Improving Sustainable Energy in Mexico: Biodigester Mixing System

Final Report

Adam Hashimoto
Peter Keros
Dan Ostahowski
Matthew Raubinger
Yue Ying

Mechanical Engineering 450 Winter 2009
Section 06: Sustainable Water and Energy Systems
Project 22
Professor Steven J. Skerlos
April 21, 2009

EXECUTIVE SUMMARY

Biodigesters are an emerging technology used in Mexican state of Michoacán to produce sustainable energy from waste. A biodigester converts animal and plant waste into biogas, which contains 50% to 60% methane. This biogas is then burned in the home instead of wood, which burns dirty and creates noxious fumes inside the home. Burning biogas can also offset carbon emissions since it produces less CO_2 per energy unit than wood.

These biodigestion systems, however, have some issues that must be addressed. To aid in the digestion, the biomass must be mixed occasionally; current methods are external and rather crude, including "massaging" the digester and having children play soccer on it.

Under the sponsorship of BLUElab and Ms. Sherri Cook, our project sets out to research, through testing, the mixing system desired for these biodigesters. The sponsors have asked us to design and prototype a mixing system that will locally suspend inorganic solids that collect on the bottom of the digester. This suspension will increase the likelihood of the solids leaving the digester during the natural plug-flow of the system. The more solids removed results in longer time needed for them to build up, thus increasing the maintenance time of the biodigester. Along with increasing maintenance time, our sponsors believe mixing may increase biogas production.

The requested system has limitations inherent to its current environment. The system must be adaptable to the varying designs found in Mexico. Because biodigesters contain animal waste, our design must not only be corrosion resistant but also sanitary and safe for the user. Further dealing with the user, the mixing motion must be comfortable and bearable, not causing fatigue during use. Finally, our design must be easy to install with a quick assembly time. Amongst all limitations, cost must be kept to a minimum in all considerations.

A functional decomposition was created as the first step for generating concepts. Using the decomposition as a guideline, many concepts for the mechanical external input of the system, the mode of torque transfer, and physical mixing mechanism were generated. These concepts were evaluated against our engineering specifications leading to our final design of a human input crank handle turning a flexible shaft to rotate a mixer with foldable fin blades. The blades will fold up to fit down a PVC pipe and, once inside, will fold out for wider mixing diameter and prevention of removal from the biodigester. The final prototype will be used in characterizing the system and will be an exact replica of the final design with the exception of aspects not needed in characterizing the mixing, such as flexible shaft length.

To characterize the mixing effectiveness of our final design, a testing rig half the size of an actual digester was manufactured. Both the prototype and the test rig were manufactured and assembled in the U of M Mechanical Engineering machine shop. In testing, sand and “Cow Manure” fertilizer were used to simulate the digester slurry. The results from testing showed that at the recommended mixing speed of 60 RPM for 30 seconds the mixing was localized, solids were visibly suspended, no fatigue occurred, and dissolved solids were removed. From this, we critiqued that the mixer have a hemispherical bottom for smoother motion and recommend further testing be done to optimize fin length and angle. Further testing should be conducted in a rig as large as the actual digester. We also recommend our design be used in research to determine if mixing in a plug flow system would increase biogas production.

TABLE OF CONTENTS

INTRODUCTION 4
BACKGROUND 4
SPECIFICATIONS/DESIGN CONSIDERATIONS 7
FUNCTIONAL DECOMPOSITION 9
CONCEPT GENERATION 9
CONCEPT SELECTION 12
CONCEPT DESCRIPTION 16
PARAMETER ANALYSIS 18
FINAL DESIGN 22
VALIDATION PLAN 30
DESIGN CRITIQUE 38
SUSTAINABILITY 39
RECOMMENDATIONS 40
CONCLUSION 41
ACKNOWLEGEMENTS 42
REFERENCES 43
APPENDIX A: Bill of Materials 45
APPENDIX B: Design Changes Since Design Review #3 46
APPENDIX C: Design Analysis Assignment 47
APPENDIX D: Energy Analysis 55
APPENDIX E: Functional Decomposition 60
APPENDIX F: Concept Generation & Selection 61
APPENDIX G: Mixing System Part Drawings 64
APPENDIX H: Stress Analysis 66
BIOGRAPHIES 75

INTRODUCTION

When plant and animal waste is anaerobically digested by bacteria, a gas is produced which contains 50-60% methane. Farmers use the waste produced by their animals and crops to make biogas and use it in their house to cook instead of burning wood. However, current systems offer little storage of the gas. In the bag-type digester system, gas is collected in a secondary bag above the anaerobic digester bag and is connected directly to the household gas burner. When the collector bag is full, excess gas will be vented to the atmosphere. This system also offers little control over the gas in terms of pressurization and metering. Most gas meters require higher pressures to operate than the system provides. This means that there is no opportunity to track how much biogas the system is producing. Once enough biogas is drawn from the bag, there is no longer enough pressure gradient to support a flame at the burner even though gas still exists in the bag. The problem presented to our team is to design a system to store biogas at higher pressure to maximize system efficiency, incorporate a gas metering system, and offer more control over the characteristics of the biogas at delivery.

After some further calculations, details of which can be found in Appendix D, we found that gas storage is not a viable option. Following that discovery, we focused our efforts on gas metering to determine how much carbon dioxide the digester is offsetting. This process would be important for agencies selling carbon credits. However, all of the research and information that we found, details of which can also be found in Appendix D, pointed at the infeasibility of such a system. Both cost and functionality prohibited us from pursuing a solution to this problem. After encountering this roadblock, we concentrated on designing a mixing element for the system. A mixing element is desired to be incorporated into the digester to improve system performance. The bottom-most layer in the digester will inherently be made of heavy, inorganic compounds like finer grains of sand. These solids accumulate over time because they are not broken down by the bacteria in the digester. If too much accumulates, the biogas production declines because less volume is available for decomposition inside the digester. While it may take several years for enough solids to build up for the digester to require emptying, removing this material requires the digester to be opened. This ruins the mixture by exposing it to air. Therefore, it would be preferable that the solids could be removed in such a way that would not require "invasive" actions.

BACKGROUND

Anaerobic digesters have been around since the 1960’s and originated in Eastern Asia. There are many different digester designs, but we will be working with only one type in this project; the Taiwanese bag system, which is based on plug-flow principles [1]. Plug-flow digesters have influent added on one side of the bag and is generally left unmixed and gradually flow towards the outlet on the opposite end as more waste in introduced. The amount of feed added is always displaces the same amount of effluent out of the outlet [2]. The other popular types of digesters are fixed-dome and floating-dome. Bag systems are an alternative to the traditional dome systems and offer easier installation and generally lower prices.

Digester Information

The key source of information for this project is Alex Eaton of the International Renewable Resources Institute (IRRI), an expert on biogas production and bag system design. Typical systems are usually 1 m wide by 1 m deep by 3 m long ($3m^3$ total volume) and use a high density polyethylene (HDPE) bag material that resists UV rays, puncture and is repairable. The plastic bladder contains slurry of 10-30% solids. There is an inlet and an outlet for the waste stream and the correct system water level is maintained by the triangle design that creates a "water-lock" so no gas can escape at these points (see schematic in Figure 1 below) [3]. The specific systems used to handle the influent and effluent are extremely varied between applications. Generally, the influent is premixed in a basin or bucket and then transferred into the digester influent pipe directly. The effluent generally flows through pipe into a holding container of sorts, where it sits until the farmer applies it to his crops or disposes of it.

Figure 1: Digester schematic

Figure 2: Actual plug-flow digester

Mainly methane and carbon dioxide are produced as the bacteria in the waste begin to break down the mixture. Biogas fills up the space at the top of the digester and expands through a tube into another bag located above the digester. At the outlet of this bag, there are a series of valves and mechanisms to control the gas. Most of the gas transport pipes and connections are made of PVC material which is very inexpensive. There is an on/off valve, a pressure blow-off valve, and a hydrogen sulfide (H_2S) removal mechanism. Despite the wide range of system designs, generally the influent and effluent tubes are about 4" in diameter and 3' in length [1]. These dimensions will be assumed throughout the design process. Also, some systems incorporate PVC pipes with bends, while others do not. We will attempt to account for these inconsistencies by designing a robust, adaptable system.

Mixing Benchmarks

Overall, and in the vocabulary of mixing, desired functions for our mixing system include solids suspension, dispersion and blending of miscible solids. Solids suspension means mixing an insoluble solid into a liquid. There are various degrees of solid suspension; complete motion, complete suspension and complete uniformity. We will not try and limit ourselves by designing around achieving a certain type, but rather around the principle that any solids suspension will be good for our system. Blending is the mixing of two or more solids into a more uniform mass and dispersion is where one phase (our solids on the bottom) are broken into discrete particles and completely surrounded by the second phase (the liquid slurry) [4,5].

In commercial digesters, mixing mechanisms vary widely. Some designs call for an internal paddle powered by an electric motor. Other digester designs use pumps to move fluid from one area in the digester to another location (usually at the fluid surface) to mix the contents [6]. Most stirring mechanisms found in digesters are permanent fixtures. However, portable applications do exist. Cleveland Eastern Mixing is a company that specializes in mixing applications. Their make a product for mixing bulk containers (55 gallon drums) that features a collapsible propeller to achieve good mixing in applications with a small entrance hole [6[. The propeller collapses to be inserted into the entrance hole, then expands when rotated due to the centripetal force. The expanded and collapsed views can be seen in Figure 3 below. The propeller comes in a variety of sizes, including a 4" diameter model that would be suitable for our application. However, the price of $170 for just the propeller was determined to be too expensive for our application. While this benchmark encapsulates our design problem well, the low rotational speed produced by most human-powered mixing limits our reliance on centripetal forces to engage the propeller.

Figure 3: Collapsible mixing impeller from Cleveland Eastern Mixing [6]

Anaerobic Digestion Effluent Concerns

Any animal waste put into the digester can carry myriad bacteria, microorganisms and viruses. When digestion occurs, many of the volatile compounds are broken down. However, the effluent cannot be treated as benign. It is very likely that not all of the harmful substances in the waste were broken down and may still be present in the effluent stream. Since there is the possibility of human contamination with direct contact and water supply contact, we have developed an engineering characteristic that the digester mixing apparatus must not be able to be removed.

In addition to health concerns of digester effluent, it is important to understand some other compounds in the material and the effects they can have. Input waste has very high nitrogen content, and the digestion processes break down most of compounds, but they often produce ammonia. High concentrations of ammonia in fertilizer over a long time period of application can have negative effects. Phosphorus and nitrogen, also found in high concentrations in the effluent, are very important for crops and is very beneficial for growth, but continued application can lead to dangerously high concentrations and end up hurting rather than helping [7]. In addition, phosphorus and nitrogen that runs off of the soil during rains can present water quality issues once it reaches a human water supply. Overall, the effluent can serve as an excellent fertilizer, but care must be taken to not over-apply or directly contact the waste.

SPECIFICATIONS/DESIGN CONSIDERATIONS

We developed customer attributes, engineering specifications, and testing parameters to help in our design. Considerations that were not able to be rigorously defined and could not be tested but were still desired by the end user were called customer attributes. Considerations that were grounded in solid engineering principles and could be accurately defined were called engineering specifications. Each specification is derived from an attribute. Considerations that could be defined in an engineering sense but were inherently unknown prior to validation were called testing parameters, which were also derived from customer attributes. The table below shows all of these considerations and their classification.

Table 1: Design Considerations for the Mixing System

Engineering Specification	Customer Attribute	Constraint	Target
Insertion Size	Adaptable	< 4" OD	< 4" OD
Lifetime	Low maintenance	> 7 years	10 years
Cost	Low cost	< $400	< $300
Ergonomics – force	Ease of use	< 16.8 lbs	2 lbs
Ergonomics – time	Ease of use	< 10 min	Up to 10 min
Expanded Size	No effluent contact	> 4" OD	12" OD
Installation Time	Quick to install	< 1 hour	~ 20 min

Testing Parameter	Customer Attribute	Target
Effectiveness of Mixing	Mixes well	Solids removed (~168 g)
Mixing Time	Low time necessary	< 10 mins
Localization of Mixing	Mixes well	33%
Settling Time	Solid removal	> 20 seconds
User Fatigue	Ease of use	Minimal

Our customer attributes reflected an idea of an effective, user-friendly system that can be immediately used. They are listed in the table above next to the specification or parameter that they helped derive. Using our customer background and information from our sponsors, the attributes included low maintenance, ease of use, adaptable to existing digesters, low cost, no effluent contact, quick installation, good and quick mixing, and solid removal. Low maintenance is necessary because the mixer will stay inside the digester between maintenance checks and we do not want the farmers to devote time away from their normal duties to take care of the system. A design that is easy to use will not burden the operator. Given that there are already a number of digesters in Mexico, our system must be able to adapt to them so that they can get the benefit of mixing immediately. If necessary, we may have to cut a small hole in the effluent pipe in which to insert our mixer. If that is the case, we can seal the hole with another piece of PVC or other plastic, secured in place with epoxy or duct tape. Cost is always important, and though the digesters are funded with government grants (i.e. no out of pocket expense for the farmer), keeping costs low will make the mixer more reasonable to purchase. Given the potentially hazardous nature of the effluent, there must be no contact with it whatsoever. Quick installation is necessary to expedite the installation of the digester and to save the user's time. The mixing itself must be quick and effective so that the user does not spend too much time away from his other duties and so that the user does not get fatigued.

The engineering specifications derived from these customer attributes provide the constraints that influenced our design. The insertion size must be less than the diameter of the effluent pipe, four inches, if our system is to be adaptable to existing digesters. Given that the digesters currently have maintenance checks every seven years, our system had to last at least that long. We targeted a ten year lifetime since the mixer will likely increase the time between maintenance checks. Our budget for ME 450 is $400, and we wanted to restrict our costs to this. Our target was $300, which is about 30-50% of the digester's cost ($600-$1000), which is reasonable considering the increased lifetime of the digesters and that the farmer is not paying out of pocket for the digesters. Also, if testing shows that there is increased biogas production from mixing, that will further mitigate costs. That said, we recognize that reducing the cost is paramount, and while our design meets our target, we are looking to further reduce costs wherever we can. Ease of use is important, so we derived a specification that the system must be ergonomic, reducing user force and time. Our targets for these were two pounds of force for user input and less than ten minutes of mixing time, derived from anthropomorphic data and a reasonable limitation of a user's time, respectively [8, 9, 10]. To account for the effluent contact, we derived an expanded size for our design that had to be bigger than the 4" diameter of the effluent pipe. Our design is twelve inches in diameter. Finally, we wanted a quick installation time for the user's sake. Our constraint was less than an hour, while our target was less than twenty minutes, which we considered reasonable since installation of the digester itself takes many hours.

There were some parts of our system that were inherently unknowable and required testing. With the paucity of information on mixing for plug flow digesters, we could not make a sound engineering judgment on how to quantify mixing effectiveness, mixing time, localization of mixing, settling time, and user fatigue. Our target for mixing effectiveness was defined by solid removal, which we found to be about 168 g based on the thickness of the solid layer, of which calculations can be found at the end of this section. Our mixing time target is based on our ergonomic assumption, ten minutes. For localization of mixing, it is necessary to keep the mixing at the end of the digester so that new waste is not mixed and removed before it has a chance to be decomposed into methane. Our target was the end third of the digester. Settling time of the solids plays a crucial role in solid removal. The attribute associated with this is "solid removal," which only implies that solids must be removed. For one person operating the mixer, we set a target settling time for twenty seconds, a conservative value considering the length of the digester. Finally, user fatigue was set at minimal since we want our system to be easy to use.

To calculate the engineering specification for mass of solid removal, we assumed that the rate a digester fills up is equal to the volume needed to clog the system during the given time which is 27 ft^3 per 7 years. Our desired flow rate is filling the same volume but in a 10 year period. Using a density of wet sand to be 52,953 g/ft3, the flow rates are as follows:

$$\frac{27\,ft^3}{7\,years}\cdot\frac{1year}{365\,days}\cdot\frac{52953\,g}{ft^3}=\frac{560\,g}{day}\qquad\frac{27\,ft^3}{10\,years}\cdot\frac{1year}{365\,days}\cdot\frac{52953\,g}{ft^3}=\frac{392\,g}{day}$$

The difference between these flow rates is the desired removal rate. If we assume that the farmer will mix once per day, the following amount of mass will have to be removed each day:

$$\left(\frac{560\,g}{day}-\frac{392\,g}{day}\right)\cdot 1\,day = 168\,g$$

FUNCTIONAL DECOMPOSITION

The functional decomposition used for our concept generation is in Appendix E. We started by breaking the system into five main functions that described our system on a broad level. We then iterated those concepts into the second and third level sub-functions to break down the system into its basic operations. Using the main functions to create our initial concepts, we then used the sub-functions to iterate into more refined concepts. This lead to our final, most refined concept which turned into our design.

CONCEPT GENERATION

With the function decomposition in mind, concepts for the mixing system were brainstormed individually by team members. We came together after the session to present our ideas to the rest of the team. All critiquing and suggestions where held off until the concept selection. In total, over 50 concepts were drawn for the mixing system. The concepts were divided into three categories: external mixing, internal mixing, and fluid displacement. Internal mixing was the method chosen as the general technique to pursue. Details of external mixing and fluid displacement mixing are detailed in Appendix F.

The internal designs involved direct contact with the inorganic solids. The concepts below in Figure 4 and 5 stem from one major design idea: a shaft that goes in the digester bag with various attachments on the end. The internal mixer concepts will be inserted into the effluent pipe of the digester to suspend the inorganics so they can be flushed out of the digester bag when more waste is added. The purpose of the attachments is to stir up and suspend the solids on the bottom of the digester bag. For a force input along the effluent pipe axis (in and out of the digester), possible attachments are a squeegee-like scraper and a rake design, shown below in Figure 4. If the force input for the shaft is rotation motion, possible attachments include an egg beater, a paddle-wheel oriented horizontally, and a propeller oriented vertically, seen below in Figure 5. In an ideal situation, no horizontal mixing (along the digester length) will occur, but rather it will be localized to mixing in only a vertical direction. This is needed to not interrupt the plug-flow operation of the digester, not allowing "new" biomass to be forced out before it undergoes complete digestion.

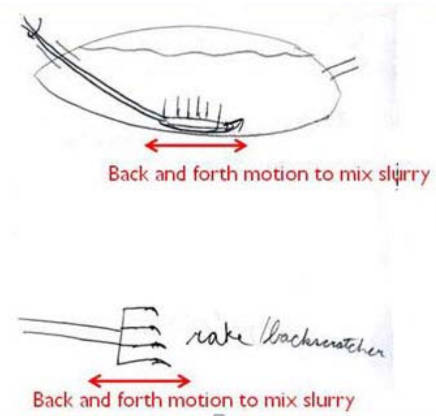


Figure 4: Lateral Input Concepts

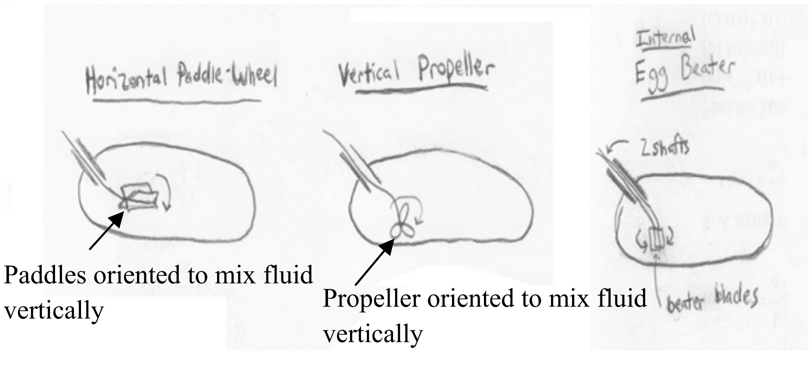


Figure 5: Rotational Input Concepts

Mixing Attachment

Within the rotational motion category of internal mixing, we generated more specific concepts and methods to achieve our overall goals. Specifically, we wanted a rotational attachment that is larger than the 4" diameter effluent tube dimension. We reasoned that a fixed impeller that can fit through a 4” diameter tube will not be able to mix enough fluid. Conversely, longer paddles can mix a larger volume of fluid, but would not be able to move through any bends in the effluent pipe during insertion. We also want to be able to mix the system while not standing directly in line with the effluent tube. The first concept to offer an increase in the diameter of the mixer is based on compliant mechanisms and is seen below in Figure 6. The three semi-rigid bars attach to a vane which will stir the slurry when rotated. The semi-rigid bars are made of a compliant material; something that is designed to bend without breaking. These bars can either be designed to be compliant in the revolute axis or in the axial direction so that when deform enough when pushed into the effluent tube and then expand to original dimensions once completely in the digester. The second concept is a collapsible propeller seen in Figure 7. Propeller blades are attached via hinges to the drive shaft and they can collapse along the shaft's length before being inserted into the digester. Once in the digester, gravity and rotational forces will make the blades expand, ending up perpendicular to the drive shaft. The next concept, seen in below in Figure 8, is based on having a hollow drive shaft and using wire inside of this hollow shaft to control the mixing blades. The mixing blades will be collapsed when inserted into the digester, and once inside, the interior wire can be pulled outward and the mixing blades will expand, offering a larger mixing diameter.

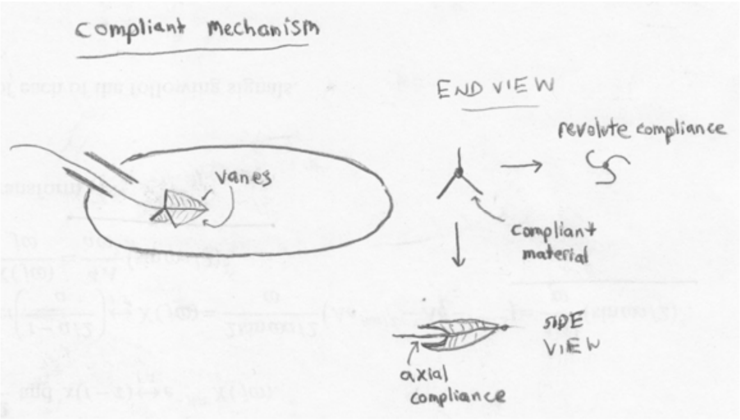


Figure 6: Compliant Mechanism Concept

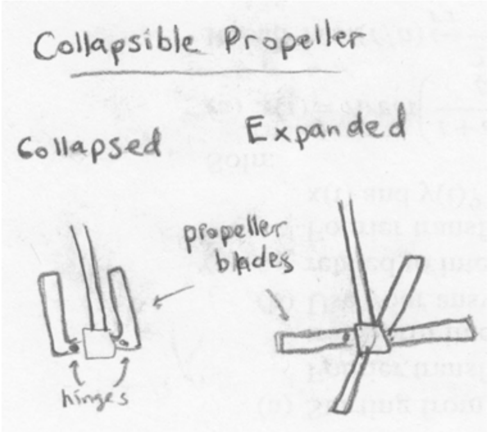


Figure 7: Collapsible Propeller Concept

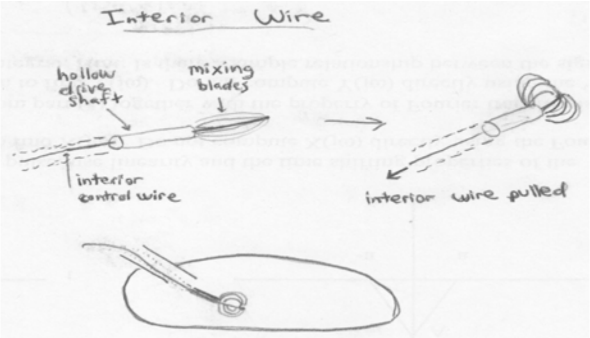


Figure 8: Interior Wire/Hollow Drive Shaft Concept

Flexible Shaft

To accommodate for bends in the tube and being able to operate the mixer out of line with the effluent tube, a flexible shaft of some type is needed. Several possibilities for this shaft were found and they are seen below in Figures 9-13. The first concept is a wire rope traditionally used to support loads in tension. The anatomy and section view are seen below in Figures 9 and 10. Multiple wire strands are wrapped around a core to increase rigidity and strength. Another concept for a flexible shaft is a braided stainless steel hose, seen in Figure 11. These hoses are typically used for plumbing applications where high pressure water is driven through them. They are hollow with a rubber lining and many fine layers of braided stainless steel over this. Another concept for a flexible shaft is a braided PVC hose seen in Figure 12. This hose is made from PVC strand sandwiched in between two layers of plastic wound with around it for increased strength and rigidity. Another concept for a flexible shaft is commonly called a flexible drive shaft, the anatomy of which is seen in Figure 13 and is the most common method of transferring torque when the end is offset from the drive motor. A flexible shaft core has multiple strands of steel wrapped around it. However, unlike, the wire rope, the flexible drive shaft has wrappings that go in opposing directions. This increases the effectiveness of the drive shaft in opposite direction of rotation.

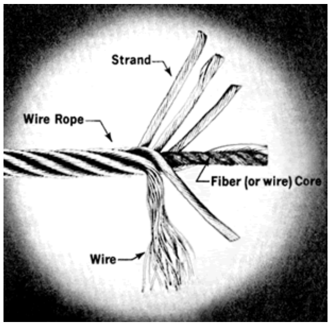


Figure 9: Anatomy of a wire rope

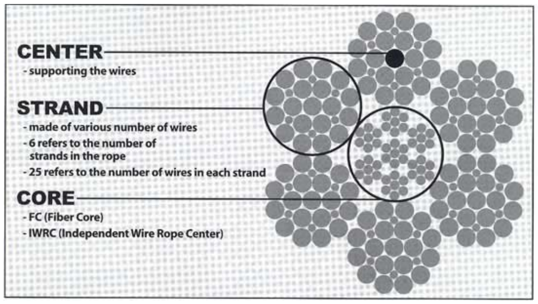


Figure 10: Cross section view of a wire rope

Figure 11: Braided Stainless steel hose

Figure 12: Braided PVC hose

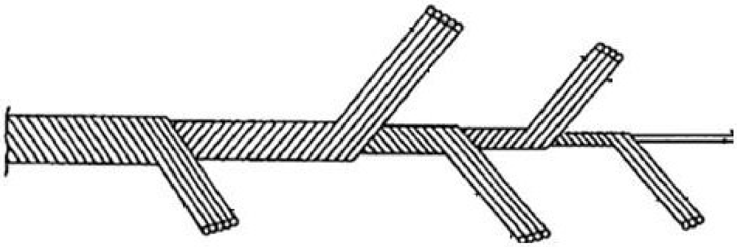


Figure 13: Flexible drive shaft anatomy

There are two main methods to generate rotary motion by human power; with the hands or legs. Hand cranks are the most common method to transfer hand motion into rotary motion while bicycles can generate rotary motion from the legs. These two methods of force input are shown below in Figures 14 and 15. Hand cranks are most effective when the locations that the hand grips do not rotate with the motion, i.e., are free to rotate themselves. A hand crank could be directly connected to the drive shaft for the mixer without any intermediate steps. Bicycle trainers are a common application where any bicycle can turn the pedaling motion into an external rotary motion, typically a small flywheel. This rotary motion could then be used to drive a shaft that is attached to a mixer.

Figure 14: Typical Hank Crank

Figure 15: A Bicycle Trainer generates external rotary motion

CONCEPT SELECTION

The first step in concept selection was to determine the general category of mixing technique. The three possible techniques were external mixing, internal mixing, and fluid displacement mixing. The proper technique to pursue was be determined by relating our engineering specifications back to concepts from these three areas and discussing which specifications were difficult to meet in each method. This process is detailed in Appendix F, with the internal mixing technique being the clear winner. After the mixing technique has been determined, the different concepts from this category were directly compared using the engineering specifications to develop the design which best solves our design problem.

Internal Mixing Concept Selection

There are three different mixing sub-functions for an internal mixing system and here we began the process of selecting a concept that best meets each sub-function to reach a final design. The three sub-functions are accepting force input, transmitting input force to mixing attachment, and mixing the biomass.

Force Input

This function was important for accepting force from the user and transmitting it efficiently to the drive shaft. The two concepts that we generated to satisfy this sub-function are a standard hand crank design and a bicycle trainer attachment.

Assembly/Installation Time The first engineering specification to use for comparison was an installation and assembly time less than one hour, with the shortest time possible preferred. While the hand crank would likely come pre-assembled on the end of a drive shaft, the bicycle attachment would require additional installation time. The bicycle would need to be secured to a trainer-type apparatus which would use the rotational energy of the bicycle's rear wheel to spin an external flywheel to which the drive shaft is attached. Also the flywheel would need to be attached to the drive shaft. This additional assembly time makes the hand crank concept more appealing since it better meets the engineering specifications.

Force Input Since the two different concepts use totally different muscle systems to produce the force, comparison becomes extremely difficult. Generally, the lower body can produce many times the force of the upper body with the same sense of effort. In this respect, the bicycle concept is preferred since larger forces can be put into the system as the user becomes fatigued at the same rate.

Maintenance Components of this sub-function should be held to the same specifications as those inside the digester and only require service every 10 years. A bicycle attachment system would require maintenance typical of a bicycle in addition to maintenance of the attachment system. The attachment trainer systems are typically designed only for indoor use, so exposure to the elements is likely to cause rust, dirt inside of rotating parts; both resulting expedient part wear. A bicycle itself requires regular maintenance such as lubrication of the chain and frequent part adjustment and replacement. A hand crank system would require minimal maintenance, especially if designed with materials resistant to the elements and no bearings. There are few moving parts, possibly no bearings or chains and thus many fewer opportunities for system failure. A clearance fit rotation of the handle will allow for rotation of the handles without the use of bearings. There is the possibility for material wear between the handle and shaft that it rotates on, but choosing a handle material with a low coefficient of friction will keep this wear to a minimum. The hand crank concept could easily meet the maintenance specification of a 10-year maintenance interval. The high cost of a bicycle trainer should also be compared to the minimal cost of a hand crank system. Based on comparison of these specifications, we will design a hand crank system to accept the force input of our mixing system.

Transmitting Force to Attachment

The next sub-function to analyze was transmitting the input force to the mixing attachment. Rotating the hand crank will create a torque for the shaft to transmit. The different ideas we had to accomplish this function were a rigid PVC rod, wire rope, braided stainless steel hose, braided PVC hose, and a flexible drive shaft.

Localized Vertical Mixing The only shaft concept that could not meet this specification was the rigid PVC shaft. With a rigid shaft, the mixing attachment will be restricted to the same angle as the effluent pipe, typically around 45°. Because of this, a combination of axial and vertical mixing would occur, which is undesired for our application and would interrupt typical plug-flow operation of the digester. Another weakness of the rigid shaft is how the operation is limited to the area directly in line with the effluent tube, so the user would likely be standing in the effluent waste pool. Because of this, the rigid shaft will not work well for our mixing system design.

Tendency to yield, buckle or fail Our team bought small sections of the four other concepts to do some preliminary testing on them. The wire rope was extremely prone to buckling. When one end of the wire was resisting motion, the wire would "buckle" or bunch up onto itself, moving into different planes of motion. The braided PVC hose was slightly prone to this as well, but the effects are lessened in both concepts by increasing the diameter. The buckling action is not desired for our application, since the torque is not transferred efficiently, so using either the wire rope or the braided PVC hose by themselves is not recommended. The flexible drive shaft was only slightly prone to buckling; needed a much larger torque and a large unconstrained length to see effects than with the two previously discussed shafts. These shafts are very capable of transmitting torques effectively and can do so in almost all configurations. The braided stainless steel hose was also resistant to buckling effects.

Price In increasing order, the price goes as follows: braided PVC hose (~$0.50/ft), wire rope (~$0.75/ft), braided stainless steel hose (~$1.67/ft), and flexible drive shaft (~$6.25/ft). All of these options are very common items and would be readily available around the globe.

Lifetime The lifetime for the drive shaft should be at least 10 years. Since the braided stainless steel and PVC hoses are hollow, they do not hold up well to extended use under torsion. Both are designed for static applications, where an internal pressure is present. The braids in the stainless steel hose began to visibly loosen after a few minutes of torsional and bending experimentation. The braided PVC hose also began to visibly deform after continued twisting, losing its round cross-section. It seemed that neither of these braided hose options would withstand continued torsional loads over a 10 year period, but would break down much sooner. Considering all of these specifications, we narrowed our force transmitting shaft down to the flexible drive shaft. Despite the high price, this shaft is designed exactly for our application; to transmit torque indirectly through its length. They are currently used in many industry applications; most commonly string trimmers/weed wackers. The flexible drive shaft was not as prone to the buckling and bunching efforts of the other choices, nor will the physical properties change over its lifetime of use. These flexible drive shafts are still not perfect; however, all reasonably priced models are only available in steel. Steel has a C-grade compatibility with sulfides and for this reason, a coating or covering of some kind will be necessary to prevent chemical corrosion in the digester. Including this anti-corrosive coating will still leave the shaft price at much less than the 316 stainless steel shaft, which was nearly double in price.

Biomass Mixing

The concepts that we generated fall into two different categories, horizontally or vertically oriented. The main point of comparison between the concepts was how reliably the mixer can operate in the desired manner, with respect to suspending solids, blending fluids, and achieving localized vertical mixing.

Both the compliant mechanism and interior wire concepts operate on the horizontal axis. Ideally, mixing paddles will spin around the horizontally-oriented drive shaft and move fluid only in the vertical direction. However, maintaining this horizontal orientation will be very difficult. Since the drive shaft will be flexible, the mixing attachment will be free to move around inside the digester, up and down, side to side and rotating around the vertical and horizontal axes. It is likely that when the mixer is not properly oriented, undesired horizontal mixing will occur. This interrupts the plug-flow operation of the system, and "newer" biomass could potentially exit without being fully broken down. We also foresee the horizontal mixing attachments sinking to the bottom and scraping the bottom of the digester as it rotates. This could cause increased wear on the digester bag material.

The vertically oriented mixer attachments would not have these orientation problems. With sufficient weight, when the mixer enters the digester, it will sink to the bottom near the effluent pipe. The concept for this mixer orientation is a collapsible propeller that expands once in the digester. Gravity and rotational forces will cause the propeller blades to fall to their operating position. The propeller will force fluids and solids vertically towards the top of the digester. Horizontal mixing will be minimal since the mixer will be resting sturdily on the digesters bottom, propellers parallel to the bottom. A sturdy, heavy base and a flexible shaft with a moderate bend radius will prevent the mixer from tilting and easily changing position.

The collapsible propeller concept was the superior mixing attachment with regard to control of orientation during mixing. Another drawback to the compliant mechanism concept was the complexity involved with designing the semi-rigid bars. These bars must have the correct geometry and material to allow for enough bending to fit into the digester effluent tube, but not too much bending such that when torque was applied to the system, the bars bend instead of effectively mixing. Another drawback to the interior wire technique was that the interior wire and hollow shaft would need to rotate in tandem to keep the mixing blades in the correct position. The complexity of allowing axial movement of the interior wire but not allowing rotation would be very difficult to implement. The collapsible propeller system shows promise of simplified assembly, proper mixing orientation, effective solids suspension, and is based on a reliable benchmark in the mixing industry. Also, manufacturing is possible with common materials and methods. Therefore, we continued developing the collapsible propeller for our design.

Upon evaluating the concepts for the three sub-functions against each other based on system specifications, we arrived at a concept for a complete mixing system. This system features a hand crank to accept the user's force, a flexible shaft to transmit this force into the digester, and a collapsible propeller mixing attachment to mix up the biomass.

CONCEPT DESCRIPTION

The basic system that our design used to mix incorporates a hand crank, flexible shaft and a collapsible propeller. Once we arrived at this general concept, we began to refine each part and develop methods for the subsystems to fit together.

Hand Crank

The hand crank is created from square stock with holes drilled in both ends. One end will be secured to the flexible shaft with a dowel/roll pin interface explained in the flexible shaft section on the next page. A hollow pipe over the flexible shaft will spin freely and allow for easy rotation. Another handle will be attached to the end of the crank shaft using a shoulder bolt. The handle will be clearance fit over the shoulder bolt to allow for easy rotation, while the shoulder bolt will be threaded into the tapped hole in the crank shaft to secure it. This assembly is shown below in Figure 16.

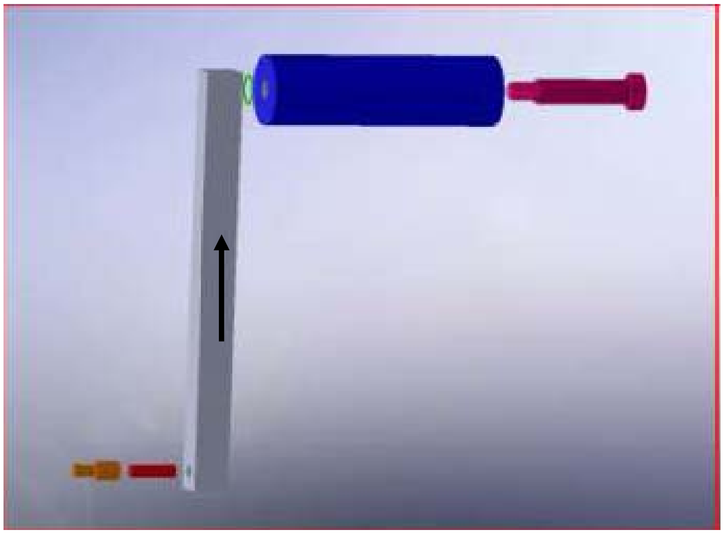


Figure 16: Hand crank assembly

The connecting bar of the handle will also have arrows on all sides of it to show the correct turning motion for mixing. The arrow shown in Figure 16 points away from the operator and points in the direction of correct turning. Arrows on the left and right faces of the connecting bar will show the appropriate clockwise (left face) and counter clockwise (right face) motions.

Flexible Shaft

A flexible shaft will connect to the mixing attachment through a dowel/roll pin interface. A dowel pin will be inserted into the female connections on the mixing hub and flexible shaft. A roll pin will be pressed into a drilled hole through the mixing hub into the dowel to secure them together and another through a hole drilled in the shaft coupling into the dowel pin.

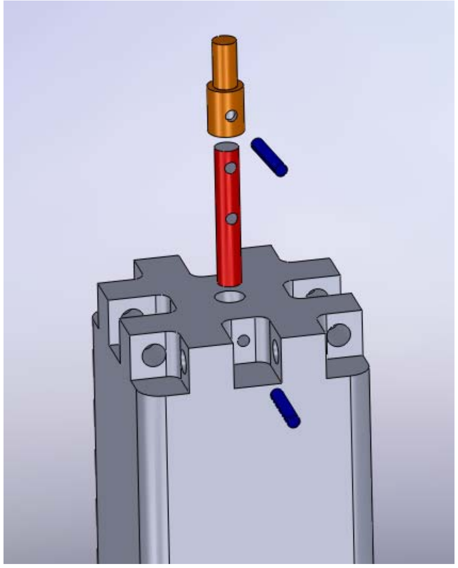


Figure 17: Flexible shaft connection

Mixing Attachment

A four-bladed collapsible impeller, seen in Figure 18, will be used to mix the digester contents. Flat stock (in red) will be welded on to an angled shaft (in blue) at a 30º angle. These fin shafts will have a hole on one end where a dowel will be inserted through to secure it to the mixing hub (in grey). A clearance fit on the fin shaft/dowel interface will allow for rotation of the fins into the upright, insertion position of Figure 19. The dowels will be press fit into the mixing hub for a strong, permanent connection. Together all of these subsystems will connect to operate as an effective mixing system. The overall drawing of the system is shown in Figure 20 on page 18.

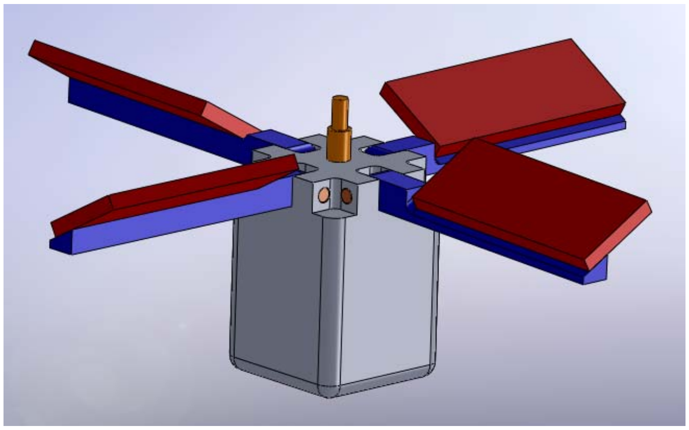


Figure 18: Mixing Attachment in mixing position

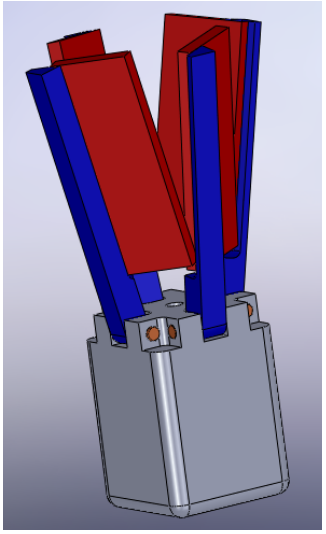


Figure 19: Mixing attachment folded up

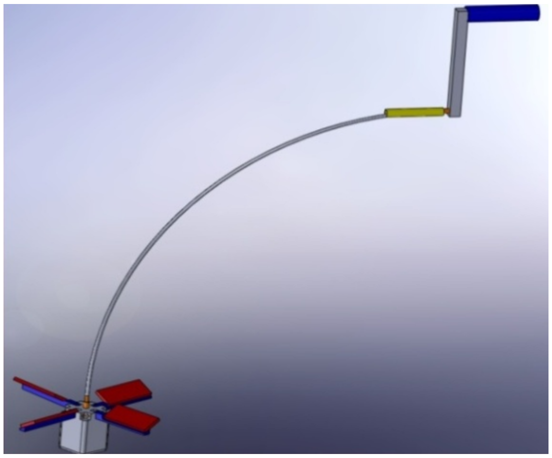


Figure 20: Complete system drawing

PARAMETER ANALYSIS

When deciding our design parameters, we took many factors into consideration. We mainly considered our engineering specifications, which put limits on the size, weight, cost, and shape of our design. Findings are listed below for each part of our mixing system. All calculations are detailed in Appendix H.

Hand Crank

For the handle, our chief specifications were that the rotation would require little force and that the motion be ergonomic. Based on anthropomorphic data, we decided the handle arm length to be 8" from the center of the flexible shaft to the center of the rotating handle; with the entire bar being 8 ¾" in length. This is the approximate length of a human forearm, and thus the rotary motion puts a minimal amount of strain on the user. The handle arm is ¾" square, which can withstand the forces induced by the rotary motion and allow for the machining necessities while minimizing the weight of the system. We will build the handle shaft out of aluminum since it is easy to obtain, strong, light, easily machined, and resistant to corrosion. There is a ¼" hole that will be threaded for the shoulder bolt and a 5/16" hole that will connect the flexible shaft to the mixing arm.

The rotating handle is 1 ¼" in diameter and 5" in length, which fits a human hand well based on anthropomorphic data. There are two holes bored into the handle: one 9/16" in diameter and 2" in length for the shoulder bolt and another 3/4" in diameter and 3" in length to insert the bolt. The shoulder bolt has a shoulder 1/2" in diameter and 2" in length, creating a clearance fit which allows for free rotation; the bolt has 3/8"-16 threads. By allowing the handle to rotate, the user‘s wrist does not get strained. To stabilize the handle, the user‘s left hand will hold a piece of braided PVC hose 5" in length and 3/4" inner diameter, allowing free motion of the shaft while supporting the weight of the system. The yield stress requirement for the handle material is 5.9MPa given a safety factor of 3. PVC can fulfill these stress criteria and will be used for the handle grips. PVC is light, inexpensive, and allows for low friction rotary motion of the shaft.

Flexible Shaft

The biggest concern with our flexible shaft was cost. We were able to find steel flexible cable in 3‘ lengths for around $60, much cheaper than other alternatives. These cables have a diameter of ¼" and a torque rating of 110in-lb; large enough to withstand the torsional forces induced by mixing, 9.2in-lb. We realize that this is a major cost to our system, but we feel that the functionality that the shafts bring warrants the high cost.

Mixing Attachment

The mixing attachment is the most intensive in terms of both machining and engineering. Among the many elements considered were the corrosive nature of the digester, the inability to remove the attachment, the range of the fins, the orientation of the mixing, and the weight of the overall system.

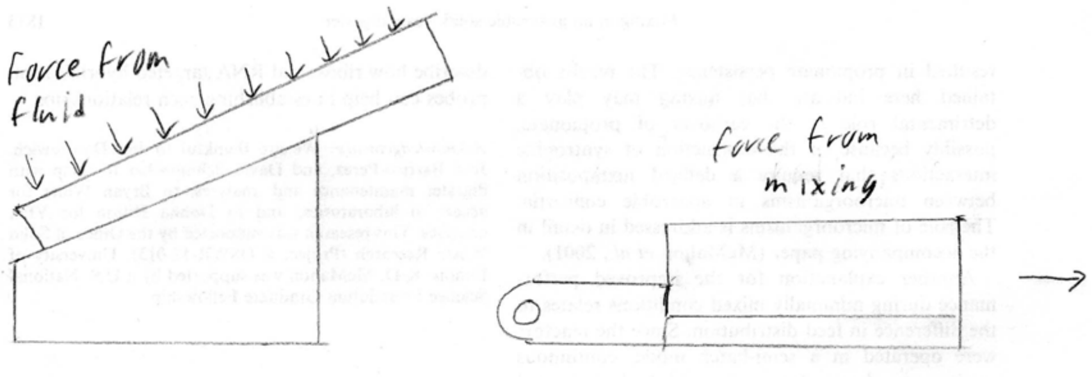
The first part to consider is the base on which the fins are attached. This base is connected to the flexible shaft and holds the entire system in place. Starting with a 2 ½" square piece of aluminum stock 4" in length, we will machine out the grooves and holes in the top. The grooves are ½" or 0.7" wide (filleted to 1/8" radius), and the holes are ¼" in diameter. The size of the stock was chosen to fit within the 4" diameter of the effluent pipe. The outer holes are meant for press fit steel dowels around which the fins will rotate.

To connect the mixing attachment to the shaft, we will use a zinc dowel inserted into the coupling on the drive shaft. We will then drill a hole through the coupling and the dowel and hammer a roll pin through it. We will do a similar process for the base, drilling through the center hole and using a roll pin to secure the dowel. We have done material fatigue testing on this, and we have found that the roll pin will fail after about 5000 years of use. Calculations can be found in Appendix H.

The mixing fins are hinged onto the dowels. The fin paddle (hereto referred to as the "fin") will be welded to the fin arm (hereto referred to as the "arm"). The arm is 5" long and made of aluminum. The end with the hinge is rounded with fillets of radius ¼” and has a hole of diameter 5/16”. This allows for free rotation in the groove and proper attachment to the dowels. The fin is made from ¼” aluminum plate and has dimensions 1 ½” by 4”. The fin is at a 30º angle with respect to the arm. The dimensions were chosen to fit in the 4" effluent pipe and maximize the area of the fin while still allowing for proper fluid flow. There was no analysis-driven reason to select fin length as we did other than preventing the mixer from being removed. Any length longer than 1 ¼” (totaling to 4” diameter when considering the 2 ½” hub and the ½” grooves) would do for sanitation purposes. Any length longer than 8” would have a negative mechanical advantage considering that our handle length is 8”. While the 4" fins performed well in our testing, we recommend further testing to find an optimal fin length.

When deciding on a design for the mixing fin, we decided that once the fins folded downward into the horizontal position, they must stay horizontal and not rise to a vertical position. All of the forces acting the fins were either in the downward direction or the radial direction. Due to the inherent motion of the mixing, a centrifugal force acted radially on the fins (see Figure 21), tending to keep the fins in the horizontal position. The fluid also created a force distribution normal to the surface of the plate (see Figure 21). Again, the resultant forces from the fluid act radially and downward. There is a viscous drag force present in the flow, but these are negligible compared to the pressure drag force of the fluid. To prove this, a model of the flow was created in a computational fluid dynamic package called FLUENT (see Figures 22 and 23, page 21). An inlet velocity of 0.958 m/s was input based on a mixing rate of 60 RPM. The fluid was modeled to be representative of manure, using a density of 1650 kg/m^3 and a viscosity of 0.59 kg/m·s [11].

The models give general trends of flow and are not accurate for quantitative purposes. To give a gauge of relative pressures, a pressure scale is given in Figure 23 on page 21 in Pascals and is only used to show trends of pressure distribution, not for exact static pressure measurements. From the models, it can be seen that a positive pressure appears on the top of the fin and less positive even negative) pressure appears on the bottom side of the fin, proving that the overall force from the flow will be downward. This will keep the fins in the horizontal position during operation. Aluminum was used since it is light, easily machined, cheap, and noncorrosive. Its mechanical properties were strong enough to withstand our calculated mixing forces. To avoid galvanic corrosion, we limited the amount of steel in our system to the dowels and the shaft. We will cover exposed metal with a corrosion-resistant coating in as many places as we can to minimize the possibility of corrosion.



Side View Front View

Figure 21: Force diagram on fin blade

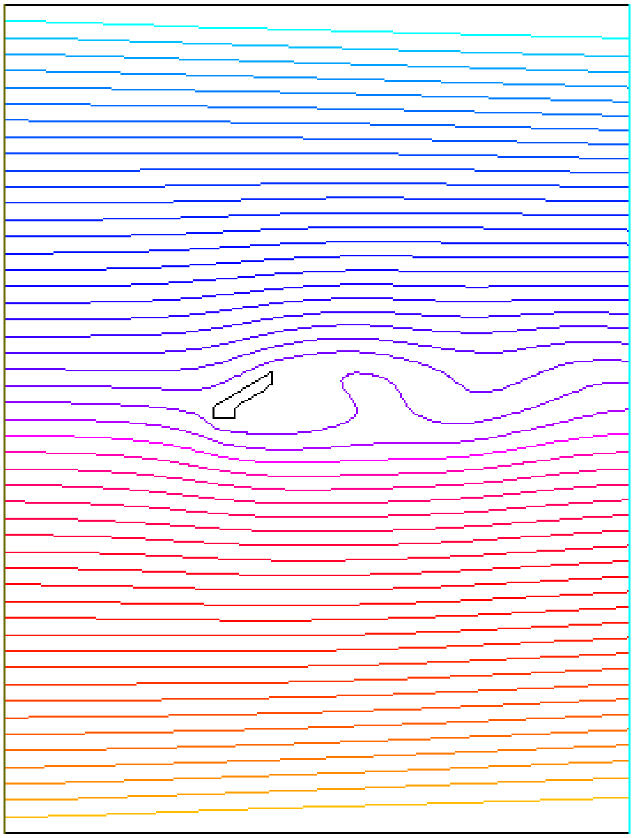


Figure 22: Contour plot showing fluid streamlines

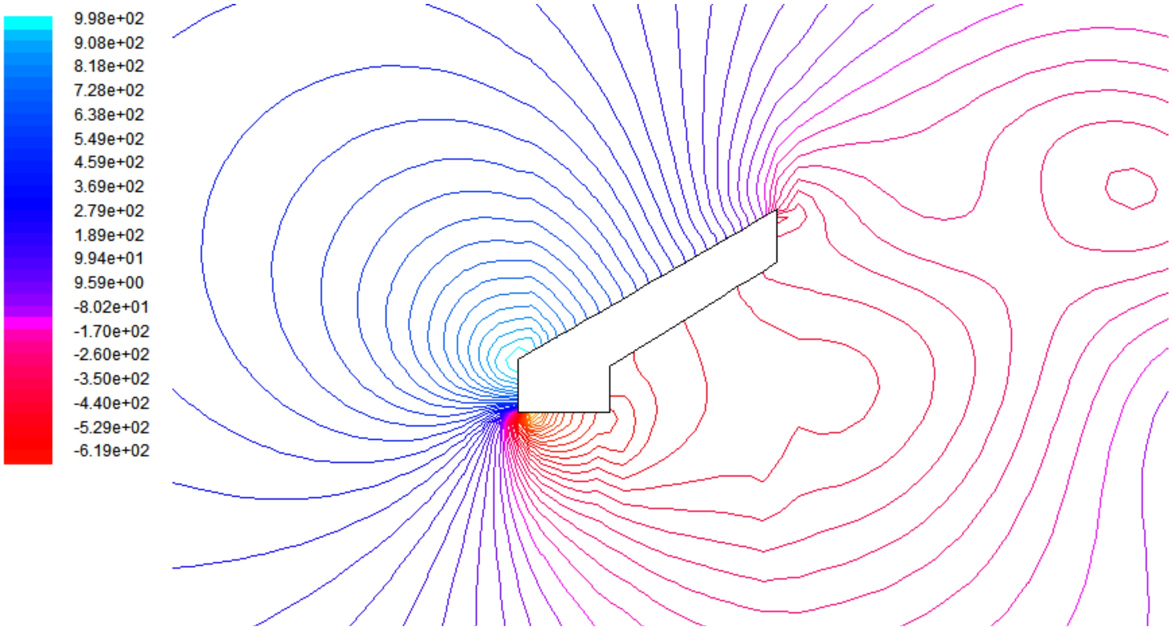
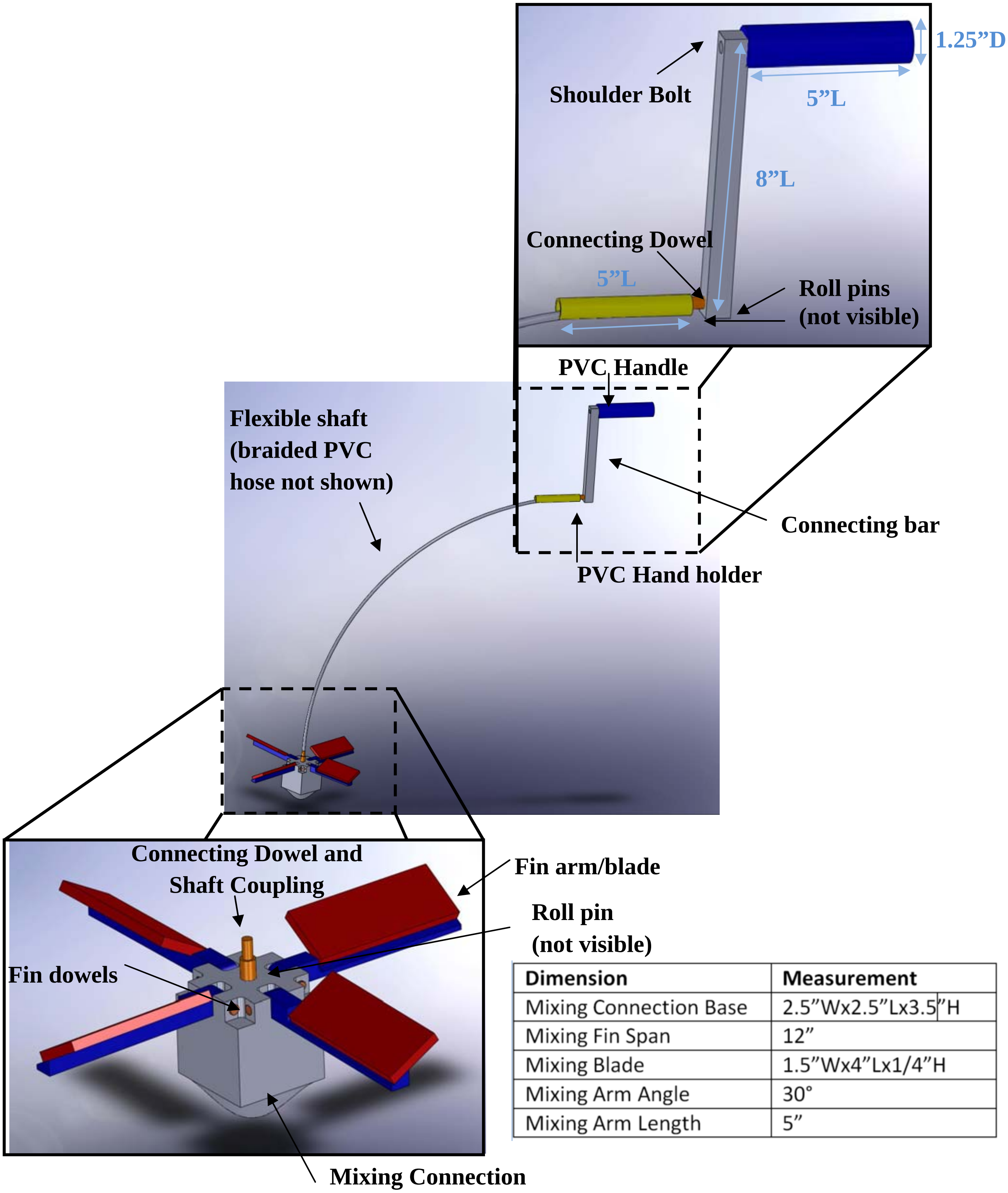


Figure 23: Contour plot showing trend of static pressure distribution of flow

FINAL DESIGN

Our final design is detailed below in a series of figures. Some basic dimensions are provided; for more detailed engineering drawings, please refer to Appendix G at the end of this report.



Dimension	Measurement
Mixing Connection Base	2.5”Wx2.5”Lx3.5”H
Mixing Fin Span	12”
Mixing Blade	1.5”Wx4”Lx1/4”H
Mixing Arm Angle	30°
Mixing Arm Length	5”

The main differences between our final design and prototype are the shape of the mixing attachment and the length of flexible shaft used. As seen below, left, in Figure 24, the bottom of the mixing attachment on the final design will have a rounded shape to it. Our prototype featured a flat bottom with rounded edges, shown on the right of Figure 24 below. Our original CAD drawings showed the rounded bottom, but because of a time constraint in manufacturing, we opted to just round the corners to have smooth surfaces.

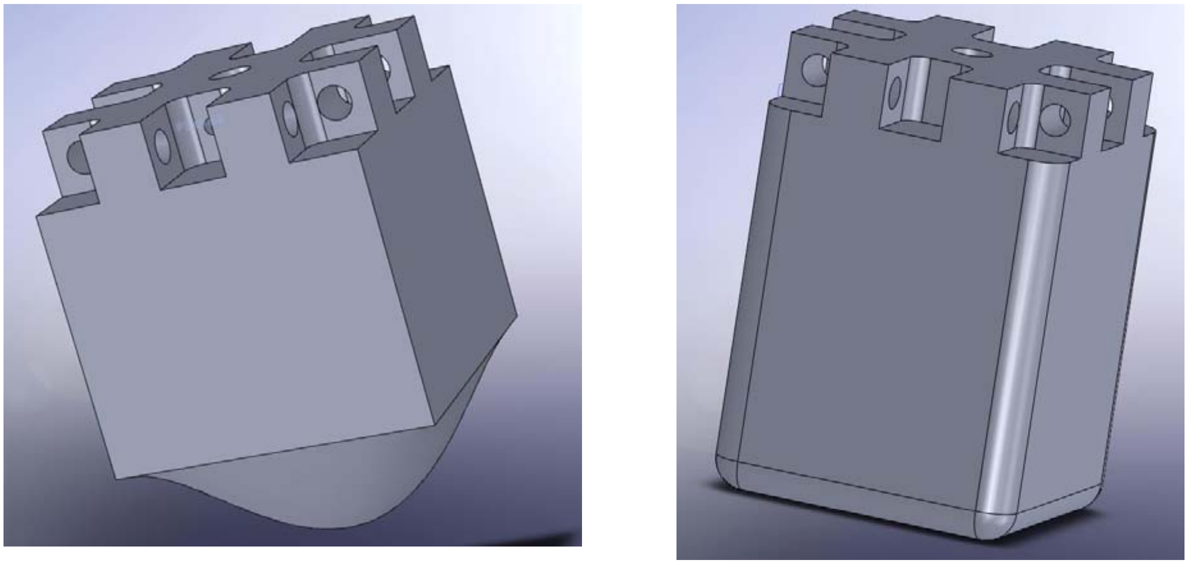


Figure 24. The mixing connection design differed slightly between the final design (left) and prototype (right).

It was observed that our mixer did ‘skip’ around some on the bottom of our test rig, which we attributed to the square edges catching the sediments as it was rotated. Thus, we are confident that a rounded bottom on the mixer is a superior design. The second difference between the prototype and final design is a longer flexible shaft. The prototype used a 3’ shaft, where the final design calls for at least 6’ to fit through longer effluent pipes. The shorter shaft was used as a ‘proof-of-concept’ for transmitting torque from the handle to the mixing attachment and to save money in prototype development.

An additional difference between the prototype and final design was the use of two set screws instead of roll pins in the handle. Set screws were used to secure the dowel to the connection bar, and another set screw to connect the same dowel to the flexible shaft coupling. This was chosen only for convenience to allow us to disassemble the mixer if necessary. Even though these set screws are located outside the digester so access for re-tightening is not an issue, they are not necessary since the handle does not need to be changed out. It also keeps the theme of using roll pins for the mixing attachment connection.

FABRICATION PLAN

As described, our prototype is a full scale model of our selected design with some minor adjustments. Presently, the fabrication of the prototype will be discussed. The Bill of Materials for our prototype can be found in Appendix A.

Prototype Manufacturing

The manufacturing of the prototype is split into two parts. The cranking mechanism is the external component that the user will be in contact with for the mechanical input. The mixing mechanism is the internal components that will physically come in contact with and mix the slurry. All milling and drilling speeds were calculated from the equation $RPM = (12 \cdot V)/(\pi \cdot D)$ where V is the cutting speed for the material and D is the diameter of the cutting tool [12]. Those reported are less than or equal to the calculated value. None of the manufacturing processes except for welding needed extra safety precautions outside of the general machine shop safety rules. Welding was completed by a professional.

Hand Crank

The cranking handle of the mixing mechanism (the handle in the user's right hand) was made out of 2" PVC rod found in the Machine Shop. Using a lathe, we turned the outer diameter of the rod to 1 ¼". The speed used for the lathe was 400 surface fpm. While still on the lathe, the chuck was changed and a center line will be drilled into one end of the PVC cylinder. From this, a 9/16" diameter hole was drilled through the rod. After, a ¾" diameter hole was drilled to its depth of 3.03", creating a counter bore. The ¾" diameter hole does not need a tolerance since it only acts as a passageway. The 9/16" diameter hole also does not need a tolerance because the shoulder bolt fits loosely inside, creating the revolute joint. After these steps were complete, the excess material that was held by the chuck was cut from the desired piece. We must note that our actual prototype was cut shorter than was planned to be cut. This subtraction of length is taken from the end with the smaller diameter hole showing. The new total length is around 4 ½".

The connecting bar from the cranking handle to the flexible shaft, manufactured from ¾" aluminum bar stock, was cut to size using the band saw. The holes were drilled using the drill press at 1150 RPM to a diameter one size smaller than prescribed in the part drawings to allow for tap or slip fit. After, a tapping tool was used to tap the cranking handle hole with 3/8"- 16 tap and to tap the set screw hole with a 10-32 tap. We reamed the flexible shaft hole to a size of 0.3125" for a slip fit. To fit with the flexible shaft hole, one of the couplings of the flexible shaft was pre-drilled and then reamed to an inner diameter of 0.3125".

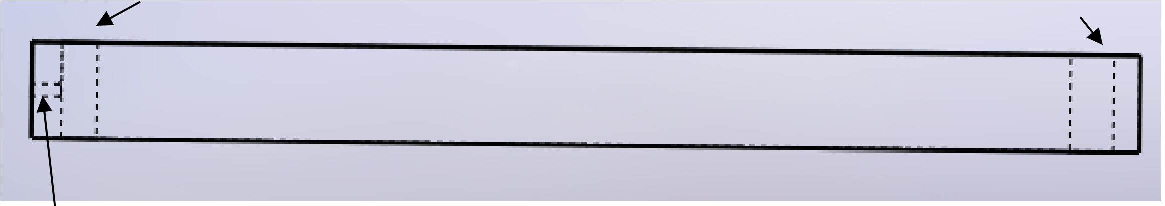


Figure 25: Schematic of Connecting Bar

Mixing Attachment
The fin blade was manufactured from spare ¼" aluminum plate and was cut to the size shown in the provided drawing in Appendix G. Tolerances are not crucial for this part. Four blades were manufactured.

The fin shaft was manufactured from 1" diameter aluminum round stock. We used 8" lengths for each shaft. To mount in the mill, a vice clamped both ends approximately 1" from each end (See Fig. 26, page 26). The flat face of the shaft (where the blade will sit) was milled first from the side (keeping the z-axis constant) at a speed of 1200 RPM with a ¼" ball mill. After, the rod was rotated 30º so the sides of the shaft could be milled square from the side with the same bit. The bar was rotated once more at 90º to mill from the side the bottom face flat. Once complete, the bar was removed from the clamps and the remaining round stock was cut off with a band saw. From this, the hole was measured for location, center punched, and drilled with a ¼" drill bit. The tolerance was not crucial because it will be a slip fit for a dowel, creating the revolute joint for the fin shaft. The curved edges of the shaft were milled into the shaft using a ¼" corner rounding end mill. We manufactured four shafts. Each shaft and blade was anodized blue. The holes did not need to be drilled again because the rack they were placed on did not allow the inner surface of the hole to be anodized.

The mixing connection created from aluminum block of size 2 ½" x 3" x 3 ½". The process used to manufacture the block is shown below:

Step	Operation	Machine	Cutting Tool	Cutting Speed	Notes
1	Cut off excess material	Band saw	Band saw	500 surface fpm	Done slowly
2	Mill edges flat	Mill	½" end mill 2-flute	1200 RPM	Shallow step sizes
3	Drill center hole	Mill	¼" drill bit	1200 RPM	Peck drilling
4	Drill dowel holes	Mill	3/16" drill bit	1200 RPM	Peck drilling
5	Drill holes for roll pin	Mill	1/8" drill bit	1200 RPM	Peck drilling
6	Mill rectangular pockets	Mill	¼" end mill	1200 RPM	Shallow step sizes
7	Round corners	Mill	¼" corner rounding end mill	400 surface fpm	Round sharp edges
8	Anodizing	-	-	-	Courtesy of Alpha Metals
9	Ream center hole	Drill Press	.3125 Ream	100 RPM	Slowly, not clamped
10	Ream dowel holes	Drill Press	.2499 Ream	100 RPM	Slowly, not clamped
11	Drill holes for roll pin	Mill	1/8" drill bit	1200 RPM	Peck drilling

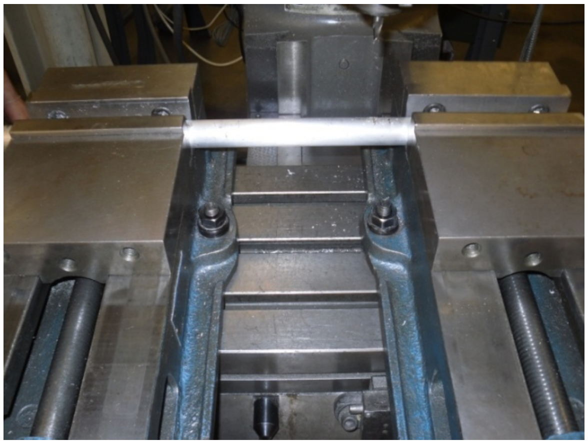


Figure 26: Clamp setup for fin shaft fabrication

It is important to note that all anodizing added 0.003” to every dimension on each part unless otherwise noted. Also, the coupling of the flexible shaft not yet manufactured was drilled and reamed to the same size as the mixing connection center hole. Furthermore, a hole perpendicular to the main hole of the coupling was drilled at a 1/8” diameter through the entire width of the coupling. This acted as a passage for a roll pin. The dowel holes were drilled by placing the dowel into both the coupling and the connection center hole, one after the other, and drilling through the already created hole and through the dowel. This ensured that the holes would line up perfectly.

Prototype Mass Production

Though the purpose of our prototype was not to be a mass production solution to the mixing problem, we can still analyze how manufacturing processes would change if it were to be mass produced. What is great about each of these aluminum parts is that each could be cast into its shape if a die of each were created. The mixing connection would have the top slots and corner fillets already shaped. It would just need the holes to be drilled and reamed. The same is true for the fin shaft. The 30º would be easy to create with a die. In fact, the blade and the shaft could be cast as one piece instead of needing a weld to connect the two. For the cranking mechanism, the PVC handle could be injection molded to its size. The connecting bar would not change in manufacturing steps. Nonetheless, the manufacturing of most of these parts can be automated. The dowels and the couplings can be shipped to us with the proper size and position of holes needed. All of these changes would minimize manufacturing time significantly. Also, the need for a trained machinist is reduced to needing a factory worker to monitor the equipment and change or move parts when needed. The assembly of the parts also does not require any special skills.

Prototype Assembly

Like manufacturing, assembly was split up into the same two sections. These two mechanisms discussed were connected by the flexible shaft which will not be shown in its entirety in these sections but was represented by a portion of flexible shaft with coupling attached. Also, the braided PVC hose slides over the entirety of the flexible shaft before both couplings are secured to their respective sections.

Hand Crank

The hand crank design is the location for torque input to the entire mixing system. Figure 27 below shows the cranking handle assembly.

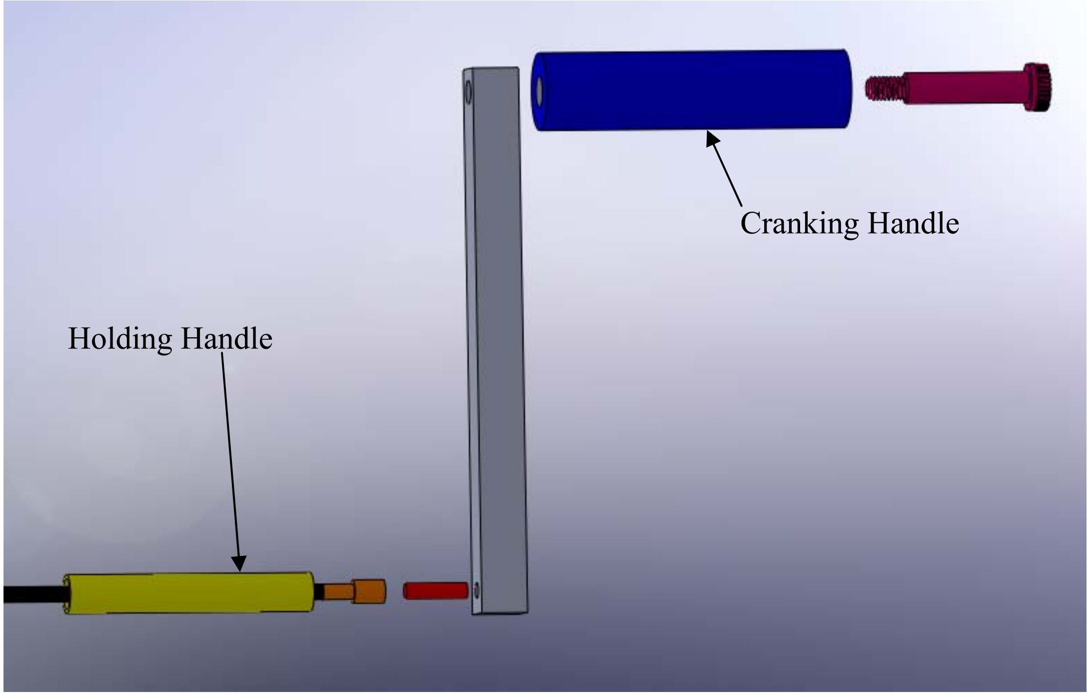


Figure 27: Exploded view of hand crank assembly

The cranking handle was assembled using the following steps.

1. The shoulder bolt was inserted into the cranking handle in the side with the ¾" hole. The bolt was then screwed into the connecting bar.

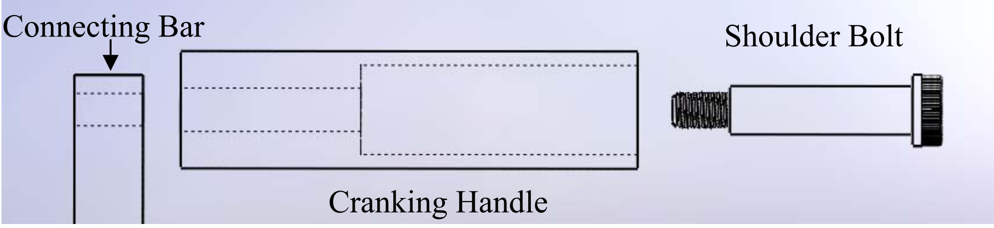


Figure 28: Hand crank assembly

2. The 5" long, ½" ID PVC braided hose holding handle was slid over the flexible shaft. A 5/16" diameter dowel was slid into both the shaft coupling and the connecting bar and securing in both by set screws. The coupling set screw came with the flexible shaft and the connecting bar set screw is 1/8"-32 and ¼" long.

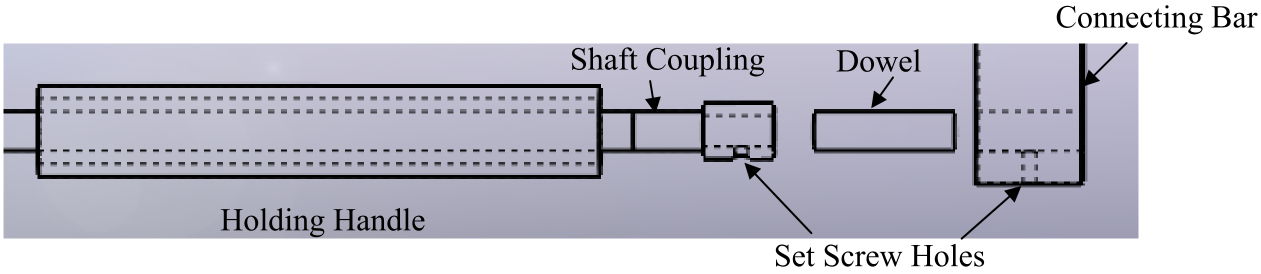


Figure 29: Holding handle assembly

Mixing Attachment

The mixing attachment is the components that were immersed in the slurry and physically mix it. Figure 30 below shows the mixing attachment.

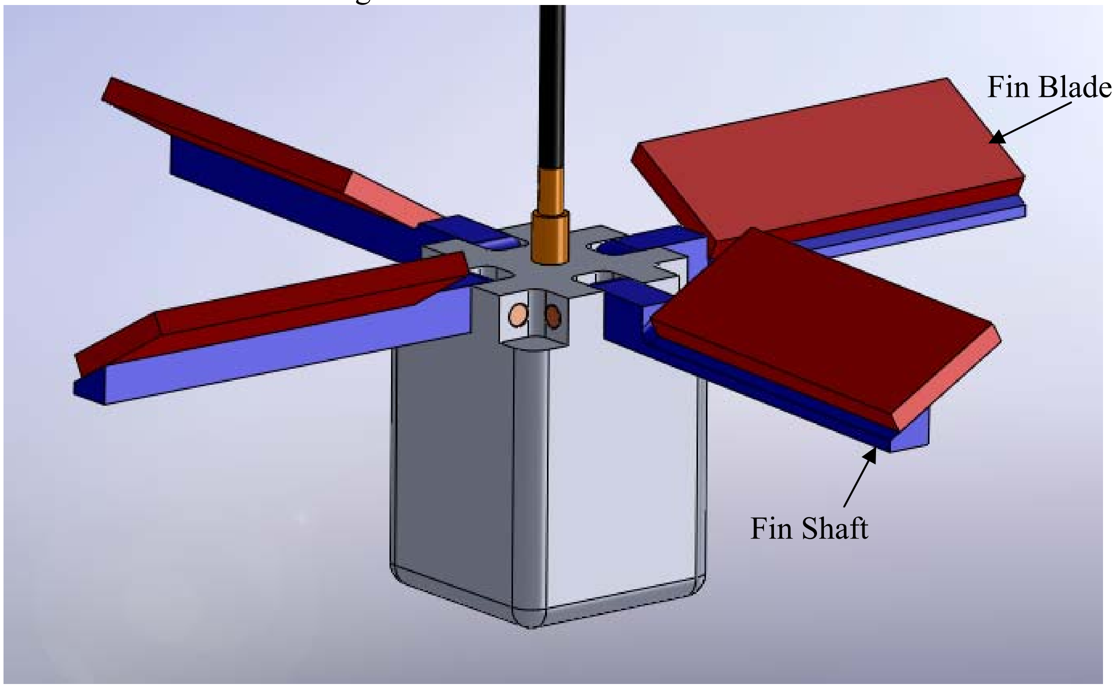


Figure 30: Mixing attachment

The mixer will be assembled using the following steps.

1. The fin blade was attached to the fin shaft by a weld along the crease in front of and behind the fin blade, shown below in Figures 31 on page 29. The machine shop technician Bob Coury completed the welding for our team.

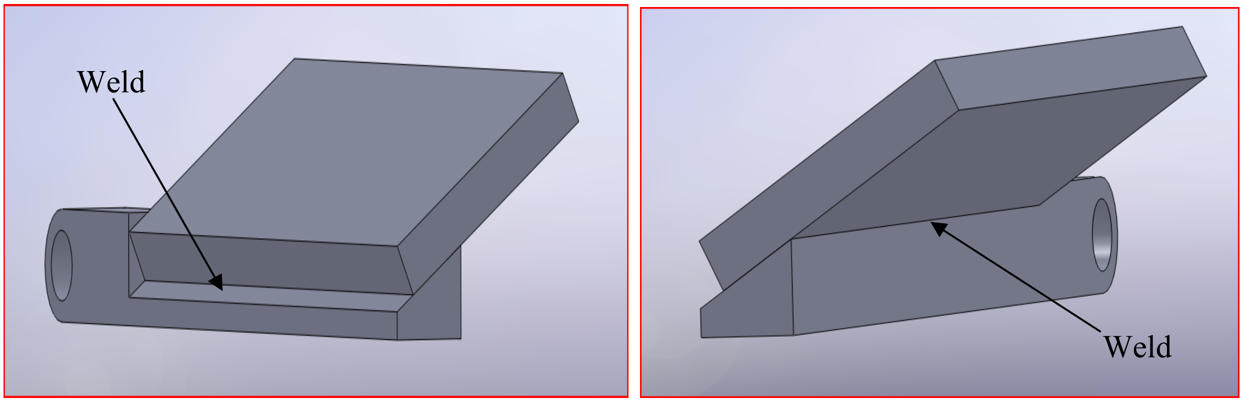


Figure 31: Weld locations for the mixing fin fabrication

2. To connect the mixing plate to the flexible shaft, a 5/16” diameter steel dowel was inserted into the mixing connection then into the coupling. Steel roll pins were pressed into their provided pathways to secure these components together. Both pins were 1/8” in diameter. The pin through the coupling was ½” long while the pin through the connection was 1 ¼” long.

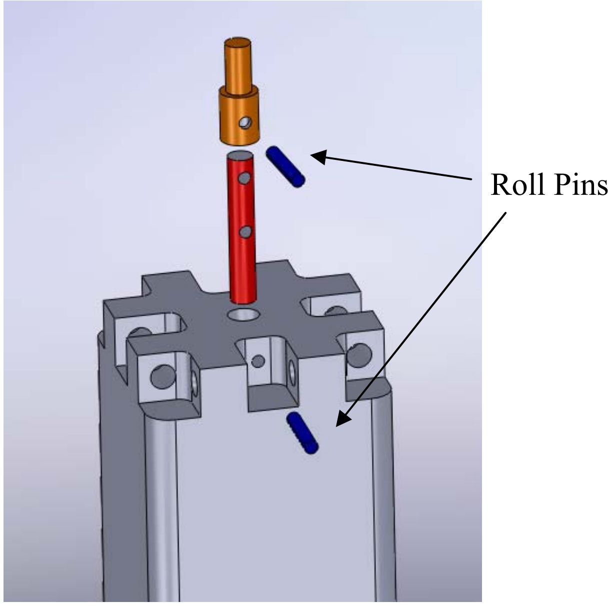


Figure 32: Exploded view of mixing connection to shaft coupling

3. The new fin sub assembly will attach to the mixing connection by a dowel pin. We aligned the hole of the fin with the holes of the connection plate. The ¼” steel dowel was then pressed through the connection holes (a press fit) and slipped through the fin hole (a slip fit) then pressed through the second hole of the connection. The revolute joint of this system is the slip fit of the fin on the dowel.

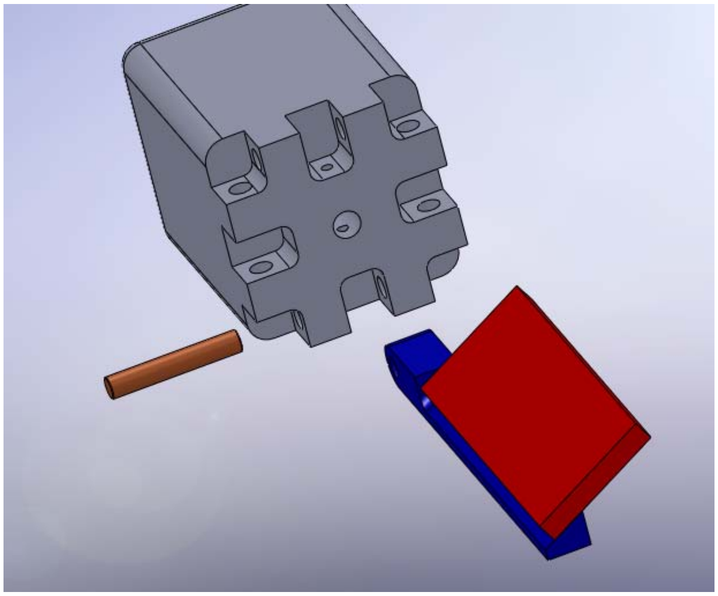


Figure 33: Exploded view of fin attachment to plate

VALIDATION PLAN

The prototype will help validate several aspects of the final design. The first area of validation involves the insertion of the mixer down the effluent pipe. We will ensure that the mixer can be folded up and fit down a 4" diameter pipe and also verify that when the blades are folded down, the mixer cannot be pulled out of the effluent pipe. Secondly, for the general operation of the mixing system, the prototype will show how the handle operates and can transmit torque from the operator to the flexible shaft. Next, we can validate the mixer's ability to mix digester contents and suspend solids through actual use of the mixing system. Sand and potting soil will be used to represent the solids inside the digester, which is an accurate substitution for digested animal and plant waste.

Our prototype will not be able to validate all functionality of the mixing system, namely the ability to remove solids. This function is less dependent on the design of the mixer and more dependent on the actual digester (and testing rig), which our project did not include. The mixing system can only suspend the solids and hope that some are removed when more waste is added.

In order to confirm the functionality of our design and observe its effects on the biodigester, we created a validation plan. This plan will characterize the flow created by our mixing system and compare our design to engineering specifications. We could not test for all of our specifications but did where we could.

The team anticipates a high level of performance, especially for mixing ability. The flexible shaft is made for situations like this one, and the input torque from the operator should be transmitted very efficiently to the mixing attachment. As for other functionality, the analysis we performed on the fin blades using CFD software tells us we do not need to worry about the blades moving up and down during operation. Overall, important design considerations were backed with thorough analysis and support from our sponsor, so we feel that our prototype's performance will be very indicative of the performance of the final design.

A description of our testing rig along with the results of our deployment, localized mixing, solid suspension, solid removal and fatigue analysis are presented in this section.

Testing Rig

The testing rig we used was created from two clear plastic storage bins. One end of each bin was cut off using a reciprocating saw. These now open sections were laid inside of the other with a 1" overlap, putting silicone sealant on the overlap, and securing it with 1/8" pop rivets placed every ¾" to 1" along the overlapping flap. The resulting size of the test rig was 60" x 19" high x 17"wide, as seen in Figure 34. Then, an effluent pipe was installed by sawing out an elliptical hole for a pipe at an angle 15º to the ground. The pipe was secured to the bin by using 5-minute epoxy and letting it sit overnight. Tape was needed over the short midline of the rig and on top of the effluent pipe to the rig to help stabilize the rig when full with water. Extra bags of sand and potting soil were also used to keep the sides from bulging out.

Figure 34: Schematic of testing rig sectioned off into 3 sections for analyzing local mixing

Deployment & Tamper Resistance

The goal of deployment test was to simulate the actual process of a mixer being inserted into 4" effluent pipe and determine if removal is possible, as shown in Figure 35 on page 32. This process includes: (1) folding up the fins when inserting the mixer in the pipe, (2) opening up the fins when clockwise rotating the mixer handle and (3) trying to remove the mixer. Our test result showed that the mixer has completed these goals well, as shown in Table 2. We used only water as the fluid for this test for increased visibility.

Figure 35: Insert the collapsed mixer into 4” diameter pipe

Table 2: Deployment of mixer into a 4” pipe is successful

The fins folded up and went through 4” pipe smoothly

As mixer rotated clockwise, fins opened up easily

Mixing Orientation

We will test that the mixer can be operated out of the “line of fire” and to the side of the effluent tube, out of the way from any exiting effluent, as shown in Table 3. The flexible shaft that connects the hand crank and the mixing attachment is meant to transfer torque around bends. The photos below show that mixing out of line with the effluent tube is possible without sacrificing mixing quality and effectiveness.

Table 3: Mixer can be used in "line of fire" and to the side of effluent tube

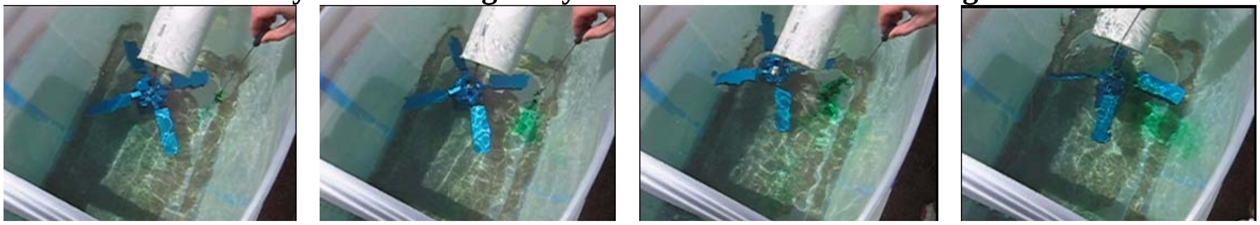
Mixing in the "line of fire" Mixing to the side of effluent tube

Localized Mixing

The goal of localized mixing testing was to compare the different effects of mixing at the effluent and influent ends of the digester. By dropping food coloring at the two ends during mixing, we found that the localized mixing was achieved, as shown in Table 4. The dye dropped in the effluent end was mixed greatly while dye in the influent end barely mixed. We used only water as the fluid for this test for increased visibility.

Table 4: Localized mixing has been achieved with our mixer

Dye was mixed greatly at the near end of the mixing



0s **1s** **2s** **3s**

Dye was barely mixed at the far end of the mixing

0s **1s** **2s** **3s**

Solids Suspension

The goal of solid suspension was to compare the different solid depths at the near, middle and far ends of the digester after mixing. In this test, we used play sand to represent the inorganic solids and water to represent the fluid. Before mixing, we set the solid depths at three locations to be equal, at 3.5". Then, we performed six tests at different combinations of speeds and times at the effluent end of the digester, and measured the new solid depths after each test. Table 5 shows the set up of solid suspension test rig. We also videotaped the process to record the settling times. The details of solid depths with six combinations at three ends are shown in Figure 36 on page 35. The settling time is shown in Table 6.

Table 5: Set up of solid suspension test rig

1. Put sand in test rig

2.Smooth out sand in test rig

3.Measure with ruler to ensure equal heights

4. Pour water into test rig with sand

We found that the solid depth decreases at the effluent end of the digester, starting at 3.5" and decreasing incrementally to 3.0". The solid depths at middle and influent end of the digester both increase, starting at 3.5" and increasing incrementally to 4". There is no clear difference of solid depths between the middle and influent end. We also found that the change of solid depth at all ends tend to increase with higher speed and longer operating time. However, there is no obvious change after the 60 RPM and 30 seconds, after which the solid seems to reach a stable state. Thus, we determined this speed and time to be our recommended usage parameters. We also found that the settling time of the large sand particles was about 4.5 seconds regardless the speed and operation time.

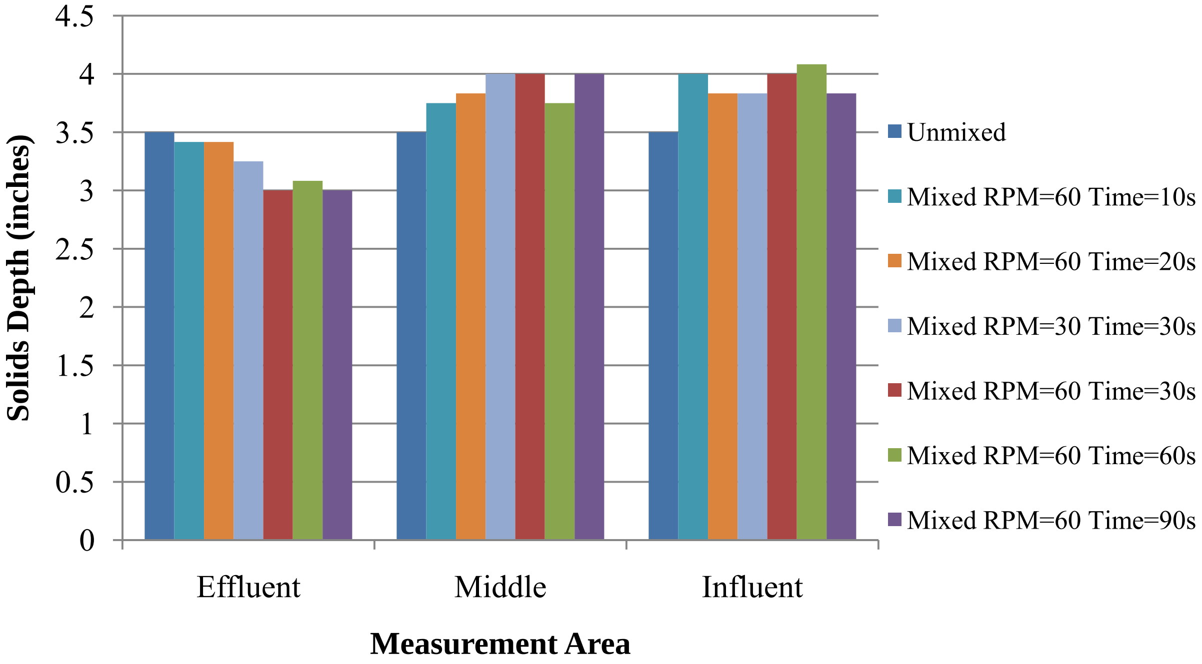


Figure 36: Solid depth decreases at the effluent end and increases at middle and influent end of digester

Table 6: Settling time is about 4.5 seconds regardless the speed and operation time

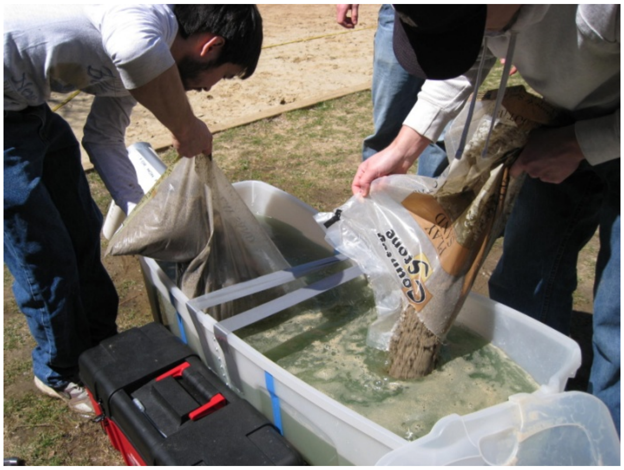
RPM	Time rotated (s)	Settling Time (s)
60	10	5
60	20	5
60	30	4
120	15	4

Solid Removal

To increase the area inside the digester available to biogas production, some degree of solids removal is desired from a mixing system. Our tests showed that a negligible amount of solids are removed from our experiment setup. We started by rotating the handle at 60 RPM and 60 seconds. After mixing, we waited for 30 seconds, and then poured one bucket of water into the influent pipe. The solid removal test procedure is shown in Table 7. However, our filter did not collect any solids. We then increased the speed to 120 RPM and reduced the waiting time to 5 seconds and still there was no solid removal. Finally, we poured two buckets of water immediately after mixing at 120 RPM; we still could not collect any solids, as shown in Table 8.

Table 7: Solid removal test procedure

1. Pour sand into test rig



2. Smooth out sand

3. Pour cow manure into test rig & smooth out

4. Drill holes in effluent pipe

5. After mixing, pour bucket of water in

6. Use a filter to collect water coming out

Table 8: No solid is removed from the solid removal test

Speed(RPM)	Mix Time(s)	Pour Time(s)	Buckets of Water	Mass of Solids Removed(g)
60	60	30	1	0
120	60	30	1	0
120	60	10	1	0
120	60	0	1	0
120	60	0	2	0

Fatigue Analysis

The goal of the fatigue test is to examine if the standard operation would cause fatigue to the user. For this setup, we again used play sand and water but this time added composted cow manure to closely represent slurry in the actual digester. From the previous solid suspension test results, we set the standard operation to be 60 RPM for 30 seconds. We got get the percent maximum voluntary contraction (%MVC) from dividing the maximum exertion by reference exertion [13]. Then the average %MVC is calculated using the equation below, in which work cycle time is defined as the standard time for an operator to use the mixer including the resting time.

$$\overline{\%MVC} = \frac{rest\ time * 0 + mixing\ time * \%MVC}{work\ cycle\ time}$$

When $\overline{\%MVC}$ is larger than 17%, the mixing job will cause fatigue. Otherwise, the job would not cause fatigue.

Our testing results showed that no fatigue will occur at an operation time of 60 RPM and 30 seconds at a two minute work cycle. We also increased the operation time and found that no fatigue occurred at 60 seconds. However, fatigue will likely occur at operation times of 90 seconds and 120 seconds and at higher RPM rates.

Table 9: No fatigue occurred at 60 RPM and 30 second standard operation. Yellow cells show fatigue.

	Person A (Female)	Person B (Male)	Person C (Male)
Max force (kg)	29.5	49	42
Exertion force (kg)	5.50	4.25	10.50
Mvc	0.19	0.09	0.25
for 30s	0.05	0.02	0.06
for 60s	0.09	0.04	0.13
for 90s	0.14	0.07	0.19
for 120s	0.19	0.09	0.25

Specifications Not Tested

There are some specifications that would be unrealistic to test given our availability of digester materials or the required time to complete a single test. The specifications below will not be tested, but we are confident that our design is robust enough to not require verification of these specifications.

Adaptability

Perhaps the most important specification for digesters already built, the mixing system needs to be adaptable to these varying digesters. We do not have the resources to go to Mexico and test our design on current digesters, but we believe that our system will work on a wide range of designs. This is because the shaft running from the crank handle to the mixing blades is flexible and can still transmit torque while bent. We are confident our design will work, though no direct testing will be performed to confirm our claim.

Low Maintenance

The digester has maintenance performed every 10 years. This is longer than the current maintenance schedule of seven years because we are hoping the stirring motion will help disperse inorganic solids and aid their removal when more material is added to the digester. While it would be unrealistic to wait that time to verify our mixer reliability, we believe that all parts that stay inside the digester will not require maintenance for 10 years. We base this on the lack of wear on our system, corrosion resistance of the materials and coatings, the strength of our materials, and the quality of our manufacturing.

DESIGN CRITIQUE

Honest critique of our design is a necessary step to further improve upon it. Our design succeeds in many aspects. Our testing shows that it will mix the biomass locally, suspend solids, and will not fatigue the user. The flexible shaft works as expected, allowing the user to stand to the side while mixing and allowing for easy torque transfer from the user to the mixer. The anticorrosion elements will last the 10 years we expect between maintenance checks. It meets a majority of our specifications, such as its adaptability to be used in existing digesters, its effectiveness of mixing, its ease of mixing, its ergonomic elements, and its sanitary operation. If anything, our design is overengineered, which is an opportunity to potentially lower cost while maintaining functionality.

Of course, there are a number of improvements that could be made to our design. We noticed that the square bottom of the mixing attachment would hit the bottom of the digester, and the anodized coating started to wear away. By manufacturing a hemispherical bottom to the attachment, we avoid this issue. We would also like to further investigate the McLube flexible coating for its use in our system. Our initial application did not seem to work, but it is possible that it was misapplied. Should it work as expected, it will greatly extend the life our system. A longer flexible shaft would be useful as well considering that 3' was not long enough for us to operate the mixer while standing up. Proper placement in the effluent pipe will help with this, but we would like to have 6'-8' for maximum performance. Further testing for solid removal would be useful, specifically to see what size particles will be removed and what will not. Finally, cost is still an issue. While our system comes to less than 30% of the total digester's cost, there are ways to reduce it. Specifics on what costs to reduce depend on what tradeoffs the designer is willing to make.

SUSTAINABILITY

A discussion of the sustainability our design requires a brief discussion on the sustainability of biodigesters. From an energy standpoint, biodigesters are sustainable since they collect energy from what is normally waste. This energy replaces wood that would normally be burned. By using waste and reducing deforestation, not only is there less energy taken from the environment, the trees that remain will reduce carbon in the atmosphere. Decomposing organic waste in the environment would release methane, a considerable pollutant; burning said methane converts it to carbon dioxide, which is still a pollutant, but less harmful. To find exact numbers for energy savings, we need to know the amount of biogas used compared to the amount of wood used, but there is currently no system to measure the biogas production in these digesters (something we considered addressing earlier in this project). Instead, we can qualitatively look at the net energy gain. By spending one day installing the digester, a small amount of time adding waste every day or two, and performing maintenance checks every seven years, farmers get a majority of their cooking fuel in biogas. This works in the farmers' favor, who now do not have to spend as much time finding and chopping wood and get what is essentially free energy from waste. Thus, standard biodigester operation is sustainable from an energy standpoint.

A mixing system will add energy costs, but may end up increasing the sustainability of the system as a whole. As we mention in our Environmental Performance section, the materials in our mixer are energy intensive to produce. Operating the mixer also requires a small input of labor. That said, there are benefits that our system will bring. Removing inorganic solids will extend the time between maintenance checks, reducing the energy input over the lifetime of the digester. It has also been theorized that mixing may increase biogas production, though no literature exists on that topic for our specific style of biodigester. The increased lifetime alone could warrant the use of the mixer, and the potential increase of biogas production (and concurrent reduction in wood consumption) would further justify its use. Again, exact numbers cannot be found given the paucity of information on the system, but it is worth conducting research for what may be an increase in the sustainability of the digester.

Looking at sustainability from an aquatic aspect, the digester inherently has a positive effect on water systems. Normally, animal waste enters the environment untreated, requiring time for the pathogens and other hazardous elements to decompose. The digester contains this decomposition, essentially removing the waste from the environment by converting it into biogas. The effluent is not nearly as hazardous as raw waste, and farmers can still use it for fertilizer. Thus, the digester is aquatically friendly in that it reduces the amount of waste that can contaminate water systems.

The effect of adding the mixer is not inherently clear, but a brief discussion brings up a few good points. Inorganic solids removed from the digester would not contaminate aquatic systems, and since our testing showed that it does not mix new waste into the end, the effluent is no more hazardous than that of an unmixed digester. If the mixer increases biogas production, less waste remains in the digester, further reducing the burden on the environment. It seems that our mixer is aquatically helpful as well.

RECOMMENDATIONS

The majority of our recommendations stem from the results of our validation testing. The first would be to modify the test rig to emulate the actual digester. We were limited by time and resources when creating our test rig, and we recommend a test rig that has the same dimensions of an actual Mexican digester (10’ x 3’ x 3’), has an influent and effluent pipe, and is transparent so fluid and solid motion can be observed. Though our data are conclusive, a full size digester would give better insight into the influence of adding more influent into the system as well as the ability of solid removal. The greater depth of the tank would also more aptly show effectiveness of mixing. Another recommendation from testing is to use an improved method to measure the inorganic solids removed. The filters we used were not sufficient in collecting the sand particles, and if they were collected, we did not have a method to measure them. The solids were smaller than we anticipated. We recommend collecting the effluent (without the potting soil added) in a large container, then separating the solids from the water by either waiting until all of the solids settle or using a centrifuge. From the volume, one can factor in the density of the sand to solve for the mass of solids removed.

The last and most important recommendation is to use our prototype for research purposes to test if mixing and suspending solids in a plug-flow digester would not only increase the maintenance time of the digester but also increase biogas production. Increasing the digester’s maintenance time would save money for organizations like IRRI who install them. A long lasting digester would be more attractive for prospective homes and governments looking to invest in this product. Even more attractive would be a digester that produces more biogas than the ordinary one. There is much potential if biogas production is increased. Rural Mexicans would have enough methane to cook for more of their cooking needs instead of just 60% of it. Thus, less wood would be burned. A buzz would penetrate the entire sustainable energy community, intriguing organizations and governments worldwide. The potential benefits are worth the efforts needed to research the possibility of increased biogas.

A proposed method of testing would be start four digesters in a similar geographical region at around the same time. Two would have our mixing system installed and two would not. Ratios of pig waste to water will have to be monitored along with influent volume and frequency. Since a metering system was found to be too expensive for this application, those cooking would have to monitor the time one was able to cook off of the biogas, ensuring to have the consistent flow of burned biogas amongst the four systems. Those digesters with the mixer would mix at the recommended speed and time with every influent addition. Two years’ worth of data would be sufficient, as it would take time for inorganic solids to build up on the bottom and thus would take time for the benefits of having those solids removed to be seen.

CONCLUSION

The use of biodigesters brings sustainable energy to Mexico, and our design will improve the usage and operation of these digesters. Our mixing system will suspend inorganic solids that accumulate on the bottom of the digester, locally mix the biomass, and potentially increase biogas production, increasing the lifetime and utility of the digester. Below are the specifications and parameters that we used for our design.

Table 10: Design Considerations for the Mixing System

Engineering Specification	Target	Result
Insertion Size	< 4” OD	4” OD
Lifetime	10 years	Expected 10 years
Cost	< $300	$175
Ergonomics – force	2 lbs	11 lbs
Ergonomics – time	Up to 10 min	30 sec
Expanded Size	12” OD	12” OD
Installation Time	~ 20 min	< 1 min

Testing Parameter	Target	Result
Effectiveness of Mixing	Solids removed (168 g)	0 g
Mixing Time	< 10 mins	30 sec
Localization of Mixing	33%	33%
Settling Time	> 20 sec	~ 5 sec
User Fatigue	Minimal	None

We met these specifications well, and our testing gave us valuable information. Our mixing system is the first step in the improvement in biodigester technology, and scientific research can now be undertaken to characterize the effects of mixing in plug-flow digesters. We found that mixing for 30 seconds at 60 RPM is sufficient to suspend solids.

We have a few recommendations for future work. First, testing should be done on a real digester or a testing rig similar to one to best characterize the system. Second, a better way to quantify the solids removed is necessary. Finally, we recommend using our prototype to test whether biogas production would increase with mixing. By working to improve biodigesters in Mexico, we reduce the impact on the environment and recover useful energy that was once lost. It is the hope of everyone on this team that our system will prove to be a positive impact for sustainability energy.

ACKNOWLEGEMENTS

The design team would like to thank the following individuals and companies:

- Dr. Steven J. Skerlos - for his guidance and advising.
- Alex Eaton of IRRI - for his invaluable information and motivation.
- Sherri Cook of UM's BLUElab - for her biological insight and overall guidance.
- Bob Coury and Marv Cressey - for all of their manufacturing wisdom.
- Yotzín Cortés-Medina - for valuable information of the people and culture in Mexico.
- Alpha Metals - for the complimentary annodizing of our prototype.
- McLube - for a sample of their McLube 1775, a flexible anti-corrosive coating
- Carpenter Brothers - Ann Arbor, MI.
- Stadium Hardware - Ann Arbor, MI.
- Jack's Hardware - Ann Arbor, MI.

This project could not have been possible without their support. Thank you very much.

REFERENCES

[1] Eaton, A. (2009, January 22). IRRI Director. (ME450 Team 22, Interviewer)

[2] Marchaim, U. (1992). *Biogas processes for sustainable development*. Kiryat Shmona, Israel: Food & Agriculture Organization of the United Nations.

[3] Food and Agriculture Organization (FAO) of the United Nations. *Biogas 2: Building a Better Biogas Unit*. Rome, Food and Agriculture Organization of the United Nations.

[4] Cleveland Eastern Mixing, 2009 ― Parameters for Mixing Equipment Specifications,‖ http://www.clevelandmixer.com/files/pdf/Parameters%20For%20Mixing.pdf

[5] Cleveland Eastern Mixing, 2009. ―Mixing Process Classifications,‖ http://www.clevelandmixer.com/files/pdf/Mixing%20Process%20Classifications_.pdf

[6] Cleveland Eastern Mixing, 2009. ―Bulk Container Agitators,‖ http://www.clevelandmixer.com/products/bulk-container-agitators/default.html

[7] *Animal By-Products and Anaerobic Digestion*. IEA Bioenergy. Retrieved February 2009. http://www.iea-biogas.net/Dokumente/IEA_ABP-Brochure_en_2.pdf

[8] Woodson, W., Tillman, P., & Tillman, B. Human Factors Design Handbook: Information and Guidelines for the Design of Systems, Facilities, Equipment, and Products for Human Use (1992) McGraw Hill Professional: NewYork

[9] Na Jin Seo and Thomas J. Armstrong, *Investigation of Grip Force, Normal Force, Contact Area, Hand Size, and Handle Size for Cylindrical Handles*, University of Michigan.

[10]National Health Survey Statures in inches and millimeters for males and females age 20 and over from National Center for Health statistics, CDC 2003

[11] El-Mashad, Hamed M. (2004). Rheological properties of dairy cattle manure. Elsevier: Bioresource Technology. (p. 534).

[12]Erik Oberg, Franklin D. Jones, Holbrook L. Horton, And Henry H. Ryffel, Machinery's Handbook, 26th edition, INDUSTRIAL PRESS INC., 2000, New York

[13] Waldemar Karwowski, (2006) *International Encyclopedia of Ergonomics and Human Factor,* CRC Press.

[14] Chemical Compatibility. Cole-Palmer. Retrieved February 2009. http://www.coleparmer.com/techinfo/ChemComp.asp

[15] FLW Incorporated, 2009. ―Material Compatability with Gases and Liquids [Database],‖ http://www.flw.com/material/index.html

[16] “Corrosion: Galvanic Corrosion.” Stainless Steel Industry of North America. http://www.ssina.com/corrosion/galvanic.html

[17]IEA 2005. Retrieved February 2009. http://www.iaea.org/inisnkm/nkm/aws/eedrb/data/MX-elcc.html

[18]Government of Western Australia, Sustainable Energy Development Office. Retrieved February 2009. http://www.home.energy.wa.gov.au/pages/energyus.asp

[19]Priyantha D. C. Wijayatunga and Rahula A. Attalage, *Analysis of household cooking energy demand and its environmental impact in Sri Lanka*, University of Moratuwa, 1 July 2002.

[20]Length: diameter ratio in polyethylene biodigesters, PigTrop. Retrieved February 2009. http://pigtrop.cirad.fr/sp/temas/medio_ambiente_y_recursos_naturales/length_diameter_ratio_in_polyethylene_biodigesters

[21]Sharma, S.K, *Improved Solid Biomass Burning Cookstoves*, RWEDP, Field Document No. 44, pp.66, Sept., 1993.

[22]K.Y. Show and D.J.Lee, *Carbon credit and emission trading: Anaerobic wastewater treatment*, National Taiwan University, May 2008.

[23]Investopedia, A Forbes Digital Company. Retrieved February 2009. http://www.investopedia.com/terms/c/carbon_credit.asp

[24] *How Anaerobic Digestion (Methane Recovery) Works*, U.S. Department of Energy, December 30, 2008. Retrieved February 2009. http://apps1.eere.energy.gov/consumer/your_workplace/farms_ranches/index.cfm/mytopic=30003

[25] Drillis R, Contini R, Average Link Length Proportions, 1966

[26] Cortés-Medina, Y. (2009, January 20). (ME450 Team 22, Interviewer)

[27] Stroot, P., McMahon, K., Mackie, R. (2000). *Anaerobic codigestion of municipal solid waste & biosolids under various mixing conditions*. Urbana, IL: Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign.

APPENDIX A: Bill of Materials

Part Description	Material	Size	Quantity	Unit	Unit Cost ($)	Total Cost	Source	Part Number	Notes
Handle									
Round PVC stock	PVC, Type I	1.25" D	10	inches	$0.26	2.62	McMaster	8749K19	can be cut to length
Shoulder Bolt	Steel	1/2" SD	1	bolt	$2.32	$2.32	McMaster	91259A720	3/8-20 thread, 2 in shoulder length
Crank bar	Steel	3/4"x3/4"	8	inches	$7.75	$7.75	McMaster	9143K191	
Roll pin	Steel	1/8" D	1	pin	$0.04	$0.04	McMaster	98296A883	1" long
Roll pin	Steel	1/8" D	1	pin	$0.04	$0.04	McMaster	98296A877	1/2" long
					Subtotal:	$12.77			
Flexible Shaft									
Flexible Cable Shaft	Steel	3’	2	shafts	$58.84	$117.68	McMaster	3787K26	shaft with female ends
Dowels to connect to handle/mixer	6061 Alum	1/4" D	8	inches		$3.00	hardware store		
Flexible Cable Cover	Braided PVC Hose	1/2" ID	6	feet	$0.50	$3.00	hardware store		
					Subtotal:	$123.68			
Mixing Attachment									
Square stock for mixing connection	6061 Alum	3"x3"x3.5"	1	block	$3.93	$3.93	ASAP Source		price based on volume
Square stock to mount fins	6061 Alum	1/2" x 1/2"	36	inches	$10.62	$10.62	McMaster	8975K478	
Fin blades	6061 Alum	1/4"x4"x12"	1	plate	$9.68	$9.68	McMaster	8975K425	unpolished
Dowel for fins	Steel	1/4" D	2	inches	$0.34	$0.68	McMaster	98381A550	
Roll pin	Steel	1/8" D	1	pin	$0.04	$0.04	McMaster	98296A883	1" long
					Subtotal:	$24.94			
Miscellaneous									
Hard Anodized coating					$130.00	$8.13	Alpha Metals		batch price
					Grand Total:	$169.51			

APPENDIX B: Design Changes Since Design Review #3

Since Design Review #3, a few things have changed in our design. Most of the changes are relatively minor and could generally be classified as refinements. The first change is that we will no longer use sleeve bearings at the fin shaft/dowel interface. We determined that a simple clearance fit will be more than sufficient to accommodate for the rotation of the joint without the added cost. Another design change is that we put a braided PVC hose over the flexible shaft to increase the overall rigidity of the shaft and prevent against buckling under large loads. The braided hose is fit to the entire length of the flexible shaft with a 5” section next to the hand crank separated to allow for a natural and easy rotating handle. Another design change involves the connections to the flexible shaft. We previously thought that a threaded rod would be threaded into both tapped female connections, but the flexible shaft coupling is extremely hard to tap. Because of this, we decided that a smooth steel dowel with a roll pin through it would be a secure a connection. The roll pin will be pressed through the coupling (and mixing hub) completely through the steel dowel. Since the roll pin must be compressed to fit into its opening, the stress induced in the pin helps create a very secure connection.

A few other design changes involve the shape of the mixing hub. First, we had to slightly increase the size of the slots that the fin shafts fit into. We modeled all dimensions to be an exact fit, but in the real world, this is hard to recreate due to tolerance issues. This change had no effect on the function of the mixer, but it just allowed the parts to fit together. Also, we strayed from the cone-shaped mixing hub bottom of our original designs to a simple rounded edge design. We did this because we had a manufacturing deadline to meet and needed to save on time. We also thought that a flat bottom would stay oriented on the bottom of the digester better while mixing. The coating methods of our original design also ended up changing. We decided to get all of our aluminum parts anodized since Alpha Metals sponsored our project and performed the anodizing for free. This put a tough, corrosion resistant coating on our prototype and was much easier than working with epoxies. We also put a McLube 1775 specialty coating on our flexible shaft. It is a Teflon-based coating that is flexible and extremely corrosion-resistant. McLube provided a free sample of this product to us. These design changes all had a positive effect on the outcome of this design and were a step forward from Design Review #3.

APPENDIX C: Design Analysis Assignment

1. Material Selection Assignment

To choose the most qualified material for the mixer design in Mexican digester, we have considered the engineering specifications such as chemical compatibility, hardness, density, yield stress as well as price. We found 6061 aluminum met all our specifications for the mixing mechanism and had the minimum cost. PVC met the stress requirement of handle design, its light weight and cheap machining cost makes it ideal for the handle. Table C.1 is a comparison of these specifications among the chosen materials.

Table C.1: Material property for mixer in anaerobic digester [14, 15]

Chemical Compatibility				Mechanical Properties			
Material	Hydrogen Sulfide (aqueous)	Methane	Ammonia	Hardness (Vickers)	Yield Stress (MPa)	Density (kg/m^3)	Price ($/kg)
Aluminum	Good	Excellent	Excellent	110	240	2700	1.35
304 Stainless steel	Fair	Excellent	Good	190	257.5	7955	6.61
316 Stainless Steel	Excellent	Excellent	Excellent	195	240	8030	10.7
PVC	Excellent	Good	Excellent	13.1	43.8	1450	1.60
Polypropylene	Excellent	Excellent	Excellent	8.7	23.7	900	2.25
Low Carbon Steel	Fair	Good	Excellent	140	322.5	7800	0.87

Corrosion Resistance

As shown in the Table C.1, aluminum, 316 stainless steel and polypropylene are among the three most non-corrosive materials in an anaerobic digester. The main chemical interaction that we were concerned was with hydrogen sulfides. A lot of common metals exhibit severe corrosion and decomposition when in the presence of hydrogen sulfides. Methane and ammonia are two other corrosive chemicals that are commonly found in anaerobic digestion system. The pH of digester is normally neutral, at 6.8~7.2. In addition to reactions between the biomass and the mixer, galvanic corrosion can occur between anodic and cathodic metals [16]. By using metals closer together on the anodic scale and using protective coatings, we can minimize the potential corrosion. Steel and aluminum are very close on the scale while stainless steel is far from both materials.

Mechanical Properties

Considering our material density specifications for mixing connection, the polypropylene and PVC can be eliminated because their density values are less than the slurry (1600 kg/m^3). This will cause the mixer to float, which will fail to suspend solids that are at the bottom of the bag. Although stainless steel has more strength and excellent in all the reagents tested, it costs around 8 times as much, while aluminum is cheaper but has only a 'good' rating (minor effect, slight corrosion) for H$_2$S, the most destructive reagent. This can be compensated for by putting a coating on all the parts submerged in the digester. An anodized coating process generally costs around $130, but because sixteen parts could fit into the anodizing bed at the same time, this would bring the cost down to less than $8.13 for each part.

Our calculation showed that all the chosen materials fulfilled the stress requirements of the mixer attachment, but only polypropylene and PVC are not suitable for dowel pins. Detail stress analysis is shown in the Appendix H. In minimizing cost at strength-limited design, we found that the 6061 aluminum is the optimal material between aluminum and stainless steel, as shown in Figure C.1. This is found by defining the y-axis as $\frac{yield\ strength^{2/3}}{density*price}$. The 6061 Aluminum is a member of age-hardening wrought Al-alloy family.

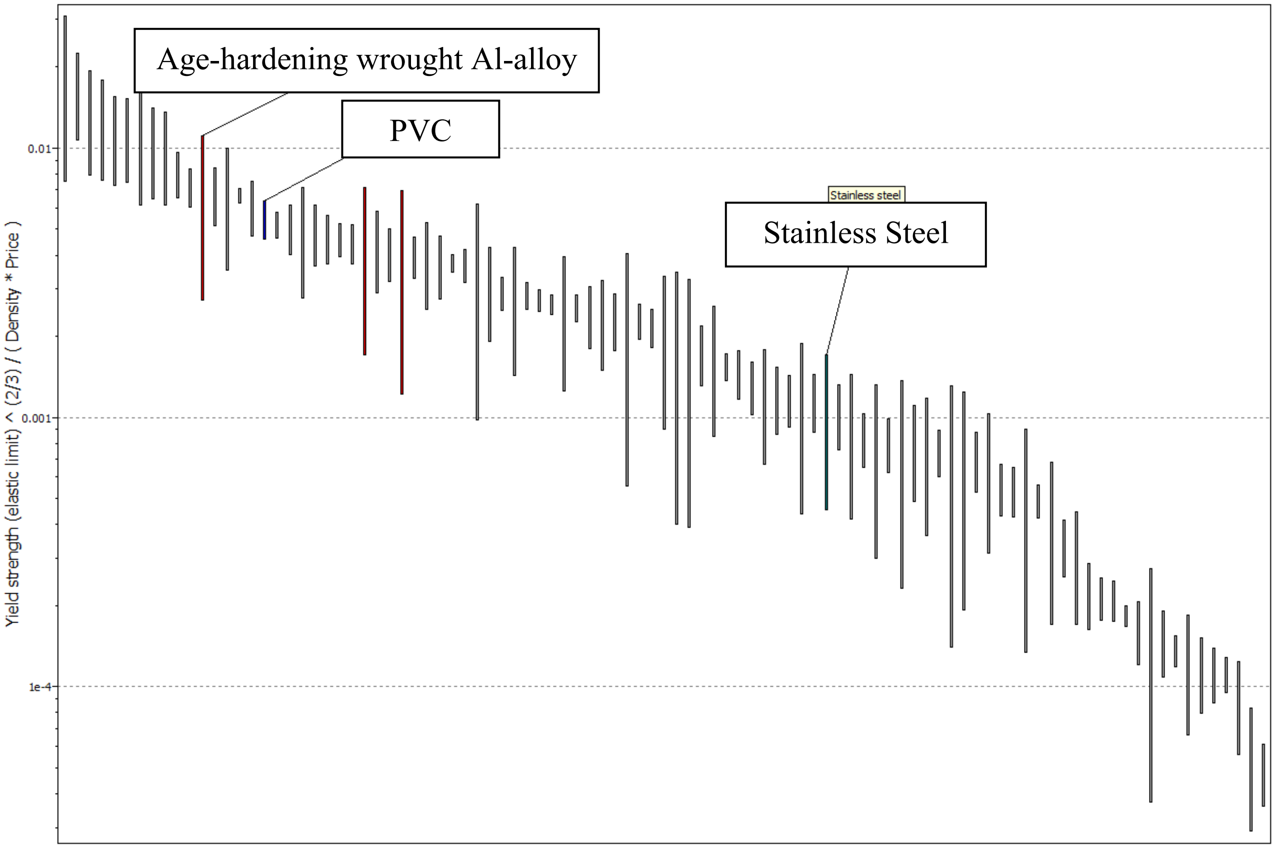


Figure C.1: Age-hardened wrought Al alloy has the optimal strength at minimum cost

Lastly, it would be ideal if the mixing connection's hardness was less than the hardness of the digester bag to eliminate any scratching that could lead to leaks. This may not be possible since HDPE's hardness rating is 50-60 compared to most metals and PVC which are around 100 [12]. This will be used as a reference as the pool of acceptable materials becomes more manageable.

2. Environmental Performance

Our final design utilizes 1.76kg total of 6061 aluminum stock and 0.14 kg of Type I PVC stock. An environmental performance analysis was run using the SimaPro 7.1 program. Figures generated from this program are shown below.

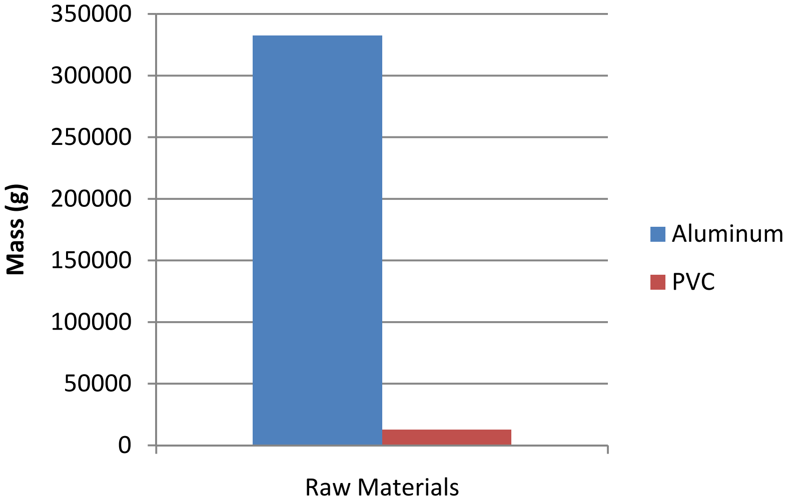


Figure C.2: Raw Material Usage Comparison

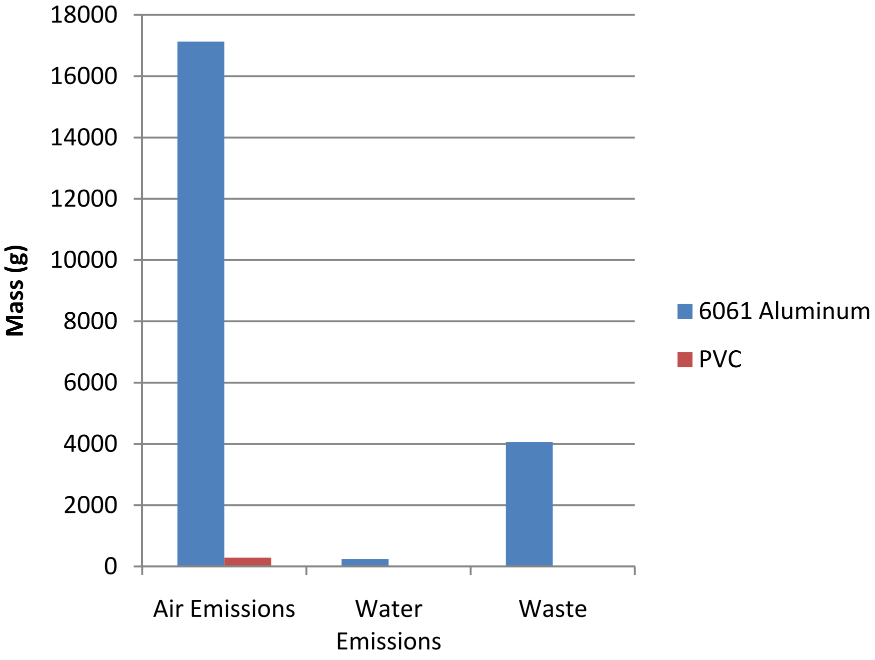
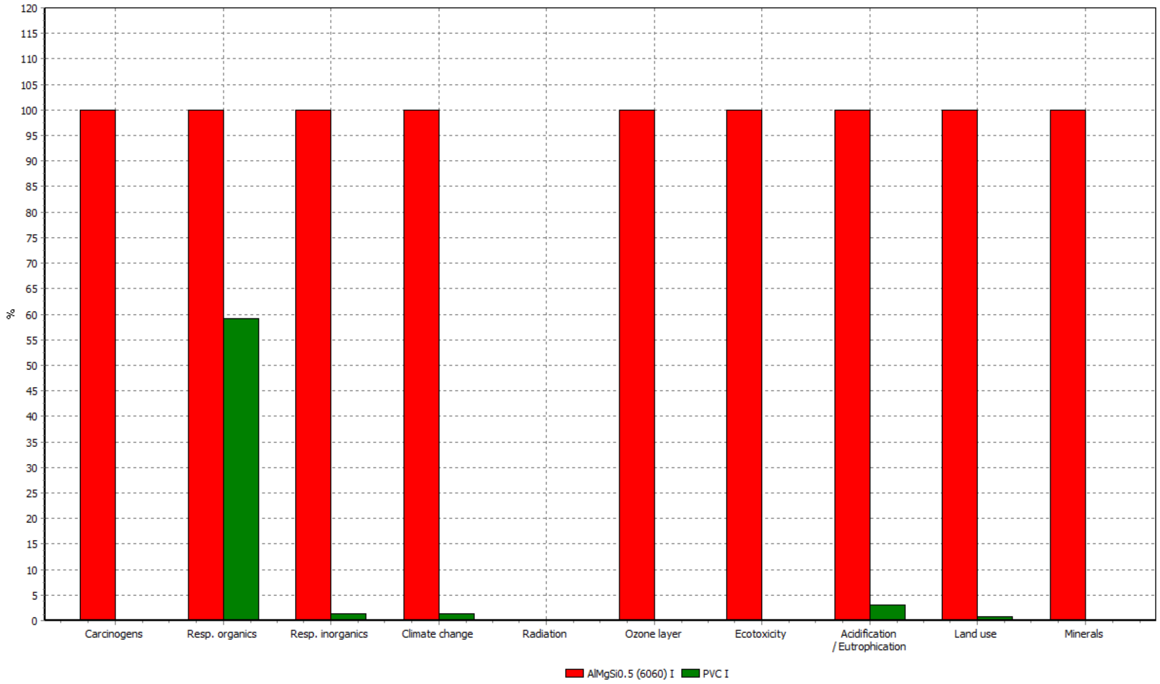
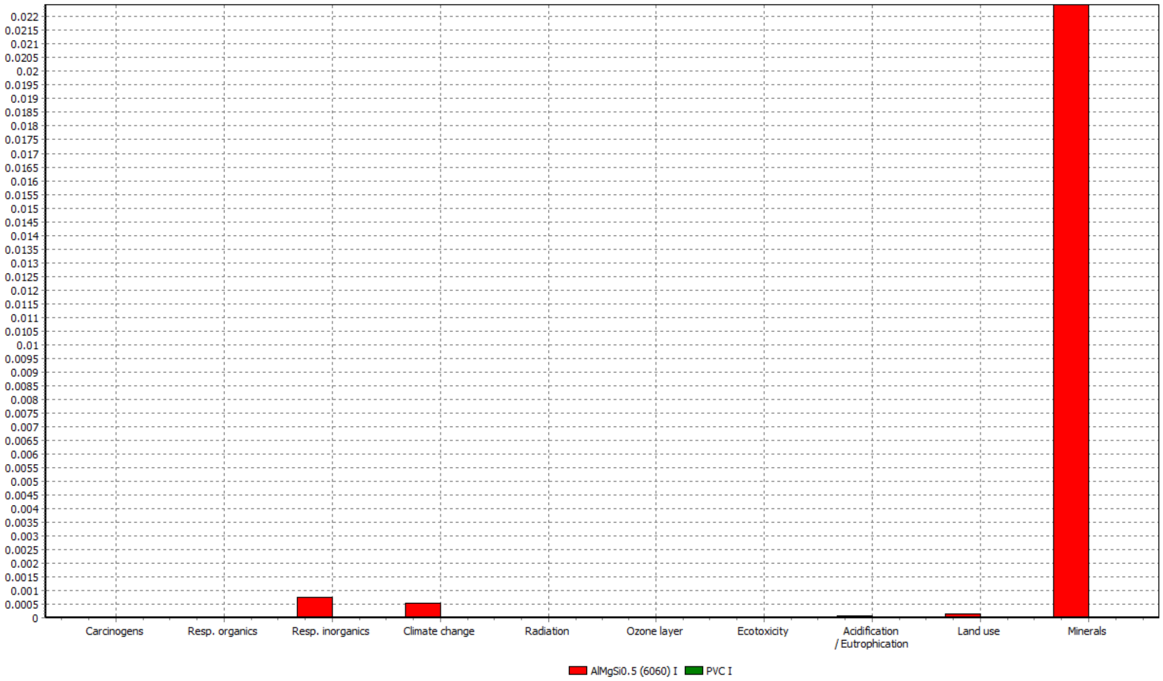


**Figure C.3: Emissions and Waste Comparison.
PVC Water emissions and waste values too small to be seen.**



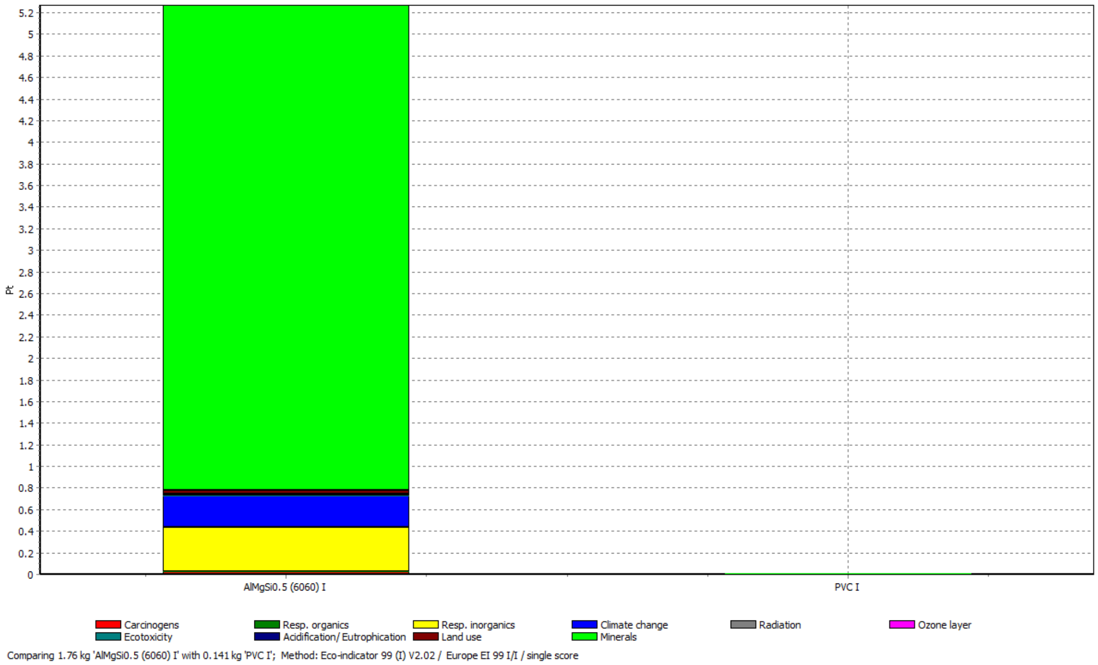
Comparing 1.76 kg 'AlMgSi0.5 (6060) I' with 0.141 kg 'PVC I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / characterization

Figure C.4: Relative Impacts in Disaggregated Damage Categories



Comparing 1.76 kg 'AlMgSi0.5 (6060) I' with 0.141 kg 'PVC I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

Figure C.5: Normalized Score in Human Health, Eco-Toxicity and Resource Categories



Comparing 1.76 kg 'AlMgSi0.5 (6060) I' with 0.141 kg 'PVC I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Figure C.6: Single Score comparison in "points"

The aluminum used in this design is much worse for the environment than the PVC. Overall more resources are needed to make it and more emissions are generated (Figure C.2, pg. 49). The meta-category of resources is the most important area to concentrate on this analysis. Aluminum requires an extremely large amount of various minerals and other resources to produce (Figure C.2), while the small mass of PVC we are using has a relatively small resource demand in comparison. Another important category for comparison is human health. Aluminum is rated very high in the categories of carcinogens and respiratory organics and inorganics. PVC has only a high rating in the resp. organics category, but it is still not as bad as aluminum in this category (Figure C.4, C.5). Overall, producing aluminum has a much larger negative impact to human health than manufacturing PVC.

While thinking of these materials in the larger scope of their entire lifetime, the environmental assessment changes slightly. During manufacture of the raw material, aluminum is much worse for the environment in all aspects (Figure C.3). However, during product manufacturing, the respiratory organic hazards for the PVC begin to play a role. While manufacturing the hand crank handle from PVC, there is good possibility for PVC dust to develop and for the user to breathe in the hazardous chemicals that are now airborne. Aluminum does not have the same health issues associated with product manufacturing as there is much less of a possibility for particles to become airborne. During the product lifetime of usage, aluminum has more hazards present. The aluminum mixer will be submerged in a very corrosive environment. Throughout its life, it will be subject to breaking down by a variety of chemicals, therefore releasing some of the harmful minerals that are used to manufacture it. These hazardous substances may eventually flow out of the digester and have the possibility of being contacted by humans transferring the effluent to their crops. PVC only has a slight possibility of breaking down by the elements over time, namely rain and wind, but these effects will be minimal compared with those of the aluminum corroding.

Few other materials offer the strength and corrosion resistance of aluminum. 316 stainless steel was a possibility explored earlier in the material selection process, but this material does not offer any improvements with regards to the environment. It is also a very resource intensive and hazardous material. Some plastics can be created without harming the environment as much but they lack the strength of metals. Plastic could be a possibility for the fin blades, however, since they are not exposed to as much stress as the mixing hub.

3. Manufacturing Process Selection Assignment

Based on the material considerations, we have selected 6061 aluminum and PVC as the main materials for mixer design. In choosing the cheapest manufacturing process for these materials, we first translated all the design requirements to constraints and objectives, as shown in Table C.2 and C.3. Then, we used CES Edupack 2008 to eliminate the processes that cannot do the job by inputting the seven attributions. After finding the feasible manufacturing process, we ranked them by costs. Finally, we examined and supported the CES selected process by exploring the details. Instead of doing the analysis on two different materials, we chose to analyze two different processes on one material due to our project using aluminum as its main material.
We found that planning/shaping is ideal for shaping 6061 aluminum used in mixer attachment design, and it is also the only candidate which fulfills all the requirements. This process creates flat machined surfaces and surfaces with prismatic features. The work piece is reciprocated in a linear motion against one or more single-point tools. It is very good in small economic batch size production; less time is needed to set up for machining compares to an alternative method.

Table C.2: Process Selection Chart for 6061 Aluminum

Objective	Constraint
Material	Metal, 6061 Aluminum steel
Shape	3-D solid
Size Range	0.01kg ~ 1 kg
Minimum Section	6.35mm ~ 89mm
Tolerance	0.1mm
Roughness	10µm
Economic Batch Size	1 ~ 100

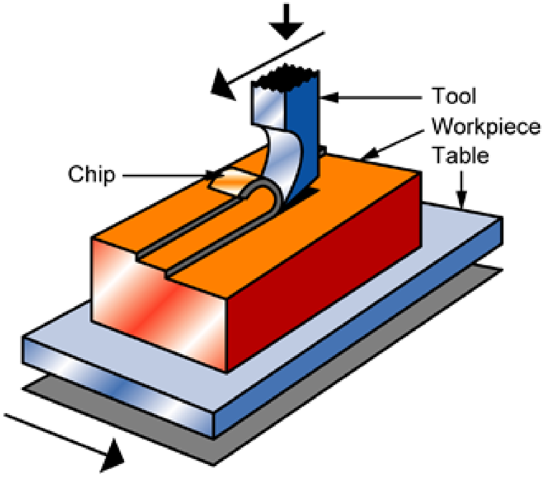


Figure C.7: Process schematic for shaping/planing

The surface treatment is essential for mixer attachment, as corrosion protection is necessary. We found that anodizing is ideal for corrosion protection for aluminum, it is the only process which fulfills all the requirements. This process forms a thin layer of Al_2O_3, and this film, though invisible, is highly protective. It is most generally applied to aluminum, the oxide formed by anodizing is hard, abrasion resistant and resists corrosion well. The oxide also allows absorbing dyes.

Table C.3: Process Selection Chart for 6061 Aluminum

Objective	Constraint
Material	Metal, 6061 Aluminum
Shape	3-D solid
Size Range	0.01kg ~ 1 kg
Coating Thickness	Less than 10 µm
Surface Roughness	A
Curved Surface Coverage	Good
Relative Tool Cost	Low

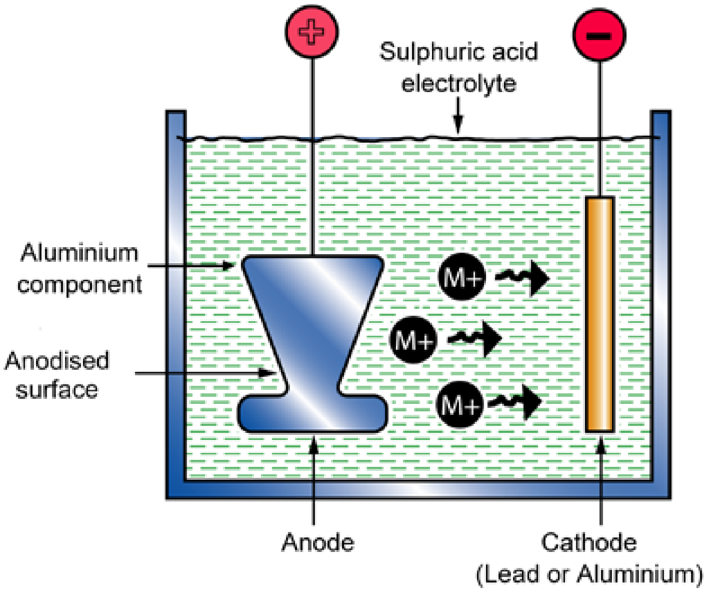
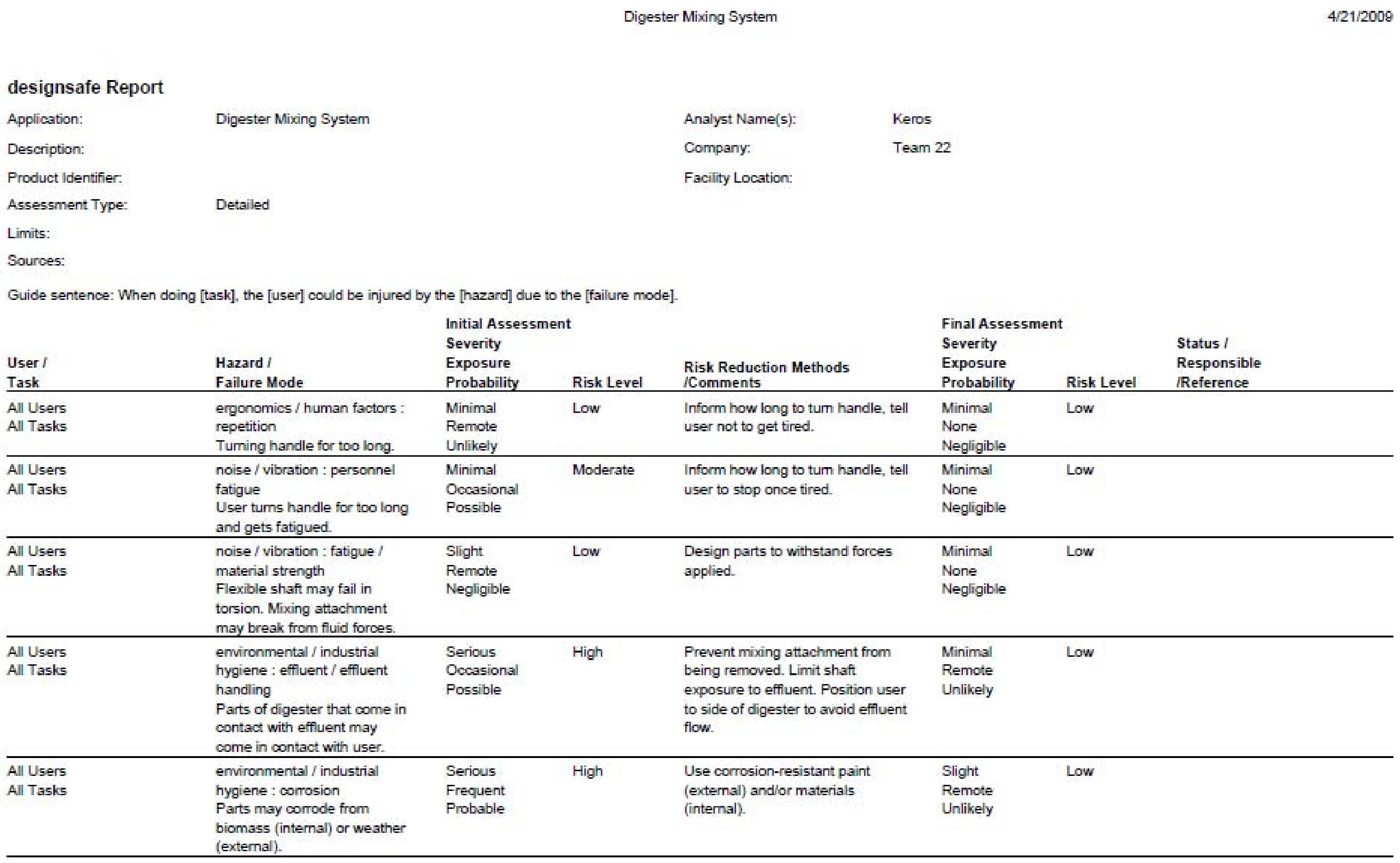


Figure C.8: Process schematic for anodizing

4. DesignSafe Report for Complete Digestion and Mixer System



Digester Mixing System 4/21/2009

designsafe Report

Application:	Digester Mixing System	Analyst Name(s):	Keros
Description:		Company:	Team 22
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	ergonomics / human factors : repetition Turning handle for too long.	Minimal Remote Unlikely	Low	Inform how long to turn handle, tell user not to get tired.	Minimal None Negligible	Low	
All Users All Tasks	noise / vibration : personnel fatigue User turns handle for too long and gets fatigued.	Minimal Occasional Possible	Moderate	Inform how long to turn handle, tell user to stop once tired.	Minimal None Negligible	Low	
All Users All Tasks	noise / vibration : fatigue / material strength Flexible shaft may fail in torsion. Mixing attachment may break from fluid forces.	Slight Remote Negligible	Low	Design parts to withstand forces applied.	Minimal None Negligible	Low	
All Users All Tasks	environmental / industrial hygiene : effluent / effluent handling Parts of digester that come in contact with effluent may come in contact with user.	Serious Occasional Possible	High	Prevent mixing attachment from being removed. Limit shaft exposure to effluent. Position user to side of digester to avoid effluent flow.	Minimal Remote Unlikely	Low	
All Users All Tasks	environmental / industrial hygiene : corrosion Parts may corrode from biomass (internal) or weather (external).	Serious Frequent Probable	High	Use corrosion-resistant paint (external) and/or materials (internal).	Slight Remote Unlikely	Low	

APPENDIX D: Energy Analysis (to show how storage is infeasible)

Energy Consumption in Mexico

By calculation, we found that the cooking energy consumption for a Mexican family of four is $1.4*10^4$ MJ /year. This is equivalent to the heat energy produced by 251.4 kg of methane. We assumed the biogas contains 60% of methane, and concluded that a volume of 0.957 m^3 of biogas is needed per day.

Based on a statistics of World Bank (2005), the energy consumption in Mexico is about 1832 kwh/capita [17]. While cooking accounts for only 12% in a typical developed country [18], it can accounts for about 53% to 65% for rural and non-electrified household sectors in developing countries [19].

Energy used for cooking per capita = 1832 kWh/capita * 53% = 971 kWh/capita

A family of four (usage * 4) = 3884 kWh/family (13,982 MJ/family)

We then calculated that the amount of methane needed for cooking energy is 251.4 kg from the enthalpy equation.

$$\begin{array}{llll} CH_4\,(g) + 2O_2\,(g) & \rightarrow CO_2\,(g) + 2H_2O\,(l) & & +\ 890\ \text{kJ/mol} \\ 16\ \text{g} & 44\ \text{g} & & +\ 890\ \text{kJ} \\ 251.4\ \text{kg} & 691.2\ \text{kg} & & +\ 13{,}982\ \text{MJ} \end{array}$$

This amount of energy for cooking is equivalent to 52% of energy use for the homes in USA.

Biogas contains 60% methane, so we calculated the amount of biogas necessary for this energy usage:

$$\text{Amount of biogas} = \frac{251.4kg}{60\%} = 419\ \text{kg}$$

At 1 atmosphere, Methane gas density (1.016 bars and 15 °C (59 °F)) is 0.68 kg/m^3, and carbon dioxide is 1.98kg/m^3. From these data, we calculated the volume of biogas necessary per day:

$$\text{Density of 60\% methane biogas} = 0.6*0.68+0.4*1.98=1.2\text{kg/m}^3$$
$$\text{Volume of biogas} = \frac{419kg}{1.2kg/m^3} = 349.2\ \text{m}^3$$
$$\text{Volume of biogas per day} = \frac{349.2m^3}{365} = 0.957\ \text{m}^3$$

Energy Generated in Mexican Digester

A digester can produce 0.6 m^3 biogas at 102.1 kPa per day, which is about 63% of the energy usage for a family of 4. Our digester's pressure is about 2" water column above atmospheric pressure:

$$\text{Pressure of our digester} = 101.56\ \text{kPa} + 1000\ \text{kg/m}^3 * 9.81\ \text{N/kg} * 0.0508\ \text{m} = 102.1\ \text{kPa}$$

To find the volume of gas in the digester, we used the Ideal Gas Law:

$$Volume\ of\ gas\ in\ digester = \frac{Pressure\ of\ atm}{Pressure\ of\ digester} * Volume\ of\ gas = \frac{101.56}{102.1} * 0.957 \approx 0.952\ m^3$$

The gas volume tends to be about 20% of the total biodigester capacity. [20]

Compressing Gas Generated into Portable Tank

We found that a pressure of 5.57 MPa is needed to compress the gas produced per day by the Mexican biodigester to a 3 gallon tank:

$$Pressure\ after\ compression = \frac{Digester\ Volume}{3\ gallon} * Digester\ Pressure = \frac{0.6}{0.011} * 102.1 = 5.57\ MPa = 807.6\ psi$$

This pressure of 5.57MPa is much too high for a manual pump to achieve in any reasonable amount of time. This is the primary reason that we changed our design objective from gas storage to mixer design.

Metering

Gas pressure metering was a desirable goal for this project to quantify gas production to use with carbon credits. The main issue that prevented gas metering from being a part of this design project was the low gas pressure. Typical biogas pressure is only slightly higher than atmospheric pressure (2-4” of water column. 0.07-0.14 psi) [1] and these systems also do not produce the flow rates that most meters require. The minimum pressure necessary for operation is 0.25 psi (6.9” of water) [21], which is higher than the typical digester pressure range. The effect of varied pressure on the performance of the meter was also unknown. This information would be necessary to understand if pumping gas through the meter in an inconsistent manner will be a problem. Carbon Credit accounting methods such as the Gold Standard require a fairly accurate system for calculating biogas burned. An inconsistent system of measuring certainly would not qualify. An additional issue was found with hydrogen sulfides possibly getting into the meter, corroding the internal metals. For all these reasons, gas metering was abandoned as a facet of this project to focus on more on a mixing system.

Carbon Credit Analysis

By installing a biodigester like the one in Mexico, in each year, the carbon dioxide emission is reduced by at least 55.8%, from 985.9 kg to 435.9 kg. It is the minimum value because the carbon dioxide that could be absorbed by the removed trees was not taken into account. A total amount of 158.5 kg methane is utilized instead of releasing directly into the atmosphere. The useful heat energy generated by the biogas is 2204.2 MJ, which is enough to boil 6560 kg water from 20 ºC to 100 ºC.

Carbon credit is a permit that allows the holder to emit one ton of carbon dioxide, ratified in conjunction with the Kyoto Protocol, its goal is to stop the increase of carbon dioxide emissions. . Credits are awarded to countries or groups that have reduced their green house gases below their emission quota. They can be traded in the international market at their current market price [22].

The traditional energy resource in rural Mexico is wood and coal. Burning wood/coal is cheap and easy accessed in rural Mexico, however, not environmental friendly. Sulfide generated in burning coal is the cause for acid rain.

From the Enthalpy equation shown below, it is know that the heat energy generated by burning 1 mole coal is 393.5kJ, less than half of which generated by 1 mole methane (890kJ/mol). At the same time, they produce the same amount of greenhouse emission, namely carbon dioxide.

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l) + 890\,kJ/mol$$
$$C(s) + O_2(g) \rightarrow CO_2(g) + 393.5\,kJ/mol$$

Moreover, trees are the lungs of nature by absorbing carbon dioxide. Killing trees for energy would have a net emission of the total amount of carbon dioxide in the atmosphere.

Lastly, by recycling and using the biogas in anaerobic digestion, we avoid the same amount of methane from going directly to the atmosphere. As introduced before, methane is 20 times more effective greenhouse gas than carbon dioxide.

We knew the energy generated by the digester makes up 63% of the total cooking consumption for a family. The amount of methane generated per year is 158.3 kg.

Amount of methane generated = 251.4kg * 63% = 158.5kg

By calculation, the heat generated by this amount of methane is 8816.7 MJ and the carbon dioxide emitted is 435.9 kg.

$$\begin{array}{llll} CH_4(g) + 2O_2(g) \rightarrow & CO_2(g) + 2H_2O(l) + & 890\,kJ/mol \\ 16\,g & 44\,g & 890\,kJ \\ 158.5\,kg & 435.9\,kg & 8816.7\,MJ \end{array}$$

To generate the same amount of heat energy, we need at least 268.9 kg coal and the carbon dioxide emit is 985.9 kg.

$$\begin{array}{lll} C(s) + O_2(g) \rightarrow & CO_2(g) + & 393.5\,kJ/mol \\ 12\,g & 44\,g & 393.5\,kJ \\ 286.9\,kg & 985.9\,kg & 8816.7\,MJ \end{array}$$

Percentage of CO_2 reduced = $\frac{985.9-435.9}{985.9} * 100\% = 55.8\%$

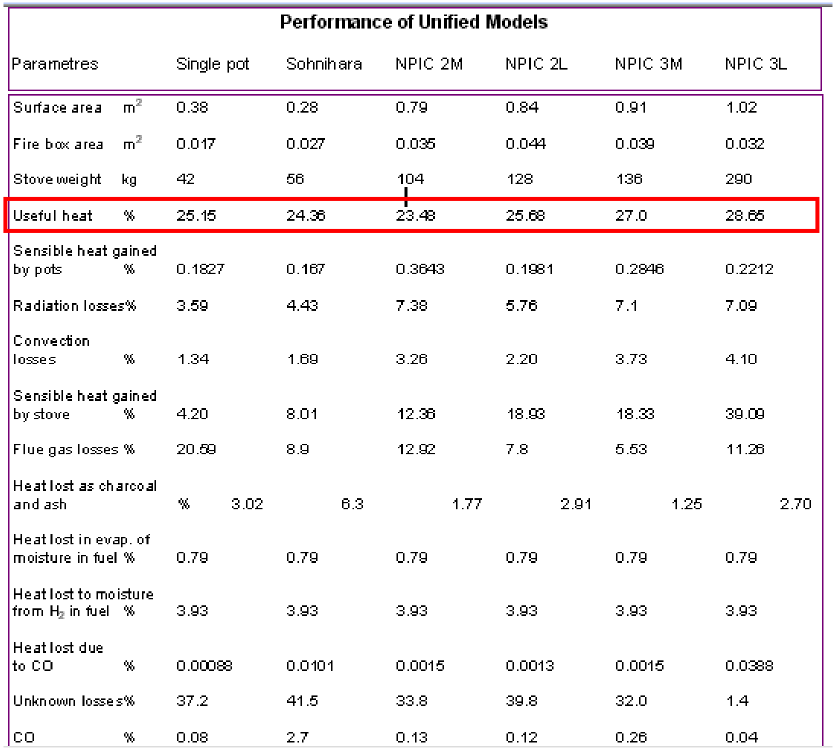
We found that the useful heat energy is 2204.2MJ. This energy is enough to boil 6560 kg water from 20 ºC to 100 ºC.

According to Figure 24, the efficiency of common gas/wood stove is about 25%.

Useful heat energy = 8816.7 * 0.25 = 2204.2 MJ

Energy to boil water = mass*C_p*ΔT = 2204.2MJ

Mass of water = $\frac{2204.2MJ}{C_p\Delta T} = \frac{2204.2MJ}{4200\,{}^{J}/_{kgK} * (100-20)°C} = 6560kg$



Performance of Unified Models

Parametres		Single pot	Sohnihara	NPIC 2M	NPIC 2L	NPIC 3M	NPIC 3L
Surface area	m^2	0.38	0.28	0.79	0.84	0.91	1.02
Fire box area	m^2	0.017	0.027	0.035	0.044	0.039	0.032
Stove weight	kg	42	56	104	128	136	290
Useful heat	%	25.15	24.36	23.48	25.68	27.0	28.65
Sensible heat gained by pots	%	0.1827	0.167	0.3643	0.1981	0.2846	0.2212
Radiation losses	%	3.59	4.43	7.38	5.76	7.1	7.09
Convection losses	%	1.34	1.69	3.26	2.20	3.73	4.10
Sensible heat gained by stove	%	4.20	8.01	12.36	18.93	18.33	39.09
Flue gas losses	%	20.59	8.9	12.92	7.8	5.53	11.26
Heat lost as charcoal and ash	%	3.02	6.3	1.77	2.91	1.25	2.70
Heat lost in evap. of moisture in fuel	%	0.79	0.79	0.79	0.79	0.79	0.79
Heat lost to moisture from H_2 in fuel	%	3.93	3.93	3.93	3.93	3.93	3.93
Heat lost due to CO	%	0.00088	0.0101	0.0015	0.0013	0.0015	0.0388
Unknown losses	%	37.2	41.5	33.8	39.8	32.0	1.4
CO	%	0.08	2.7	0.13	0.12	0.26	0.04

Figure D.1: Efficiency of Conventional Gas/Wood Stove [21]

There are three main sources for carbon credit saved in the Mexican digester project. They are (1) the methane that is produced from the waste is burned instead of going directly to the environment, (2) for the same heat energy, methane emits only half the carbon dioxide of wood, which is the farmer's original energy resource, and (3) the saved trees can recycle the carbon dioxide.

Assuming the price for one unit of carbon credit is \$30. The total baseline CH_4 emission is translated into CO_2 equivalent emissions by multiplying by its GWP of 21 [23]. Therefore, without taking the saved trees into account, the credit saved is

$$(0.1585 * 21) \text{ ton } *\$30 + (0.9859 - 0.4359) \text{ ton } *\$30 = \$116.36$$

Cost of the Mexican digester is \$400-600, the payback time would be

$$\text{Payback time} = \frac{cost\ of\ Mexican\ digester}{money\ saved\ per\ year} = \frac{\$500}{\$116.36} = 4.30\ years$$

This value is a high estimate. With the value of the amount of CO_2 sequestered by trees factored in, the payback time would only decrease. For now, this is sufficient. We will continue with researching the metrics of tree sequestration.

Calibration of Carbon Credit in Mexican Digester

Once the pressure is calibrated, the amount of biogas inside the 0.255 m^3 storage at 20°C can be calculated using the following equation.

$$\text{Amount of biogas in kg} = \frac{MPV}{RT} = \frac{27.2\,{}^{g}/_{mol} * 10^{-3} * 0.255m^3}{8.314\,{}^{J}/_{molK} * (273+20)K} * Pressure = 2.8 * 10^{-6} * Pressure$$

Where pressure is in Pa, and M = 16 * 0.6 + 44 * 0.4 = 27.2 g/mol.

The energy generated from the biogas can be calculated using the equation:

$$\text{Energy generated in kJ} = \frac{mass * 890kJ}{16 * 10^{-3}\text{kg}} = 5.56 * 10^4 * mass\ of\ biogas$$

Amount of water can be boiled from 20°C to 100°C with this energy:

$$\text{Amount of water in kg} = \frac{Energy\ generated}{Energy\ to\ boil\ water} = \frac{5.56 * 10^4 * 0.25 * mass}{4.2\,{}^{kJ}/_{kgK} * (100-20)℃} = 41.4 * \text{mass of biogas}$$

APPENDIX E: Functional Decomposition

Design Problem: Create a mixing system for a biodigester to suspend inorganic solids.

Level 1:

1. Mix biomass
2. Prevent contact with effluent
3. Mix internally
4. Input externally
5. Remain inside digester between maintenance checks

Multi-Level:

1. Mix biomass
    a. Suspend inorganic solids that collect on bottom of digester
    b. Mix in vertical direction, not axial
        i. Prevent influent from mixing with effluent
        ii. Preserve plug-flow model
    c. Mix without use of electricity
        i. Manual mixing required
2. Prevent contact with effluent
    a. Prevent removal of internal mixing parts once inserted
    b. External input must be away from effluent stream
    c. Parts that come in contact with effluent must not come in contact with user
3. Mix internally
    a. Actual mixing takes place inside digester
4. Input externally
    a. Motion outside must transfer to motion inside
    b. Must be easy to mix by user
        i. Little force required by user
5. Remain inside digester between maintenance checks
    a. Internal system must not require maintenance
        i. Maintenance checks likely to increase to every 10 years
    b. Withstand conditions of biodigester
        i. Withstand water and chemical corrosion

APPENDIX F: Concept Generation & Selection

CONCEPT GENERATION

External

The external concepts involve designs that mix the sediments in the digester bag while being entirely outside the bag itself. One of our mixing concepts was a camshaft system, shown at the left, below in Figure F.1. The idea was to put a series of camshafts beneath the digester controlled by a crank. Turning the crank would move different cams up and down, disturbing the inorganic solids that collect on the bottom of the digester and thus mixing the solids into the solution. Another mixing concept was a “see-saw” mechanism (Figure F.1 below, right) consisting of boards with one end placed beneath the digester and the other out of the trench, creating a lever system. Standing on the free end would raise the bottom of the digester, and repeated motion would disturb the inorganic solids.

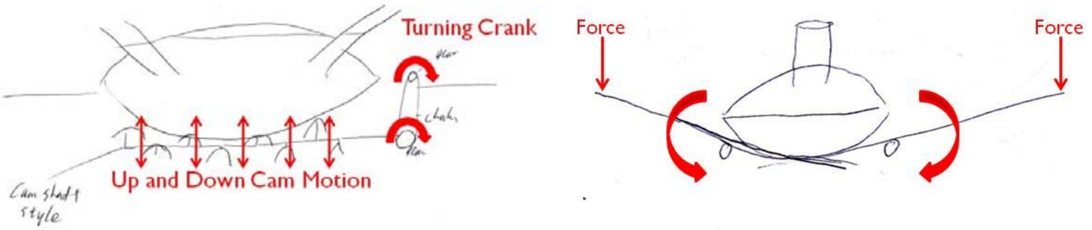


Figure F.1: External mixing system concepts; camshaft (left) and see-saw (right)

Fluid Displacement

These designs used fluid displacement from the digester to perturb the solids. The first concept is a gas-bubbling design (Figure F.2) that will take biogas and divert it from the reservoir bag to underneath the digester bag where it will bubble up through the solids. Another concept in this family extracts the digester fluid from one location in the bag, moves it out and then pumps it back into the bag near the bottom where the solids are to disturb them into suspension (Figure F.2). The pump could be either manually or electrically powered and is a closed-loop system. Similar to this concept would use a gravity-fed reservoir (Figure F.2) instead of a pump to move the fluid. The reservoir would be placed lower than the digester bag so fluid would tend to flow into it. It would then be manually lifted through a series of pulleys to a height above the bag where the fluid would then want to flow out of the reservoir.

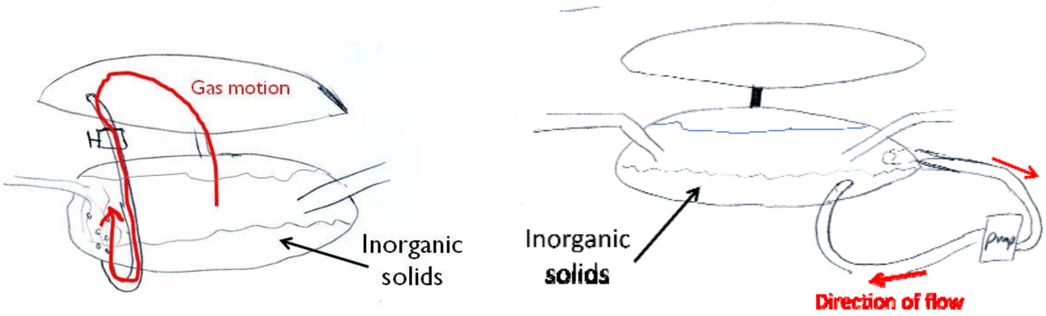


Figure F.2: Fluid Displacement Concepts

CONCEPT SELECTION

Mixing Technique Selection

Assembly/Installation

The first specification used to compare the three mixing techniques is the assembly/installation. The most plausible scenario is for our mixing system to be implemented on a digester in current operation. For the process to go smoothly, a minimal amount of work should be needed to prepare the digester for mixing system implementation.

With this in mind, the fluid displacement technique would require some moderate assembly and installation time. For both the gas and liquid bubbling system, an additional pump is necessary. Both of these systems also require that additional holes be put in the digester bag, violating other specification of safety and sanitation with regards to methane gas and biomass contact. Overall for the bubbling systems, hose routing, new digester holes, pump assembly and connecting everything will likely require much more time than the one hour allotted by our engineering specification. The gravity fed reservoir will also require extensive installation and assembly due to the pulley system, hose routing and connections.

In comparison, the external mixing concepts stand out as being extremely hard to implement. For both the camshaft and see-saw concepts, the digester bag would need to be drained and moved elsewhere since both concepts involve inserting something under the digester. This process would clearly take more than one hour as we specified. However, in the case of installing the mixing system for a *new* digester system, the consideration of draining the digester no longer applies. The camshaft concept would require additional labor to install the rotating shafts and then the drive mechanism. The see-saw installation would require moving dirt around to create a suitable pivot point and trench to extend under the digester, could interfere with nearby structures.

The internal mixing technique concepts will take much less time and effort for assembly and installation. All of the concepts use the current effluent hole as the point of entry into the digester, so no new holes in the digester will be needed. Most of the concepts would likely arrive at the farm fully assembled, so the only installation step would be to insert the mixer into the digester. However, if rotary motion will be provided via a bicycle, an additional step of setting up the bicycle mounting system is necessary. Overall, the installation and assembly of the internal mixers will easily meet the one hour specification, making internal mixing the favored technique with regards to installation.

Maintenance

Another specification by which to compare the three mixing techniques is maintenance. The parts inside the digester must be able to function properly with maintenance only performed every 10 years. Therefore, minimal fasteners are desired, sharp corners minimized and concave surfaces minimized (may be sites for solid accumulation).

The fluid displacement systems stand out as performing poorly in this category. The gas bubbling concept has small holes in a pipe along the bottom of the digester and these holes will be subject to a harsh environment of sludge and inorganic solids. The fluid flow concepts move the biomass around to accomplish mixing, but the biomass is extremely viscous and has many solids in it. All of these fluid displacement systems will be prone to clogging, leading to overall poor performance.

The maintenance issues for the internal and external mixing systems are much less significant than those of the fluid displacement technique. The key maintenance issues for internal mixing system are material corrosion and fastener failure; both of which can be minimized with a robust design. The important maintenance consideration for the external mixing system is the nature and 'the elements'. Rain and varying temperatures are hard on any system that is exposed outdoors and the proper materials would be needed to prevent degradation.

Force Input

The final important specification with which to compare the three mixing techniques is force input. As discussed earlier in the engineering specifications section, an input force of more than 16.8 pounds by the arms must not be necessary for operation of the mixing system. The see-saw external mixing system concept needs much too force. With the maximum reasonable beam length of 10', 200 pounds of input force is necessary. Even if a person's body weight is used, 200 pounds is still too large. This could be satisfied by using at least two people to perform the mixing, but this would violate another engineering specification for one-person mixing. Both the internal and fluid displacement mixing methods need much more design work done before the input force can be reasonable determined. The input force specification was important to consider, since it effectively eliminated the see-saw mixing concept from consideration.

After considering three very important engineering specifications between different mixing methods, we can eliminate external and fluid displacement techniques from further consideration. Our external mixing concepts require far too much assembly time and the see-saw mixing requires far too much force. The fluid displacement methods require substantial assembly time, safety concerns and a serious problem maintenance problem. From this point on, only internal mixing concepts will be further analyzed.

APPENDIX G: Mixing System Part Drawings

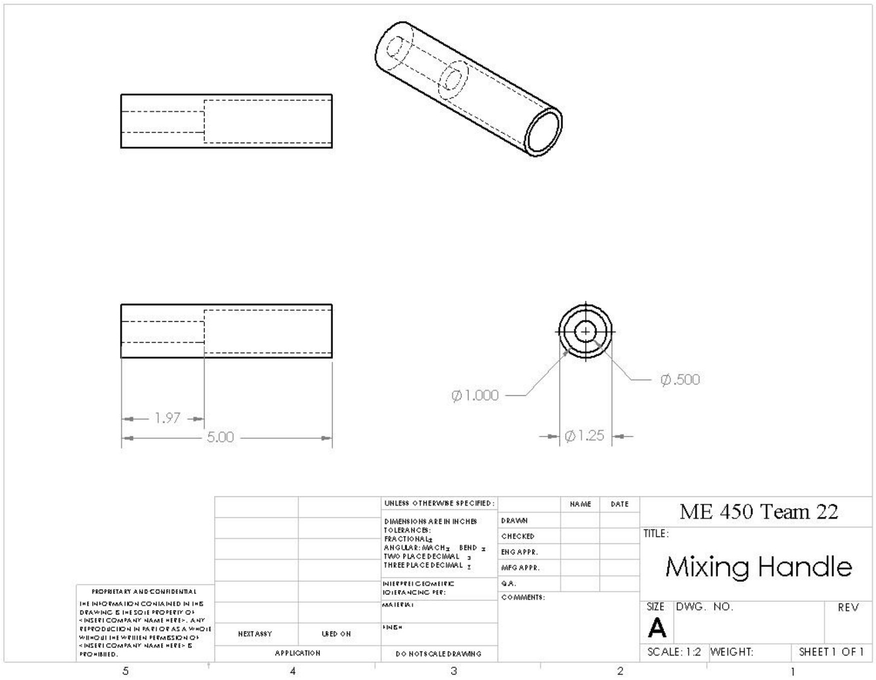


Figure G.1: Cranking Handle

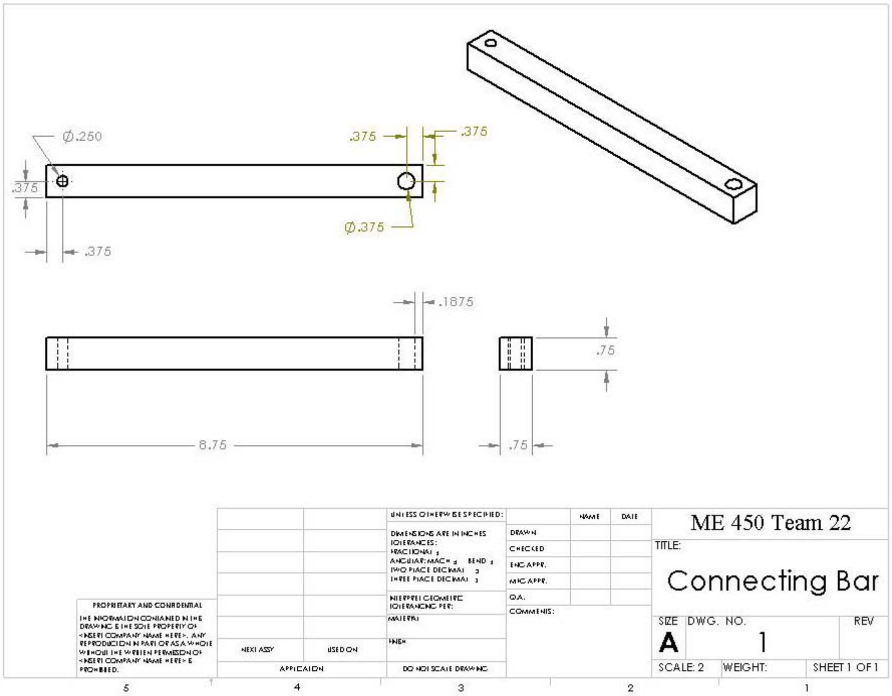


Figure G.2: Connection Bar

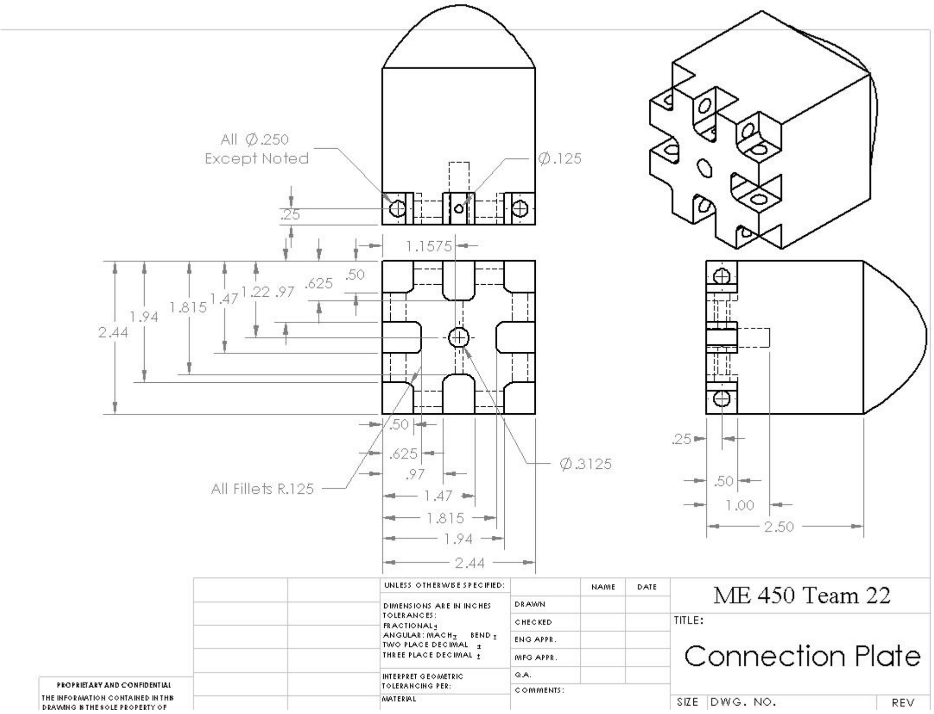


Figure G.3: Mixing Connection

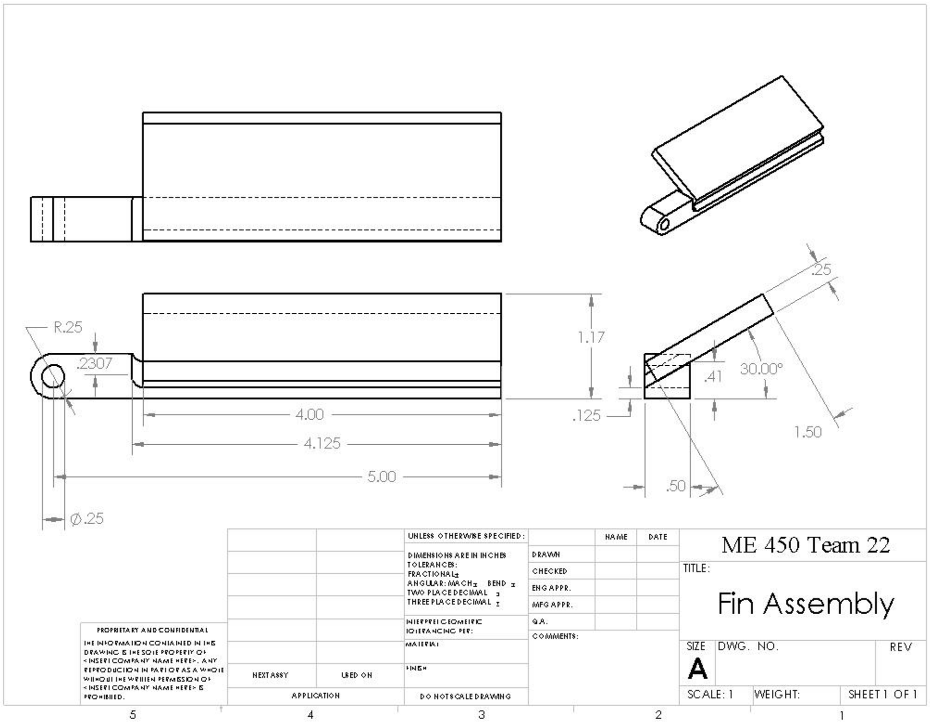


Figure G.4: Fin Assembly

APPENDIX H: Stress Analysis

Drag Force on Fin

The normal drag force acting on the fin was estimated to be 3.4 N. This is derived from the equation below.

$$F_d = \frac{1}{2}\rho v^2 C_d A$$

In which the density (ρ) is approximately the density of potting soil, at 1067 kg/m^3. The velocity (v) is obtained from 60 RPM and an output arm of 6”. The coefficient of drag on a flat plate is 1.2.

Handle Shaft

The yield stress requirement for the handle material is 5.9MPa given a safety factor of 3. PVC can fulfill these stress criteria.

We set the radius of rotation to be 0.20 m (8”), which is half of the length of forearm.

For 5% males, Forearm = (0.145+0.108) * 1636 mm = 413.9mm =0.414m [8, 9]

Total Torque applied to the handle= F *r = 75N * 0.20 m =15.5 Nm

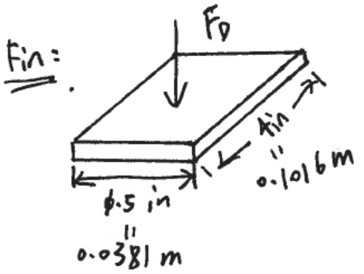
D = 1.25” =0.03175 m

Polar moment of inertia $J = \frac{\pi}{32} d^4 = 9.98 * 10^{-8}$

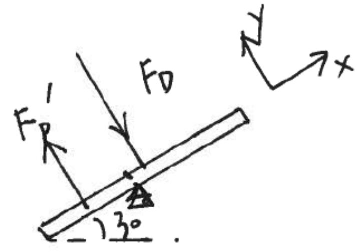
Maximum Shear Stress = $\tau = \frac{Tc}{J} = \frac{15.5Nm*0.0127m/2}{9.98*10^{-8}} = 1.97 * 10^6 Pa$=1.97 MPa

The following pages contain force analysis on the key parts of our mixing attachment. The parts of interest are the dowel pins and roll pins.

Fin:



$$\sigma = \frac{F_D}{A} = \frac{3.408N}{0.0381 \times 0.1016\ m^2} = 880.4\ Pa$$



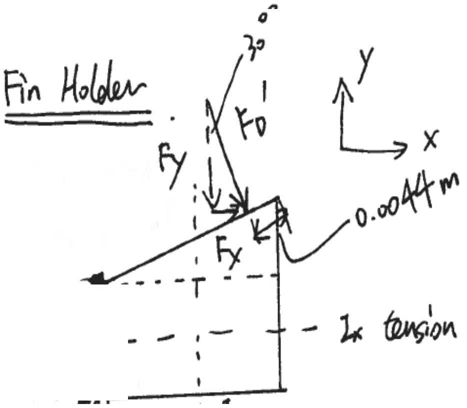
$$\Sigma F_y = 0 \quad \Rightarrow \quad F_D' = F_D$$

$$\Sigma M_z = 0. \quad \Rightarrow \quad X_1 = X_2$$

$$X_1 = \frac{0.0381}{2}\ m - \frac{0.5 \times 0.0254}{\cos 30^\circ}\ m$$

$$= 0.0044\ m = X_2$$

Fin Holder



$$F_z = F_D' \times \cos 30^\circ = 2.95\ N$$

$$F_x = F_D' \times \sin 30^\circ = 1.70N$$

1x tension stress $\sigma_1 = \frac{F_D'}{A} = \frac{3.408N}{0.1016 \times 0.015} = 2285\ \overset{Pa}{\cancel{N}}$

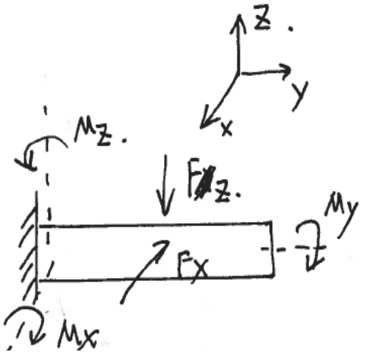
$$I_x = \frac{1}{12} \times b \times h^3 + \frac{1}{36} \times b \times h^3 + Ad^2$$

$$= 2.71 \times 10^{-10} + 1.62 \times 10^{-9} = 1.89 \times 10^{-9}\ m^4$$

$$I_z = \frac{1}{12} bh^3 + \frac{1}{36} bh^3 + Ad^2$$

$$= 1.08 \times 10^{-9} + 6.29 \times 10^{-10} = 1.71 \times 10^{-9}\ m^4$$

$$M_z = F_x \times \frac{L}{2} = 0.09\ Nm.$$



$$M_X = F_y \times \frac{L}{2} = 0.15\ Nm.$$

$$\sigma_{y_1} = \frac{M_X c}{I_z} = \frac{0.09\ Nm \times 0.00635\ m}{1.71\times10^{-9}\ m^4} = 3.34\times10^5$$

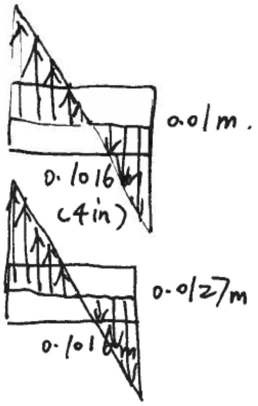
$$\sigma_{y_2} = \frac{M_x c}{I_x} = \frac{0.15\ Nm \times (0.00635+0.00737)m}{1.89\times10^{-9}\ m^4}$$

$$= 0.83\ MPa$$

$$M_{y_1} = F_y \times (0.00635-0.0038)m$$
$$= 2.95N \times 0.00255\ m$$
$$= 0.0075\ Nm$$

$$M_{y_2} = F_x \times (0.005+\overset{09}{a}1428)\ m$$
$$= 1.7N \times \cancel{0.1478\ m}\ 0.006428\ m$$

$$= \cancel{0.251\ Nm}.$$



$$I_x = \frac{1}{12}bh^3 = 8.47\times10^{-9}\ m^4$$

$$I_y = \frac{1}{12}bh^3 = 1.73\times10^{-8}\ m^4$$

$$\therefore \sigma_{x_1} = \frac{M_{y_1} c_1}{I_y} = \frac{0.0075\ Nm \times (\frac{0.0127}{2}\ m)}{1.73\times10^{-8}\ m^4}$$

$$= 2753\ Pa$$

$$\sigma_{x_2} = \frac{M_{y_2} C_2}{I_x} = \frac{\cancel{0.251}\ 0.0109\ Nm \times 0.005\ m}{8.47\times10^{-9}\ m^4}$$

$$= 6435\ Pa$$

$$\therefore \text{total stress} = \sqrt{\sigma_1^2 + (\sigma_{y_1}+\sigma_{y_2})^2 + (\sigma_{x_1}+\sigma_{x_2})^2}$$

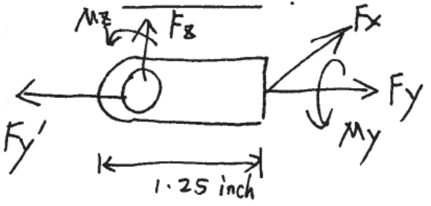
$$= \sqrt{2285^2 + (1.164\times10^6)^2 + 9188^2}$$

$$= 1.164\times10^6 = 1.164\ MPa$$

For Aluminium : $\sigma_{yield} = 30 \sim 500\ MPa$

$$\therefore \boxed{\text{total stress} \ll \sigma_{yield}.\ \text{with SF} = 3}$$

Fin Joint



= 0.03175 m.

A = 0.5 in × 0.5 in

$= 1.61 \times 10^{-4}\,m^2$

Axial load.

$M_y = -(0.0075 + 0.0109) = -0.0184\,Nm$

$M_z = 0.09\,Nm$.

total $F_y = (\sigma_{y_1} + \sigma_{y_2})A = 1.164 \times 10^6 \times 0.000127$

$= 147.8\,N$

total $F_x = (\sigma_{x_1} + \sigma_{x_2})A' + 1.7N$

$= 9188^{Pa} \times 0.01 \times 0.1016\,m^2 + 1.7\,N$

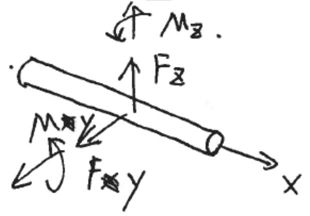
$= 11.0\,N$

Displacement.

$$\delta = \frac{F_y L}{AE} = \frac{147.8N \times 0.03175m}{1.61 \times 10^{-4} m^2 \times 75\,GPa}.$$

$= 3.89 \times 10^{-7}\,m$.

Dowel Pin



$F_y = -147.8\,N$.

$M_z = 0.09\,Nm$

$M_y = 0.0184\,Nm$.

use $d = \frac{1}{4}$in

$= 6.35 \times 10^{-3}m$

$\therefore r = 3.175 \times 10^{-3}m$

~~$I_x = \frac{\pi}{4} r^4 = \frac{\pi}{4} \times (6.35 \times 10^{-3} m)^4$~~

~~$= \frac{\pi}{4} \times 1.626 \times 10^{-9}$~~

~~$= 1.277 \times 10^{-9}\,m^4$~~

$I_x = \frac{\pi}{4} r^4 = \frac{\pi}{4} \times (3.175 \times 10^{-3} m)^4$

$= \frac{\pi}{4} \times 1.016 \times 10^{-10} m^4$

$= 7.98 \times 10^{-11}\,m^4$.

Contine <u>Dowel Pin</u>.

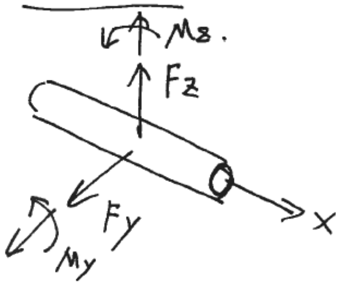
$$\sigma_{x_1} = \frac{M_z c}{I_x} = \frac{0.09 \times 3.175 \times 10^{-3}}{7.98 \times 10^{-11}}$$

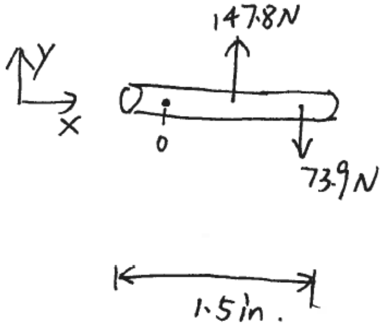
$$= 3.58 \times 10^{6}\ Pa = 3.58\ MPa$$

$$\sigma_{x_2} = \frac{M_y c}{I_x} = \frac{0.0184 \times 3.175 \times 10^{-3}}{7.98 \times 10^{-11}}$$

$$= 0.732\ MPa.$$

<u>Dowel Pin</u>.





$\phi = 0.25$ in.

$$F_y = -147.8\ N$$

$$I_x = \frac{\pi}{4} r^4 = \frac{\pi}{4} \times (3.175 \times 10^{-3}\ m)^4$$

$$= \frac{\pi}{4} \times 1.016 \times 10^{-10}\ m^4$$

$$= 7.98 \times 10^{-11}\ m^4$$

$$M_z = 147.8\ N \times \left(\frac{2.50}{2} - 0.5 - \frac{0.5}{2}\right) \times 0.0254$$

$$= 147.8\ N \times 0.0127\ m$$

$$= 1.877\ N{\cdot}m$$

$$\sigma_x = \frac{M_z c}{I} = \frac{1.877\ Nm \times 3.175 \times 10^{-3}\ m}{7.98 \times 10^{-11}\ m^4}$$

$$= 74.68\ MPa$$

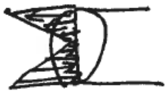
SF = 3.

σ ~~total~~ = 224.04 MPa.

- For Aluminium 6061, only T6 series are ok.
- For steel, all steels work.

$$\sigma_y = \frac{F_y}{A_y} = \frac{147.8\,N}{0.0254m \times 0.00635m}$$

$$= 0.916\ MPa.$$



$$\sigma_{total} = \sqrt{\sigma_x^2 + \sigma_y^2}$$

$$= 74.69\ MPa.$$

SF = 3

$\sigma_{total} = 224.06\ MPa$.

- ok for only T_6 of 6061 Aluminium
- ok for all steels.

Displacement of Dowel Pin

$F_x = \sigma_x \times A = 74.68 MPa \times \pi (3.175 \times 10^{-3} m$

$= 2365\ N.$

$$\delta = \frac{PL}{AE} = \frac{2365N \times 0.0381m}{3.167 \times 10^{-5} m^2 \times E}.$$

- For T6 6061 AL.

$E = 69.75$ GPa $\quad \delta = 4.08 \times 10^{-5} m$

$= 0.0016\ in$

- For 316 strainless steel.

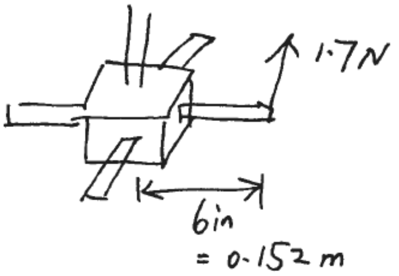
$E = 197.5\ GPa.$

$\delta = 1.44 \times 10^{-5} m$

$= 5.67 \times 10^{-4}\ in.$

flexible shaft .

torque rating = 110 in·pound.



$$T = 0.152m \times 1.7N \times 4$$
$$= 1.036\ N{\cdot}m$$

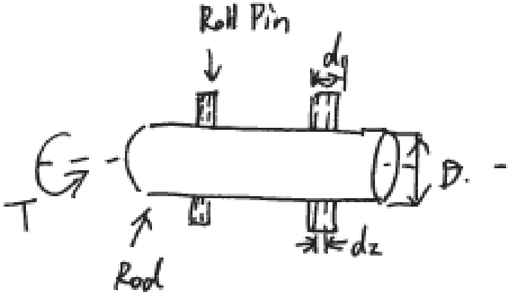
Assume pure torque transmission.

Then the T in flexible shaft is also 1.036 Nm

< ~~110 inp~~ 110 in·pound =

Force to rotate the handle.

$$F = \frac{T}{L} = \frac{1.036\ N{\cdot}m}{8in \times 0.0254 m/in}$$
$$= 5.098\ N$$



Diameter for Roll Pin

- steel roll pin. $\geqslant 250\,MPa$
- $d_1 = 0.0079375\,m\,(0.3125\,in)$
- $d_2 = 0.0072263\,m$.
- $D = 0.0079375\,m$

$$T = 2 \cdot \frac{\pi}{4}(d_1^2 - d_2^2)\,\tau_y \frac{D}{2}.$$

$$1.036 = \frac{\pi}{4}(1.0784 \times 10^{-5})\,m^2 \times \tau_y \times 0.0039688$$

$$\therefore \tau_y \cancel{x} = 30.8\,MPa$$

For steel, it fulfills the requirement.

stress-related fatigue analysis

$$\sigma_a = A N_f^{\,B}$$

steel SAE 1015 $\Rightarrow A = 927 \times 10^6 \quad B = -0.138$

$$\therefore \sigma_a A_1 = \tau_a A_2.$$

$$\sigma_a\left(\pi \frac{d_1^2}{4} - \pi \frac{d_2^2}{4}\right) = \tau_a \cancel{\left(\frac{\pi}{4} d_1^2\right.} \quad (\pi d_1 D)$$

$$\therefore \sigma_a = \frac{30.8 \times 10^6\,Pa \times \pi \times 0.0072}{\frac{\pi}{4}(1.0784 \times 10^{-5})\,m^2}$$

$$= 71.98\,MPa$$

$$\therefore N_f = \sqrt[B]{\frac{\sigma_a}{A}} = 1.1 \times 10^8$$

Fatigue of Dowel Pin-

$\sigma_a =$ ~~32~~ 74.69 MPa.

For 6061 AL → $A \approx 839 \times 10^6$ ~~k~~Pa $b = -0.10$

$$\sigma_a = A N_f^{B}$$

$$74.69 \times 10^6 = 839 \times 10^6 N_f^{-0.102}$$

$$\therefore N_f = 2.0 \times 10^{10}$$

Assume 60 RPM for 60s

the use time is $t = \dfrac{2.0 \times 10^{10}}{60\,\text{RPM} \times 1\,\text{M}/\text{day} \times 365}$

$= 9 \times 10^5$ yrs.

The usage time for roll pin.

$$t = \frac{1.1 \times 10^8}{60\,\text{RPM} \times 1\,\text{M}/\text{day} \times 365\,\text{days}/\text{yr}}$$

$$= 5 \times 10^3 \text{ yrs}.$$

BIOGRAPHIES

Adam Hashimoto

Adam Hashimoto is a fifth year senior enrolled in the Dual-Degree Engineering Program with Albion College and the University of Michigan. His boyhood was spent moving around with family, living near the beaches of Florida, on a farm in Clio, Michigan, and finally in the city in Center Line, MI. In high school, Adam was very active, being the captain of the cross country, soccer, wrestling, and track teams, attending the Macomb Mathematics Science & Technology Center along with his home high school, being active in community service and worship activities at his church, and keeping good grades to be valedictorian. Not wanting to jump straight into a big university, he decided to study for three years at Albion College. There, his ambition did not change, double majoring in Physics and Music, working five jobs (Tour Guide, Recording Technician for the Music Department, Math Tutor, Online Editor for the school newspaper, and freshman orientation leader), leading Chapel services, playing on the Ultimate Frisbee club team, participating in a slew of intramural sports (soccer, ultimate, softball, racquetball, wallyball, dodgeball, floor hockey), and organizing two concerts for the fingerstyle guitarist, Michael Gulezian. His interest in sustainability flourished while he worked as the Mechanical Technician on the research project Calories to Kilowatts, the premise being to harness the mechanical energy from exercise machines in batteries as electrical energy through generators run backwards. After, Adam transferred to U of M where he is now focusing his energies on Mechanical Engineering. Last spring break, he went on a service trip to Honduras (see photo) to help divert water to build a new bridge in a rural community. He has had a heart for Latin America ever since. Also, Adam is planning on getting married on August 29, 2009.

Peter Keros

Peter Keros, born and raised in Bloomfield Hills, MI, is one of those loud, annoying, overachieving students who does everything, drinks lots of fancy coffee, and never sleeps. He always raises his hand in class and loves the sound of his own voice, much to the chagrin of others. Among his many commitments are the Michigan Marching Band (4-year clarinet player), Michigan Athletic Bands (Men’s and Women’s Basketball), Campus Band, Kappa Kappa Psi, honorary band fraternity, Orthodox Christian Fellowship, Hazing Prevention Task Force, and Hellenic Student Association. The movie *My Big Fat Greek Wedding* basically describes his life, down to the lambs roasting on the lawn and the family restaurant.

Bluewashed by his mother, a Michigan alumna, from birth, he came to Ann Arbor not knowing what he wanted to do, other than desiring a graduate degree of some sort. Being of the nerdy persuasion, engineering called to him as both a way to increase his technical curiosity and have a platform for future study. Mechanical

Engineering in particular struck him because of its broad nature. This was helpful in that he started focusing on materials and mechanics but, after being involved with both design optimization and combustion research, has decided to study advanced combustion and energy studies.

He will attend the University of Michigan for graduate school next year, working for his M.S.E. in Mechanical Engineering, studying spark-assisted HCCI for his thesis under the direction of Arthur F. Thurneau Professor Margaret Wooldridge. His future plans are eventually to go to law school (preferably at Michigan), focusing on patent and environmental law, and to own his own law and engineering firms. Other hobbies include role-playing video games, music, watching sports, skiing, cooking, eating, beating Phi Mu Alpha in football, and $2 pitchers at Mitch's.

Dan Ostahowski
Dan Ostahowski is a senior in Mechanical Engineering and was born and raised in Midland, MI. He became interested in engineering by working on bicycles and cars growing up and wondering how everything works. After four years of undergraduate work, he still has no idea what to do with his life. This summer he will be working for the Montana Conservation Corps living outdoors, building hiking trails and doing other conservation projects. His career plans are still unknown but his passion for the outdoors and environment could take him in a variety of directions, but most likely west, and hopefully away from Corporate America and office work. When he is not outside, he can usually be found working on his truck, bikes or motorcycle, or enjoying some good music. Some of his other interests include food that is way too spicy, backpacking, hunting, dogs, any kind of skiing and relaxing with friends.

Matthew Raubinger
Matt Raubinger is a 5th-year senior dual majoring in Mechanical and Industrial & Operations Engineering. Starting out as solely an IOE, he added the Mechanical curriculum during his junior year to increase his technical knowledge, interest in design, and also diversify his engineering skills.

Matt's passion for the environment has grown greatly over his time in college. While not majoring in Environmental Engineering, he has taken every opportunity to take environment related classes, including CEE 490: Sustainable Energy in South America. This class studies the feasibility of hydropower in the Patagonian region of Chile. It may be no surprise that Matt wants to pursue a career in alternative energy, though he is unsure which technology to focus on.

Matt was born in Royal Oak, MI and has lived in Troy, MI for most of his life with his Mom, Dad, and sister Sarah, 21 (U of M junior, Nueroscience). His interests include ultimate frisbee, volleyball, lacrosse, skiing, and hockey. He also enjoys cooking, photography, and all outdoor activities. On campus, Matt is a brother of the Chi Psi Fraternity, holding several past officer positions and is the current President of Green Greeks. He also loves IM sports, including broomball, volleyball, flag football, and inner tube water polo.

Yue Ying

Ying Yue, a senior Mechanical Engineering, was born and raised in Southern China. Her name pronounces “music” in Chinese, and her nickname is “Muz”. She has been away from family and studied in different places since the age of 12. Very different from nowadays, Muz used to speak a lot and fast, and she was the school debate team leader in high school. With the ability to immediately capture illogical things and think broadly, she has always been an outspoken team player.

Muz has a heart for nature and all living things. Raising money to rebuild a primary school in Guizhou, China, volunteering in New Orleans was meaningful to her. Her dream vocation is to live in rain forest under survival conditions, but she has never had a chance yet. She is interested in sustainable energy because she cannot afford her dream rain forest to be gone forever. Muz’s ultimate goal is to be a balanced, optimistic and aspirant person.