Development of a Little Millet Mill

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Executive Summary

Renewed efforts are being made to encourage the cultivation of Little Millet in South East Asian in an attempt to empower rural communities through increased food securities and reduced malnutrition as millet is nutritionally superior to commonly consumed grains such as rice. In order to encourage cultivation of little millet, efficient post harvest machinery is to be developed.

The design group, focused on the development of a mill to efficiently de-hull and separate detached hull from cleaned grain in a continuous process. Field research and prototyping began in the summer of 2011 in Dharwad, India and continued through the fall months with a completion date set in February 2012. The goal was set to achieve a milling efficiency of 95% with broken grains accounting for fewer than 2%. The mill was also to be designed with portability in mind as the prototype would be used an educational tool in India.

Best results were found in the development of a rubber-roller mill whereby milling occurs by shear stress applied to the grain. The efficiency of a double pass process yielded a milling efficiency slightly higher than 95%. Separation was achieved using a centrifugal fan. Through experimentation and optimization, 100% separation was achieved. The prototype was shipped to India on February 17th, 2012.

1. INTRODUCTION

Traditionally, a staple food of Indian farmers' and villagers' diet, *Panicum sumatrense*, commonly known as Little Millet, has of late, been replaced by other grains, but mainly rice. According to Dr. Nirmala Yenagi, project director from the University of Agricultural Sciences, Dharwad, India, this shift is attributed to government dispersal programs of rice along with the limited availability of millet milling and processing machinery. The issue that arises with the shift in consumption from little millet to rice is that farmers and villagers are no longer getting the nutrients they need to keep them healthy and fit to be productive. As can be seen in Table 1, little millet has significantly higher levels of fat and dietary fiber. If integrated properly into rural diets, little millet can prove to be a vital aid in combating malnutrition and other dietary related ailments.

Food (100g)	Protein (g)	Fat (g)	Carbohydrates (g)	Dietary Fibre (g)	Minerals(g)	Ca (mg%)	P (mg%)
Wheat	11.8	1.5	71.2	12.9	1.5	41	308
Rice	6.8	0.5	78.2	5.2	0.6	10	160
Maize	11.1	3.6	66.2	10.5	1.5	20	348
Sorghum	10.4	1.9	72.6	12	1.6	25	222
Oats	11.6	5.2	69.8	20	2.9	94	385
Foxtail Millet	12.3	4.3	60.9	14	3	31	290
Little Millet	8.7	5.3	75.7	12.2	1.7	17	220
Barnyard Millet	11.6	4.8	74.3	13.7	3.7	14	121
(Gowda, 2007)							

Figure 1 – Nutritional Facts of Grains for Human Consumption

With the goal to empower rural communities through continued development, and increased food securities, there have been various renewed efforts by the International Development Research Centre (IDRC) to encourage farmers and villagers to resume consumption of many types of millets, including Little, Foxtail, Barnyard and Ragi. The project spearheaded by the IDRC, relies on the collaborative efforts of both McGill University and the University of Agricultural Science in Dharwad (UASD), India. The project is quite multi-faceted in nature whereby efforts to encourage rural regions of India to resume consumption of little millet are spread across a multitude of disciplines. From food and home sciences to engineering, efforts from across the board are working toward the same goal. This design project falls under the umbrella of this IDRC project. The task of the design team: to develop suitable machinery for the milling of little millet in rural regions of India. To learn about little millet milling and processing, the design team spent the summer of 2011 in Dharwad, India. During the field study, with the guidance of Dr. Valerie Orsat and Dr. Sam Sotocinal, Department of Bioresource Engineering, McGill University, the team was able to explore various milling and processing techniques employed in India. Furthermore, while in India still, the team was able to fabricate a rough prototype of a centrifugal mill whereby the results were to be used as a starting point in the senior capstone project.

1.1 Goals

In the fall of 2011, based on the field study conducted in the summer prior, the team decided upon a design along with a set of criteria by which the level of effectiveness of the design could be gauged to complete the task required by the IDRC project. Keeping in mind the machinery is to be designed for rural use, the criteria are as follows.

1.1.1 Milling Efficiency

The milling efficiency evaluates the mill's ability to remove the outer hull, or shell, of the grain and to limit broken grains. This is essentially the criterion that gauges how well the mill performs its job. A perfect mill would achieve 100% efficiency, however, the goal was set to achieve approximately 95% efficiency to account for reality and to keep the broken grains under 2%. In other words, 95% of the grains recovered should be de-hulled.

1.1.2 Degree of Separation Achieved

The degree of separation evaluates the mill's ability to separate the removed hulls from the cleaned grains exiting the machine. The idea is to be able to collect a batch of only cleaned grains while the removed hulls can be collected separately. The goal set forth by the team was to achieve 100% separation.

1.1.3 Cost

The cost includes the cost of fabrication, maintenance and operation of the mill. Costs were to be minimized as much as possible.

1.1.4 Ease of Use

The ease of use evaluates the skill level or experience required to operate the mill. Because the mill is being designed for village use, there should be little to no learning curve. Ideally, a simple on/off switch should be the extent of operation. This was the goal for the team.

1.1.5 Level of Maintenance Required

The level of maintenance evaluates the number and nature of tasks that must be performed on a routine basis to keep the mill running at full efficiency. Again, because the mill is being designed for village use, little to no maintenance was the goal because resources are not as readily available in rural regions of India as they are in more developed or even urban regions.

1.1.6 Environmental Working Conditions

Environmental working conditions pertain to the conditions created by the mill while it is in operation. Typically, small grain mills create a lot of particulate matter in the air. Furthermore, it is not uncommon for these mills to be located in a small unventilated building within the village. It was therefore of interest to minimize negative environmental working conditions. This includes particulate matter in the air as well as sound pollution.

1.1.7 Milling Capacity

The milling capacity evaluates the mill's processing capacity. The goal was to achieve approximately 100 kilograms per hour.

1.1.8 Ease of Transport

The ease of transport criterion evaluates the ease of assembly and transport. Because the design was destined for rural India, the team decided to try and maximize the ease of transport and assembly.

1.1.9 Pre-Treatments Required

The pre-treatments required criterion evaluates the number and nature of pre-treatments that are required to be performed on the whole grain before entering the mill. Pre-treatments under consideration include de-stoning, de-glumming, aspiration and grading. These treatments occur in sequence to remove stones, the glume from the grain husk, any dust on the grain, and finally to sort the grain based on their weight. Naturally, the goal was to suppress the need for any pre-treatments.

1.1.10 Energy Inputs

This final criterion evaluates the electrical or fuel demands of the mill. These were to be minimized as much as possible as power sources in rural India are scarce and therefore, not to be taken advantage of.

1.2 Constraints

With the goals and criteria set-forth, the team also had to consider constraints involved with the project. The project called for a prototype to be shipped to India by the end of the month of February 2012 to be used as a *tabletop* model for educational purposes. For this reason, because of the early deadline, the team had to account for these time constraints. Furthermore, because the prototype was to be shipped and used a *tabletop* model for educational purposes, the team had scaled down the mill. This was essentially an unavoidable compromise to increase portability at the risk of decreasing the efficiency and capacity of the mill.

1.3 The Chosen Design

Because there exists a multitude of existing milling techniques, using the aforementioned criteria and constraints, the team performed a multi-criteria decision analysis to determine which milling technique would be the most viable and beneficial for the project. With the use of a Pugh Chart, the team decided on a two-step design that incorporated rubber-roller milling techniques with centrifugal milling techniques and the separation would occur with the use of a horizontal air stream generated by the centrifugal portion of the mill.

The design intended for milling to occur in a continuous process as follows:

Hopper → *Rubber Roller Mill* → *Centrifugal Mill* → *Separation*

The two-step process was an *over-design* decided upon for multiple reasons. Firstly, due to the sizing constraints, milling efficiency using a single process, such as centrifugal milling, was projected to decrease; therefore, incorporating a dual process would more safely ensure desirable results. Furthermore, both milling processes were to be tested independently. In the case that one of the milling processes was able to meet the performance requirements alone, the other would be put to use in a separate process. For example, if the centrifugal mill was able achieve a desirable performance level without the use of the rubber rollers, with some slight modification, the rubber rollers could be used in a post-milling process whereby the cleaned grains would undergo polishing and would then immediately be ready for market trading. If however the rubber rollers were sufficient independently, the centrifugal portion of the mill could be used for the separation process thus eliminating the need for a horizontal airstream. The design therefore incorporated pseudo-redundancies to ensure the success of the project.

Due to the portability constraints and the availability of materials, the team decided on a centrifugal rotor 8 inches in diameter and 2 large sized skateboard wheels for rubber rollers. This would ensure the sizing needs were met and the rest of the prototype would be built around these key components.

2. ANALYSIS & SPECIFICATION

The design can be described by four systems: the rubber-roller mill, the centrifugal mill, the separation and the pulley system that connects the centrifugal mill as well as the rubber-roller mill to each other and to the motor shaft. Each of these systems is governed by a separate set of principles.

2.1 Rubber-Roller Mill

The rubber-roller mill works on the principle of shear stress. The idea being that the two rollers rotating in opposite directions in conjunction with the high coefficient of friction of rubber, the shear force exerted on the whole grain will remove the hull. The shear force required to remove the hull from the grain can be found using Equation 1[1].

Equation 1

$$\tau = \gamma G$$

where,

τ; shear stress,

γ; shear strain,

G; shear modulus of the material

and,

Equation 2

$$G = \frac{E}{2(1 + v)}$$

where,

E; Young's modulus,

v; Poisson's ratio

Unfortunately, such physical properties of little millet are not readily available; therefore, experimentation was conducted to determine adequate relative velocities between the rollers to de-hull whole grains. It was found in literature that for rice de-hulling, using rubber-rollers, the desired relative velocities followed a ratio of 4:5 (Lantin, 1999). However, at the suggestion of Dr. Sam Sotocinal, a ratio of 2:3 was also to be considered. Visual inspection after testing clearly indicated that a ratio of 2:3 was favorable for little millet. Moreover, the spacing between the rollers was to be determined for little millet. This was to be conducted experimentally, therefore, the spacing between the rollers had to be variable and user controllable. The method by which this was completed is outlined in section 3.9.

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[1] Equations 1 through 6 found at formulae.com, full references can be found in section 7.

2.2 Centrifugal Mill

The centrifugal mill works on the principle of force. At the center of the centrifugal mill, in the case of this design, is an 7 3/4-inch rotor with 8 impellers blades mounted directly to an electric motor and enclosed in a circular casing. The grains are drawn into the mill through an inlet in the front casing and the spinning impeller-mounted rotor achieves de-hulling from the centrifugal force. The rotor assembly is offset within the casing causing a spacing gradient between the inner casing and the outer rotor edge. When the rotor is spinning, it acts like a fan whereby air is drawn in through an inlet in the front of the casing and blows air out of the exhaust. The spacing gradient makes for a pressure gradient within the machine. This directs the grains from high pressure to low pressure and out. The highest pressure corresponds with the smallest spacing. The rotor was therefore placed strategically offset to circulate the grains properly and ensure that the grains travel the longest path through the mill.

The governing equation of force is represented in Equation 3.

Equation 3

$$F = ma$$

where,

F; force,

m; mass,

a; acceleration

furthermore, it is known that;

Equation 4

$$a = \frac{v^2}{r}$$

where,

a; centripetal acceleration,

v; velocity,

r; radius of the rotor

and,

Equation 5

$$v = 2\pi r(RPM)$$

From these equations, when the impact force needed to de-hull little millet is known, the RPM and rotor diameter could be optimized. However, due size constraints as discussed in section 1.2 and due to the lack of literature and instrumentation tools to determine the required impact force, the RPM was also determined experimentally.

2.3 Separation System

The separation system makes use of an air stream to separate cleaned grains from detached hulls. This principle relies on the difference in physical characteristics of a cleaned grain with its detached hull. The air velocity required to achieve separation could be found by determining the terminal velocities of each. The terminal velocity could be found using Equation 6.

Equation 6

$$v_t = \sqrt{\frac{2mg}{\rho A C_d}}$$

where,

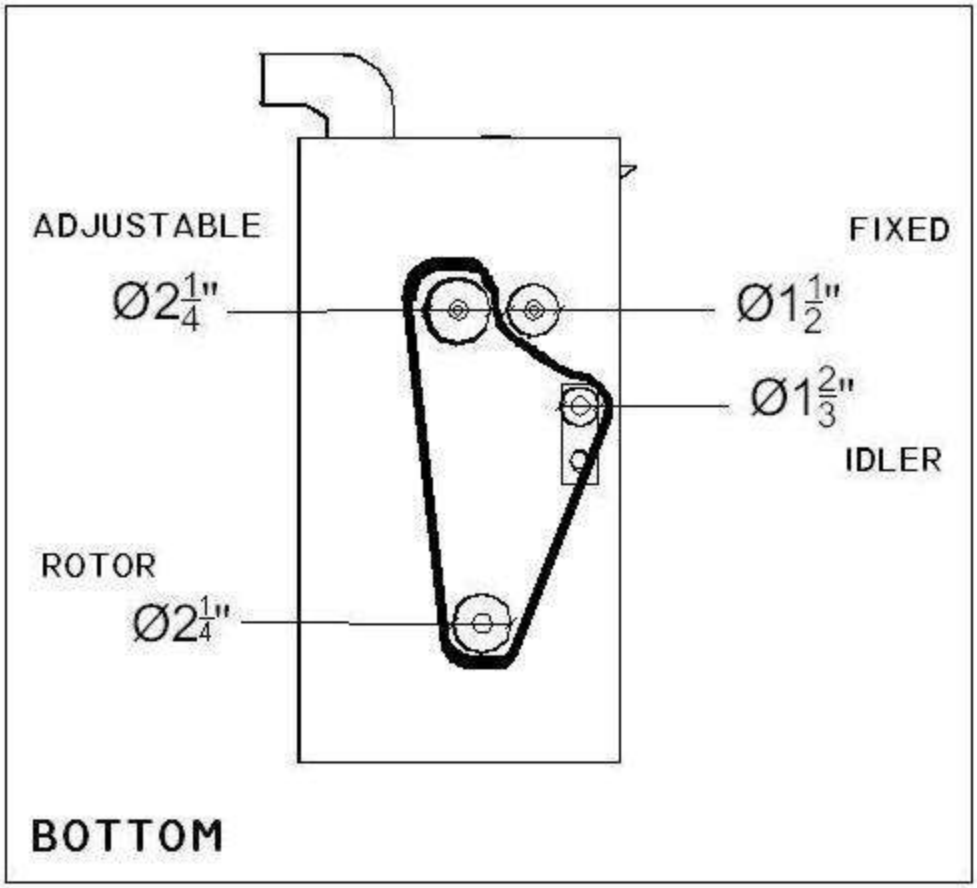
v_t; terminal velocity,
m; mass of the cleaned grain or hull,
g; acceleration due to gravity,
ρ; density of the fluid through which the object is falling: in this case, air,
A; projected area of the object, cleaned grain or hull
C_d; drag coefficient

Again, due to the lack of published properties and characteristics of little millet, the drag coefficient is unknown. The terminal velocities were therefore determined experimentally. Using a clear plastic vertical air column attached to a blower fixed with a throttle, a mixture of grain and hull was dropped into the air column. Air velocities were recorded using a hand held anemometer while the throttle was adjusted to the air speed that suspended the particles in the column. The terminal velocity of cleaned grain was determined to be 4.30 meters per second and the terminal velocity of the hulls to be 1.39 meters per second. Therefore, the air velocity required to separate cleaned grain from hull must be in the range of 1.39 m/s to 4.30 m/s.

2.4 Pulley System

The pulley system is essentially in place to tie the centrifugal mill to the rubber-roller mill. Having both systems tied together allows for the use of a single electric motor thus keep energy inputs as low as possible. The pulley system is comprised of 4 pulleys and a single rubber belt. The first pulley is located on the axel between the motor shaft and the centrifugal rotor. It had a diameter of 2.25". The second and third pulleys were located on the axels of each rubber-roller. The diameters of these two pulleys were fabricated to be different. The belt passes above one pulley and below the other pulley. This allowed for the rollers to spin in opposing directions at different RPMs. This is what causes the shearing action to mill the whole grain and as it was mentioned in section 2.1, the desired RPM ratio for little millet milling using rubber-rollers was found to be 2:3, therefore the diameters of the pulleys attached to the rollers were 1 ½" and 2 ¼". Lastly, the fourth pulley was simply an idler pulley to maintain tension in the belt. This was required due to the fact that the belt passes the underside of one of the roller pulleys. Its diameter was 1.67”. The following sketch depicts the pulley system.

Figure 2 – Pulley System



Note: All views (i.e. Top, Bottom, Right, Left, Front, Back) in this document are relative to the AutoCAD orientation of each piece.

3. PROTOTYPING & FABRICATION

A note on the construction of the mill and the machines and tools used:
Constructing the mill ourselves provided us with the wonderful opportunity to learn how to operate and adjust many different tools and machines. Furthermore, many tricks were learnt while being taught by Dr. Sam Sotocinal and Scott Manktelow. Below is a list of all the tools used:

- 60 Ton Hydraulic Press
- Acetylene Torch
- Air Buffer
- Angle Grinder
- Bandsaw
- Belt Sander
- CNC Press Brake
- Dead Blow Hammer
- Drill Press
- Electric Drill
- Hand Held Metal Punch
- Horizontal Bandsaw
- Lathe Machine
- Lever Operated Metal Punch
- MIG/TIG Welder
- Radial Arm Drill Press
- Screwdriver Set
- Socket Set
- Solder
- Spot Welder
- Tap Set
- Two Pound Hammer
- Wheel Grinder

3.1 Centrifugal Casing

The production of the centrifugal casing was the very first undertaking of the physical build of the mill. For the reasons previously stated, the casing was designed to be 8 inches in diameter. The casing needed to have a constant radius of curvature from the 3 o'clock position to the 6 o'clock position travelling counter-clockwise from the 3 o'clock position. After the 6 o'clock position, the casing needed to open up until a 2 ½ inch spacing was created between the start point and end of the casing. The 2 ½ inch spacing was selected to decrease the velocity of the air-particle mixture to 20% (1.25sq. in/6.25 sq in) of its original velocity as governed by mass flow = V*A, which was estimated as :

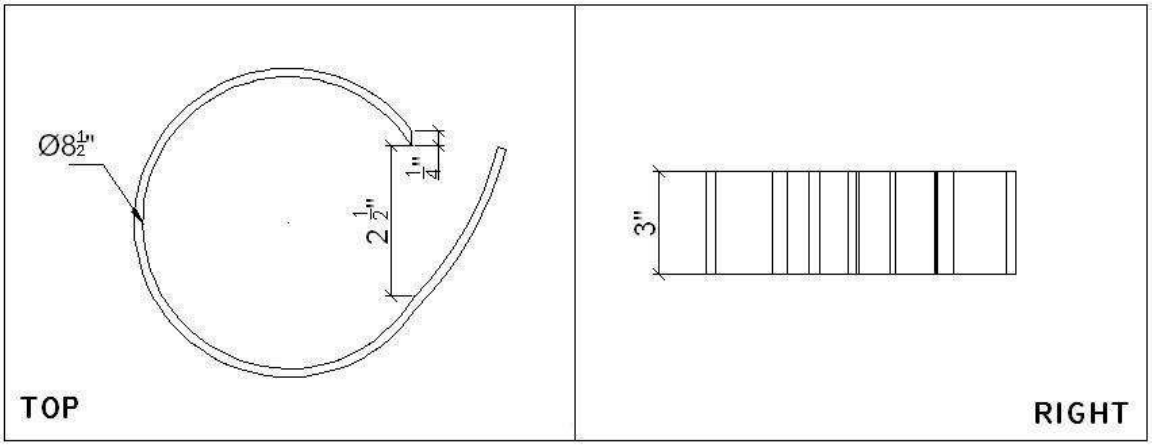
Equation 7

$$Velocity\ at\ edge = RPM\pi d = 1100\ RPM \cdot 3.14 \cdot 7.75" = 37.18\ ft/\sec\ (11.33\ m/s)$$

Equation 8

$$Velocity\ at\ exhaust = 37.18\ ft/sec \cdot 0.2 = 7.44\ ft/\sec\ \ (2.27\ m/s)$$

Figure 3 - Centrifugal Casing



It was important for the wall from the 6 o'clock position onward to open at a constant rate to try to induce laminar flow conditions. A wall profile which varies too quickly would affect the Reynolds number (DeGraaff et al., 1999) which could result in turbulence, or a dead zone. Furthermore, a turbulent spot could result in a dead zone within the centrifugal section of the mill, causing the detention of grain. As there is no pressure buildup within the mill since the inflow is equals to the outflow out, a 6mm casing thickness was deemed appropriate to be able to withstand any forces exerted by the mill. Furthermore, in the case of a catastrophic failure of the rotor shaft, the force of the rotor would be F= ½ mv^2. The weight of the rotor was calculated to be:

Equation 9

$$Mass\ of\ rotor = volume \cdot density = \pi \cdot (d^2/4) \cdot thickness$$
$$= \pi \cdot [(7\ ¾")2]/4 \cdot 0.5" \cdot 2700\ \frac{kg}{m^3} \cdot 1.6387 \cdot 10^{-5}\ \frac{m^3}{inch}$$
$$= 1.04\ kg$$

Plugging this into the equation for force:

Equation 10

$$F = ½\, mv^2 = 0.5 \cdot 1.04kg \cdot (1000m/s)^2 = 0.52MPa$$

A 6mm sheet of steel will not fail unless the impact force exceeds ~450MPa as seen from Fig. 28 (Appendix A), therefore, our 6mm steel is a safe material to use.

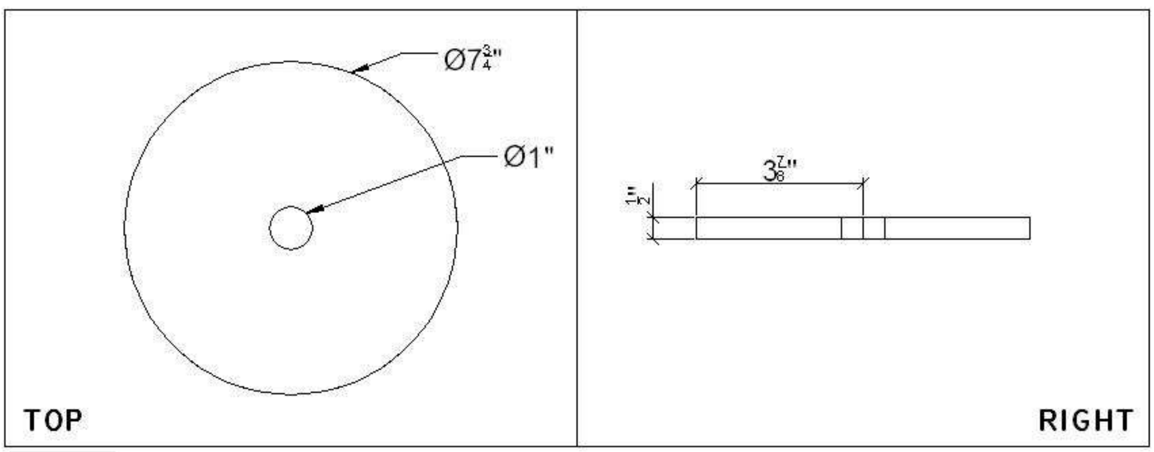
The production of the centrifugal mill casing began with a steel pipe having a diameter of 8 inches, and wall thickness of 6mm. A cut was made through the pipe at the 3 o'clock position. Pressure was applied to the pipe with the 60 ton hydraulic press, which caused the walls of the pipe to deflect outward. The deflection was done in steps, checking the progress with a scaled sketch of the desired profile. It was a painstakingly slow process.

If more than one replicate is to be made, this process should be replaced with the use of a mould. Pouring a mould would allow for the exact desired profile to be created, with exact replicates being built each time. In addition, a poured mould would prevent the metal from being weakened from any bending.

3.2 Rotor

A lightweight, 8-inch rotor capable of holding the 8 impellers was the goal. To achieve this goal, a circular piece of aluminum with a thickness of ½ inch was cut with a band saw. Aluminum was chosen as it has a low density compared to its strength (Fig. 28, Appendix A). Furthermore, there are no significant forces acting on the rotor, so the lightest available metal was most desirable. Aluminum is available in India. The main drawback of aluminum is that it cannot be welded to steel; however, aluminum-aluminum welding is possible. Using the band saw did not result in a perfect circle, so adjustments to the profile were made with a belt sander which resulted in a rotor of diameter 7 ¾”. A hole was required at the center of the rotor to attach the rotor to its shaft.

Figure 4 - Rotor



The size of the screw to connect the rotor shaft to the rotor was determined using the equation for bolt load force:

Equation 11

$$F_b = F_p + \frac{k_b}{k_b + k_j} Fe \qquad F_j = F_p - \frac{k_j}{k_b + k_j} Fe$$

where F_b = bolt load, F_p = pre-load from tightening, F_e = external load

F_j = joint clamping load, k_b = bolt spring rate (EA/L), k_j = joint spring rate

(Curious Inventor)

It is a valid assumption that 1/7 of the external force is felt by the bolt (Curious Inventor). The external force in this case is the shear while the rotor is speeding up, making it fractionally faster than the bolt.

The rotor is speeding up as a result of the torque produced by the motor. Torque of a motor is found by:

Equation 12

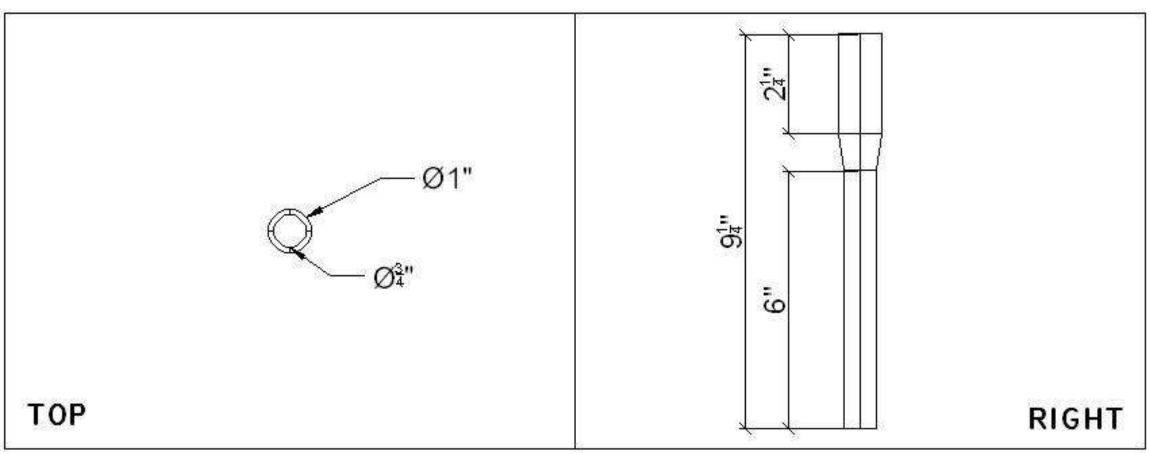
$$Torque = Hp * RPM = 1 * 1100 RPM = 1100 lb * ft$$

(The Engineering ToolBox)

This is the total torque generated by the motor. However, as the bolt is in line with the axis of rotation, the only force on the bolt is due to imbalances. Imbalances are calculated in section 3.3. As the displacement was so small, it was decided that a grade 5 bolt would be ample to hold the rotor in place (Fig. 29, Appendix A).

A ¼" hole was drilled and tapped so that a bolt could be used to attach the rotor to the shaft.

Figure 5 - Rotor Shaft



To create the decreasing pressure within the centrifugal mill from the 3 o'clock position traveling counter-clockwise, the rotor needed to be located off center relative to the casing. This decreasing pressure gradient was used to direct the grain along the longest path, as particles move from areas of high pressure to areas of lower pressure (Newton, 2012). Using the ideal gas law,

Equation 13

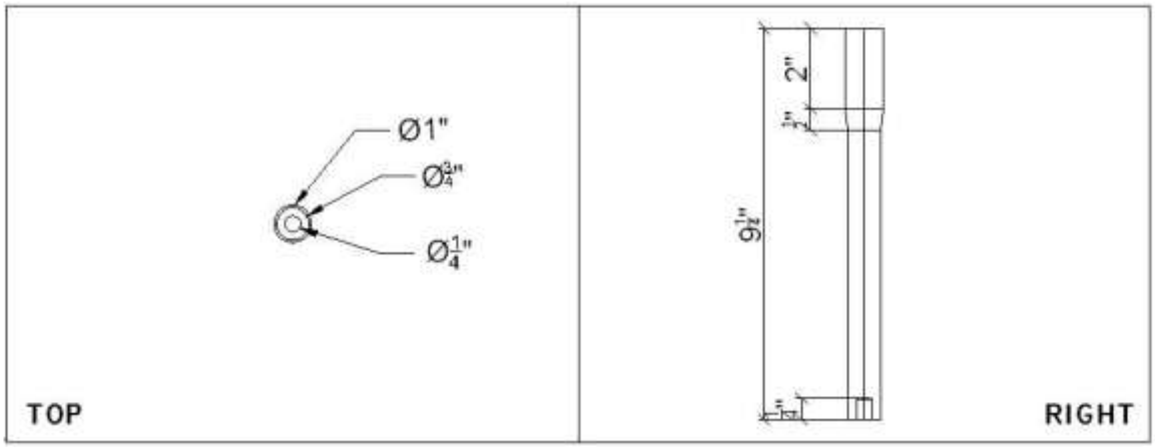
$$PV = nRT$$

while holding n, R and T constant, it is observed that a decrease in volume results in an increased pressure. Therefore, a decreased spacing between the impeller and the wall of the centrifugal mill would result in the desired pressure increase. It was decided that the minimum spacing would be ⅛ of an inch, as this was large enough to allow grains to pass between the impellers and the wall, while providing extra space in case the rotor vibrated violently. The location of the center point for the shaft hole to be drilled in the back plate was found by drawing a line from the desired point of minimum spacing between the centrifugal casing and rotor (1/8 inch), across the diameter of the casing and measuring one radius length of the rotor (3 7/8 inches) (Fig. 34, Appendix B).

3.3 Shafts

The shafts were the most intricate pieces to build on the mill. Two identical shafts were built to power the rollers, and a different, longer shaft, was built to couple the rotor with the motor shaft. As seen in the renderings (Fig. 35, Appendix B) the shafts for the rollers were designed to match the inner profile of the rollers themselves. This was done using the lathe machine, through several iterations. However, before the milling began, holes were also drilled at one end, purely to increase the precision while milling the pieces on the lathe machine. The short ¼" holes allowed the pieces to be better centered on the lathe machine by using the self-driving center. The cutting tooth was brought in and out as the tooth traveled the length of the section being cut to match the roller. All three shafts had the same diameter at one end, ¾" diameter, which was the inner diameter of the bearings. All three shafts also had a hole, drilled and tapped into the front end to facilitate the fastening to the rollers and the rotor.

Figure 6 - Rubber Roller Shaft



These holes were drilled using the lathe machine. To start each hole, a center drill was placed in the drill chuck attached to the tail-side stock, while the piece was held in the universal chuck. After the center drilled started the hole, the size was increased through three iterations of increasing drill-bit diameter. The Milling Speed table (Fig. 30, Appendix A) was consulted for all lathing processes during the build.

3.4 Impellers

As identified during the India 2011 trials and as presented in the Design II report, the optimal number of impellers on the centrifugal rotor was found to be 8. The impellers were designed based on the optimal impeller shape for a centrifugal pump designed to move an air-particle mixture, which is a slightly curved impeller in the direction of travel. The impellers were shaped from pieces of aluminum using a 60 ton hand-operated hydraulic press. Aluminum was chosen as it was available to the team and available in India; in addition, aluminum impellers were required in order to weld them to the aluminum rotor. Furthermore, using aluminum instead of another metal, such as steel, resulted in a lighter set of impellers. Lighter impellers resulted in decreased risk of vibration during operation. The height of the impellers was determined using the casing height, rotor thickness, and the desired clearance between the back of the rotor and the back plate.

Equation 14

$$Casing\ height = rotor\ thickness + impeller\ height + clearance$$
$$3 = \frac{1}{2} + impeller\ height + \frac{1}{8}$$
$$impeller\ height = 3 - \frac{1}{2} - \frac{1}{8} = 1.375 inches$$

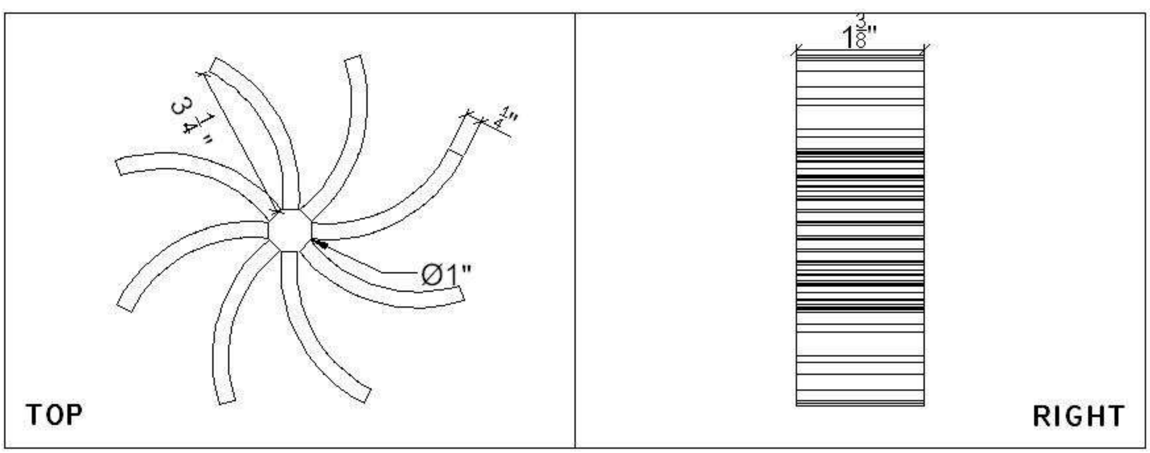
Once one impeller with the desired profile was formed, it was used as the guide for the remaining 7 in an attempt to make a set of identical impellers. It was important to achieve this, as large variance between the impellers would result in a rotor without an equal weight distribution, and would cause vibrations during operation. Minor adjustments to the impellers were made using a hammer and anvil.

The impellers were initially four and a half inches long. One end of the impellers was bent by pressing it into a half circle frame with a circle having the same curvature attached to the 60 ton hydraulic press. Once the curve was produced, the flat sides were cut, creating an effective length of 3 ¼ inches which formed a one inch gap at the center of the rotor between the tails of the impellers. This was done in an attempt to limit the amount of damage which could be sustained to someone's fingers if they entered the inlet. Furthermore, by having this gap at the center, where the inlet of the face plate was located, grains would not be directed back out the inlet by the impellers. The impellers were welded to the rotor equidistant from each other.

The flat part of the impellers were parallel to radial lines from the center of the rotor, as the studies conducted in the India 2011 field study showed this was the optimal configuration.

As with the casing, a poured mould technique could be used to recreate the impellers on a larger scale.

Figure 7 – Impellers



3.5 Pulleys

The two pulleys for the rubber rollers were designed to have a diameter ratio of 2:3. This ratio was achieved by taking two pieces of solid steel pipe measuring 2 ¼" diameter and decreasing the diameter of one until the desired ratio was achieved, a diameter of 1½ inches. The alteration in the diameter was practically achieved using a lathe machine. The length of the pulleys was determined from the width of the belt. A ½ inch clearance on either side of the belt was desirable to avoid the belt slipping off the pulleys. As the pulley was to be powered by a v-channel belt, a ½ inch thick channel, matching the profile of the belt was created using the lathe machine on the pulley of the left roller. The same could not be done to the second pulley, and it passed underneath the pulley, instead of on top, as the pulley needed to be spun in the opposite direction than the other. To reduce the slippage between the belt and the second pulley, the surface was roughened using a beveler and the lathe machine.

As the pulleys needed to be attached to the shafts of the rollers, a ¾" hole was drilled using the lathe machine. While the pulleys were designed to fit tightly to the shaft, set screws were also used to hold the pulleys in place. Holes were drilled and tapped to ¼" for set screws to grip onto the shaft, a widely accepted method to marry two pieces together. The set screws used were a harder material than the shafts, to facilitate entrenchment of the screw point into the shaft (Ruland, 2010).

Figure 8 - Pulley for Adjustable Rubber Roller

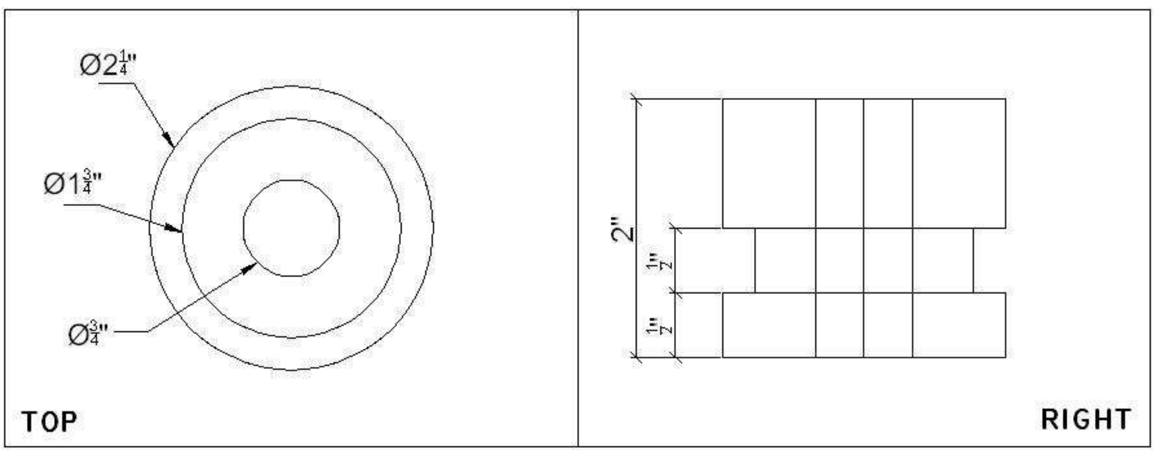
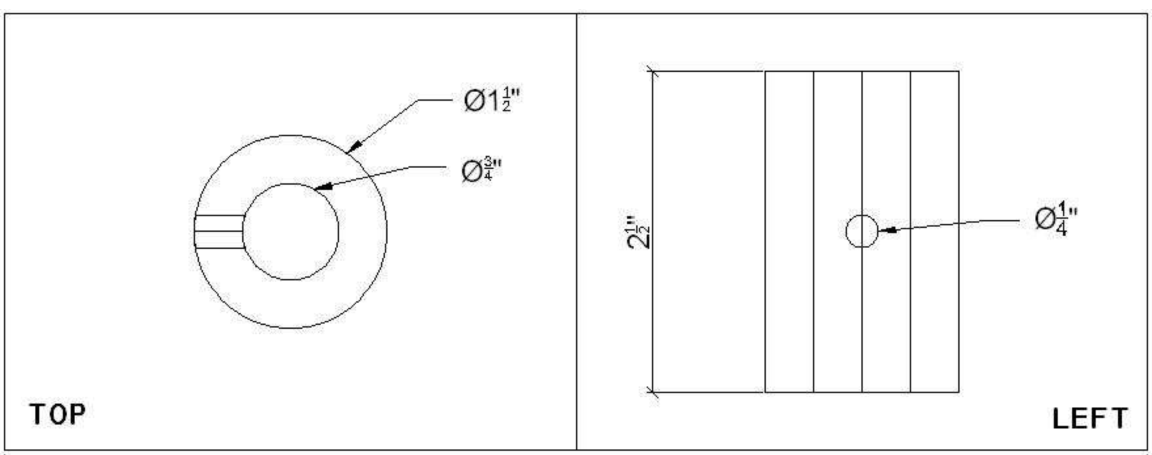


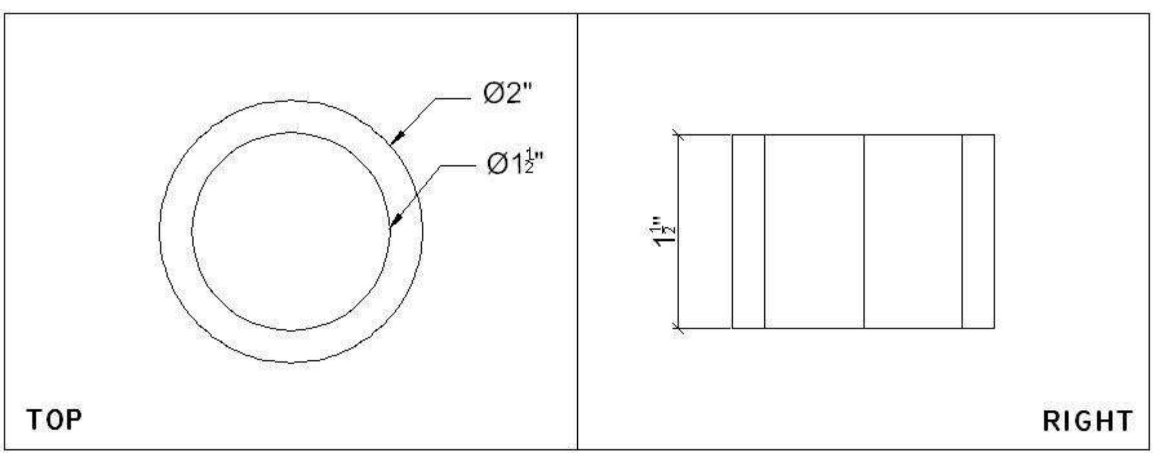
Figure 9 - Pulley for Fixed Rubber Roller



3.6 Bearing casings

To facilitate the rotation of all shafts, bearings were added to the shafts and placed against the back plate. Since the rotational speed of a bearing is dictated by the amount of frictional heat generated and the rate at which heat can be transferred away from the bearing (SKF), the only consideration when selecting the bearings was the outside diameter of the shafts and the internal diameter of the bearings. As such, 6204 2RS bearings were used. The 2RS designation refers to the 2 rubber seals on the face of the bearings which prevent dust from entering into them. Two bearings were used for each shaft in an attempt to limit the wear exerted on the bearings due to imbalances resulting in vibrations. The vibrations could cause the shafts to no longer be perpendicular to the bearings, therefore by using two bearings, each bearing is able to counteract any vertical movement of the shaft. A bearing further from the imbalance experiences a larger displacement (Harris and Piersol, 2002). As such the bearings should be as close to the imbalance, the rotor, as possible, resulting in the desired location of the bearing being the back plate. To hold the bearings in place, three sets of identical bearing casings were built. The casings were built from 2" diameter steel pipe. Their internal diameters matched the outside diameter of the bearings exactly using the lathe machine. This was an iterative process, with minor adjustments being made with a hand file; if the space for the bearings was too large, the possibility of them slipping out of the casing would exist. While this would not be a dangerous situation, since the bearings would be confined to the shaft, it was an undesirable outcome. Since there are no forces being exerted on the walls of the bearing casing, except for the very negligible pressure caused by minor vibrations, the walls of the casing can be made very thin; however, due to time limitations, it was deemed unnecessary to reduce the outside diameter beyond the initial diameter of the steel pipe.

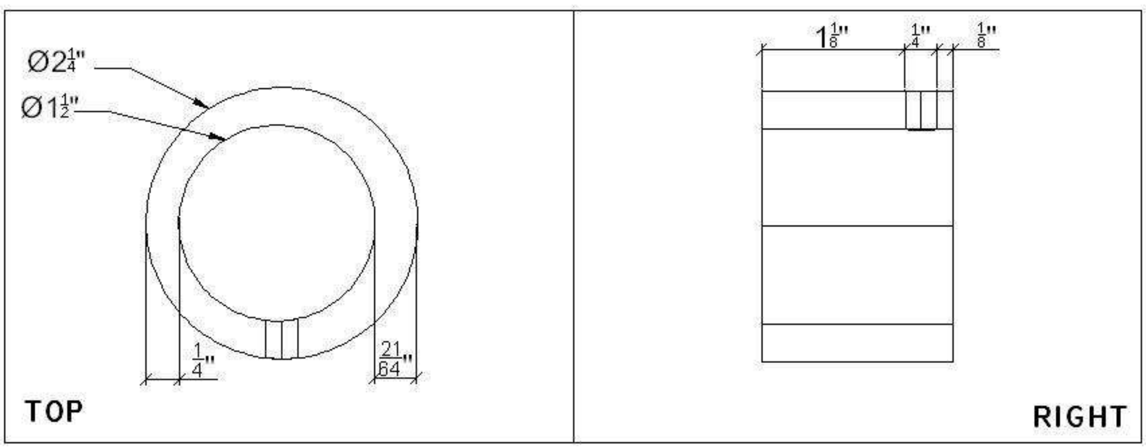
Figure 10 - Bearing Casing



3.7 Eccentric circle

A crucial part of the design was being able to adjust the spacing between the two rubber rollers. This critical function was achieved using an eccentric circle, which fit into the bearing casing of the left roller, when viewed from the back. The hole in the back plate for the shaft of the left roller was offset from the center point of the bearing casing. This resulted in a varying wall thickness. The wall thickness ranged from ¼" to 21/64". This varying wall thickness meant that depending on the orientation of the piece, the shaft would either be more to the left or right of the bearing casing. Naturally, as the shaft changed positions, so would the roller itself. To facilitate the adjustment of the eccentric casing, a hole was drilled and taped through the wall. As the eccentric casing is not totally encased by the bearing casing, the screw protrudes from the eccentric casing, and can easily be turned by hand. To lock the eccentric casing in place, a set screw was used which passes through the bearing casing and grips the eccentric casing.

Figure 11 - Eccentric Casing



3.8 Hopper

The original hopper was built from four identical pieces, with a top width of 6 inches and a bottom width of 2 inches, and a height of 8 inches. The 3mm pieces of galvanized steel were cut on the hydraulic press cutter. The press brake was used to create a ¼ inch lip on one of the edges of the piece. The pieces were fitted together creating a square cross section at the top and at the bottom. They were then spot welded together. Care was taken to ensure the cooling system was running whenever the spot welder was used. The effective volume of the original hopper was:

Equation 15

$$
\begin{aligned}
Vol_{eff} &= (⅓ \cdot (area_{\,base} \cdot height_{total})) - (1/3 \cdot (area_{\,base} \cdot height_{\,top})) \\
&= ⅓ \cdot ((6 - 0.25)^2) \cdot 8) - (⅓ \cdot (2 - 0.25)^2 \cdot 2.66) \\
&= 84.6\, cubic\ inches = 84.6 cu.in \cdot \frac{16.387ml}{cu}.in = 1.386L
\end{aligned}
$$

Enlarging the hopper would be as simple as extending the side walls. A slide was implemented at the bottom of the hopper to be used to control the flow of the feedstock. The hopper was positioned directly above the center of the roller configuration. While the hopper did not leak and provided full control of the flow, the results were not ideal. It was observed after the very first trial that some of the grains were not passing through the rollers, but bouncing off of them and bypassing the shearing action. This needed correction, and it was understood that in order to ensure all the grains passed through the roller, singulation of the grain was required. Furthermore, it was hypothesized that introducing the ribbon of grain from the side of the rollers, instead of having them falling vertically would reduce the initial velocity of the grain and limit the possibility of them bouncing away from the space between the two rollers. Those were the goals for the second iteration of the hopper.

3.9 Idler pulley

To create the necessary tension in the belt for operation, and to achieve the desired orientation, an idler was installed to the right of both rollers. This idler consisted of a hollow cylinder with an outer diameter of 1 2/3 inches, enclosing two ball bearings. This cylinder was attached to a piece of ¼ inch thick steel. This steel piece had a hole drilled in the end opposite of the cylinder, which was used to pin the idler to the back plate. As the idler was simply pinned, the tension could be increased by pulling the idler towards the exterior of the mill. The desirable tension in the belt was calculated using the formula presented below:

The following equations were taken from Clark Transmission's website.
A Super Blue Ribbon AP V-Belt was used in the development of the mill.

Equation 16

$$T_s = \frac{Design\ Hp * K}{Q * S} + T_c$$

S = belt speed, feet per minute/1000
Q = number of belts on drive
T_c = add-on tension allowance for centrifugal force, from Fig. 31 in Appendix A

Equation 17

$$\mathrm{K = Fig.\,32\ (Appendix\ A)\ value\ based\ on}\ \frac{D - d}{C}$$

C = center distance between pulleys, in inches
D = large sheave pitch diameter, in inches
d = small sheave pitch diameter, in inches
As the value of K increases as the difference between the two sheaves changes, the greatest difference of the system will be used to ensure the required tension is not less than the largest requirement of the system.

Equation 18

$$\frac{D-d}{C} = \frac{2.25-1.75}{9.4375} = 0.0529$$

Using linear interpolation and the table values, a K value of 25.0368

Equation 19

$$S = RPM * d_{circumference\ pulley} = 1100 * \pi * 2.25$$
$$= 7771.5 in/\min = 647.625 ft\ per\ min\ /1000$$

S = 0.647625ft/1000 per minute, therefore through linear interpolation T_c = 0.1449
Finally,

Equation 20

$$T_s = \frac{1 * 25.0368}{1 * .647625} + 0.1449$$

T_s = 38.804lbs

Checking the tension can be done using minimum and maximum deflection forces, found through the equations:

Equation 21

$$P_{min} = \frac{T_s + Y}{16}$$

Equation 22

$$P_{max} = \frac{1.5T_s + Y}{16}$$

Y is given in Fig. 33 (Appendix A). For an AP belt Y = 5.00

$$P_{min} = \frac{38.804 + 5}{16} = 2.73 lbs \quad P_{max} = \frac{(1.5 * 38.804) + 5}{16} = 3.95$$

These values indicate the belt should not deflect unless 2.73 pound force in exerted, and maximal deflection will occur if 3.95 pound force or higher is exerted.

Figure 12 - Idler Pulley

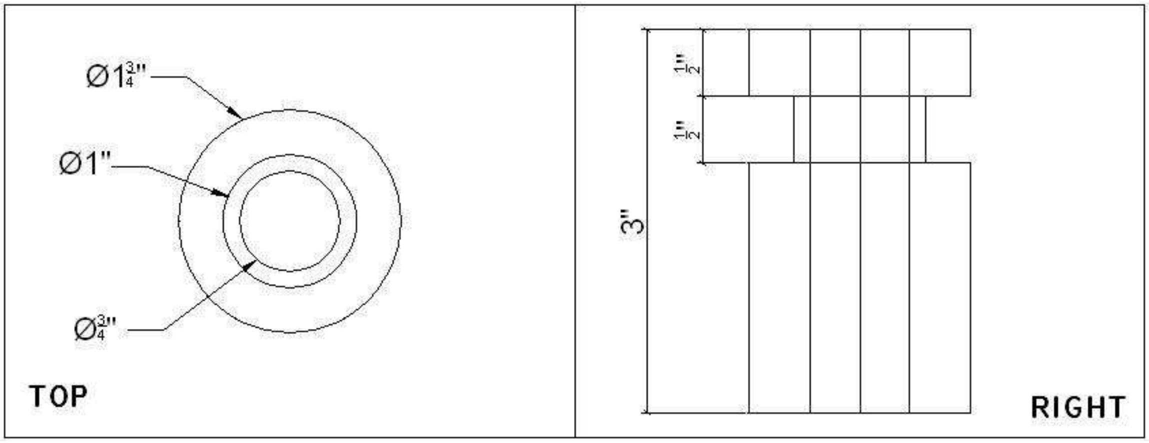


Figure 13 - Idler Pulley Plate

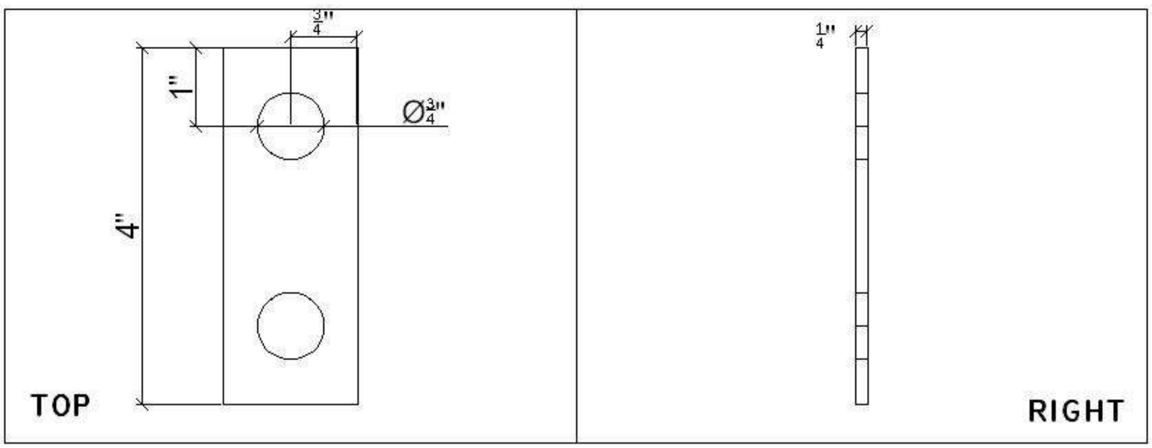
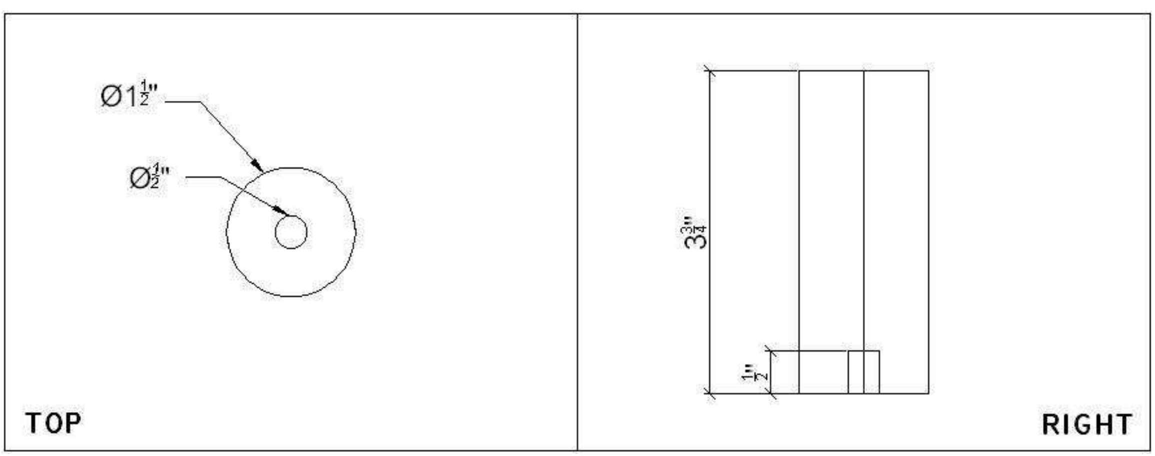


Figure 14 - Idler Pulley Shaft



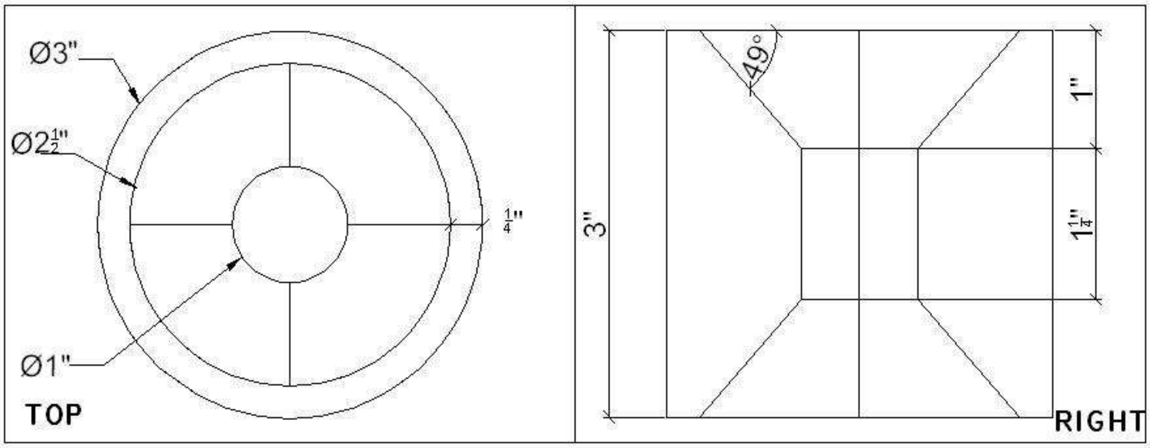
3.10 Separation

The initial plan to achieve separation of the grain from the hull, was to replicate the design used in India 2011. As the grain/air mixture exited the exhaust it entered a chamber with a square cross-sectional length of 355.6 mm. The larger cross sectional area is used to decrease the particle and air velocity in this part of the machine. This cross-sectional area was achieved over a horizontal distance of 355.6mm, with constant cross-sectional area increase in an attempt to create laminar flow conditions. The expansion unit was fabricated out of sheet metal. The length of the chamber 610mm and its top and sidewalls were fabricated from a gunnysack. The gunnysack was used in an attempt to diffuse air out the walls and roof to increase mass flow through the system. The lower section of the separation chamber was fabricated from sheet metal. The grains slid through the separation unit and were collected at the lowest point. They then fell horizontally and crossed through a perpendicular air stream. The air stream blew the hull and any other light materials a distance ranging from 178 to 406mm, while the grain was shifted horizontally a distance ranging from 0 to 152.4mm. This resulted in complete separation of the hull and grain. While this method could have effectively been used, a more elegant technique was developed as described later on.

3.11 Rollers

While the production model needed to use, hard, durable, food grade rubber for the rollers, our model did not need to use food grade plastic, as our model was to prove a concept. It is a safe assumption that the rubber we selected, which was not food grade, has a food grade counterpart available in India. The search for a hard, durable rubber roller which was readily available to the team led to longboard wheels. The wheels are designed to roll over pavement and keep their shape when rolling over rocks: ideal characteristics for us. Furthermore, they came ready to be mounted to a shaft. Larger wheels would provide a larger area for the removal of husks. Abec11 wheels, with a diameter of 3 inches and a length of 3 inches, were procured. No modifications to the wheels were required.

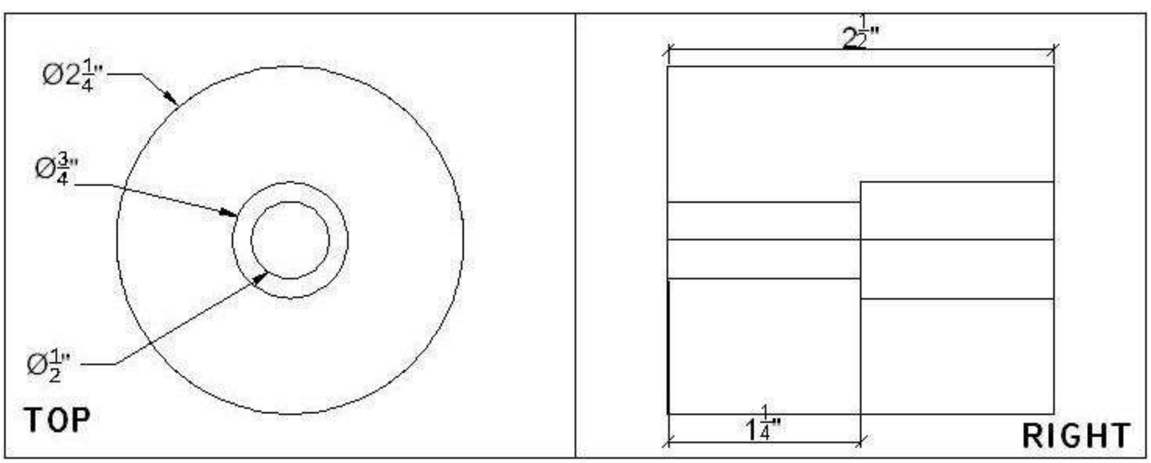
Figure 15 - Rubber Rollers



3.12 Coupler

The shaft of the electric motor needed to be coupled to the rotor shaft, which was also the drive shaft for the belt and allowed the motor and rotor shaft to be disconnected. The motor shaft was ½ inch in diameter. Although the rotor shaft could have been built to the same size as the motor shaft, it was suggested by Dr. Sotocinal that for safety the rotor shaft should be larger. In addition, in order to drill a ¼ inch bolt hole in the rotor shaft, the rotor shaft had to have a larger diameter than that of the motor shaft to allow for clearance. The rotor shaft was also limited by the inner diameter of bearing of ¾". A steel collar was built, with a hole drilled through the center. Half of the hole matched the diameter of the motor shaft of ½ an inch, while the other half was drilled to the size of the rotor shaft, ¾ of an inch. Holes were drilled and tapped at either end of the collar for set screws.

Figure 16 – Coupler



3.13 Motor Mount

The electric motor used to power the mill was a 1hp, b-face electric motor. The shaft of the motor was fixed at the same height as the rotor shaft by constructing a frame, onto which the motor was mounted with four bolts passing through the flange of the motor. Since this piece would vary depending on the motor being used, detailed drawings and dimensions are not provided.

3.2 Drawings

See Appendix B for more views.

Figure 18 - 3D Front View

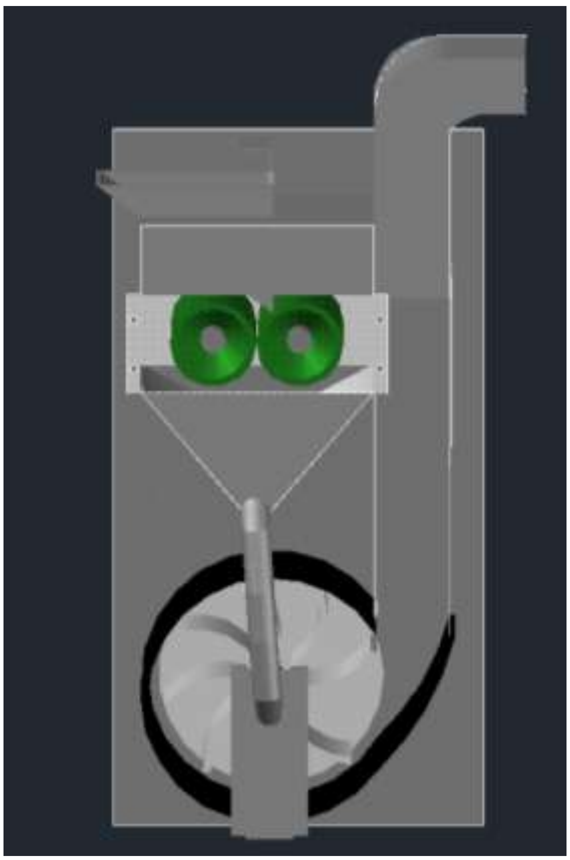


Figure 17 - 3D Back View

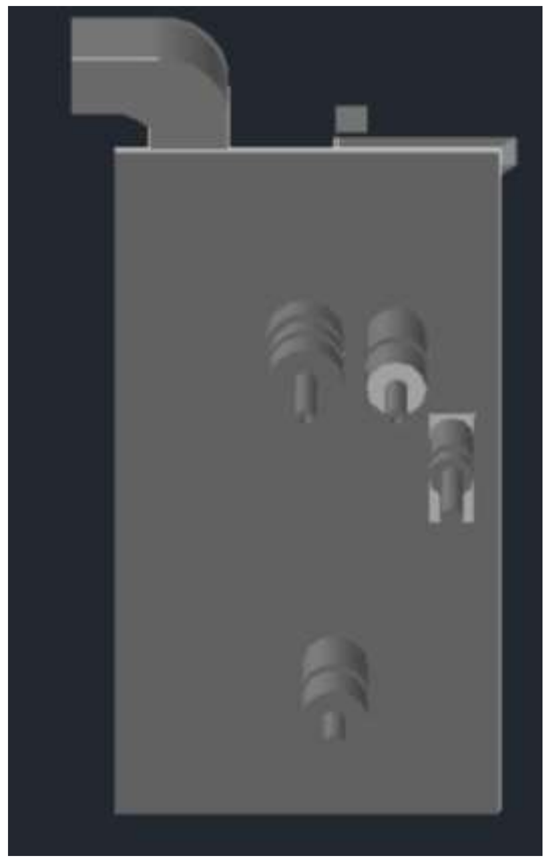
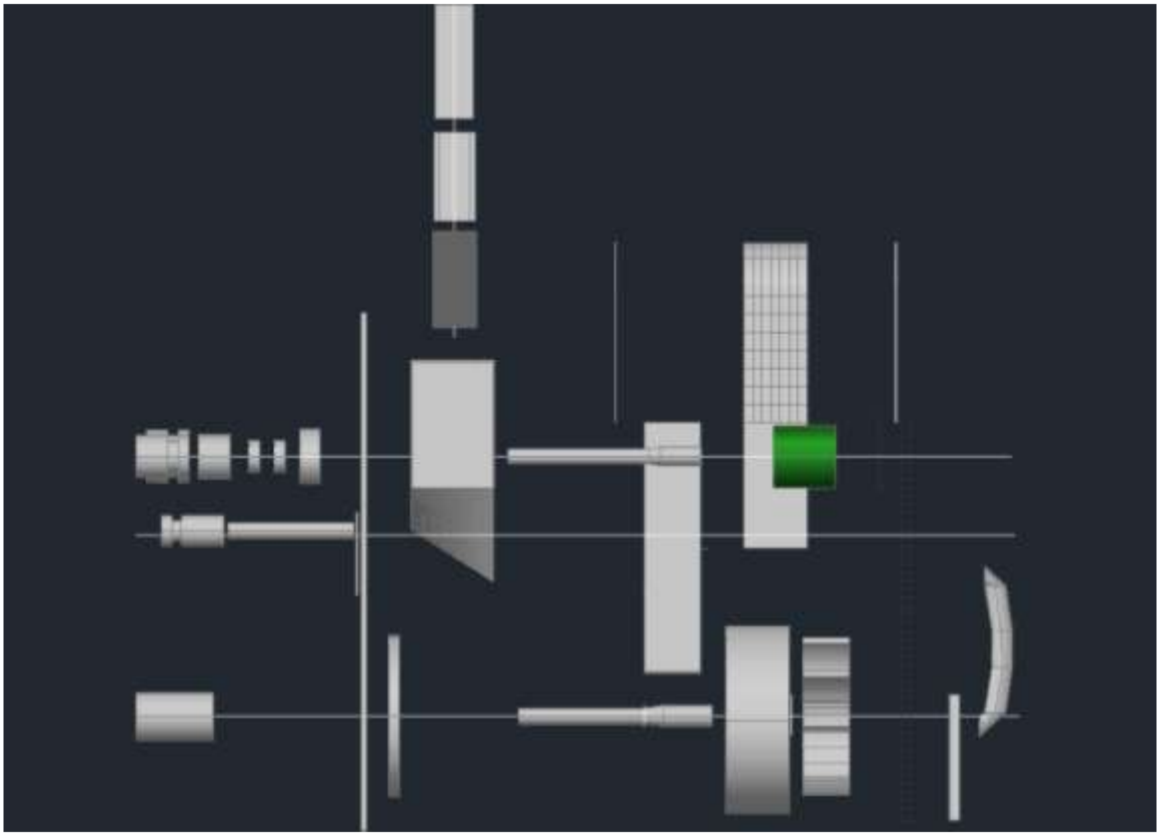


Figure 20 - Exploded View



4. TESTING & RESULTS

4.1 Methods

After the fabrication of the mill, testing was conducted to determine the optimal settings by which the mill achieves the best results. Testing was carried out using 50-g samples of whole grain little millet from Dharwad, India. Each sample was recovered in entirety and analyzed by hand counting. From each processed lot, a random sample was taken and sorted and counted by hand into three categories: whole grain, cleaned grain and broken grain where a broken grain can be defined as a grain that has lost over 25% of its mass. The random samples were taken with a bottle cap of volume 5.5mL; the volume was determined with the use of a pipette. This method proved to be extensively time consuming as each bottle cap holds in the range of 1950-2200 grains. Due to the time constraints involved in the project and the time-intensive test analysis, some tests were carried out and analyzed visually. In certain cases, it was clear to the team that certain modifications or settings did not work. In these cases, hand counting was not performed.

4.2 Centrifugal & Roller Mills

The first three tests performed on the mill were to determine the best configuration for milling. Essentially, the tests were to evaluate milling efficiency and number of broken grains. This was the starting point. The first test evaluated the centrifugal mill alone, the second evaluated the rubber-roller mill alone and the third test evaluated the two mills combined. During these tests, the results were quite conclusive and visual inspection of the output product was sufficient to make informed decisions. The tests were carried out using 50-g samples. The entirety of the output was collected and detached hulls were separated using the vertical air stream.

4.2.1 Centrifugal Mill

As the team projected it would, the centrifugal mill displayed a low efficiency. This was most likely due to the small sized rotor. Over 50% of the recovered lot did not experience de-hulling. The samples were passed through the mill at various RPMs; however, the milling efficiency did not experience a significant change. Second pass trials were also conducted. Though the milling efficiency did improve, the number of broken grains was found to be too high.

4.2.2 Combined Mills

The combined mill boasted the highest efficiency. After one pass, the efficiency was estimated at around 70%. After a second pass, the efficiency was found to be closer to 90%. It was with confidence that the 95% efficiency goal could be reached with this configuration, however, as was the case with the centrifugal mill, the broken grains were too high in number.

4.2.3 Rubber-Roller Mill

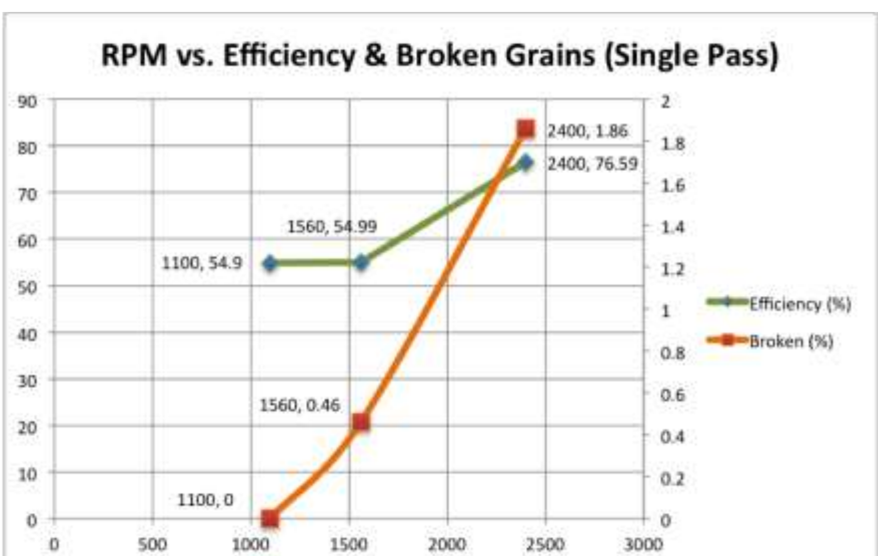
Finally, the rubber-roller mill was tested independently. The results after the first pass were found to be marginally lower than the combined configuration. After a second pass, again, the efficiency was marginally lower than the combined configuration, however, the number of broken grains was found to be significantly lower than the two other configurations. For this reason, the team decided to pursue this configuration. To achieve the goal of 95% milling efficiency with no more than 2% broken grains, further and more precise testing was required.

To maximize the efficiency of the rubber-roller mill, two parameters were to be optimized. First, the optimal RPM of the rollers would have to be determined and second, the optimal roller spacing would also have to be determined.

4.3 RPM

The RPM was measured using a hand-held tachometer with a light sensor. A piece of tape was placed on the pulleys for the light sensor to read the RPM at which the roller pulleys were rotating. Three different RPMs were tested and analyzed using the counting method. The following graph shows the efficiency (%) and broken grain (%) as functions of RPM after a single pass through the rubber rollers.

Figure 21 – RPM vs. Efficiency & Broken Grains (Single Pass)



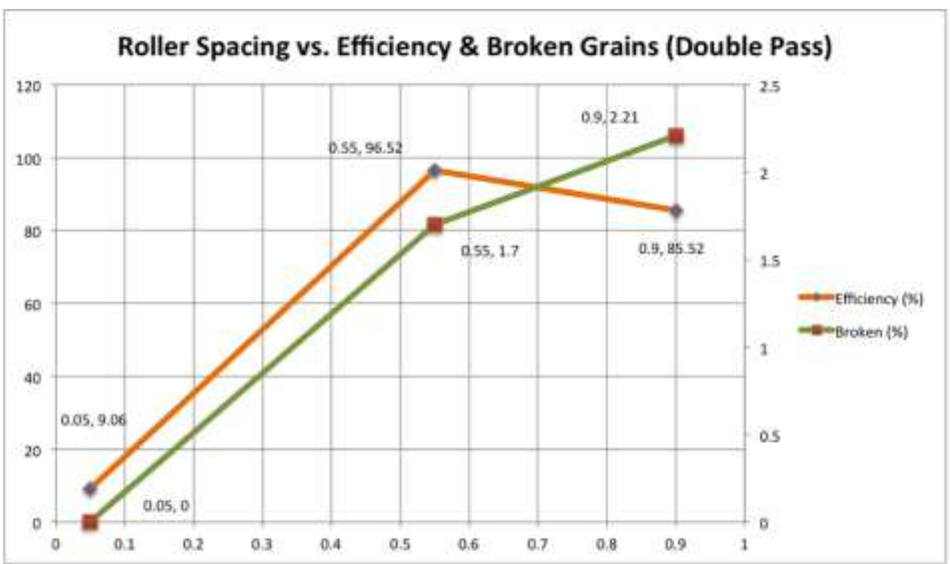
At 1100 RPM (minimum), the milling efficiency was found to be 54.9% with 0% broken grains. At 1560 RPM (intermediate), the milling efficiency was found to be 54.99% with 0.46% broken grains. And at 2400 RPM (maximum), the milling efficiency was found to be 76.59% with 1.86% broken grains.

Bearing in mind that these results are from single pass trials, the team decided to work with 1100 RPM to keep the broken grains to a minimum. It was believed that with optimal spacing and a second pass, the 95% efficiency goal could be achieved with limited broken grains. It should be noted that 1100 RPM is the rotational velocity of the roller coupled with the motor shaft at a 1:1 ratio. Keeping with the rollers relative velocity of 2:3, the second roller had a rotational velocity of 1640 RPM and as outlined in section 2.4, this was achieved with a pulley system.

4.4 Roller Spacing

The spacing between the rollers was determined using a metric Feeler Gauge. Again, three different spacings were tested and analyzed using the counting method. Similar to the RPM tests, the following graph shows the efficiency (%) and broken grains (%) as a function of spacing after a double pass through the rubber rollers at 1100 and 1640 RPM.

Figure 22 – Roller Spacing vs. Efficiency & Broken Grains (Double Pass)



At a spacing of 0.05 mm, the milling efficiency was found to be 9.06% with 0% broken. It was found that the spacing was too small; therefore, the grains entering the rubber rollers from the hopper could not pass between the rollers. With 0.55 mm spacing, the milling efficiency was found to be 96.52% with 1.7% broken grains. And with a spacing of 0.9 mm, the milling efficiency was found to be 85.52% with 2.21% broken grains.

Needless to say, the optimal spacing setting was found to be 0.55 mm. The goal to produce a mill with 95% milling efficiency with less than 2% broken grains had be achieved.

5. REVISIONS & FINAL CONFIGURATION

Once the milling goals were achieved, the final revisions were to be made before the mill was to be shipped to India. This included revisions to the hopper and the separation portions of the mill.

5.1 Hopper

In the end, instead of basing the dimensions of the hopper on a desirable capacity, it was decided that the hopper should fit within the profile of the front and back plate of the mill. This was a compromise in reducing the capacity of the mill with increasing the portability of the mill. With the new hopper, the capacity of mill was to found 20 kilograms per hour. This is well below the goal of 100 kilograms per hour, but because the mill is to be used as an educational tool where portability is a priority, the compromise is justifiable. It should however be noted that the capacity could be increased with larger rubber rollers.

The revised hopper incorporated a gate that acted as a throttle for the feed rate to allow for singulation. Furthermore, the revised hopper was designed to introduce the grains from the side of the rollers as opposed to having them fall vertically from directly above. This reduced the incoming velocity of the grain and a drastic improvement was noticed whereby grains were no longer found to be bouncing away from the space between the two rollers. The hopper is triangular in shape with a top horizontal length of 6 inches, a depth of 4 inches and a width of 2 inches. There is a metal vertical slide that controls the flow of grain which is held by a guide; the slide measured 5 ½ inches long, 1 ¾" wide and had a 1 inch horizontal lip to allow the mill operator pull the slide, while the guide wrapped the slide fairly snugly.

Figure 23 - Hopper

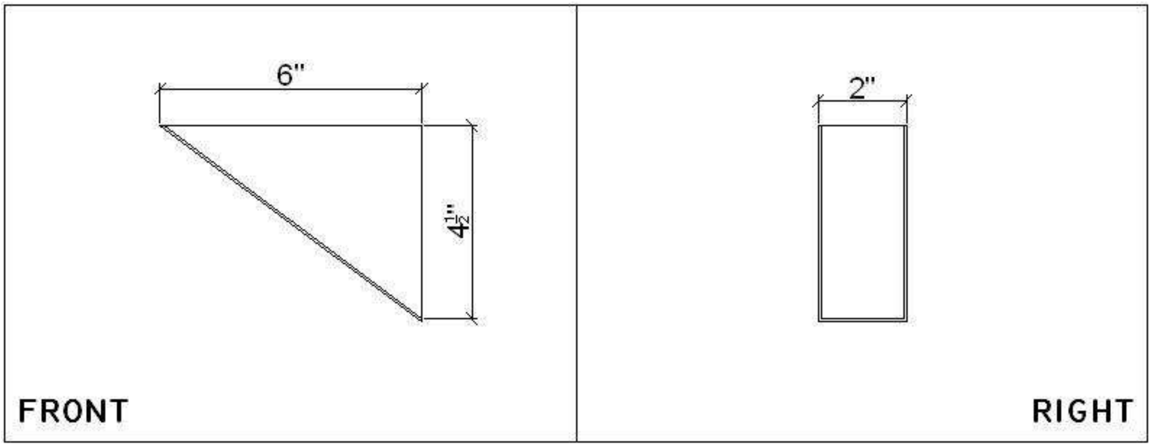


Figure 24 - Hopper Slide

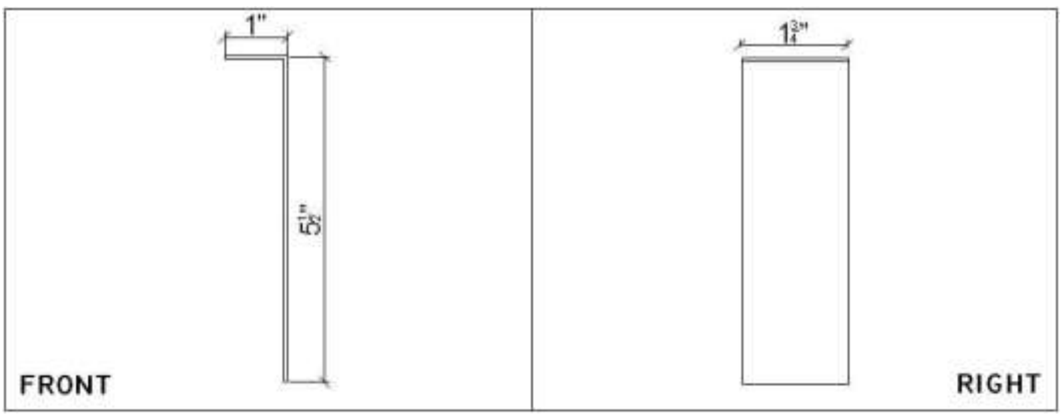
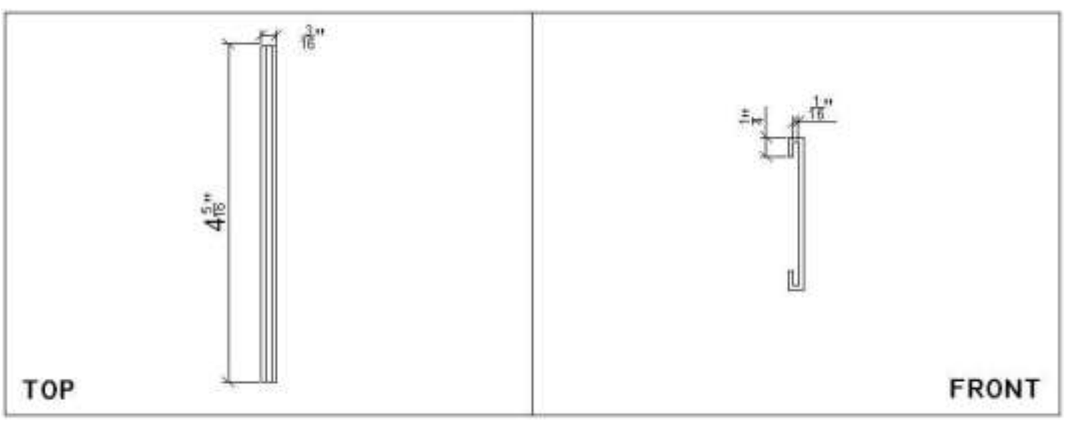


Figure 25 - Hopper Slide Guide



5.2 Separation

Because the milling efficiency goals were achieved with the use of the rubber rollers independent of the centrifugal mill, it was decided the centrifugal portion of the mill would be used for achieving separation. This would keep the profile of the machine to a minimum, as a horizontal air column would no longer be needed for separation. The idea is that if the grain/hull mixture exiting the rubber roller mill was directed in a path that crossed the inlet of the centrifugal mill, the suction of the impeller-mounted rotor would draw in the hulls while the cleaned grain continues to fall. Due to time constraints, this was process was designed entirely by experimentation.

In the final working design, the grain/hull mixture exiting the rubber-roller mill was directed to 1" below the centrifugal inlet. Because the RPM was optimized for milling, the suction from the centrifugal inlet was not entirely controllable; therefore, to achieve separation without cross contamination of the hulls and grains, the mixture was to be dropped below the inlet. The suction drew the detached hulls into the centrifugal mill while the cleaned grains continued falling. The final result are two separate lots that are recuperated from the mill: one lot of cleaned grains only and one lot of detached hulls. The goal to achieve 100% separation was achieved with this design.

5.3 Final Configuration & Specifications

The final configuration of the mill is as follows:

Figure 26 - Constructed Millet Mill

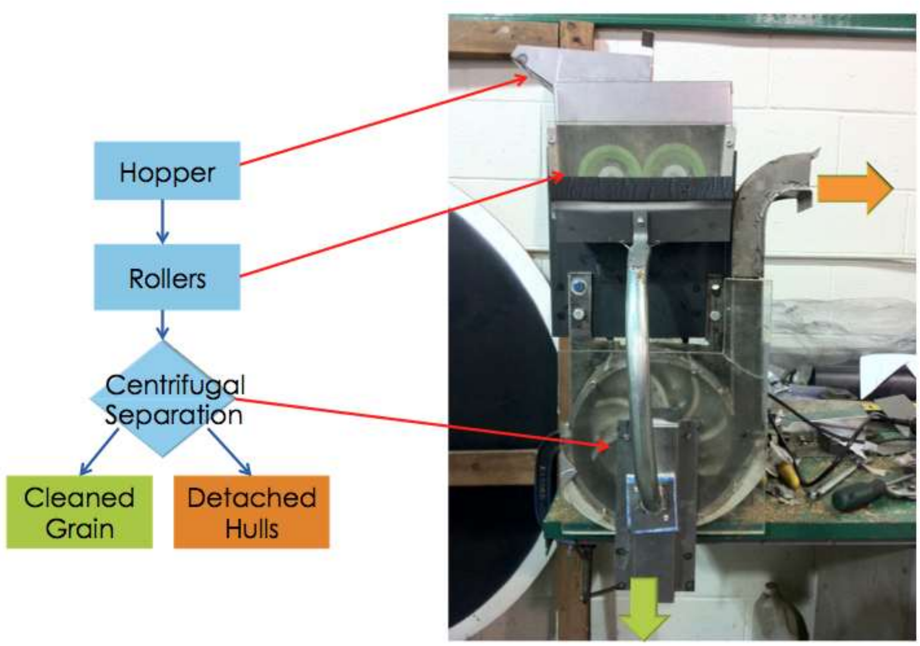


Figure 27 - Constructed Mill: Back View

The mill has the following specifications:

Figure 28 - Millet Mill Specifications

Motor	Single Phase 1 HP, B face permanent electromagnet motor
RPM (motor)	1100 RPM
RPM (rollers)	at a ratio of 2:3 – 1100:1640 RPM
Roller Spacing	0.55 mm

6. CONCLUSION

The goal of creating an efficient, portable and easy to use mill for little millet has been achieved. The efficiency of the designed rubber roller and centrifugal mill combination is 96.52% with only 1.7% broken grains, with the RPM for the motor and one rubber roller at 1100 and another rubber roller of RPM 1640 with a 0.55mm spacing between the rubber rollers.

The achieved efficiency stated above satisfies the criteria of achieving 95% milling efficiency with less than 2% broken grains. The mill is portable since it was built as compactly as possible around the parameters of the rotor and rubber rollers, each measuring less than 8 inches in diameter. This mill is easy to use since it employs an on/off switch to perform the milling and also uses a simple plate that is manually controlled to release the grain. As compared to the other mills evaluated in the Design 2 report (Swan et al., 2011), this milling combination requires less human labour, therefore it makes it easier for the mill operator to use.

The level of maintenance required on the mill is minimal since the parts are properly enclosed. Even though there are many moving parts, they are expected to have a long lifespan since the chosen materials are strong metals and the rubber rollers used are designed to withstand high forces on pavement which are greater than the force exerted by the millet.

The environmental conditions to the mill operator are favourable since the rubber rollers and the centrifugal mill are each contained within a casing, therefore any dust that is created from the milling process is contained.

Since the milling efficiency is greater than 95% and achieves 100% separation, there is no need for pre-treatments since these results achieve the stated goals. The milling capacity of 20 kg per hour is not as high as the goal of 100 kg per hour, but since this is a prototype of the mill and to be used for demonstration purposes and proof of concepts, this is an adequate capacity. In order to increase milling capacity, longer rubber rollers could be used which would allow for more contact area available for the grains.

An estimated cost of the materials of this mill is $581 CND if constructed in India (Appendix D). Compared to other mills as evaluated in the Design 2 report (Swan et al., 2011), this is an affordable mill, especially given the other criteria it satisfies.

Energy inputs are kept to a minimum since only one motor is used for both the rubber roller milling and the centrifugal fan operations.

The rubber roller and centrifugal mill combination was designed, built, prototyped, tested and optimized to achieve the goals of the project. Since it resulted in a high milling efficiency and separation of the grains and hulls, this mill can be used to further the adoption of millet by rural farmers in India.

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8. Appendix A – References for Construction

Figure 29 - Strength Density of Materials

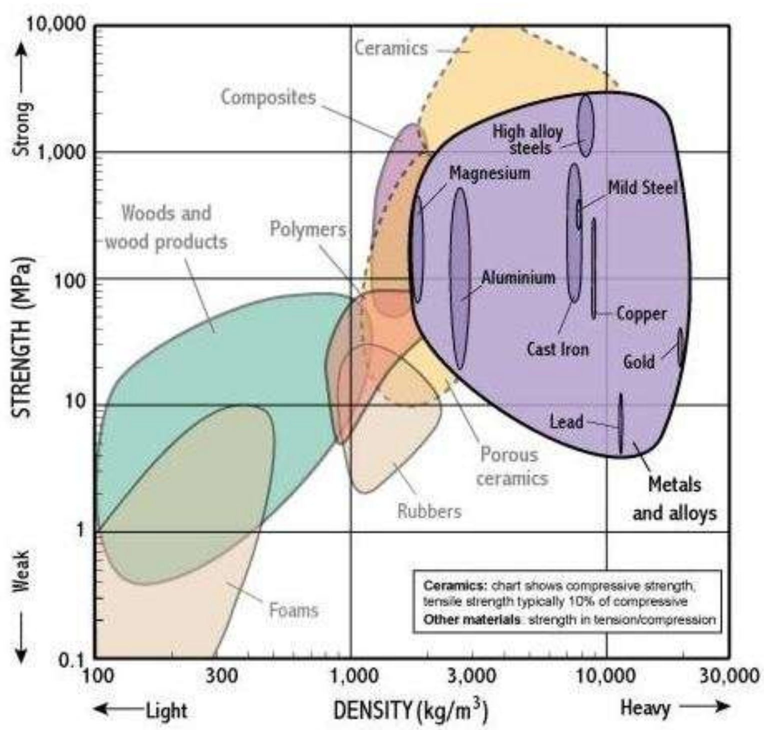


Figure 30 - Bolt Grade and Strength

Common Inch / Imperial SAE Grades: (all values in ksi or 1000 lbs / square inch)

Head Marking	Grade	Diameter (in)	Proof Strength	Yield Strength	Tensile (Ultimate) Strength
	2	1/4 to 3/4	55	57	74
		3/4 to 1-1/2	33	36	60
	5	1/4 to 1	85	92	120
		1 to 1-1/2	74	81	105
	8	1/4 to 1-1/2	120	130	150

Figure 31 - Milling Speeds

TABLE 8-1. Milling Machine Cutting Speeds for High-Speed Steel Milling Cutters.

MATERIAL	CUTTING SPEED (sfpm)[1, 2]			
	PLAIN MILLING CUTTERS		END MILLING CUTTERS	
	Roughing	Finishing	Roughing	Finishing
Aluminum..................	400 to 1,000	400 to 1,000	400 to 1,000	400 to 1,000
Brass, composition.........	125 to 200	90 to 200	90 to 150	90 to 150
Brass, yellow................	150 to 200	100 to 250	100 to 200	100 to 200
Bronze, phosphor and manganese	30 to 80	25 to 100	30 to 80	30 to 80
Cast iron (hard)	25 to 40	10 to 30	25 to 40	20 to 45
Cast iron (soft and medium)	40 to 75	25 to 80	35 to 65	30 to 80
Monel metal	50 to 75	50 to 75	40 to 60	40 to 60
Steel, hard..................	25 to 50	25 to 70	25 to 50	25 to 70
Steel, soft...................	60 to 120	45 to 110	50 to 85	45 to 100

1 For carbon steel cutters, decrease values by 50 percent. 2 For carbide-tipped cutters, increase values by 100 percent.

Figure 32 - Centrifugal Tension Add-On Values

TABLE 31 - Tc CENTRIFUGAL TENSION ADD-ON VALUES FOR CALCULATING STATIC STRAND TENSION (Ts) OF INDIVIDUAL V-BELTS. (FOR BANDED BELTS SEE TABLE 32)

S fpm/1000	POWER-WEDGE COG-BELT			SUPER POWER WEDGE		SUPER BLUE RIBBON				GOLD RIBBON COG & SUPER II			
	3VX	5VX	8VX	5V	8V	AP	BP	CP	DP	AX A	BX B	CX C	DX D
0.50	0.05	0.13	0.44	0.15	0.41	0.08	0.13	0.25	0.47	0.08	0.13	0.22	0.50
0.75	0.11	0.30	0.98	0.34	0.92	0.19	0.30	0.56	1.05	0.17	0.28	0.50	1.12
1.00	0.19	0.54	1.74	0.61	1.64	0.33	0.54	0.99	1.87	0.31	0.50	0.89	1.98
1.25	0.30	0.84	2.72	0.96	2.56	0.52	0.84	1.54	2.92	0.48	0.78	1.39	3.10
1.50	0.44	1.21	3.92	1.38	3.69	0.75	1.21	2.22	4.20	0.69	1.13	2.00	4.46
1.75	0.59	1.65	5.34	1.88	5.02	1.02	1.65	3.03	5.72	0.94	1.53	2.72	6.08
2.00	0.78	2.16	6.97	2.45	6.56	1.33	2.16	3.95	7.47	1.23	2.00	3.55	7.94
2.25	0.98	2.73	8.82	3.10	8.30	1.68	2.73	5.00	9.46	1.55	2.53	4.50	10.05
2.50	1.21	3.37	10.89	3.83	10.24	2.08	3.37	6.17	11.67	1.91	3.13	5.55	12.40
2.75	1.47	4.08	13.18	4.63	12.40	2.51	4.08	7.47	14.12	2.32	3.78	6.72	15.01
3.00	1.75	4.85	15.68	5.51	14.75	2.99	4.85	8.89	16.81	2.76	4.50	8.00	17.86
3.25	2.05	5.70	18.41	6.47	17.31	3.51	5.70	10.43	19.73	3.23	5.29	9.39	20.96
3.50	2.38	6.61	21.35	7.50	20.08	4.07	6.61	12.10	22.88	3.75	6.13	10.89	24.31
3.75	2.73	7.58	24.51	8.61	23.05	4.67	7.58	13.89	26.27	4.31	7.04	12.50	27.90
4.00	3.11	8.63	27.88	9.80	26.23	5.31	8.63	15.80	29.88	4.90	8.01	14.22	31.75
4.25	3.51	9.74	31.48	11.06	29.61	6.00	9.74	17.84	33.74	5.53	9.04	16.05	35.84
4.50	3.93	10.92	35.29	12.40	33.19	6.73	10.92	20.00	37.82	6.20	10.13	17.99	40.18
4.75	4.38	12.17	39.32	13.82	36.98	7.49	12.17	22.29	42.14	6.91	11.29	20.05	44.77
5.00	4.85	13.48	43.57	15.31	40.98	8.30	13.48	24.69	46.69	7.66	12.51	22.21	49.61
5.25	5.35	14.86	48.03	16.88	45.18	9.15	14.86	27.23	51.48	8.44	13.79	24.49	54.69
5.50	5.87	16.31	52.72	18.53	49.58	10.05	16.31	29.88	56.50	9.26	15.14	26.88	60.02
5.75	6.42	17.83	57.62	20.25	54.19	10.98	17.83	32.66	61.75	10.13	16.54	29.38	65.60
6.00	6.99	19.41	62.74	22.05	59.01	11.96	19.41	35.56	67.24	11.03	18.01	31.99	71.43
6.25	7.58	21.06	68.07	23.93	64.03	12.97	21.06	38.59	72.96	11.96	19.55	34.71	77.51
6.50	8.20	22.78	73.63	25.88	69.25	14.03	22.78	41.73	78.91	12.94	21.14	37.54	83.83
6.75	8.84	24.57	79.40	27.91	74.68	15.13	24.57	45.01	85.10	13.95	22.80	40.49	90.41
7.00	9.51	26.42	85.39	30.01	80.32	16.27	26.42	48.40	91.52	15.01	24.52	43.54	97.23

NOTE: When value of S is greater than 6.00, special sheaves and/or dynamic balancing may be necessary. See the Carlisle V-Belt Drive Design catalog (102161)

(Carlisle)

Figure 33 - V-Belt Tensioning

V-BELT TENSIONING
(Continued)

Table 29 Factors Table

Arc of Contact (degrees)	$\frac{(D-d)}{C}$	A	B	H	K	M	N (C_q)	O
180	0.000	—	1.000	2.000	24.750	1.000	1.00	0.75
179	0.017	57.297	1.000	2.000	24.843	1.000	1.00	0.75
178	0.035	28.649	1.000	2.000	24.937	1.000	1.00	0.76
177	0.052	19.101	1.000	1.999	25.032	1.000	0.99	0.76
176	0.070	14.327	0.999	1.999	25.129	0.999	0.99	0.76
175	0.087	11.463	0.999	1.998	25.227	0.999	0.99	0.76
174	0.105	9.554	0.998	1.997	25.326	0.999	0.99	0.77
173	0.122	8.190	0.998	1.996	25.427	0.998	0.98	0.77
172	0.140	7.168	0.997	1.995	25.529	0.998	0.98	0.77
171	0.157	6.373	0.996	1.994	25.632	0.997	0.9	0.77
170	0.174	5.737	0.996	1.992	25.737	0.996	0.98	0.77
169	0.192	5.217	0.995	1.991	25.844	0.995	0.97	0.78
168	0.209	4.783	0.994	1.989	25.952	0.995	0.97	0.78
167	0.226	4.417	0.993	1.987	26.061	0.994	0.97	0.78
166	0.244	4.103	0.992	1.985	26.172	0.993	0.97	0.78
165	0.261	3.831	0.991	1.983	26.285	0.992	0.96	0.79
164	0.278	3.593	0.990	1.981	26.399	0.990	0.96	0.79
163	0.296	3.383	0.988	1.978	26.515	0.989	0.96	0.79
162	0.313	3.196	0.987	1.975	26.633	0.988	0.96	0.79
161	0.330	3.029	0.986	1.973	26.752	0.987	0.95	0.80
160	0.347	2.879	0.984	1.970	26.873	0.985	0.95	0.80
159	0.364	2.744	0.983	1.967	26.996	0.984	0.95	0.80
158	0.382	2.620	0.981	1.963	27.120	0.982	0.95	0.80
157	0.399	2.508	0.979	1.960	27.247	0.980	0.94	0.81
156	0.416	2.405	0.977	1.956	27.375	0.979	0.94	0.81
155	0.433	2.310	0.975	1.953	27.505	0.977	0.94	0.81
154	0.450	2.223	0.973	1.949	27.638	0.975	0.93	0.81
153	0.467	2.142	0.971	1.945	27.772	0.973	0.93	0.81
152	0.484	2.067	0.969	1.941	27.908	0.971	0.93	0.82
151	0.501	1.997	0.967	1.936	28.046	0.969	0.93	0.82
150	0.518	1.932	0.965	1.932	28.187	0.967	0.92	0.82
149	0.534	1.871	0.962	0.927	28.329	0.965	0.92	0.82
148	0.551	1.814	0.960	1.923	28.474	0.963	0.92	0.83
147	0.568	1.760	0.957	1.918	28.621	0.961	0.91	0.83
146	0.585	1.710	0.954	1.913	28.771	0.959	0.91	0.83
145	0.601	1.663	0.952	1.907	28.922	0.956	0.91	0.83
144	0.618	1.618	0.949	1.902	29.076	0.954	0.91	0.83
143	0.635	1.576	0.946	1.897	29.233	0.952	0.90	0.84
142	0.651	1.536	0.943	1.891	29.392	0.949	0.90	0.84
141	0.668	1.498	0.940	1.885	29.553	0.947	0.90	0.84
Arc of Contact (degrees)	$\frac{(D-d)}{C}$	A	B	H	K	M	N (C_q)	O
140	0.684	1.462	0.936	1.879	29.718	0.944	0.89	0.84
139	0.700	1.428	0.933	1.873	29.884	0.942	0.89	0.84
138	0.717	1.395	0.930	1.867	30.054	0.939	0.89	0.85
137	0.733	1.364	0.926	1.861	30.226	0.936	0.88	0.85
136	0.749	1.335	0.922	1.854	30.402	0.934	0.88	0.85
135	0.765	1.307	0.919	1.848	30.580	0.931	0.88	0.85
134	0.781	1.280	0.915	1.841	30.761	0.928	0.87	0.85
133	0.797	1.254	0.911	1.834	30.945	0.925	0.87	0.86
132	0.813	1.229	0.907	1.827	31.132	0.923	0.87	0.86
131	0.829	1.206	0.903	1.820	31.323	0.920	0.86	0.86
130	0.845	1.183	0.898	1.813	31.516	0.917	0.86	0.86
129	0.861	1.161	0.894	1.805	31.713	0.914	0.86	0.86
128	0.877	1.141	0.889	1.798	31.914	0.911	0.85	0.85
127	0.892	1.121	0.885	1.790	32.118	0.908	0.85	0.85
126	0.908	1.101	0.880	1.782	32.325	0.905	0.84	0.84
125	0.939	1.065	0.870	1.766	32.752	0.899	0.84	0.84
123	0.954	1.048	0.864	1.758	32.970	0.896	0.83	0.83
122	0.970	1.031	0.859	1.749	33.193	0.893	0.83	0.83
121	0.985	1.015	0.853	1.741	33.420	0.890	0.83	0.83
120	1.000	1.000	0.847	1.732	33.651	0.887	0.82	0.82
119	1.015	0.985	0.841	1.723	33.886	0.884	0.82	0.82
118	1.030	0.971	0.835	1.714	34.126	0.880	0.81	0.81
117	1.045	0.957	0.829	1.705	34.370	0.877	0.81	0.81
116	1.060	0.944	0.822	1.696	34.618	0.874	0.81	0.81
115	1.075	0.931	0.815	1.687	34.871	0.871	0.80	0.80
114	1.089	0.918	0.808	1.677	35.130	0.868	0.80	0.80
113	1.104	0.906	0.801	1.668	35.393	0.865	0.79	0.79
112	1.118	0.894	0.793	1.658	35.661	0.861	0.79	0.79
111	1.133	0.883	0.785	1.648	35.934	0.858	0.79	0.79
110	1.147	0.872	0.776	1.638	36.213	0.855	0.78	0.78
109	1.161	0.861	0.767	1.628	36.497	0.852	0.78	0.78
108	1.176	0.851	0.757	1.618	36.787	0.849	0.77	0.77
107	1.190	0.841	0.747	1.608	37.083	0.845	0.77	0.77
106	1.204	0.831	0.736	1.597	37.385	0.842	0.77	0.77
105	1.218	0.821	0.724	1.587	37.693	0.839	0.76	0.76
104	1.231	0.812	0.710	1.576	38.008	0.836	0.76	0.76
103	1.245	0.803	0.694	1.565	38.328	0.833	0.75	0.75
102	1.259	0.795	0.675	1.554	38.656	0.830	0.75	0.75
101	1.272	0.786	0.644	1.543	38.991	0.826	0.74	0.74

(Carlisle)

Figure 34 - Factors C & Y

TABLE 30 - FACTORS Cc & Y

BELT CROSS SECTION	Cc SINGLE BELTS	Cc BANDED BELTS	Y
A	0.72	-	6.00
AP	0.72	0.86	5.00
AX	0.68	0.81	6.00
B	0.99	-	9.00
BP	1.09	1.36	8.00
BX	0.95	1.17	9.00
C	2.09	-	18.00
CP	1.84	2.24	18.00
CX	1.69	-	19.00
DP	3.65	4.19	28.00
DX	3.83	4.78	40.00
3VX	0.55	0.47	4.00
5VX/5V	1.25	1.32	11.00
8V	2.95	3.46	25.00
8VX	2.95	3.46	30.00

(Carlisle)

9. Appendix B – Mill Drawings

Figure 35 - Back Plate

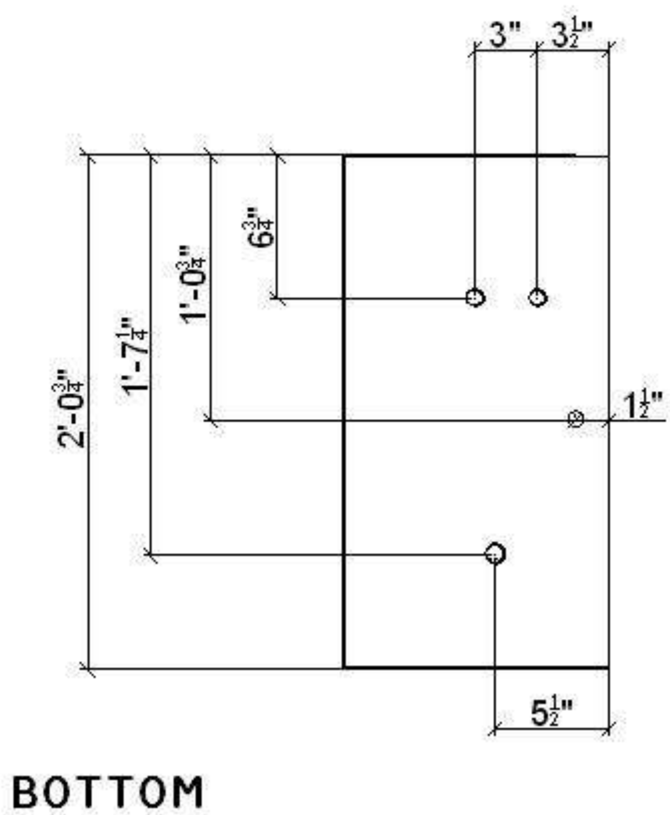


Figure 36 - Roller with Shaft

Figure 37 - 3D Side View

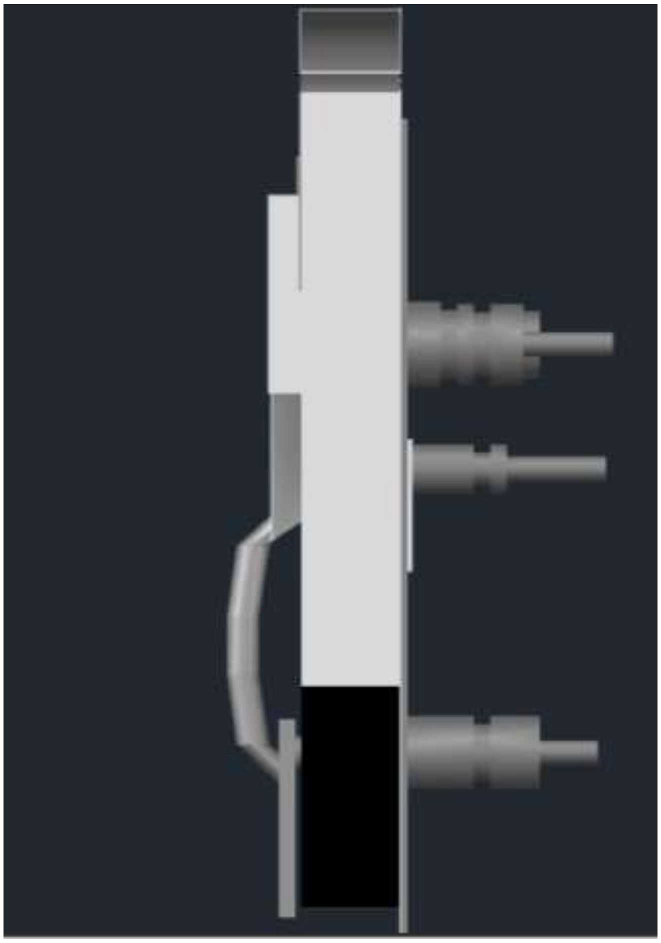


Figure 38 - Isometric View 1

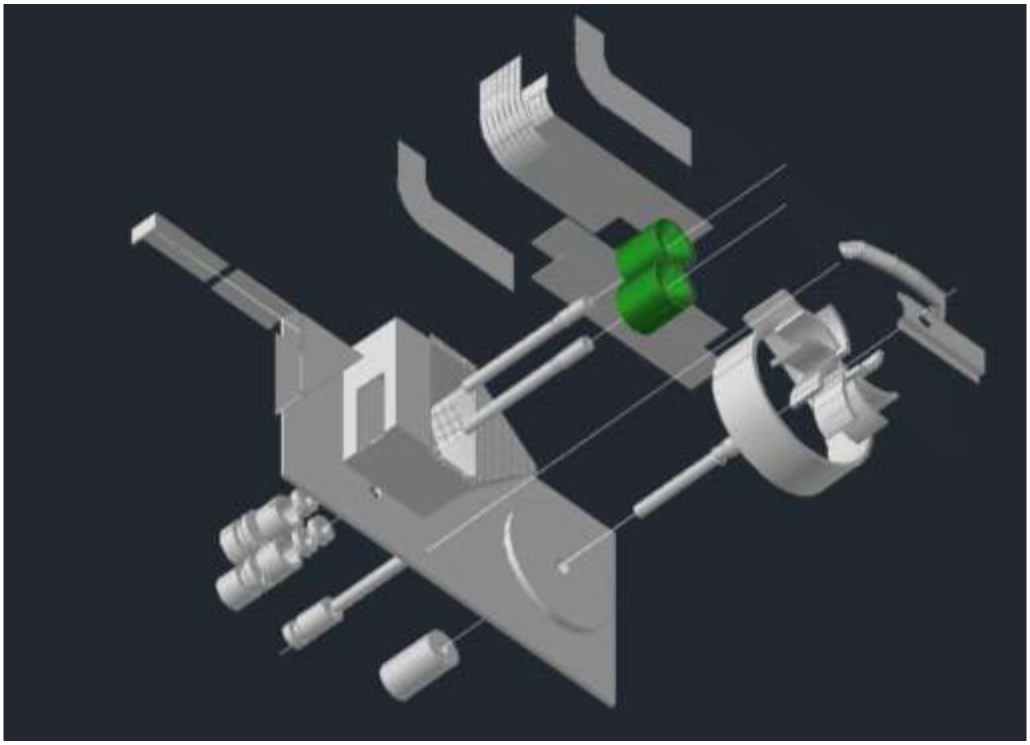
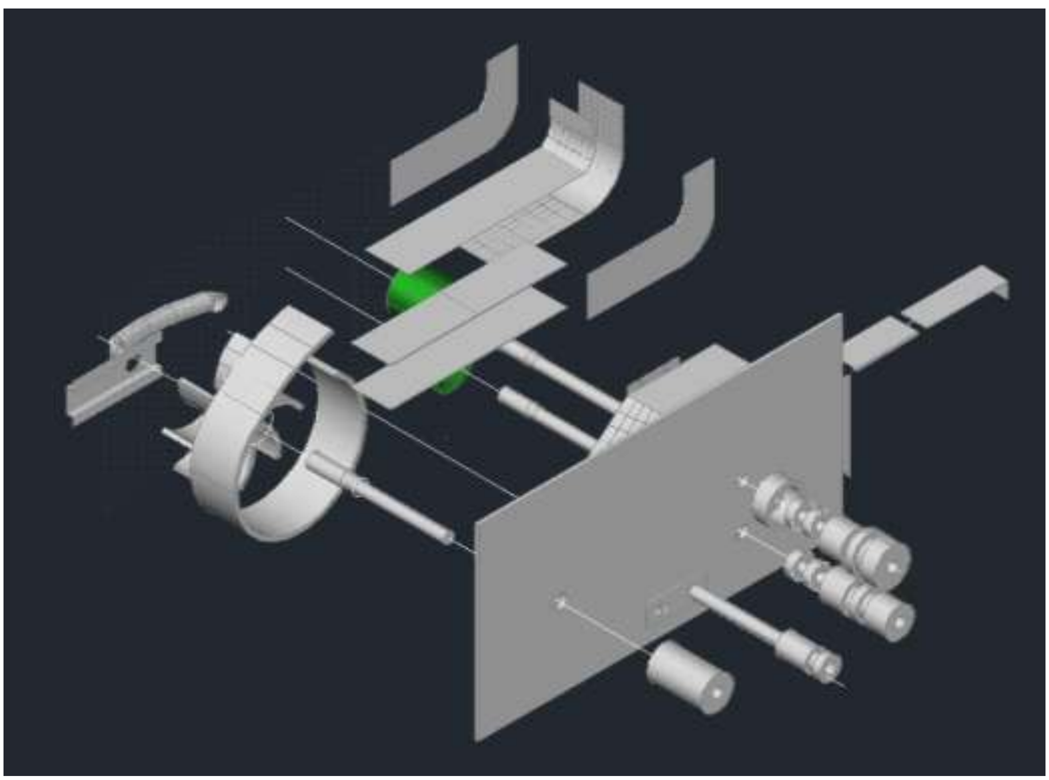


Figure 39 - Isometric View 2



10. Appendix C – Photos

Photos were taken by the team (2012).

Figure 40 - Rubber Rollers

Figure 41 - Rubber Roller and Idler Pulleys

Figure 42 –View with Motor

11. Appendix D – Estimated Costs

From the AutoCAD model the volume of Mild Steel required is 93 cubic inches.
The resultant mass is

$$Mass = \rho * V$$

$$Mass = 7850\, kg/cu.m * (93\ cu\ in * 0.000016387(\frac{\text{cu m}}{\text{cu in}})) = 11.96\text{kg}$$

$$Cost = mass * price/tonne$$

$$Cost = \left(\frac{11.96kg}{1000}\right) * \frac{801USD}{tonne} = 95USD$$

Price from http://www.worldsteelprices.com/

From the AutoCAD model the volume of Aluminum required is 37.81 cubic inches.

$$Mass = \rho * V$$

$$Mass = 2700\, kg/cu.m * (37.81\ cu\ in * 0.000016387(\frac{\text{cu m}}{\text{cu in}})) = 1.67\text{kg}$$

$$1.67\text{kg} * 2.20\text{lb/kg} = 3.67\text{lb}$$

$$Cost = mass * price/lb$$

$$Cost = (3.67lb) * \frac{0.92USD}{pound} = 3.37USD$$

Price from http://www.metalprices.com/pubcharts/Public/Aluminum_Price_Charts.asp

While these estimations are sound, it does not represent all the cost induced by transportation and labor. Dr. Sotocinal said that he would charge $1800 CND if he was to build the mill. This would include parts, labor and the motor. This is the pricing in a North American context. When the team was conducting their field research, a quote of 30000INR (581CND) was given, not including the motor.