mill. The crusher rollers were similar to the ones designed by Ducasse (1993), except that both rollers had protruding flanges and round surfaces, similar to a Krajewski crusher (Hugot, 1986). The three roller mill was composed of two bottom rollers and one larger top roller. The front and top roller were specified as grooved, and the rear roller was described as being smooth (Brune and Schmidt, 1983). A bagasse chopper/blower was placed after the final mill roller. There was a juice collection bin below the mill section with a pipe connected to the bottom. Juice from this collection bin was to be pumped into a separate collection tank.

2.1.7 US Pat. 4168660: Sugar Mill

Zelle (1979) designed a four roller sugar mill. All of the rollers had radial V grooves. The rollers were arranged such there was one front roller, two center rollers placed one above the other, and one rear roller (Zelle, 1979). Material entered vertically from the top. It then passed between the front roller and the top middle roller, then between the two middle rollers, then between the rear roller and the bottom middle roller. Material then exited the mill vertically downward. With sufficient framework, a tandem of these mills could be set up vertically. This would reduce the tandem's footprint to that of only one mill. This would allow sugar milling plants to be built on smaller plots of land.

2.1.8 US Pat. 6039276: Apparatus & Method for Crushing Sugar Cane

Hatt et al. (2000) designed a sugar mill composed of sets of two grooved rollers meshed with one another. These rollers were arranged such that cane could move vertically downward through the press. The rollers had radial V grooves with juice channels, or messchaerts, cut into their surfaces (Hatt et al., 2000). This design also incorporated scrapers to remove material stuck in the grooves and messchaerts of the rollers. Hatt et al. (2000) called for multiple sets of rollers to be set up in tandem. Being a vertical mill, this design allowed for a smaller footprint than standard sugar mills, much like Zelle's (1979) design.

2.2 Handbook of Cane Sugar Engineering

Much of the redesign of the OSU in-field sweet sorghum press was based on recommendations from the Handbook of Cane Sugar Engineering (Hugot, 1986). The chapters on crushers and mills were of particular usefulness to this research. In these chapters, Hugot (1986) described the design process of rollers used to crush and mill sugar cane in explicit detail.

2.2.1 Overview of Sugar Milling

Before being milled, sugar canes are crushed and shredded (Hugot, 1986). The canes are first crushed by large rollers to release the pithy inner portion from the tough outer shell, releasing 40 to 80% of the juice in the cane in the process (Hugot, 1986). After being crushed, the canes pass through a shredder which opens up the cell walls to release more sugar. A typical shredder can open 80 to 90% of the cell walls of the canes (Hugot, 1986). Once the cell walls are opened, the shredded canes pass through a series of three-roller mills, referred to as a tandem. The pitch of the rollers within the tandem often decreases linearly for the first three mills and remains constant thereafter (Hugot, 1986). An example of this setup would be 40 x 50 mm for the first mill, 20 x 25 mm for the second mill, and 10 x 13 mm for each additional mill. A typical tandem is composed of between three and eight mills (Hugot, 1986). Applied hydraulic pressures as high as 11 MPa are common in sugar milling (Hugot, 1986). These applied pressures translate into projected pressures as high as 40 MPa. To further aid in sugar extraction, water or dilute juice is sprayed onto the shredded canes to dissolve out the remaining sugar. Once the canes pass through a sugar mill, more than 90% of the juice has been extracted (Hugot, 1986).

2.2.2 Roller Design

There are two types of rollers used in sugar production: crusher and mill rollers (Hugot, 1986). Both roller types have circumferential V grooving, with the main differences being the pitch and “chevron grooves,” which can be seen in Figure 2.2. Crusher rollers typically have a coarser, deeper pitch than mill rollers (Hugot, 1986; Meade-Chen, 1977). This allows for greater variation in input. The “chevron grooves” are grooves cut into the V grooving which spiral around the longitudinal axis. Often, two grooves are cut in opposite directions starting at opposite ends of the roller, meeting in a wide V, or chevron, shape in the center of the roller. These grooves create sharp edged tooth-like shapes in the V grooving which help feed material through the crusher and into the mills (Hugot, 1986).

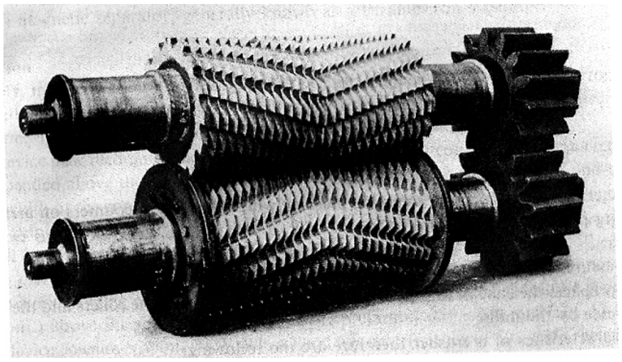

Figure 2.2: Crusher rollers with chevron grooves and circumferential V grooves (Hugot, 1986)

Roller grooving pitch depends upon the type and size of the roller, and the material being fed into the roll gap (Hugot, 1986). For crushers, Hugot suggested setting the pitch to 0.075D, where D is the mean diameter of the roller and pitch is defined as the distance from tip to tip on two adjacent grooves. Hugot (1986) went on to state that this may not always be practical, and that many sugar producers tend to size the pitch of these rollers in proportion to the feedstock, citing several examples of appropriate sizes. For mill rolls, Hugot (1986) pointed out that pitch often decreases from the first mill to the final mill in a train, giving several examples from around the world. The reason for transitioning from coarse to fine grooving is that finer grooving tends to have higher efficiency but poorer feeding characteristics. As the cane passes through the mills, it becomes more homogenized and feeding becomes less of an issue. The depth of the grooves is typically equal or nearly equal to the pitch (Hugot, 1986). This helps prevent material from becoming stuck in the grooves.

There are three types of roller grooving used in sugar milling: top, bottom, and universal (Hugot, 1986). Top and bottom rollers are used together while universal rollers serve as both top and bottom. In a non-universal setup, the center of a top roller is chosen to be either the highest or lowest point in a groove, and the corresponding bottom roller is the opposite. This allows the rollers to mesh together. It also allows rollers with different pitches to be used together if the pitches are an integer multiple of one another (Hugot, 1986). The center plane of a universal roller is placed at the midpoint of a groove slope, as represented by Plane A-A in Figure 2.3. This allows a single roller design to serve as both top and bottom roller by simply placing end A of the top roller on the same side as end B of the bottom roller (Hugot, 1986). Sugar producers tend to use non-universal rollers. Universal rollers require a symmetrical drive system, but this is not the typical setup for sugar mills. Sugar mills are typically driven by large gears mounted on one side of the rollers. Moving these massive gears from one side of a universal roller to the other would greatly reduce their convenience. Sugar millers also tend to use non-universal rollers because they can be used as replacement rollers anywhere in the mill train as long as all of the pitches are even multiples of one another (Hugot, 1986).

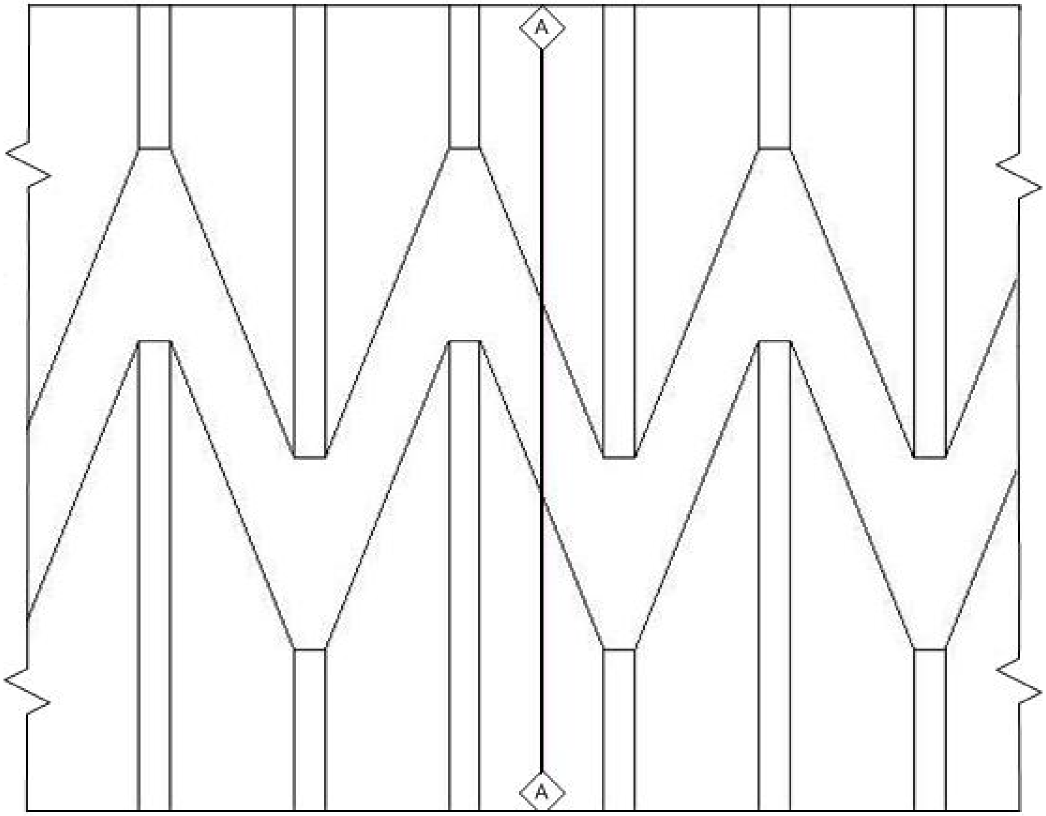

Figure 2.3: Center planes (A-A) of two meshed universal rollers

2.2.2 Machine Parameters

There are many parameters which must be considered when operating a sugar mill. Among the most important parameters are pressure on the rollers, maximum roller lift, roll gap, and speed (Hugot, 1986). Finding the proper settings for these parameters is generally regarded as both an art and a science (Hugot, 1986). Direct mathematical solutions are often impossible to achieve (Hugot, 1986, 1986; Meade-Chen, 1977), and the machine must be set using empirical data from trial runs.

In most sugar mills, the top roller has hydraulic cylinders attached to each end (Hugot, 1986, 1986; Meade-Chen, 1977). A force is applied to these cylinders, using either hydraulics or pneumatics, which crushes the sugar cane while also allowing the top roller to move upward to avoid plugging when throughput is high (Hugot, 1986, 1986; Meade-Chen, 1977). There are many theoretical factors which can be considered when setting the mill pressure, but the optimum pressure in practice is often held to be the maximum pressure attainable without encountering frequent plugging.

Many of the other parameters are typically set in a similar manner. The maximum roller lift is chosen such that it balances the need for foreign objects to occasionally pass through with the need to keep the roll gaps small for higher efficiency. Likewise, the minimum roll gap is chosen as small as possible, but large enough to prevent plugging (Hugot, 1986).

Speed in milling is either specified as rotational speed of the rollers or linear speed at the mean diameter of the rollers (Hugot, 1986). Hugot (1986) gives three empirical formulas used in industrial practice for maximum rotational speed (n_M) in rotations per minute (RPM) given mean diameter (D) in meters:

$$n_m = 6.37 - 1.83D \qquad \textbf{Equation 2.1}$$

$$n_m = \sqrt{67 - 21.4D^2} \qquad \textbf{Equation 2.2}$$

$$n_m = \frac{10.5}{D + 0.73}. \qquad \textbf{Equation 2.3}$$

The last of these formulas is only valid for diameters ranging from 0.6 to 1.5 meters. Hugot (1986) also lists one formula for maximum linear speed:

$$V_m = \frac{33D}{D + 0.73}, \qquad \textbf{Equation 2.4}$$

where V_M is maximum linear speed in meters per minute given diameter (D) in meters. Hugot (1986) noted that mill capacity tended to drop if peripheral speed was set above approximately 24 meters per minute.

CHAPTER III

METHODOLOGY

In order to improve throughput and efficiency, several new components were designed and tested. Two sets of circumferentially grooved rollers were designed according to practices from the sugar milling industry. A hydraulic pressure system was also added to the second and third top rollers. Since plugging was almost nonexistent in the first roll gap, a hydraulic pressure system was deemed unnecessary for this roller. Efficiency data was then gathered and analyzed using SAS® Version 9.1.3.

3.1 Design Process

After a review of the literature pertaining to the sugar milling industry, it was decided that the OSU in-field sweet sorghum press needed to be redesigned to include grooved rollers and a hydraulic pressure system. These modifications were expected to provide improved throughput and juicing efficiency. The hydraulic system was designed to allow the top rollers to move vertically while maintaining a constant force on the stalks. This allowed the press to accommodate larger stalks without plugging while maintaining juicing efficiency. The grooved rollers were expected to improve both throughput and juicing efficiency by increasing the degree to which the stalks were broken down.

3.1.1 Rollers

Hugot (1986) suggested that crusher roller grooving pitch and height should be equal to roughly .075 multiplied by the mean diameter of the roller. The press was originally equipped with 152-mm diameter smooth rollers. This would imply a maximum grooving of approximately 11.4 mm in pitch and height. Hugot (1986) also stated that roller grooving was sized relative to the size of the incoming cane, resulting in grooving as fine as 9.5 x 6.4 mm (pitch x height). This information led to the decision to use pitches between 12.7 x 12.7 mm and 6.4 x 6.4 mm for the new rollers. Budget limitations restricted the maximum number of grooved rollers to four out of the six total rollers. Based on the trend in the sugar milling industry to use progressively finer grooving along a mill train (Hugot, 1986), the first roller was redesigned to have 12.7 x 12.7 mm grooving, the second roller was redesigned for 6.4 x 6.4 mm grooving, and the third roller was left smooth. The pitches were set equal to the heights based on common sugar milling practice (Hugot, 1986).

Due to the geometry of the press frame and bearing housings, the rollers were limited to a 152-mm outer diameter. This made the mean diameter slightly different for each roller. The mean diameter is simply the algebraic average of the outer diameter and the diameter at the base of the grooving. The mean diameter is one of the roller measurements typically specified in the sugar milling industry (Hugot, 1986). The mean diameters of the redesigned rollers were 146 mm, 149 mm, and 152 mm for the front, middle, and rear roller pairs, respectively. The rollers were originally designed to all have a 152-mm mean diameter, but the cost of retooling the press to accommodate these rollers was deemed prohibitively high. In addition, the 4.2% maximum deviation to a

146-mm mean diameter from the ideal 152-mm roller diameter was considered tolerable.

Once the roller specifications were determined, the type of grooving was considered. Since the drive system of the OSU sweet sorghum press was much more symmetrical than that of a sugar mill, universal rollers were chosen. Since the press was never intended to operate with mixed pitch rollers, the interchangeability issues noted in the literature review were not an issue. In order to properly mesh the rollers, the rollers were arranged such that end A of each top roller was meshed with end B of the corresponding bottom roller, as shown in Figure 3.1. The grooved roller press configuration is shown in Figure 3.2, with detailed drawings in Appendix B.

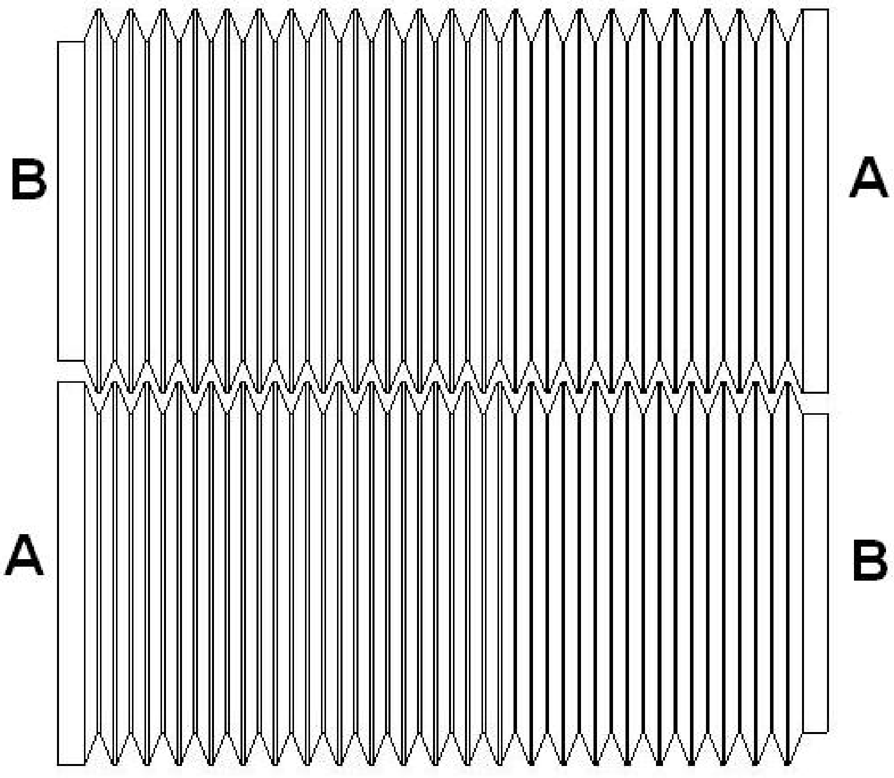

Figure 3.1: Meshed universal rollers with ends labeled

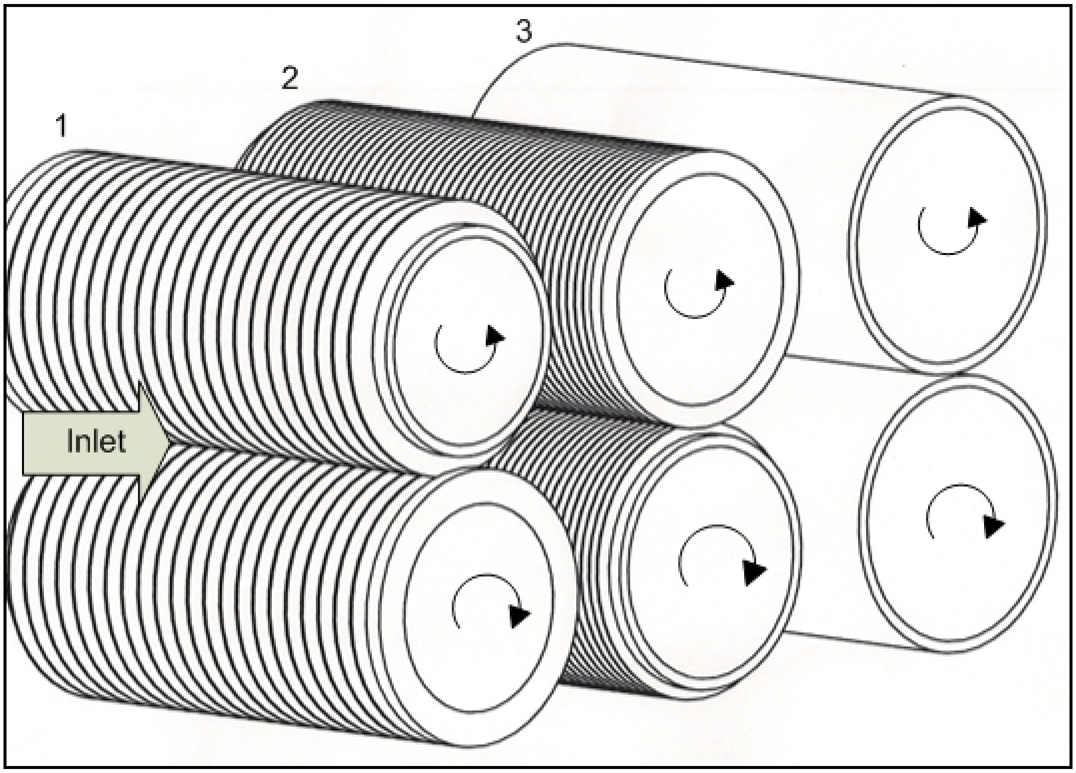

Figure 3.2: Configuration of redesigned rollers

The first and second sets of rollers shown in Figure 3.2 were manufactured using the drawings in Appendix B. Employees of the OSU Biosystems and Agricultural Engineering Laboratory fabricated the rollers from mild steel tubing using custom made lathe tooling. The tubing used to produce the first rollers had a wall thickness of 19 mm and an outer diameter of 152 mm. The tubing used to produce the second rollers also had an outer diameter of 152 mm, but had 13-mm thick walls. This provided a 6-mm thick steel cylinder attached to the base of the grooving of both grooved roller sets for structural rigidity.

3.1.2 Hydraulic Pressure System

The primary plugging locations in the press prior to the redesign were in the roll gaps of the second and third sets of rollers. In order to reduce this plugging, the second and third top rollers were fitted with hydraulic cylinders at each end. These cylinders were sized such that they could provide approximately 13 kN of total force, based on a recommendation from McClune (2008b). The resulting cylinders had a 51 mm bore and were rated for pressures up to 6.9 MPa. These cylinders were capable of producing 13 kN of force per roller at a pressure of 3.4 MPa. The pressure control system designed by Mr. Wayne Kiner of the OSU Biosystems and Agricultural Engineering Laboratory (Figure 3.3) had a minimum controllable pressure of 1.7 MPa, and the hydraulic pressure supply unit had a maximum pressure of 6.2 MPa. This yielded a range of selectable forces of approximately 8 to 25 kN per roller.

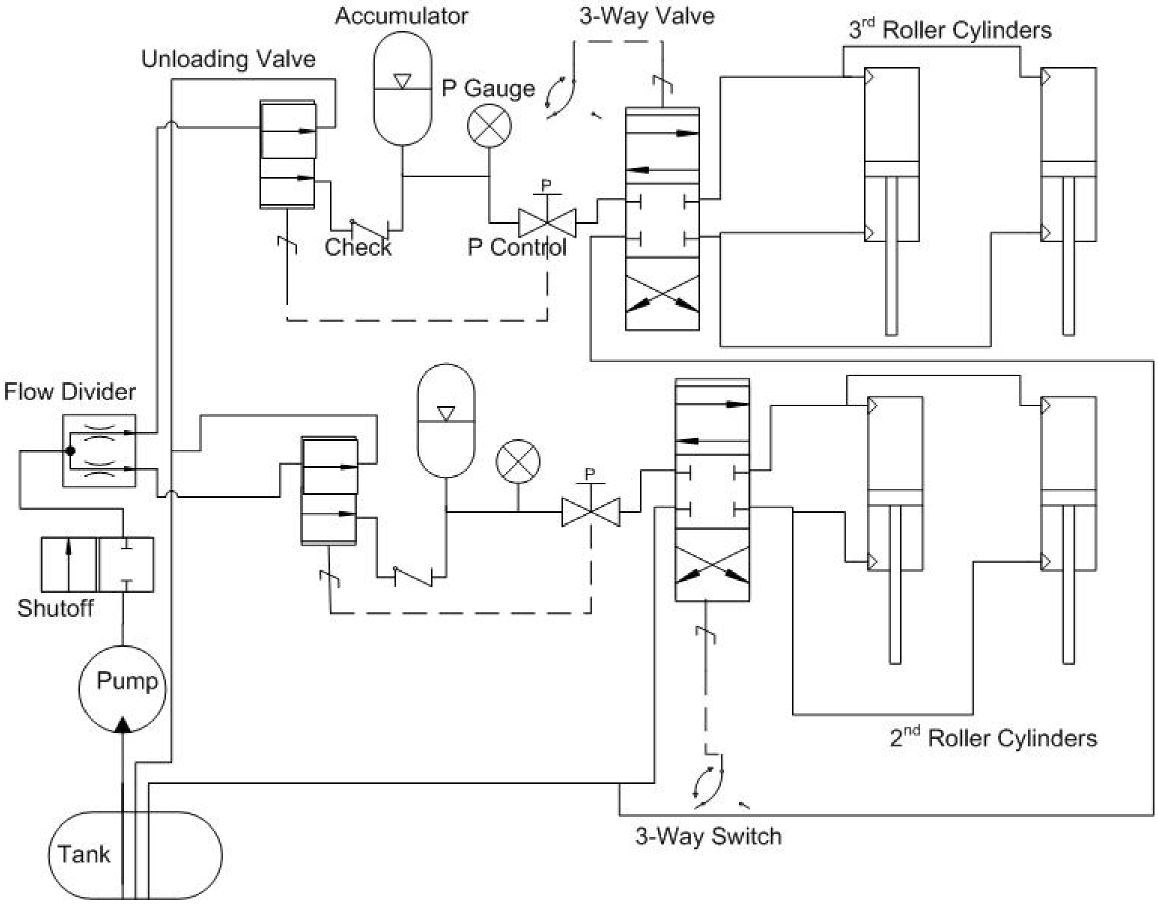

Figure 3.3: Schematic of the hydraulic pressure system

The pressure system consisted of a portable gasoline-powered hydraulic power pack connected to two hydraulic circuits, as shown in Figure 3.3. Each hydraulic circuit contained of a set of hydraulic rams, an accumulator, a pressure adjustment valve, and an electrically actuated control valve. The electrically actuated valves were designed to allow the user to open the rollers to their maximum vertical position to allow a plug to pass through by flipping a switch on the front of the machine.

3.2 Data Collection

All data was collected using the second planting of M81 variety sweet sorghum at the OSU EFAW plots in Stillwater, Oklahoma, during the month of October, 2008. This experimental design was developed to reduce variability in the data by isolating several variables. By having only a single value for variety, planting, month, roll gap, lift, rotational speed, and location, the chances of variability due to the effects of these variables was reduced. While some of these variables may have an effect on efficiency, those effects were not the focus of this research. Time constraints prevented testing of the press in its original configuration.

3.2.1 Efficiency

There is no clear consensus regarding the definition of efficiency for this type of press. For this study, juicing efficiency is defined as the percentage of total liquids removed from the stalks. The formula which was used for efficiency throughout this research was:

$$\eta = \frac{m_j}{M_s m_s}, \qquad \textbf{Equation 3.1}$$

where m_j was the mass of juice collected, M_s was the wet-basis gravimetric moisture content of whole stalks, and m_s was the mass of whole stalks before being pressed. Mass of whole stalks and volume of juice was directly measured for each repetition (see Appendix A). Moisture content of the whole stalks was measured each day that stalks were pressed using representative whole stalks. These stalks were cut into approximately 0.3-m lengths, weighed, dried for several weeks, and weighed again. The difference in the two weights divided by the pre-drying weight was the moisture content of the stalks. The mass of juice was obtained by multiplying the volume of juice from each pressing by the average density of sweet sorghum juice, 1.05 kg/l (Bellmer, 2009). This efficiency term was chosen rather than one of the sugar content based efficiency terms used in the sugar milling industry because it is less dependent upon external factors like plant physiology, and was thus a better representation of the efficiency of the press.

3.2.2 Juice Extraction

Enough stalks for an entire day's pressing were cut prior to pressing. The stalks were gathered into approximately 13.6-kg bundles and weighed. Each bundle was assigned a treatment. Each treatment was repeated at least three times. Due to the amount of time required to change rollers, not all treatments could be tested on the same day. Grooved rollers were tested at various pressure combinations, then the press was refitted with smooth rollers, then the smooth rollers were tested at various pressure combinations within the next 7 days.

A single treatment was defined as a combination of three variables: pressure on the second roller (P2), pressure on the third roller (P3), and roller type. These pressures represent the hydraulic pressures used as machine settings. For the purposes of analysis, these pressures were converted into projected pressures (PP2 and PP3) using a modified form of Equation 10.6 from Hugot (1986):

$$PP = \frac{2\pi\rho^2 P}{\beta L}$$ **Equation 3.2**

$$\beta = \sqrt{r^2 - (r - \frac{t-e}{2})^2} \ ,$$ **Equation 3.3**

where PP is the applied force divided by the projected area normal to the force under the portion of the roller in contact with the stalks, P is the system hydraulic pressure, ρ is the radius of the hydraulic cylinders, β is the width of the roller section in contact with stalks, L is the length of the roller, r is the mean radius of the roller, t is the thickness of the incoming stalks, and e is the roll gap. This is represented schematically in Figure 3.4. Due to the degree of variation in pressure noted when pressing, all PP values were rounded to the nearest 0.5 MPa and should be treated as nominal values. The actual projected pressures were distributed about the nominal values and varied by plus or minus a maximum of 0.5 MPa.

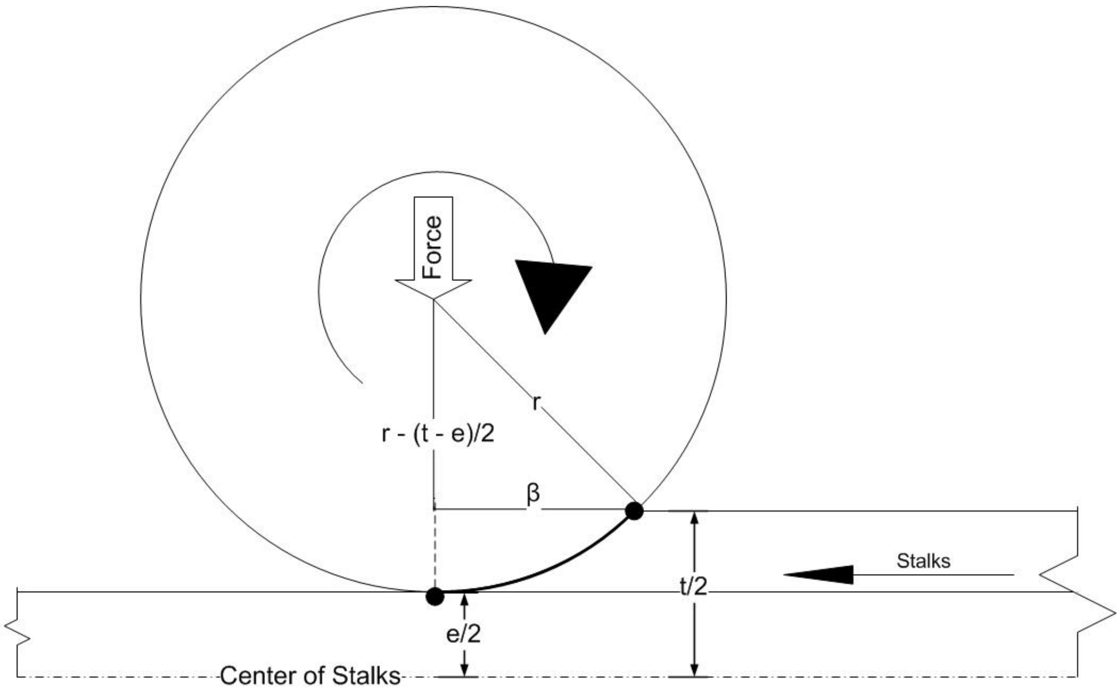

Figure 3.4: Diagram of parameters used in calculating projected pressures

Not all combinations of variables were possible due to issues with plugging. Initial testing showed that plugging was primarily an issue when P3 was set higher than P2. Other possible treatments were omitted due to lack of available stalks and time. These treatments involved setting P3 to the open position, and were not of particular interest. The open position was used to approximate a pressure equal to zero. This was achieved by reversing flow in the hydraulic rams in order to raise a top roller to its maximum height, thereby creating the largest possible roll gap for that set of rollers.

Treatments were assigned a random order, and all three repetitions of each treatment were performed before moving to the next treatment. For each repetition, a bundle of stalks was fed through the press at a rate of one to five stalks at a time, depending on stalk diameter. This was done in an attempt to keep a constant volume of stalks in the press for the duration of the each repetition. Once all of the stalks passed through the press, the drip pan was scraped of all plant matter and remaining juice. All of the juice fell into the drip pan, was strained through a plastic mesh, and was collected in a bucket. After each repetition, the contents of the plastic mesh were squeezed in order to collect the juice trapped therein. The volume of the juice was then measured using a graduated cylinder.

3.3 Statistical Analysis

All of the data was entered into an Excel spreadsheet in order to calculate efficiencies using Equation 3.1, as shown in Appendix A. Once efficiencies had been calculated, these numbers were entered into SAS® along with their corresponding treatments. Each treatment was entered in as three separate variables. Efficiency was modeled as a function of P2, P3, roller type, and all of the corresponding two and three way interactions using the Mixed Model Procedure in SAS® (proc Mixed). This initial analysis revealed no significant three-way interaction ($F=1.35$, $p=0.2711$), but it indicated that all two-way interactions were significant.

The presence of these interactions meant that none of the main effects could be considered. Instead, the average efficiencies of all of the treatments were compared using the Ryan-Einot-Gabriel-Welsch (REGW) multiple range test in SAS®, which preserved experiment-wise error rate. This test arranged the treatments from highest to lowest mean efficiency and enumerated which groups were not significantly different ($\alpha=0.05$). These results were somewhat difficult to interpret directly due to the number of treatments and the interactions between them, so the average efficiencies were entered into an Excel spreadsheet, and smoothed-line X-Y charts were constructed for the following cases: PP2=0, PP2=PP3, PP2= 4.5 MPa, PP3=1.5 MPa, and PP3=3 MPa. These five cases were chosen because they each showed some behavior of interest, as outlined in Chapter IV. The effects seen in these cases were evaluated using the Slice command within the Mixed Procedure in SAS®. The data was sliced such that the presence of an effect of any one variable could be evaluated for given values of the other two variables.

In order to gain further insight into the data, a Least Significant Difference (LSD) t-test was performed. The results of this test were used to construct a grouping diagram similar to the output of the REGW test. Experiment-wise error rate was not preserved in the LSD test. The SAS® code used to evaluate the data can be found in Appendix C.

CHAPTER IV

FINDINGS

The effects of redesigning the press on throughput and feeding were immediately apparent, but the effects on efficiency required careful data analysis. The grooved rollers had feeding properties which were vastly superior to the smooth rollers. Less force was needed to get stalks into the press, and the press would actually self-feed if stalks of a small enough diameter were left too close to the first roll gap. The hydraulic pressure system greatly reduced the number and severity of plugs. Very few plugs required manual removal; most plugs were removed simply by switching the rollers between the open and closed positions.

4.1 Efficiency

The effects of the treatments on efficiency were complicated by the interactions between roller type, PP1, and PP2. The results of the REGW and LSD multiple comparison tests are shown in Table 4.1. The REGW groupings represent a conservative analysis which preserved the experiment-wise error rate and significance level of 0.05. The LSD test showed more differences in the treatments, essentially breaking each of the top three REGW groupings into two or three smaller groupings. However, it should be noted that these groupings carry with them a significantly higher experiment-wise error rate than the REGW groupings.

Table 4.1: Statistical groupings of treatment efficiencies

Treatment (PP2-PP3-Roll) (MPa)	Mean Efficiency	REGW Grouping	LSD Grouping
4.5-3-Grooved	44.13%	A	A
4.5-3-Smooth	43.26%	A	A
3-3-Grooved	43.18%	A	A
4.5-4.5-Grooved	40.80%	A B	A B
3-3-Smooth	38.05%	A B C	B C
1.5-1.5-Grooved	37.90%	A B C	B C
4.5-1.5-Smooth	37.23%	A B C	B C
4.5-4.5-Smooth	36.60%	A B C	B C D
4.5-1.5-Grooved	34.95%	B C	C D E
3-1.5-Smooth	34.80%	B C	C D E
0-3-Grooved	34.30%	C	C D E
1.5-1.5-Smooth	32.23%	C	D E
0-1.5-Smooth	31.46%	C	E
0-3-Smooth	31.30%	C	E
0-1.5-Grooved	31.06%	C	E
3-1.5-Grooved	30.30%	C	E
0-0-Smooth	16.56%	D	F
0-0-Grooved	6.43%	E	G

Table 4.1 shows the compiled results of the REGW test and the LSD test. There are three treatments which appear in only the A group for both tests: 4.5-3-Grooved, 4.5-3-Smooth, and 3-3-Grooved. The other treatments in the A groups also appear in the B groups, and are not significantly different from those treatments at the α=0.05 level. This was highly unexpected. The 4.5-4.5 MPa pressure groups were expected to yield the highest efficiency, but that behavior was not observed. These results seem to indicate that simply increasing pressure may not yield higher efficiencies. This was likely caused by increased plugging when PP3 was at the 4.5 MPa level. Each plug required pressure to be momentarily removed from the cylinders, thereby reducing the pressing efficiency.

4.1.1 Slice Analysis

Table 4.2: Slice Effects

Slice	PP2 (MPa)	PP3 (MPa)	Roller Type	F Value	Pr > F
1*	0	0	-	20.45	<0.0001
2	0	1.5	-	0.03	0.8592
3	0	3	-	2.05	0.1603
4*	1.5	1.5	-	6.4	0.0156
5	3	1.5	-	3.51	0.0684
6*	3	3	-	7.76	0.0082
7	4.5	1.5	-	0.83	0.3677
8	4.5	3	-	0.15	0.701
9	4.5	4.5	-	3.51	0.0684
10*	0	-	Grooved	92.53	<0.0001
11*	0	-	Smooth	30.56	<0.0001
12*	3	-	Grooved	39.4	<0.0001
13	3	-	Smooth	2.4	0.1291
14*	4.5	-	Grooved	6.73	0.0031
15*	4.5	-	Smooth	5.39	0.0085
16*	-	1.5	Grooved	4.66	0.0071
17	-	1.5	Smooth	2.74	0.0564
18*	-	3	Grooved	12.47	<0.0001
19*	-	3	Smooth	16.74	<0.0001

*Statistically significant effect present

The slice tests in Table 4.2 provide information about the existence of an effect due to one variable while the other two variables are held constant. The entries marked with a hyphen represent the variable under consideration for each row. For example, the hyphen in the “Roller Type” column of the first line of the table (Slice 1) along with the asterisk after the slice number in the “Slice" column indicate that there is an effect due to roller type when both projected pressures are set to 0. As illustrated in Table 4.2 and the following charts, roller type only had a significant effect on pressing efficiency for three treatments. Significant effects due to projected pressures were observed in all but two slices when roller type is held constant. Slice 17 may have an effect on efficiency, but the result of the test was just outside of the α=0.05 detection level (F=2.74, p=0.0564).

4.1.1.1 Uniform Pressure

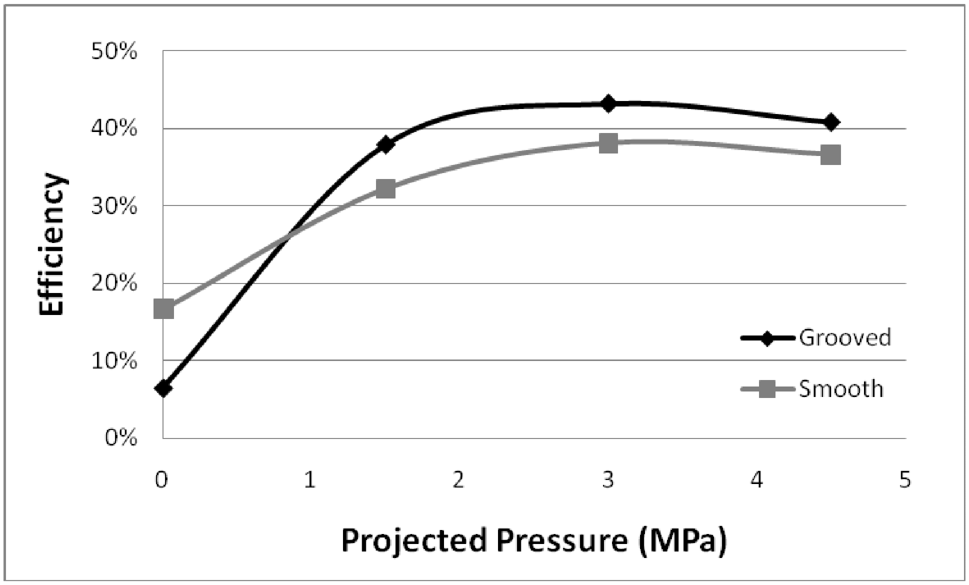

Figure 4.1: Mean pressing efficiency when pressure on the second roller (PP2) equals the pressure on the third roller (PP3)

Figure 4.1 shows effects on efficiency when PP1 and PP2 were set to the same value in each treatment. Increasing pressure under these conditions had a larger effect for the grooved rollers than the smooth rollers. This can be attributed to the fact that the first rollers lacked a vertical movement system. Having vertically fixed first rollers led to a smaller throat area for the smooth rollers than the grooved rollers for the same roll gap. Forcing the stalks through a smaller area led to a higher efficiency at the 0 MPa pressure condition. The 0 pressure treatments effectively removed the second and third rollers; almost no juice was observed from stalks passing through these rollers in the open position. As pressure increased from 0 to 1.5 MPa, pressing efficiency increased for both roller types. Above 1.5 MPa, only marginal improvements were noted for each roller type. Roller type had a significant effect on efficiency at every uniform projected pressure except 4.5 MPa, as seen in Slices 1, 4, 6, and 8 in Table 4.2. This implies that the two roller types respond differently to uniform pressure conditions below 4.5 MPa.

4.1.1.2 Open Second Roller

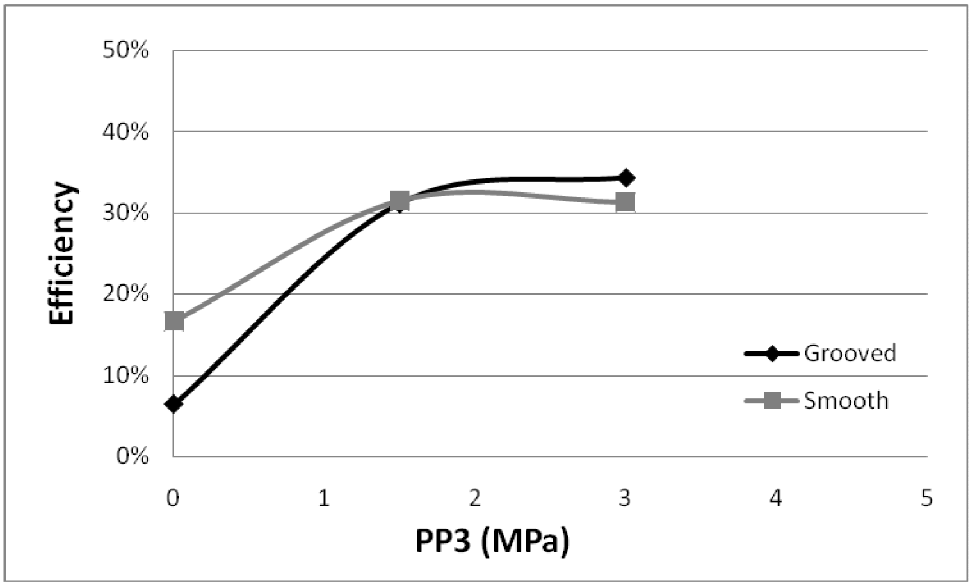

Figure 4.2: Efficiency with the second rollers set to maximum gap and varied pressure on the third roller (PP3)

An attempt was made to isolate the effect of the third roller by removing pressure from the second roller. This was based on the assumption that roller type and the two pressures were independent variables. The interactions found in the statistical analysis invalidated this assumption, but some valuable data was still gathered from this experiment, as shown in Figure 4.2. The shapes of these curves are similar to those in Figure 4.1, but Slices 1, 2, and 3 in Table 4.2 indicated that roller type only had a significant effect at the uniform 0-pressure condition. Slices 10 and 11 (Table 4.2) indicated a significant effect due to PP3 for both roller types. These results imply that the rollers responded almost identically to conditions when PP2 was set to 0 and PP3 was above 0. Efficiency improved when PP3 was raised from 0 to 1.5 MPa, but raising the pressure from 1.5 to 3 MPa yielded no significant change (α=0.05). This test was not run at the 4.5 MPa level due to severe plugging.

4.1.1.3 Constant Single Pressures

In order to better understand the interactions between PP2, PP3, and roller type, graphs were constructed with either PP2 or PP3 held constant. These graphs show that the interactions are complex. No clear explicit relation between all three variables appears to exist.

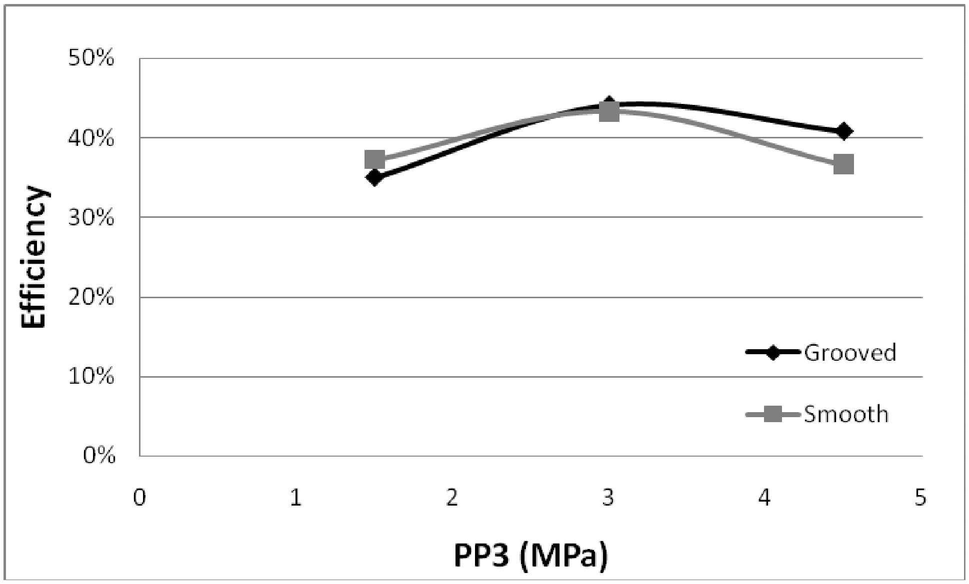

Figure 4.3: Efficiency due to 4.5 MPa on the second roller (PP2) and varied pressure on the third roller (PP3)

When PP2 was held constant at 4.5 MPa, both roller types behaved in the same manner according to Slices 7, 8, and 9 (Table 4.2). Slices 14 and 15 (Table 4.2) indicated that manipulating PP3 had a significant effect for both roller types. Figure 4.3 shows that efficiency increased marginally as PP3 was increased from 1.5 to 3 MPa. When PP3 was increased from 3 to 4.5 MPa, efficiency decreased slightly. This drop in efficiency was likely caused by increased plugging at high pressures. As mentioned in Section 4.1, this plugging was caused by the excess pressure not allowing the roller to lift properly over larger stalks.

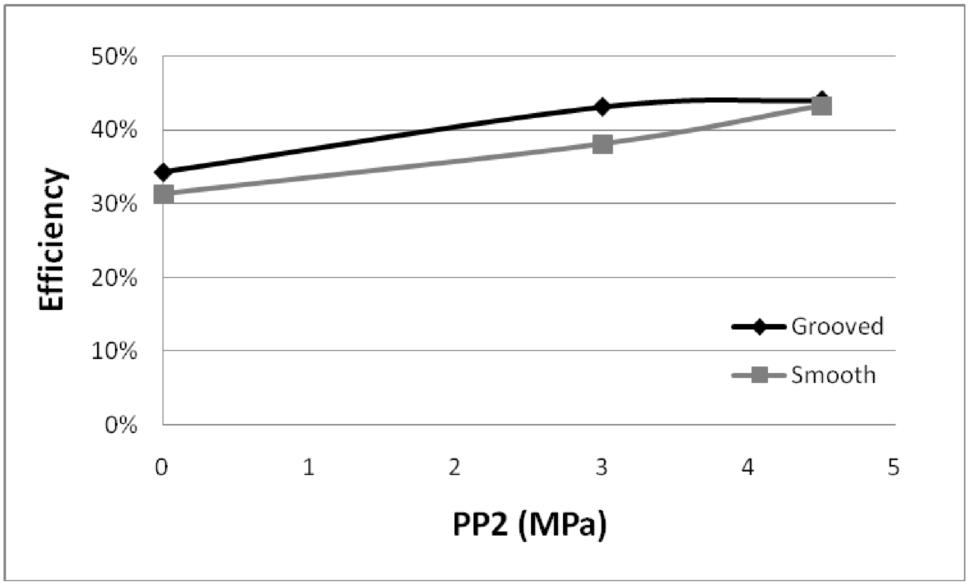

Figure 4.4: Efficiency due to 3 MPa on the third roller (PP3) and varied pressure on the second roller (PP2)

Slices 18 and 19 (Table 4.2) indicated a significant effect due to changes in PP2 for both roller types when PP3 was held constant at 3 MPa. Slices 3, 4, and 8 (Table 4.2) only indicated an effect due to roller type when PP2 and PP3 were both set to 3 MPa, indicating that the two types of rollers behaved in similar manners, but slightly differently at the 3 MPa level. As shown in Figure 4.4, increasing PP2 from 0 to 3 MPa yielded a significant increase in pressing efficiency for both roller types ($\alpha=0.05$). Further increasing the projected pressure gave a marginal increase in efficiency when using smooth rollers, but provided no change in efficiency when using grooved rollers.

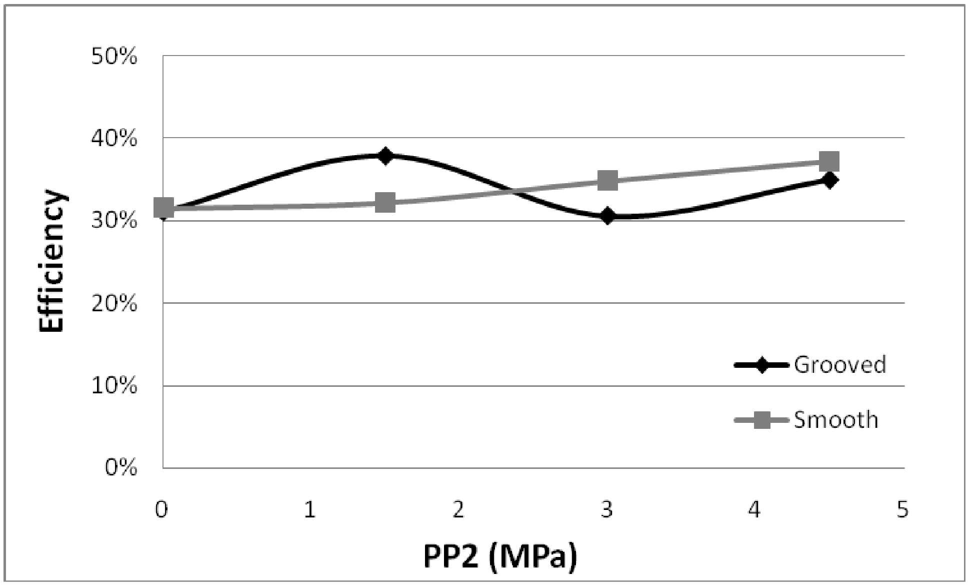

Figure 4.5: Efficiency due to 1.5 MPa on the third roller (PP3) and varied pressure on the second roller (PP2)

Holding PP3 constant at 1.5 MPa while varying PP2 provided highly unexpected results, as seen in Figure 4.5. Increasing PP2 only had a marginal effect for smooth rollers in these conditions (F=2.74, p=0.0564). Efficiency appeared to behave erratically with increasing pressure when using grooved rollers, but an effect due to roller type was only observed when PP2 was set to 1.5 MPa (Slices 2, 5, 5, and 7 in Table 4.2), indicating that both roller types behaved in a similar manner for all values of PP2 except 1.5 MPa.

4.2 Energy and Power Requirements

While not the focus of this research, energy and power requirements are always important when discussing machinery. The OSU in-field sweet sorghum press was powered by a 4.5-kW gasoline engine, and the hydraulic system was powered by a 3.7-kW gasoline engine. The maximum total power requirement was therefore 8.2-kW. The power estimate equations provided by Hugot (1986) were not used in this analysis because they required too many parameters which were not applicable to this press. A conservative estimate of energy consumption based on field observations would be approximately 0.15 kW-hr per kg of stalks crushed. This estimate is based on a 13.6 kg sample, a 15-minute pressing time, and both engines supplying their maximum power. The actual energy usage was often lower than this, because neither engine was run at full throttle during most pressings; only the hydraulic power pack's engine was run at full throttle during treatments involving 4.5 MPa projected pressures.

CHAPTER V

CONCLUSIONS

The goals of this research were to improve throughput and maximize efficiency. The grooved rollers and pressure system greatly reduced the frequency and severity of plugging. Both roller types exhibited plugging when PP3 was set to a higher value than PP2. The grooved rollers also increased the gripping ability of the first set of rollers. The grooved rollers tended to have slightly higher efficiencies than the smooth rollers at non-zero pressures, with some exceptions. These results indicate that the optimum machine setting should include the grooved rollers. The pressures should be set such that PP2 is greater than or equal to PP3 to avoid plugging. These factors narrow the selection range of the optimum operating point to two treatments: 3-3-Grooved and 4.5-3-Grooved. Hugot (1986) stated that all mill power requirements except friction are directly proportional to the pressure applied to the rollers, so the optimum setup is clearly the one requiring the least hydraulic pressure in the highest efficiency groupings. For the OSU in-field sweet sorghum press, a projected pressure of 3 MPa should be applied to the second and third top rollers with grooved rollers installed in the first and second positions. Further study may be necessary to determine if grooves are necessary on the third pair of rollers or if hydraulic cylinders are necessary for the first top roller.

5.1 Fulfillment of objectives

The specific objectives of this research are listed in Section 1.1. The conclusions regarding those objectives are as follows:

1. The grooved rollers provided superior grip on the stalks.
2. The relationship between efficiency and roller type is dependent upon the forces exerted by the hydraulic system.
3. The hydraulic pressure system allows vertical movement and prevents plugging when properly configured.
4. The difference between the efficiencies of the roller types depends on the settings of the pressure system, with grooved rollers having a slightly higher efficiency at the optimum operating pressure.

5.2 Future Research

Further improvements to the press may be possible using techniques from the sugar milling industry. The following techniques presented by Hugot (1986) may improve the efficiency and throughput with few changes to the techniques or the press:

1. Shred or chop stalks before pressing
2. Add hydraulic cylinders to the first top roller
3. Convey exiting bagasse away from the press if the press is to remain stationary in the field
4. Cut Messchaert grooves into the bases of some roller grooves
5. Add a vacuum system to decrease reabsorption of juice into the stalks
6. Cut chevron grooves into the first set of rollers

7. Add a fourth set of rollers
8. Develop a method to estimate the sugar content of whole sweet sorghum stalks in the field

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APPENDICES

Appendix A.1: Foreword to Field Data

It should be noted that these data were collected using machine parameter pressures (P2 and P3) rather than projected pressures. The net effect is exactly the same, because projected pressure is directly proportional to the pressures in the press's hydraulic system. This is only true for this press because all of the rollers are of approximately the same diameter, and specific projected pressures were only reported within 0.5 MPa. Projected pressures of 0, 1.5, 3, and 4.5 MPa correspond with pressures in the press's hydraulic system of 0, 300, 600, and 900 psi respectively.

Treatments were labeled using a three digit alphanumeric code representing P2, P3, and roller type. For example, 96G represents the treatment in which P2=900, P3=600, and the roller type was grooved.

Appendix A.2: Field Data and Calculations

9-Oct	Trt	Total (lb)	Stalks (lb)	Juice (mL)	Juice (Gal.)	Juice (lb)	MC Stalks	Efficiency
	66G	41	30.5	3760	0.993	8.741	0.627	0.457
		42	31.5	3800	1.004	8.834	0.627	0.447
		40	29.5	3300	0.872	7.672	0.627	0.414
	00G	40	29.5	380	0.100	0.883	0.627	0.048
		41	30.5	480	0.127	1.116	0.627	0.058
		41	30.5	720	0.190	1.674	0.627	0.087
	06G	41	30.5	3000	0.793	6.974	0.627	0.364
		40	29.5	2760	0.729	6.416	0.627	0.347
		42	31.5	2700	0.713	6.277	0.627	0.318
	03G	42	31.5	2300	0.608	5.347	0.627	0.271
		42	31.5	2980	0.787	6.928	0.627	0.351
		44	33.5	2800	0.740	6.509	0.627	0.310
	33G	41	30.5	2940	0.777	6.835	0.627	0.357
		42	31.5	3400	0.898	7.904	0.627	0.400
		38	27.5	2820	0.745	6.556	0.627	0.380
	99G	42	31.5	3220	0.851	7.486	0.627	0.379
		39	28.5	3020	0.798	7.021	0.627	0.393
		40	29.5	3600	0.951	8.369	0.627	0.452
	96G	41	30.5	3800	1.004	8.834	0.627	0.462
		38	27.5	3200	0.845	7.439	0.627	0.431
		38	27.5	3200	0.845	7.439	0.627	0.431

Canvas: 10.5 lb

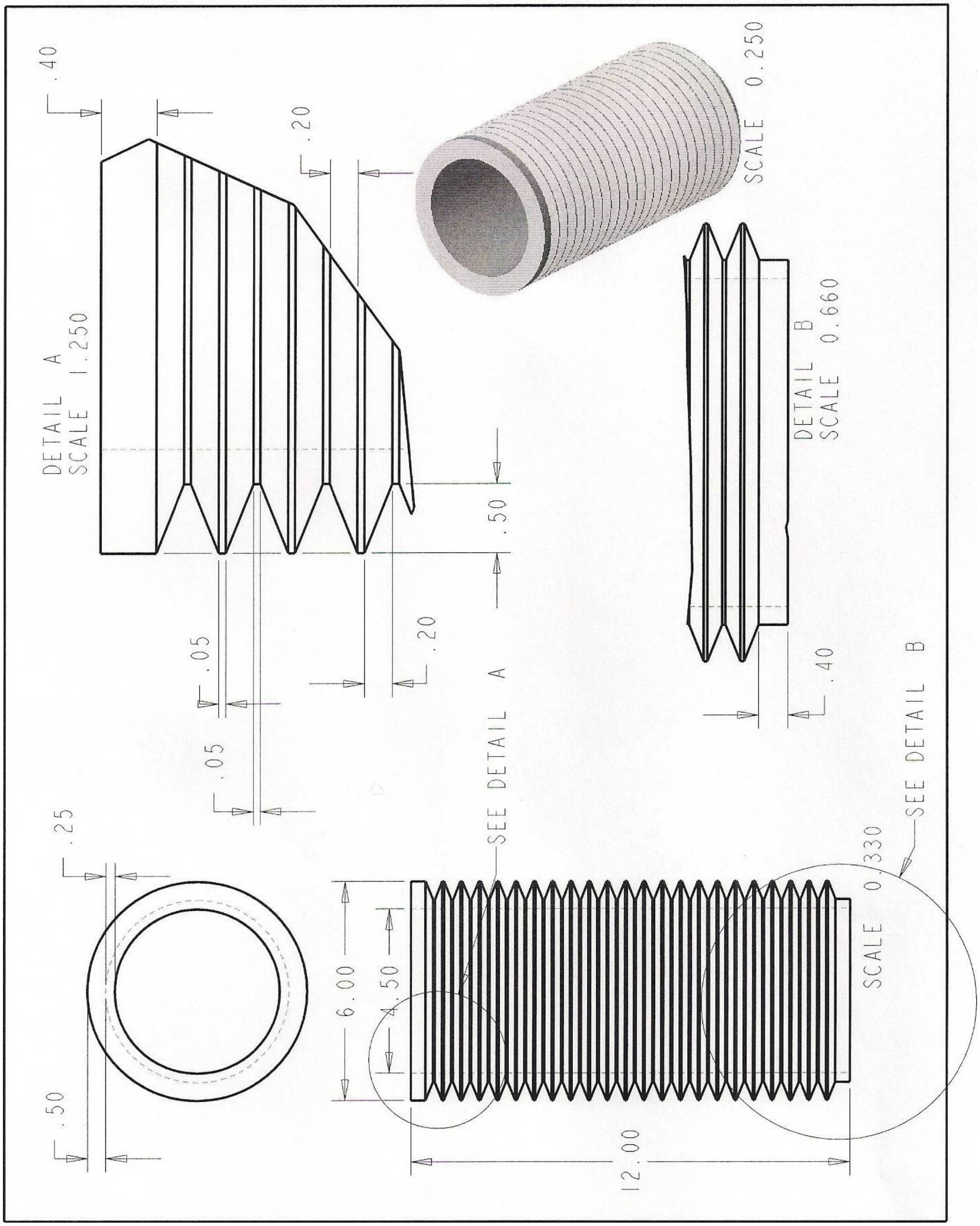
16-Oct	Trt	Total (lb)	Stalks (lb)	Juice (mL)	Juice (Gal.)	Juice (lb)	MC Stalks	Efficiency
	00S	41	30.5	1300	0.343	3.022	0.696	0.142
		42	31.5	1700	0.449	3.952	0.696	0.180
		41	30.5	1600	0.423	3.720	0.696	0.175
	93S	41	30.5	3200	0.845	7.439	0.696	0.351
		42	31.5	3700	0.977	8.601	0.696	0.393
		41	30.5	3400	0.898	7.904	0.696	0.373
	03S	42	31.5	3000	0.793	6.974	0.696	0.318
		42	31.5	2800	0.740	6.509	0.696	0.297
		41	30.5	3000	0.793	6.974	0.696	0.329
	33S	41	30.5	3240	0.856	7.532	0.696	0.355
		42	31.5	2950	0.779	6.858	0.696	0.313
		42	31.5	2820	0.745	6.556	0.696	0.299
	99S	42	31.5	3660	0.967	8.508	0.696	0.388
		41	30.5	2960	0.782	6.881	0.696	0.324
		41	30.5	3520	0.930	8.183	0.696	0.386
	63S	41	30.5	3320	0.877	7.718	0.696	0.364
		41	30.5		0.000	0.000	0.696	0.000
		41	30.5		0.000	0.000	0.696	0.000
	66S	40	29.5	3000	0.793	6.974	0.696	0.340
		40	29.5	3300	0.872	7.672	0.696	0.374
		41	30.5	3600	0.951	8.369	0.696	0.394
		42	31.5	3900	1.030	9.066	0.696	0.414
	96S	42	31.5	4200	1.110	9.764	0.696	0.446
		41	30.5	4000	1.057	9.299	0.696	0.438
		42	31.5	3900	1.030	9.066	0.696	0.414
	06S	41	30.5	2540	0.671	5.905	0.696	0.278
		42	31.5	3200	0.845	7.439	0.696	0.340
		42	31.5	3140	0.830	7.300	0.696	0.333
		42	31.5	2840	0.750	6.602	0.696	0.301

Canvas: 10.5 lb

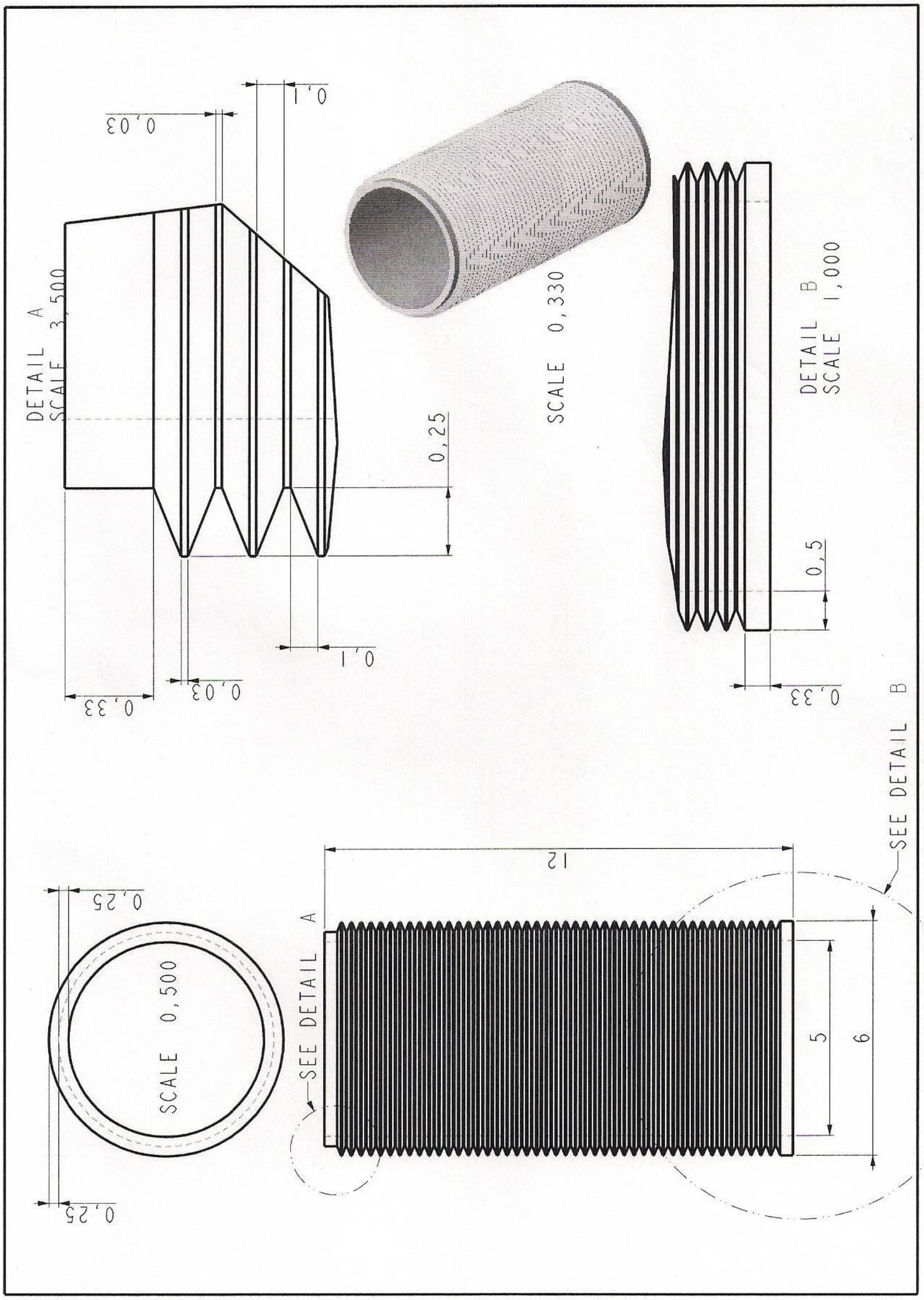
20-Oct	Trt	Total (lb)	Stalks (lb)	Juice (mL)	Juice (Gal.)	Juice (lb)	MC Stalks	Efficiency
	63G	35	24.5	2040	0.539	4.742	0.666	0.291
		35	24.5	1900	0.502	4.417	0.666	0.271
		35	24.5	2500	0.660	5.812	0.666	0.356
	93G	35	24.5	2300	0.608	5.347	0.666	0.328
		35	24.5	2600	0.687	6.044	0.666	0.371
	66G	35	24.5	3000	0.793	6.974	0.666	0.428
		35	24.5	2900	0.766	6.742	0.666	0.413

Canvas: 10.5 lb

Appendix B: Detailed Part Drawings



First Roller: All dimensions in inches



Second Roller: All dimensions in inches

Appendix C: SAS® Program

See Appendix A.1 for an explanation of treatment names.

```
options pageno=1;
data combined;
input trtmnt $ eff @@;
cards;

00G 0.048 00G 0.058 00G 0.087
00S 0.142 00S 0.180 00S 0.175
03G 0.271 03G 0.351 03G 0.310
03S 0.318 03S 0.297 03S 0.329
06G 0.364 06G 0.347 06G 0.318
06S 0.278 06S 0.340 06S 0.333 06S 0.301
33G 0.357 33G 0.400 33G 0.380
33S 0.355 33S 0.313 33S 0.299
63G 0.291 63G 0.271 63G 0.356
63S 0.364 63S 0.351 63S 0.329
66G 0.428 66G 0.413 66G 0.457 66G 0.447 66G 0.414
66S 0.340 66S 0.374 66S 0.394 66S 0.414
93G 0.328 93G 0.371
93S 0.351 93S 0.393 93S 0.373
96G 0.462 96G 0.431 96G 0.431
96S 0.446 96S 0.438 96S 0.414
99G 0.379 99G 0.393 99G 0.452
99S 0.388 99S 0.324 99S 0.386
```

```
data split;
input p2 $ p3 $ roll $ eff @@;
cards;

0 0 G 0.048 0 0 G 0.058 0 0 G 0.087
0 0 S 0.142 0 0 S 0.180 0 0 S 0.175
0 3 G 0.271 0 3 G 0.351 0 3 G 0.310
0 3 S 0.318 0 3 S 0.297 0 3 S 0.329
0 6 G 0.364 0 6 G 0.347 0 6 G 0.318
0 6 S 0.278 0 6 S 0.340 0 6 S 0.333 0 6 S 0.301
3 3 G 0.357 3 3 G 0.400 3 3 G 0.380
3 3 S 0.355 3 3 S 0.313 3 3 S 0.299
6 3 G 0.291 6 3 G 0.271 6 3 G 0.356
6 3 S 0.364 6 3 S 0.351 6 3 S 0.329
6 6 G 0.428 6 6 G 0.413 6 6 G 0.457 6 6 G 0.447 6 6 G 0.414
6 6 S 0.340 6 6 S 0.374 6 6 S 0.394 6 6 S 0.414
9 3 G 0.328 9 3 G 0.371
9 3 S 0.351 9 3 S 0.393 9 3 S 0.373
9 6 G 0.462 9 6 G 0.431 9 6 G 0.431
9 6 S 0.446 9 6 S 0.438 9 6 S 0.414
9 9 G 0.379 9 9 G 0.393 9 9 G 0.452
9 9 S 0.388 9 9 S 0.324 9 9 S 0.386




proc mixed data=split;
class p2 p3 roll;
model eff=p2 p3 roll p2*roll p3*roll p2*p3 p2*p3*roll /ddfm=satterth;
lsmeans p2*p3*roll/slice=(p2*p3 p2*roll p3*roll) diff;


proc glm data=combined;
class trtmnt;
model eff=trtmnt;
means trtmnt/regwq;
means trtmnt/lsd;

run;
quit;
```

Appendix D: SAS® Output

```
                    The Mixed Procedure

                     Model Information

Data Set                     WORK.SPLIT
Dependent Variable           eff
Covariance Structure         Diagonal
Estimation Method            REML
Residual Variance Method     Profile
Fixed Effects SE Method      Model-Based
Degrees of Freedom Method    Residual


               Class Level Information

  Class    Levels    Values

  p2            4    0 3 6 9
  p3            4    0 3 6 9
  roll          2    G S


                     Dimensions

         Covariance Parameters            1
         Columns in X                    54
         Columns in Z                     0
         Subjects                         1
         Max Obs Per Subject             57


               Number of Observations

     Number of Observations Read             57
     Number of Observations Used             57
     Number of Observations Not Used          0


                Covariance Parameter
                      Estimates

                Cov Parm     Estimate

                Residual     0.000753


                   Fit Statistics

        -2 Res Log Likelihood          -149.3
        AIC (smaller is better)        -147.3
        AICC (smaller is better)       -147.2
        BIC (smaller is better)        -145.7
```

```
                                   The Mixed Procedure

                             Type 3 Tests of Fixed Effects

                                    Num     Den
                      Effect         DF      DF    F Value    Pr > F

                      p2              3      39      17.14    <.0001
                      p3              3      39      91.38    <.0001
                      roll            1      39       0.19    0.6680
                      p2*roll         3      39       3.29    0.0305
                      p3*roll         3      39       9.86    <.0001
                      p2*p3           2      39       5.50    0.0079
                      p2*p3*roll      2      39       1.35    0.2711


                                   Least Squares Means

                                                  Standard
 Effect        p2    p3    roll    Estimate        Error      DF    t Value    Pr > |t|

 p2*p3*roll    0     0     G        0.06433      0.01584      39       4.06      0.0002
 p2*p3*roll    0     0     S         0.1657      0.01584      39      10.46      <.0001
 p2*p3*roll    0     3     G         0.3107      0.01584      39      19.61      <.0001
 p2*p3*roll    0     3     S         0.3147      0.01584      39      19.86      <.0001
 p2*p3*roll    0     6     G         0.3430      0.01584      39      21.65      <.0001
 p2*p3*roll    0     6     S         0.3130      0.01372      39      22.81      <.0001
 p2*p3*roll    3     3     G         0.3790      0.01584      39      23.92      <.0001
 p2*p3*roll    3     3     S         0.3223      0.01584      39      20.34      <.0001
 p2*p3*roll    6     3     G         0.3060      0.01584      39      19.31      <.0001
 p2*p3*roll    6     3     S         0.3480      0.01584      39      21.96      <.0001
 p2*p3*roll    6     6     G         0.4318      0.01227      39      35.18      <.0001
 p2*p3*roll    6     6     S         0.3805      0.01372      39      27.73      <.0001
 p2*p3*roll    9     3     G         0.3495      0.01941      39      18.01      <.0001
 p2*p3*roll    9     3     S         0.3723      0.01584      39      23.50      <.0001
 p2*p3*roll    9     6     G         0.4413      0.01584      39      27.85      <.0001
 p2*p3*roll    9     6     S         0.4327      0.01584      39      27.31      <.0001
 p2*p3*roll    9     9     G         0.4080      0.01584      39      25.75      <.0001
 p2*p3*roll    9     9     S         0.3660      0.01584      39      23.10      <.0001


                           Differences of Least Squares Means

                                                         Standard
 Effect      p2  p3  roll  _p2  _p3  _roll  Estimate      Error    DF  t Value  Pr > |t|

 p2*p3*roll  0   0   G     0    0    S       -0.1013    0.02241    39    -4.52    <.0001
 p2*p3*roll  0   0   G     0    3    G       -0.2463    0.02241    39   -10.99    <.0001
 p2*p3*roll  0   0   G     0    3    S       -0.2503    0.02241    39   -11.17    <.0001
 p2*p3*roll  0   0   G     0    6    G       -0.2787    0.02241    39   -12.44    <.0001
 p2*p3*roll  0   0   G     0    6    S       -0.2487    0.02096    39   -11.86    <.0001
 p2*p3*roll  0   0   G     3    3    G       -0.3147    0.02241    39   -14.04    <.0001
 p2*p3*roll  0   0   G     3    3    S       -0.2580    0.02241    39   -11.51    <.0001
```

```
                                The Mixed Procedure

                         Differences of Least Squares Means

                                                         Standard
Effect      p2  p3  roll  _p2  _p3  _roll  Estimate      Error    DF  t Value  Pr > |t|

p2*p3*roll  0   0   G     6    3    G       -0.2417   0.02241    39   -10.78    <.0001
p2*p3*roll  0   0   G     6    3    S       -0.2837   0.02241    39   -12.66    <.0001
p2*p3*roll  0   0   G     6    6    G       -0.3675   0.02004    39   -18.33    <.0001
p2*p3*roll  0   0   G     6    6    S       -0.3162   0.02096    39   -15.08    <.0001
p2*p3*roll  0   0   G     9    3    G       -0.2852   0.02505    39   -11.38    <.0001
p2*p3*roll  0   0   G     9    3    S       -0.3080   0.02241    39   -13.75    <.0001
p2*p3*roll  0   0   G     9    6    G       -0.3770   0.02241    39   -16.82    <.0001
p2*p3*roll  0   0   G     9    6    S       -0.3683   0.02241    39   -16.44    <.0001
p2*p3*roll  0   0   G     9    9    G       -0.3437   0.02241    39   -15.34    <.0001
p2*p3*roll  0   0   G     9    9    S       -0.3017   0.02241    39   -13.46    <.0001
p2*p3*roll  0   0   S     0    3    G       -0.1450   0.02241    39    -6.47    <.0001
p2*p3*roll  0   0   S     0    3    S       -0.1490   0.02241    39    -6.65    <.0001
p2*p3*roll  0   0   S     0    6    G       -0.1773   0.02241    39    -7.91    <.0001
p2*p3*roll  0   0   S     0    6    S       -0.1473   0.02096    39    -7.03    <.0001
p2*p3*roll  0   0   S     3    3    G       -0.2133   0.02241    39    -9.52    <.0001
p2*p3*roll  0   0   S     3    3    S       -0.1567   0.02241    39    -6.99    <.0001
p2*p3*roll  0   0   S     6    3    G       -0.1403   0.02241    39    -6.26    <.0001
p2*p3*roll  0   0   S     6    3    S       -0.1823   0.02241    39    -8.14    <.0001
p2*p3*roll  0   0   S     6    6    G       -0.2661   0.02004    39   -13.28    <.0001
p2*p3*roll  0   0   S     6    6    S       -0.2148   0.02096    39   -10.25    <.0001
p2*p3*roll  0   0   S     9    3    G       -0.1838   0.02505    39    -7.34    <.0001
p2*p3*roll  0   0   S     9    3    S       -0.2067   0.02241    39    -9.22    <.0001
p2*p3*roll  0   0   S     9    6    G       -0.2757   0.02241    39   -12.30    <.0001
p2*p3*roll  0   0   S     9    6    S       -0.2670   0.02241    39   -11.92    <.0001
p2*p3*roll  0   0   S     9    9    G       -0.2423   0.02241    39   -10.81    <.0001
p2*p3*roll  0   0   S     9    9    S       -0.2003   0.02241    39    -8.94    <.0001
p2*p3*roll  0   3   G     0    3    S      -0.00400   0.02241    39    -0.18    0.8592
p2*p3*roll  0   3   G     0    6    G      -0.03233   0.02241    39    -1.44    0.1570
p2*p3*roll  0   3   G     0    6    S      -0.00233   0.02096    39    -0.11    0.9119
p2*p3*roll  0   3   G     3    3    G      -0.06833   0.02241    39    -3.05    0.0041
p2*p3*roll  0   3   G     3    3    S      -0.01167   0.02241    39    -0.52    0.6056
p2*p3*roll  0   3   G     6    3    G      0.004667   0.02241    39     0.21    0.8361
p2*p3*roll  0   3   G     6    3    S      -0.03733   0.02241    39    -1.67    0.1037
p2*p3*roll  0   3   G     6    6    G       -0.1211   0.02004    39    -6.04    <.0001
p2*p3*roll  0   3   G     6    6    S      -0.06983   0.02096    39    -3.33    0.0019
p2*p3*roll  0   3   G     9    3    G      -0.03883   0.02505    39    -1.55    0.1292
p2*p3*roll  0   3   G     9    3    S      -0.06167   0.02241    39    -2.75    0.0089
p2*p3*roll  0   3   G     9    6    G       -0.1307   0.02241    39    -5.83    <.0001
p2*p3*roll  0   3   G     9    6    S       -0.1220   0.02241    39    -5.44    <.0001
p2*p3*roll  0   3   G     9    9    G      -0.09733   0.02241    39    -4.34    <.0001
p2*p3*roll  0   3   G     9    9    S      -0.05533   0.02241    39    -2.47    0.0180
p2*p3*roll  0   3   S     0    6    G      -0.02833   0.02241    39    -1.26    0.2136
p2*p3*roll  0   3   S     0    6    S      0.001667   0.02096    39     0.08    0.9370
p2*p3*roll  0   3   S     3    3    G      -0.06433   0.02241    39    -2.87    0.0066
p2*p3*roll  0   3   S     3    3    S      -0.00767   0.02241    39    -0.34    0.7341
p2*p3*roll  0   3   S     6    3    G      0.008667   0.02241    39     0.39    0.7010
```

```
                                 The Mixed Procedure

                          Differences of Least Squares Means

                                                     Standard
Effect      p2  p3  roll  _p2  _p3  _roll  Estimate     Error    DF  t Value  Pr > |t|

p2*p3*roll  0   3   S     6    3    S      -0.03333   0.02241    39    -1.49    0.1449
p2*p3*roll  0   3   S     6    6    G       -0.1171   0.02004    39    -5.84    <.0001
p2*p3*roll  0   3   S     6    6    S      -0.06583   0.02096    39    -3.14    0.0032
p2*p3*roll  0   3   S     9    3    G      -0.03483   0.02505    39    -1.39    0.1723
p2*p3*roll  0   3   S     9    3    S      -0.05767   0.02241    39    -2.57    0.0140
p2*p3*roll  0   3   S     9    6    G       -0.1267   0.02241    39    -5.65    <.0001
p2*p3*roll  0   3   S     9    6    S       -0.1180   0.02241    39    -5.27    <.0001
p2*p3*roll  0   3   S     9    9    G      -0.09333   0.02241    39    -4.17    0.0002
p2*p3*roll  0   3   S     9    9    S      -0.05133   0.02241    39    -2.29    0.0275
p2*p3*roll  0   6   G     0    6    S       0.03000   0.02096    39     1.43    0.1603
p2*p3*roll  0   6   G     3    3    G      -0.03600   0.02241    39    -1.61    0.1162
p2*p3*roll  0   6   G     3    3    S       0.02067   0.02241    39     0.92    0.3620
p2*p3*roll  0   6   G     6    3    G       0.03700   0.02241    39     1.65    0.1067
p2*p3*roll  0   6   G     6    3    S      -0.00500   0.02241    39    -0.22    0.8246
p2*p3*roll  0   6   G     6    6    G      -0.08880   0.02004    39    -4.43    <.0001
p2*p3*roll  0   6   G     6    6    S      -0.03750   0.02096    39    -1.79    0.0814
p2*p3*roll  0   6   G     9    3    G      -0.00650   0.02505    39    -0.26    0.7967
p2*p3*roll  0   6   G     9    3    S      -0.02933   0.02241    39    -1.31    0.1982
p2*p3*roll  0   6   G     9    6    G      -0.09833   0.02241    39    -4.39    <.0001
p2*p3*roll  0   6   G     9    6    S      -0.08967   0.02241    39    -4.00    0.0003
p2*p3*roll  0   6   G     9    9    G      -0.06500   0.02241    39    -2.90    0.0061
p2*p3*roll  0   6   G     9    9    S      -0.02300   0.02241    39    -1.03    0.3110
p2*p3*roll  0   6   S     3    3    G      -0.06600   0.02096    39    -3.15    0.0031
p2*p3*roll  0   6   S     3    3    S      -0.00933   0.02096    39    -0.45    0.6586
p2*p3*roll  0   6   S     6    3    G      0.007000   0.02096    39     0.33    0.7402
p2*p3*roll  0   6   S     6    3    S      -0.03500   0.02096    39    -1.67    0.1030
p2*p3*roll  0   6   S     6    6    G       -0.1188   0.01841    39    -6.45    <.0001
p2*p3*roll  0   6   S     6    6    S      -0.06750   0.01941    39    -3.48    0.0013
p2*p3*roll  0   6   S     9    3    G      -0.03650   0.02377    39    -1.54    0.1327
p2*p3*roll  0   6   S     9    3    S      -0.05933   0.02096    39    -2.83    0.0073
p2*p3*roll  0   6   S     9    6    G       -0.1283   0.02096    39    -6.12    <.0001
p2*p3*roll  0   6   S     9    6    S       -0.1197   0.02096    39    -5.71    <.0001
p2*p3*roll  0   6   S     9    9    G      -0.09500   0.02096    39    -4.53    <.0001
p2*p3*roll  0   6   S     9    9    S      -0.05300   0.02096    39    -2.53    0.0156
p2*p3*roll  3   3   G     3    3    S       0.05667   0.02241    39     2.53    0.0156
p2*p3*roll  3   3   G     6    3    G       0.07300   0.02241    39     3.26    0.0023
p2*p3*roll  3   3   G     6    3    S       0.03100   0.02241    39     1.38    0.1744
p2*p3*roll  3   3   G     6    6    G      -0.05280   0.02004    39    -2.63    0.0120
p2*p3*roll  3   3   G     6    6    S      -0.00150   0.02096    39    -0.07    0.9433
p2*p3*roll  3   3   G     9    3    G       0.02950   0.02505    39     1.18    0.2461
p2*p3*roll  3   3   G     9    3    S      0.006667   0.02241    39     0.30    0.7677
p2*p3*roll  3   3   G     9    6    G      -0.06233   0.02241    39    -2.78    0.0083
p2*p3*roll  3   3   G     9    6    S      -0.05367   0.02241    39    -2.39    0.0215
p2*p3*roll  3   3   G     9    9    G      -0.02900   0.02241    39    -1.29    0.2032
p2*p3*roll  3   3   G     9    9    S       0.01300   0.02241    39     0.58    0.5651
p2*p3*roll  3   3   S     6    3    G       0.01633   0.02241    39     0.73    0.4704
```

```
                            The Mixed Procedure

                     Differences of Least Squares Means

                                                          Standard
Effect      p2  p3  roll  _p2  _p3  _roll  Estimate      Error    DF  t Value  Pr > |t|

p2*p3*roll  3   3   S     6    3    S      -0.02567    0.02241    39    -1.15    0.2590
p2*p3*roll  3   3   S     6    6    G       -0.1095    0.02004    39    -5.46    <.0001
p2*p3*roll  3   3   S     6    6    S      -0.05817    0.02096    39    -2.78    0.0084
p2*p3*roll  3   3   S     9    3    G      -0.02717    0.02505    39    -1.08    0.2849
p2*p3*roll  3   3   S     9    3    S      -0.05000    0.02241    39    -2.23    0.0315
p2*p3*roll  3   3   S     9    6    G       -0.1190    0.02241    39    -5.31    <.0001
p2*p3*roll  3   3   S     9    6    S       -0.1103    0.02241    39    -4.92    <.0001
p2*p3*roll  3   3   S     9    9    G      -0.08567    0.02241    39    -3.82    0.0005
p2*p3*roll  3   3   S     9    9    S      -0.04367    0.02241    39    -1.95    0.0585
p2*p3*roll  6   3   G     6    3    S      -0.04200    0.02241    39    -1.87    0.0684
p2*p3*roll  6   3   G     6    6    G       -0.1258    0.02004    39    -6.28    <.0001
p2*p3*roll  6   3   G     6    6    S      -0.07450    0.02096    39    -3.55    0.0010
p2*p3*roll  6   3   G     9    3    G      -0.04350    0.02505    39    -1.74    0.0904
p2*p3*roll  6   3   G     9    3    S      -0.06633    0.02241    39    -2.96    0.0052
p2*p3*roll  6   3   G     9    6    G       -0.1353    0.02241    39    -6.04    <.0001
p2*p3*roll  6   3   G     9    6    S       -0.1267    0.02241    39    -5.65    <.0001
p2*p3*roll  6   3   G     9    9    G       -0.1020    0.02241    39    -4.55    <.0001
p2*p3*roll  6   3   G     9    9    S      -0.06000    0.02241    39    -2.68    0.0108
p2*p3*roll  6   3   S     6    6    G      -0.08380    0.02004    39    -4.18    0.0002
p2*p3*roll  6   3   S     6    6    S      -0.03250    0.02096    39    -1.55    0.1291
p2*p3*roll  6   3   S     9    3    G      -0.00150    0.02505    39    -0.06    0.9526
p2*p3*roll  6   3   S     9    3    S      -0.02433    0.02241    39    -1.09    0.2842
p2*p3*roll  6   3   S     9    6    G      -0.09333    0.02241    39    -4.17    0.0002
p2*p3*roll  6   3   S     9    6    S      -0.08467    0.02241    39    -3.78    0.0005
p2*p3*roll  6   3   S     9    9    G      -0.06000    0.02241    39    -2.68    0.0108
p2*p3*roll  6   3   S     9    9    S      -0.01800    0.02241    39    -0.80    0.4267
p2*p3*roll  6   6   G     6    6    S       0.05130    0.01841    39     2.79    0.0082
p2*p3*roll  6   6   G     9    3    G       0.08230    0.02296    39     3.58    0.0009
p2*p3*roll  6   6   G     9    3    S       0.05947    0.02004    39     2.97    0.0051
p2*p3*roll  6   6   G     9    6    G      -0.00953    0.02004    39    -0.48    0.6370
p2*p3*roll  6   6   G     9    6    S      -0.00087    0.02004    39    -0.04    0.9657
p2*p3*roll  6   6   G     9    9    G       0.02380    0.02004    39     1.19    0.2422
p2*p3*roll  6   6   G     9    9    S       0.06580    0.02004    39     3.28    0.0022
p2*p3*roll  6   6   S     9    3    G       0.03100    0.02377    39     1.30    0.1998
p2*p3*roll  6   6   S     9    3    S      0.008167    0.02096    39     0.39    0.6989
p2*p3*roll  6   6   S     9    6    G      -0.06083    0.02096    39    -2.90    0.0061
p2*p3*roll  6   6   S     9    6    S      -0.05217    0.02096    39    -2.49    0.0172
p2*p3*roll  6   6   S     9    9    G      -0.02750    0.02096    39    -1.31    0.1972
p2*p3*roll  6   6   S     9    9    S       0.01450    0.02096    39     0.69    0.4932
p2*p3*roll  9   3   G     9    3    S      -0.02283    0.02505    39    -0.91    0.3677
p2*p3*roll  9   3   G     9    6    G      -0.09183    0.02505    39    -3.67    0.0007
p2*p3*roll  9   3   G     9    6    S      -0.08317    0.02505    39    -3.32    0.0020
p2*p3*roll  9   3   G     9    9    G      -0.05850    0.02505    39    -2.34    0.0248
p2*p3*roll  9   3   G     9    9    S      -0.01650    0.02505    39    -0.66    0.5140
p2*p3*roll  9   3   S     9    6    G      -0.06900    0.02241    39    -3.08    0.0038
p2*p3*roll  9   3   S     9    6    S      -0.06033    0.02241    39    -2.69    0.0104
```

```
                                    The SAS System       23:02 Saturday, March 21, 2009   6

                                 The Mixed Procedure

                          Differences of Least Squares Means

                                                     Standard
Effect      p2  p3  roll  _p2  _p3  _roll  Estimate     Error    DF  t Value  Pr > |t|

p2*p3*roll  9   3   S     9    9    G      -0.03567   0.02241    39    -1.59    0.1195
p2*p3*roll  9   3   S     9    9    S      0.006333   0.02241    39     0.28    0.7789
p2*p3*roll  9   6   G     9    6    S      0.008667   0.02241    39     0.39    0.7010
p2*p3*roll  9   6   G     9    9    G       0.03333   0.02241    39     1.49    0.1449
p2*p3*roll  9   6   G     9    9    S       0.07533   0.02241    39     3.36    0.0017
p2*p3*roll  9   6   S     9    9    G       0.02467   0.02241    39     1.10    0.2777
p2*p3*roll  9   6   S     9    9    S       0.06667   0.02241    39     2.98    0.0050
p2*p3*roll  9   9   G     9    9    S       0.04200   0.02241    39     1.87    0.0684


                               Tests of Effect Slices

                                                    Num     Den
         Effect        p2    p3    roll      DF      DF    F Value    Pr > F

         p2*p3*roll    0     0                1      39      20.45    <.0001
         p2*p3*roll    0     3                1      39       0.03    0.8592
         p2*p3*roll    0     6                1      39       2.05    0.1603
         p2*p3*roll    3     3                1      39       6.40    0.0156
         p2*p3*roll    6     3                1      39       3.51    0.0684
         p2*p3*roll    6     6                1      39       7.76    0.0082
         p2*p3*roll    9     3                1      39       0.83    0.3677
         p2*p3*roll    9     6                1      39       0.15    0.7010
         p2*p3*roll    9     9                1      39       3.51    0.0684
         p2*p3*roll    0           G          2      39      92.53    <.0001
         p2*p3*roll    0           S          2      39      30.56    <.0001
         p2*p3*roll    3           G          0       .        .       .
         p2*p3*roll    3           S          0       .        .       .
         p2*p3*roll    6           G          1      39      39.40    <.0001
         p2*p3*roll    6           S          1      39       2.40    0.1291
         p2*p3*roll    9           G          2      39       6.73    0.0031
         p2*p3*roll    9           S          2      39       5.39    0.0085
         p2*p3*roll          0     G          0       .        .       .
         p2*p3*roll          0     S          0       .        .       .
         p2*p3*roll          3     G          3      39       4.66    0.0071
         p2*p3*roll          3     S          3      39       2.74    0.0564
         p2*p3*roll          6     G          2      39      12.47    <.0001
         p2*p3*roll          6     S          2      39      16.74    <.0001
         p2*p3*roll          9     G          0       .        .       .
         p2*p3*roll          9     S          0       .        .       .
```

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                                          The SAS System       23:02 Saturday, March 21, 2009   7

                                        The GLM Procedure

                                     Class Level Information

Class         Levels    Values

trtmnt            18    00G 00S 03G 03S 06G 06S 33G 33S 63G 63S 66G 66S 93G 93S 96G 96S 99G 99S


                            Number of Observations Read          57
                            Number of Observations Used          57
                                          The SAS System       23:02 Saturday, March 21, 2009   8

                                        The GLM Procedure

Dependent Variable: eff

                                                Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                       17      0.46023051      0.02707238      35.94    <.0001

      Error                       39      0.02937363      0.00075317

      Corrected Total             56      0.48960414


                       R-Square     Coeff Var      Root MSE      eff Mean

                       0.940005      8.082592      0.027444      0.339544


      Source                      DF       Type I SS     Mean Square    F Value    Pr > F

      trtmnt                      17      0.46023051      0.02707238      35.94    <.0001


      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      trtmnt                      17      0.46023051      0.02707238      35.94    <.0001
```

```
                                      The GLM Procedure

                    Ryan-Einot-Gabriel-Welsch Multiple Range Test for eff

                NOTE: This test controls the Type I experimentwise error rate.


                             Alpha                           0.05
                             Error Degrees of Freedom          39
                             Error Mean Square           0.000753
                             Harmonic Mean of Cell Sizes 3.068182

                               NOTE: Cell sizes are not equal.


Number of Means            2            3            4            5            6            7
Critical Range     0.0648568    0.0698774    0.0726438    0.0745187    0.0759202     0.077029

Number of Means            8            9           10           11           12           13
Critical Range     0.0779397    0.0787079     0.079369    0.0799468     0.080458    0.0809149

   Number of Means            14             15             16             17             18
   Critical Range     0.0813268      0.0817007      0.0820423      0.0820423      0.0826455


                  Means with the same letter are not significantly different.


                       REGWQ Grouping          Mean      N    trtmnt

                               A            0.44133      3    96G
                               A
                               A            0.43267      3    96S
                               A
                               A            0.43180      5    66G
                               A
                          B    A            0.40800      3    99G
                          B    A
                          B    A    C       0.38050      4    66S
                          B    A    C
                          B    A    C       0.37900      3    33G
                          B    A    C
                          B    A    C       0.37233      3    93S
                          B    A    C
                          B    A    C       0.36600      3    99S
                          B         C
                          B         C       0.34950      2    93G
                          B         C
                          B         C       0.34800      3    63S
                          B         C
                          B         C       0.34300      3    06G
                                    C
                                    C       0.32233      3    33S
```

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                       The GLM Procedure

           Ryan-Einot-Gabriel-Welsch Multiple Range Test for eff

         Means with the same letter are not significantly different.


    REGWQ Grouping          Mean      N    trtmnt

                 C
                 C       0.31467      3    03S
                 C
                 C       0.31300      4    06S
                 C
                 C       0.31067      3    03G
                 C
                 C       0.30600      3    63G

            D            0.16567      3    00S

            E            0.06433      3    00G
```

```
                                  The GLM Procedure

                                t Tests (LSD) for eff

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
                                        rate.


                         Alpha                         0.05
                         Error Degrees of Freedom        39
                         Error Mean Square         0.000753
                         Critical Value of t        2.02269


               Comparisons significant at the 0.05 level are indicated by ***.


                                  Difference
                       trtmnt        Between      95% Confidence
                     Comparison        Means          Limits

                     96G - 96S       0.00867    -0.03666  0.05399
                     96G - 66G       0.00953    -0.03101  0.05007
                     96G - 99G       0.03333    -0.01199  0.07866
                     96G - 66S       0.06083     0.01844  0.10323  ***
                     96G - 33G       0.06233     0.01701  0.10766  ***
                     96G - 93S       0.06900     0.02368  0.11432  ***
                     96G - 99S       0.07533     0.03001  0.12066  ***
                     96G - 93G       0.09183     0.04116  0.14251  ***
                     96G - 63S       0.09333     0.04801  0.13866  ***
                     96G - 06G       0.09833     0.05301  0.14366  ***
                     96G - 33S       0.11900     0.07368  0.16432  ***
                     96G - 03S       0.12667     0.08134  0.17199  ***
                     96G - 06S       0.12833     0.08594  0.17073  ***
                     96G - 03G       0.13067     0.08534  0.17599  ***
                     96G - 63G       0.13533     0.09001  0.18066  ***
                     96G - 00S       0.27567     0.23034  0.32099  ***
                     96G - 00G       0.37700     0.33168  0.42232  ***
                     96S - 96G      -0.00867    -0.05399  0.03666
                     96S - 66G       0.00087    -0.03967  0.04141
                     96S - 99G       0.02467    -0.02066  0.06999
                     96S - 66S       0.05217     0.00977  0.09456  ***
                     96S - 33G       0.05367     0.00834  0.09899  ***
                     96S - 93S       0.06033     0.01501  0.10566  ***
                     96S - 99S       0.06667     0.02134  0.11199  ***
                     96S - 93G       0.08317     0.03249  0.13384  ***
                     96S - 63S       0.08467     0.03934  0.12999  ***
                     96S - 06G       0.08967     0.04434  0.13499  ***
                     96S - 33S       0.11033     0.06501  0.15566  ***
                     96S - 03S       0.11800     0.07268  0.16332  ***
                     96S - 06S       0.11967     0.07727  0.16206  ***
                     96S - 03G       0.12200     0.07668  0.16732  ***
                     96S - 63G       0.12667     0.08134  0.17199  ***
```

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                        The SAS System       23:02 Saturday, March 21, 2009  12

                      The GLM Procedure

                    t Tests (LSD) for eff

Comparisons significant at the 0.05 level are indicated by ***.


                    Difference
        trtmnt         Between      95% Confidence
      Comparison         Means          Limits

      96S - 00S        0.26700     0.22168  0.31232  ***
      96S - 00G        0.36833     0.32301  0.41366  ***
      66G - 96G       -0.00953    -0.05007  0.03101
      66G - 96S       -0.00087    -0.04141  0.03967
      66G - 99G        0.02380    -0.01674  0.06434
      66G - 66S        0.05130     0.01406  0.08854  ***
      66G - 33G        0.05280     0.01226  0.09334  ***
      66G - 93S        0.05947     0.01893  0.10001  ***
      66G - 99S        0.06580     0.02526  0.10634  ***
      66G - 93G        0.08230     0.03586  0.12874  ***
      66G - 63S        0.08380     0.04326  0.12434  ***
      66G - 06G        0.08880     0.04826  0.12934  ***
      66G - 33S        0.10947     0.06893  0.15001  ***
      66G - 03S        0.11713     0.07659  0.15767  ***
      66G - 06S        0.11880     0.08156  0.15604  ***
      66G - 03G        0.12113     0.08059  0.16167  ***
      66G - 63G        0.12580     0.08526  0.16634  ***
      66G - 00S        0.26613     0.22559  0.30667  ***
      66G - 00G        0.36747     0.32693  0.40801  ***
      99G - 96G       -0.03333    -0.07866  0.01199
      99G - 96S       -0.02467    -0.06999  0.02066
      99G - 66G       -0.02380    -0.06434  0.01674
      99G - 66S        0.02750    -0.01490  0.06990
      99G - 33G        0.02900    -0.01632  0.07432
      99G - 93S        0.03567    -0.00966  0.08099
      99G - 99S        0.04200    -0.00332  0.08732
      99G - 93G        0.05850     0.00783  0.10917  ***
      99G - 63S        0.06000     0.01468  0.10532  ***
      99G - 06G        0.06500     0.01968  0.11032  ***
      99G - 33S        0.08567     0.04034  0.13099  ***
      99G - 03S        0.09333     0.04801  0.13866  ***
      99G - 06S        0.09500     0.05260  0.13740  ***
      99G - 03G        0.09733     0.05201  0.14266  ***
      99G - 63G        0.10200     0.05668  0.14732  ***
      99G - 00S        0.24233     0.19701  0.28766  ***
      99G - 00G        0.34367     0.29834  0.38899  ***
      66S - 96G       -0.06083    -0.10323 -0.01844  ***
      66S - 96S       -0.05217    -0.09456 -0.00977  ***
      66S - 66G       -0.05130    -0.08854 -0.01406  ***
      66S - 99G       -0.02750    -0.06990  0.01490
      66S - 33G        0.00150    -0.04090  0.04390
      66S - 93S        0.00817    -0.03423  0.05056
```

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                        The SAS System       23:02 Saturday, March 21, 2009  13

                      The GLM Procedure

                    t Tests (LSD) for eff

Comparisons significant at the 0.05 level are indicated by ***.


                    Difference
        trtmnt         Between      95% Confidence
      Comparison         Means          Limits

      66S - 99S        0.01450    -0.02790  0.05690
      66S - 93G        0.03100    -0.01707  0.07907
      66S - 63S        0.03250    -0.00990  0.07490
      66S - 06G        0.03750    -0.00490  0.07990
      66S - 33S        0.05817     0.01577  0.10056  ***
      66S - 03S        0.06583     0.02344  0.10823  ***
      66S - 06S        0.06750     0.02825  0.10675  ***
      66S - 03G        0.06983     0.02744  0.11223  ***
      66S - 63G        0.07450     0.03210  0.11690  ***
      66S - 00S        0.21483     0.17244  0.25723  ***
      66S - 00G        0.31617     0.27377  0.35856  ***
      33G - 96G       -0.06233    -0.10766 -0.01701  ***
      33G - 96S       -0.05367    -0.09899 -0.00834  ***
      33G - 66G       -0.05280    -0.09334 -0.01226  ***
      33G - 99G       -0.02900    -0.07432  0.01632
      33G - 66S       -0.00150    -0.04390  0.04090
      33G - 93S        0.00667    -0.03866  0.05199
      33G - 99S        0.01300    -0.03232  0.05832
      33G - 93G        0.02950    -0.02117  0.08017
      33G - 63S        0.03100    -0.01432  0.07632
      33G - 06G        0.03600    -0.00932  0.08132
      33G - 33S        0.05667     0.01134  0.10199  ***
      33G - 03S        0.06433     0.01901  0.10966  ***
      33G - 06S        0.06600     0.02360  0.10840  ***
      33G - 03G        0.06833     0.02301  0.11366  ***
      33G - 63G        0.07300     0.02768  0.11832  ***
      33G - 00S        0.21333     0.16801  0.25866  ***
      33G - 00G        0.31467     0.26934  0.35999  ***
      93S - 96G       -0.06900    -0.11432 -0.02368  ***
      93S - 96S       -0.06033    -0.10566 -0.01501  ***
      93S - 66G       -0.05947    -0.10001 -0.01893  ***
      93S - 99G       -0.03567    -0.08099  0.00966
      93S - 66S       -0.00817    -0.05056  0.03423
      93S - 33G       -0.00667    -0.05199  0.03866
      93S - 99S        0.00633    -0.03899  0.05166
      93S - 93G        0.02283    -0.02784  0.07351
      93S - 63S        0.02433    -0.02099  0.06966
      93S - 06G        0.02933    -0.01599  0.07466
      93S - 33S        0.05000     0.00468  0.09532  ***
      93S - 03S        0.05767     0.01234  0.10299  ***
      93S - 06S        0.05933     0.01694  0.10173  ***
      93S - 03G        0.06167     0.01634  0.10699  ***
```

```
                                The GLM Procedure

                              t Tests (LSD) for eff

                 Comparisons significant at the 0.05 level are indicated by ***.


                             Difference
                  trtmnt        Between      95% Confidence
                Comparison        Means          Limits

                93S - 63G       0.06633     0.02101  0.11166  ***
                93S - 00S       0.20667     0.16134  0.25199  ***
                93S - 00G       0.30800     0.26268  0.35332  ***
                99S - 96G      -0.07533    -0.12066 -0.03001  ***
                99S - 96S      -0.06667    -0.11199 -0.02134  ***
                99S - 66G      -0.06580    -0.10634 -0.02526  ***
                99S - 99G      -0.04200    -0.08732  0.00332
                99S - 66S      -0.01450    -0.05690  0.02790
                99S - 33G      -0.01300    -0.05832  0.03232
                99S - 93S      -0.00633    -0.05166  0.03899
                99S - 93G       0.01650    -0.03417  0.06717
                99S - 63S       0.01800    -0.02732  0.06332
                99S - 06G       0.02300    -0.02232  0.06832
                99S - 33S       0.04367    -0.00166  0.08899
                99S - 03S       0.05133     0.00601  0.09666  ***
                99S - 06S       0.05300     0.01060  0.09540  ***
                99S - 03G       0.05533     0.01001  0.10066  ***
                99S - 63G       0.06000     0.01468  0.10532  ***
                99S - 00S       0.20033     0.15501  0.24566  ***
                99S - 00G       0.30167     0.25634  0.34699  ***
                93G - 96G      -0.09183    -0.14251 -0.04116  ***
                93G - 96S      -0.08317    -0.13384 -0.03249  ***
                93G - 66G      -0.08230    -0.12874 -0.03586  ***
                93G - 99G      -0.05850    -0.10917 -0.00783  ***
                93G - 66S      -0.03100    -0.07907  0.01707
                93G - 33G      -0.02950    -0.08017  0.02117
                93G - 93S      -0.02283    -0.07351  0.02784
                93G - 99S      -0.01650    -0.06717  0.03417
                93G - 63S       0.00150    -0.04917  0.05217
                93G - 06G       0.00650    -0.04417  0.05717
                93G - 33S       0.02717    -0.02351  0.07784
                93G - 03S       0.03483    -0.01584  0.08551
                93G - 06S       0.03650    -0.01157  0.08457
                93G - 03G       0.03883    -0.01184  0.08951
                93G - 63G       0.04350    -0.00717  0.09417
                93G - 00S       0.18383     0.13316  0.23451  ***
                93G - 00G       0.28517     0.23449  0.33584  ***
                63S - 96G      -0.09333    -0.13866 -0.04801  ***
                63S - 96S      -0.08467    -0.12999 -0.03934  ***
                63S - 66G      -0.08380    -0.12434 -0.04326  ***
                63S - 99G      -0.06000    -0.10532 -0.01468  ***
                63S - 66S      -0.03250    -0.07490  0.00990
```

```
                         The GLM Procedure

                       t Tests (LSD) for eff

Comparisons significant at the 0.05 level are indicated by ***.


                     Difference
      trtmnt           Between      95% Confidence
    Comparison           Means          Limits

    63S - 33G         -0.03100    -0.07632  0.01432
    63S - 93S         -0.02433    -0.06966  0.02099
    63S - 99S         -0.01800    -0.06332  0.02732
    63S - 93G         -0.00150    -0.05217  0.04917
    63S - 06G          0.00500    -0.04032  0.05032
    63S - 33S          0.02567    -0.01966  0.07099
    63S - 03S          0.03333    -0.01199  0.07866
    63S - 06S          0.03500    -0.00740  0.07740
    63S - 03G          0.03733    -0.00799  0.08266
    63S - 63G          0.04200    -0.00332  0.08732
    63S - 00S          0.18233     0.13701  0.22766  ***
    63S - 00G          0.28367     0.23834  0.32899  ***
    06G - 96G         -0.09833    -0.14366 -0.05301  ***
    06G - 96S         -0.08967    -0.13499 -0.04434  ***
    06G - 66G         -0.08880    -0.12934 -0.04826  ***
    06G - 99G         -0.06500    -0.11032 -0.01968  ***
    06G - 66S         -0.03750    -0.07990  0.00490
    06G - 33G         -0.03600    -0.08132  0.00932
    06G - 93S         -0.02933    -0.07466  0.01599
    06G - 99S         -0.02300    -0.06832  0.02232
    06G - 93G         -0.00650    -0.05717  0.04417
    06G - 63S         -0.00500    -0.05032  0.04032
    06G - 33S          0.02067    -0.02466  0.06599
    06G - 03S          0.02833    -0.01699  0.07366
    06G - 06S          0.03000    -0.01240  0.07240
    06G - 03G          0.03233    -0.01299  0.07766
    06G - 63G          0.03700    -0.00832  0.08232
    06G - 00S          0.17733     0.13201  0.22266  ***
    06G - 00G          0.27867     0.23334  0.32399  ***
    33S - 96G         -0.11900    -0.16432 -0.07368  ***
    33S - 96S         -0.11033    -0.15566 -0.06501  ***
    33S - 66G         -0.10947    -0.15001 -0.06893  ***
    33S - 99G         -0.08567    -0.13099 -0.04034  ***
    33S - 66S         -0.05817    -0.10056 -0.01577  ***
    33S - 33G         -0.05667    -0.10199 -0.01134  ***
    33S - 93S         -0.05000    -0.09532 -0.00468  ***
    33S - 99S         -0.04367    -0.08899  0.00166
    33S - 93G         -0.02717    -0.07784  0.02351
    33S - 63S         -0.02567    -0.07099  0.01966
    33S - 06G         -0.02067    -0.06599  0.02466
    33S - 03S          0.00767    -0.03766  0.05299
    33S - 06S          0.00933    -0.03306  0.05173
```

```
                      The GLM Procedure

                    t Tests (LSD) for eff

Comparisons significant at the 0.05 level are indicated by ***.


                    Difference
        trtmnt         Between      95% Confidence
      Comparison         Means          Limits

      33S - 03G        0.01167    -0.03366  0.05699
      33S - 63G        0.01633    -0.02899  0.06166
      33S - 00S        0.15667     0.11134  0.20199  ***
      33S - 00G        0.25800     0.21268  0.30332  ***
      03S - 96G       -0.12667    -0.17199 -0.08134  ***
      03S - 96S       -0.11800    -0.16332 -0.07268  ***
      03S - 66G       -0.11713    -0.15767 -0.07659  ***
      03S - 99G       -0.09333    -0.13866 -0.04801  ***
      03S - 66S       -0.06583    -0.10823 -0.02344  ***
      03S - 33G       -0.06433    -0.10966 -0.01901  ***
      03S - 93S       -0.05767    -0.10299 -0.01234  ***
      03S - 99S       -0.05133    -0.09666 -0.00601  ***
      03S - 93G       -0.03483    -0.08551  0.01584
      03S - 63S       -0.03333    -0.07866  0.01199
      03S - 06G       -0.02833    -0.07366  0.01699
      03S - 33S       -0.00767    -0.05299  0.03766
      03S - 06S        0.00167    -0.04073  0.04406
      03S - 03G        0.00400    -0.04132  0.04932
      03S - 63G        0.00867    -0.03666  0.05399
      03S - 00S        0.14900     0.10368  0.19432  ***
      03S - 00G        0.25033     0.20501  0.29566  ***
      06S - 96G       -0.12833    -0.17073 -0.08594  ***
      06S - 96S       -0.11967    -0.16206 -0.07727  ***
      06S - 66G       -0.11880    -0.15604 -0.08156  ***
      06S - 99G       -0.09500    -0.13740 -0.05260  ***
      06S - 66S       -0.06750    -0.10675 -0.02825  ***
      06S - 33G       -0.06600    -0.10840 -0.02360  ***
      06S - 93S       -0.05933    -0.10173 -0.01694  ***
      06S - 99S       -0.05300    -0.09540 -0.01060  ***
      06S - 93G       -0.03650    -0.08457  0.01157
      06S - 63S       -0.03500    -0.07740  0.00740
      06S - 06G       -0.03000    -0.07240  0.01240
      06S - 33S       -0.00933    -0.05173  0.03306
      06S - 03S       -0.00167    -0.04406  0.04073
      06S - 03G        0.00233    -0.04006  0.04473
      06S - 63G        0.00700    -0.03540  0.04940
      06S - 00S        0.14733     0.10494  0.18973  ***
      06S - 00G        0.24867     0.20627  0.29106  ***
      03G - 96G       -0.13067    -0.17599 -0.08534  ***
      03G - 96S       -0.12200    -0.16732 -0.07668  ***
      03G - 66G       -0.12113    -0.16167 -0.08059  ***
      03G - 99G       -0.09733    -0.14266 -0.05201  ***
```

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                    The GLM Procedure

                  t Tests (LSD) for eff

Comparisons significant at the 0.05 level are indicated by ***.


                      Difference
      trtmnt             Between      95% Confidence
    Comparison             Means          Limits

    03G - 66S       -0.06983    -0.11223 -0.02744  ***
    03G - 33G       -0.06833    -0.11366 -0.02301  ***
    03G - 93S       -0.06167    -0.10699 -0.01634  ***
    03G - 99S       -0.05533    -0.10066 -0.01001  ***
    03G - 93G       -0.03883    -0.08951  0.01184
    03G - 63S       -0.03733    -0.08266  0.00799
    03G - 06G       -0.03233    -0.07766  0.01299
    03G - 33S       -0.01167    -0.05699  0.03366
    03G - 03S       -0.00400    -0.04932  0.04132
    03G - 06S       -0.00233    -0.04473  0.04006
    03G - 63G        0.00467    -0.04066  0.04999
    03G - 00S        0.14500     0.09968  0.19032  ***
    03G - 00G        0.24633     0.20101  0.29166  ***
    63G - 96G       -0.13533    -0.18066 -0.09001  ***
    63G - 96S       -0.12667    -0.17199 -0.08134  ***
    63G - 66G       -0.12580    -0.16634 -0.08526  ***
    63G - 99G       -0.10200    -0.14732 -0.05668  ***
    63G - 66S       -0.07450    -0.11690 -0.03210  ***
    63G - 33G       -0.07300    -0.11832 -0.02768  ***
    63G - 93S       -0.06633    -0.11166 -0.02101  ***
    63G - 99S       -0.06000    -0.10532 -0.01468  ***
    63G - 93G       -0.04350    -0.09417  0.00717
    63G - 63S       -0.04200    -0.08732  0.00332
    63G - 06G       -0.03700    -0.08232  0.00832
    63G - 33S       -0.01633    -0.06166  0.02899
    63G - 03S       -0.00867    -0.05399  0.03666
    63G - 06S       -0.00700    -0.04940  0.03540
    63G - 03G       -0.00467    -0.04999  0.04066
    63G - 00S        0.14033     0.09501  0.18566  ***
    63G - 00G        0.24167     0.19634  0.28699  ***
    00S - 96G       -0.27567    -0.32099 -0.23034  ***
    00S - 96S       -0.26700    -0.31232 -0.22168  ***
    00S - 66G       -0.26613    -0.30667 -0.22559  ***
    00S - 99G       -0.24233    -0.28766 -0.19701  ***
    00S - 66S       -0.21483    -0.25723 -0.17244  ***
    00S - 33G       -0.21333    -0.25866 -0.16801  ***
    00S - 93S       -0.20667    -0.25199 -0.16134  ***
    00S - 99S       -0.20033    -0.24566 -0.15501  ***
    00S - 93G       -0.18383    -0.23451 -0.13316  ***
    00S - 63S       -0.18233    -0.22766 -0.13701  ***
    00S - 06G       -0.17733    -0.22266 -0.13201  ***
    00S - 33S       -0.15667    -0.20199 -0.11134  ***
```

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                                The SAS System       23:02 Saturday, March 21, 2009  18

                               The GLM Procedure

                             t Tests (LSD) for eff

             Comparisons significant at the 0.05 level are indicated by ***.


                               Difference
                   trtmnt         Between      95% Confidence
                 Comparison         Means          Limits

                 00S - 03S       -0.14900    -0.19432 -0.10368  ***
                 00S - 06S       -0.14733    -0.18973 -0.10494  ***
                 00S - 03G       -0.14500    -0.19032 -0.09968  ***
                 00S - 63G       -0.14033    -0.18566 -0.09501  ***
                 00S - 00G        0.10133     0.05601  0.14666  ***
                 00G - 96G       -0.37700    -0.42232 -0.33168  ***
                 00G - 96S       -0.36833    -0.41366 -0.32301  ***
                 00G - 66G       -0.36747    -0.40801 -0.32693  ***
                 00G - 99G       -0.34367    -0.38899 -0.29834  ***
                 00G - 66S       -0.31617    -0.35856 -0.27377  ***
                 00G - 33G       -0.31467    -0.35999 -0.26934  ***
                 00G - 93S       -0.30800    -0.35332 -0.26268  ***
                 00G - 99S       -0.30167    -0.34699 -0.25634  ***
                 00G - 93G       -0.28517    -0.33584 -0.23449  ***
                 00G - 63S       -0.28367    -0.32899 -0.23834  ***
                 00G - 06G       -0.27867    -0.32399 -0.23334  ***
                 00G - 33S       -0.25800    -0.30332 -0.21268  ***
                 00G - 03S       -0.25033    -0.29566 -0.20501  ***
                 00G - 06S       -0.24867    -0.29106 -0.20627  ***
                 00G - 03G       -0.24633    -0.29166 -0.20101  ***
                 00G - 63G       -0.24167    -0.28699 -0.19634  ***
                 00G - 00S       -0.10133    -0.14666 -0.05601  ***
```

VITA

Clinton Travis Cosgrove

Candidate for the Degree of

Master of Science

Thesis: EFFECTS OF A HYDRAULIC PRESSURE SYSTEM AND GROOVED ROLLERS ON AN IN-FIELD SWEET SORGHUM PRESS

Major Field: Biosystems Engineering

Biographical:

Personal Data: Born in McAlester, Oklahoma on January 10, 1984, the son of H. Travis Cosgrove and Peggy L. Cosgrove.

Education:
Graduated from Savanna Public High School, Savanna, OK, in May, 2002. Received bachelor of science in Biosystems and agricultural engineering from Oklahoma State University, Stillwater, OK in May 2007. Completed the requirements for the Master of Science in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2009.

Experience: Employed by Weatherford International as an engineering intern during the summer of 2006. Employed by OSU Department of Biosystems and Agricultural Engineering as a graduate research assistant from May 2007 to present.

Professional Memberships: American Society of Agricultural and Biological Engineers (ASABE), The Honor Society of Phi Kappa Phi, Alpha Epsilon (The Honor Society of Agricultural Engineering)

Name: Clinton Travis Cosgrove Date of Degree: May, 2009

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: EFFECTS OF A HYDRAULIC PRESSURE SYSTEM AND GROOVED ROLLERS ON AN IN-FIELD SWEET SORGHUM PRESS

Pages in Study: 69 Candidate for the Degree of Master of Science

Major Field: Biosystems Engineering

Scope and Method of Study: The specific objectives of this study were to redesign the rollers of an in-field sweet sorghum press for better grip on stalks and better juicing efficiency, implement a system to allow rollers to move vertically to prevent plugging, and compare the efficiencies of the redesigned and original rollers. The new rollers were designed based on sugar milling technology. A hydraulic pressure system was designed and implemented to allow vertical movement of two of the top rollers. Projected pressure levels of 0, 1.5, 3, and 4.5 MPa were chosen for evaluation. Several pressure combinations were evaluated with each roller type, but not all combinations could be evaluated due to plugging and time constraints. The treatments were compared using the Ryan-Einot-Gabriel-Welsch and LSD multiple comparison tests in SAS®.

Findings and Conclusions: Improvements in throughput of sweet sorghum stalks were observed when using grooved rollers with the hydraulic pressure system. Stalk grip was improved, and plugging was observed less frequently. When plugging did occur, it was less severe than that which occurred using the original design of the press. The statistical analysis of the treatment efficiencies showed that the optimum operating point for grooved rollers was a uniform projected pressure of 3 MPa. This resulted in a juicing efficiency of 43.2%. This treatment was in the top statistical efficiency group and had a lower power requirement than the other treatments in this group. Similar efficiencies were observed with smooth rollers, but these rollers had poor throughput characteristics.

ADVISER'S APPROVAL: Dr. Raymond L. Huhnke