Biogas Compressor Project

Dave Baron
Jessica Leginski
Alisyn Malek
Tim Murphy
Adam Smith

ME450, Winter ’08
Professor Skerlos, Section 6, Project 29
Department of Mechanical Engineering
University of Michigan
Ann Arbor, MI 48109-2125

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EXECUTIVE SUMMARY

Biogas is becoming an increasingly important source of energy for rural areas in developing countries, as can be seen by the increased construction of biodigesters. Biogas has become an important fuel source because it is driven by readily available biomass. Because of this, there is a need to increase the versatility and availability of this natural fuel source to accommodate increased use. This biogas is produced by biodigesters that are currently in place. At the moment there is no system available to store the gas that these digesters produce, so all the gas that is created must be used at the same rate that it is produced. If the gas is not used at this rate the system vents the excess gas into the atmosphere, adding more harmful greenhouse gases and wasting fuel. Currently, to utilize the biogas, any system must be directly attached to the biodigester.

The University of Michigan BLUELab is currently building a small-scale biodigester for testing optimal biogas production parameters and measuring gases produced. They have asked us to design and prototype a system to compress this gas, essentially making a traditionally stationary energy source portable. Although we will be working closely with the BLUELab, John Deere has offered to financially sponsor our project. As the project requirements were initially given to us by the BLUELab, and because the system we design will directly interact with their biodigester, the BLUELab biodigester team will still serve as a primary contact group.

The system that has been requested has many limitations due to the nature and environment of the location of implementation. Our design must use off-grid power because in many developing countries electricity is not readily available. Since the biodigesters are relatively inexpensive, the compression system must also be inexpensive in order to maintain economic feasibility. Lastly, our final design must be easy to implement. This means that construction must be relatively simple and the components must be easy to acquire, as well as maintain.

During the concept generation phase of our project, several ideas were formed regarding the method of compression. After extensive evaluation, our team reached a consensus that we would model our prototype compressor after a piston-cylinder. The final design will provide a large lever (to incorporate a mechanical advantage) which allows users to stand and compress using a downward arm motion and a valve system, which will allow for variable work input for compression. The final prototype will be able to compress the biogas to approximately 35 psi in a 7 gallon air tank. In addition to the compressor, there will also be a glass jar with steel wool to act as a hydrogen sulfide scrubber in-line with the inlet of the biogas to the compression system.

The design dimensions and materials were determined using various parameter analyses and strength as well as lifetime considerations. The design was finalized and constructed in a basic machine shop. The final design includes a hydrogen sulfide scrubber (to reduce the corrosiveness of the biogas), the frame to support three piston-cylinders, the piston-cylinders, and a high pressure air storage tank. Once constructed, the design was tested to ensure that it could compress gas in the high-pressure tank to 35 PSI and presented at the Design Expo. A copy of this report was circulated to sponsors and other interested parties affiliated with this project.

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ABSTRACT

Biogas digesters are being employed in many rural communities in the developing world to collect farm animal waste and convert it to biogas through anaerobic bacterial processes. Biogas is a clean-burning, renewable fuel that is 60-70% methane and can be used to power household appliances and generate electricity. However, there is no existing method of off-grid compression to allow storage of sufficient amounts of this gas for convenient use in this application. The compressor needs to operate on an off-grid power supply due to the nature of implementation plans for developing world rural areas. After research and consideration, it was determined that this could be achieved through manual input. Several innovative concepts and compression methods were generated and we have decided a piston cylinder system to be the most viable compression method. The best compression mechanism was determined to be a modified bicycle pump because it is inexpensive, easy to acquire, requires sensible effort, and can reach the desired pressure with a reasonable amount of time and effort. The ideal goal is to compress the equivalent of 6 hours of energy into a storage container that is portable, available, and uses standard fittings. It was decided that an air tank is the most practical and compatible storage container. After testing several bicycle pump models and a 7 gallon air tank, the portability and compression to 35 psi to be practical and sufficient. Through parameter analysis, optimal dimensions and scaling options for our prototype were decided. The design incorporates a multi-cylinder compression and valve system which allows toggling of high volume and high pressure modes. This will allow the user to stand at a safe distance from the piston-cylinders and apply a downward for onto a lever arm, which will make compression easy given small input forces. A prototype was successfully constructed and was able to compress to 35 psi with a reasonable amount of time and using a reasonable input force. From testing, we observed that it took an average of 4.5 minutes to compress air to 25 psi, and 10 minutes to compress air to 35 psi. Our fabrication techniques were relatively simple and universal as were all materials used. The prototype was validated through stress and finite elements analysis, as well as analyses on safety, environmental sustainability, manufacturability, material selection, and assembly. This system, including the piston-cylinder system, steel frame, air tank, and hydrogen sulfide scrubber, can be recreated for approximately $350.

PROBLEM DESCRIPTION

Biogas is a clean-burning, easily produced, natural fuel that is becoming a more important source of energy in rural, developing countries for cooking and heating. Anaerobic bacteria that break down the biomass produce this fuel. Currently there is no way to store the gas that these digesters produce, which means that to utilize this energy source, the stovetop or other device must have a direct feed to the biodigester. If all of the biogas produced is not used, the system will vent this gas, which is composed primarily of methane, into the atmosphere. Aside from the loss of fuel, methane is approximately 23 times worse for the atmosphere as a greenhouse gas than carbon dioxide. Although it degrades far quicker in the atmosphere than carbon dioxide, it is still a huge concern for the environment as we face climate change problems.

The University of Michigan BLUELAB has proposed and been granted funds to recreate a small-scale biodigester, similar in design to current digesters in the Philippines. In doing this they will be able to measure biogas output, test for optimal conditions, and troubleshoot any potential problems in implementing these in other areas.

We were given the task of designing a compressor system that will be able to compress the biogas using an off-grid power supply and make it portable and convenient. This allows storage of any excess fuel that would otherwise be vented as well as making the option of a single biodigester, shared communally, a feasible power source. Our ideal project outcome was a system which combines scrubbing, compression and storage of biogas for portable and future use. Main criteria for the system are simplicity and safety. We aimed for a cost under $400 to create the prototype with all supplies being universal, off-the-shelf components. In meeting these criteria, our design and implementation methodology can be recreated relatively easily in any country.

BACKGROUND INFORMATION AND RELAVENT LITERATURE

The range of application of biogas technology with which we are working is currently being limited to applications in the developing world such as India, Africa, and the Philippines for uses such as cooking fuel and heating homes [1, 2]. Biogas is defined as the mixture of methane and carbon dioxide produced by the bacterial decomposition of sewage, manure, garbage, or plant crops [3]. There is not currently a large corporate market for this small-scale approach to biogas generation, as it is not as lucrative as larger scale approaches as well as other forms of fuel. Due to this fact, most of the information gathered was academic in nature, the most useful source of which was a presentation for a Biogas conference, which took place in 2000 and was given by Ron Shannon of Australia [4]. Most research in this area is currently being done to explore biogas generation through anaerobic digestion in an effort to develop inexpensive and effective methods for promoting digestion of animal and human waste. Anaerobic digestion is the breaking down of organic matter by microorganisms in an oxygen poor environment, and results in biogas [5]. There are two different types of digesters as well, Mesophilic and Thermophilic, which refers to the temperature at which they operate and the corresponding bacteria which thrive in that environment [4]. Mesophilic digesters operate near 30°C (86°F), and in warmer climates often require no additional heating. Thermophilic digesters operate around 60°C (140°F), and thus require additional heating and are often only practical for large industrial uses.

For the production of biogas, organic material, such as animal and plant waste is placed along with water into an oxygen free tank, or in some cases plastic membrane for digestion. Figure 1, below, shows a common mechanism for gas collection in a continuous digester, utilizing the variable volume design of a gasometer in order to accommodate the increasing methane. In this case, the gas outlet is located at the bottom of the tank, as it is easier to install in the case of a solid walled digester and does not require elasticity in design. The organic matter is fed into the vessel and the resulting gas is outlet through a pipe that inlets above the waste liquid levels in the tank. Similar mechanisms are achieved using plastic membranes, which are contained in secure enclosures in the ground [6].

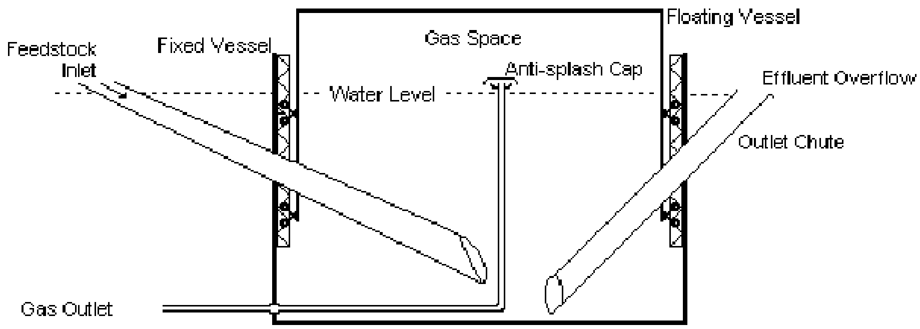

Figure 1. A schematic of an organic waste digester including a modified gasometer [4]

Another area of research includes attempting to simulate and model methane generation from different types of waste in different environments in order to better understand the process [7, 8].

There are currently multiple US patents for biogas digestion technology, many dealing with biodiesel generation, although some are biogas specific regarding construction of digesters. USPN 7,186,339B1*, *Anaerobic Digester System for Animal Waste Stabilization and Biogas Recovery*, addresses the design of a flexible bladder digester, which is the form incorporated in our biodigester, as well as transmission of the biogas from the bladder to a storage container, but it does not address any methods of compression. USPN 7,005,068*, *Method and Apparatus for Treating Animal and Wastewater,* addresses uses of biogas as well as details regarding digestion methods and in line 41 of the claim it suggests that the biogas can be compressed for storage, but does not specifically outline compression methods to be used. One notable patent in the area of bio-diesel usage that should be mentioned is USPN 5501185*, *Biogas driven generator set*, which outlines a method to use biogas in a bio-diesel engine, and includes a pumping process to boost the pressure of the biogas for pumping into engine regulator.

In addition to biogas generation, another important aspect of biogas compression is the scrubbing of the biogas in order to remove impurities that are generated during the digestion process such as CO_2 (carbon dioxide) and H_2S (hydrogen sulfide). There are many different methods of biogas scrubbing, each with varying degrees of effectiveness. Many methods of scrubbing the biogas of single or multiple impurities are discussed in Kapdi's work [9], although few methods seem economically feasible for small scale developing world operation. The scrubbing is viewed as very important as hydrogen sulfide is highly corrosive to the cooking and heating systems that would utilize the biogas, and the presence of carbon dioxide makes the gas more difficult to compress and store, although it does not increase the volatility [9]. A simple method for hydrogen sulfide utilizing steel wool in a glass bottle is modeled in Figure 2, and seems to be the most viable option for low cost, easy implementation hydrogen sulfide removal [4].

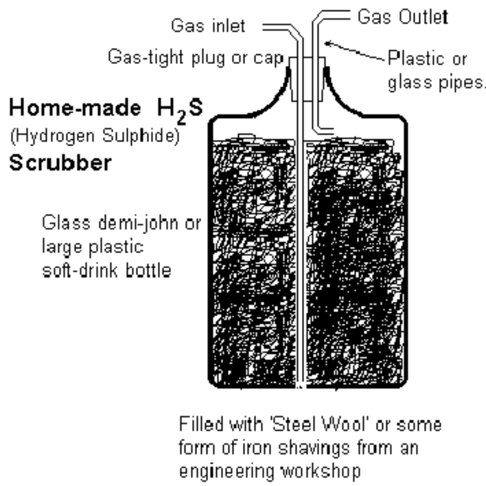

Figure 2. Model device for homemade hydrogen sulfide scrubber [4]

In this method of sulfide removal, the gas reacts with the steel wool, creating black iron sulfide. The iron sulfide generation begins at the bottom of the container, and once the steel wool is 75% black (i.e. 75% of it has been turned into iron sulfide); the wool should be removed and replaced. The used wool can be reused after exposure to air. This oxidizes the wool to rust, which can be reused in the system, as it will react with the hydrogen sulfide [4].

For carbon dioxide removal, as well as additional hydrogen sulfide removal a method of water spray cross-flow can be used [4, 9]. In this method the biogas enters one end of a tube and experiences water streams flowing in the opposite direction, effectively removing a good deal of carbon dioxide from the gas. This design can be varied and the wastewater can be re-used in the process [9].

Scrubbing has also been a strong area of technical development and patenting. USPN 7160456*, *Method and equipment for processing of organic material,* outlines the use of a second chamber and ammonia in order to remove CO_2 from biogas. Complementally, USPN 6709592*, *Removal of sulfur compounds from wastewater*, outlines a dual chamber digester method for sulfide removal. USPN 6221652* *Process for biological removal of sulfide,* outlines a method in which and aqueous washing liquid is treated with sulfide oxidizing bacteria. There is also a patent for a method of wet scrubbing, discussed above for the removal of $CO_{2,}$ which outlines the process and design by which this would take place. USPN 7033822*, *Self-contained and streamlined methane and/or high purity hydrogen generation system,* outlines a method for hydrogen specific generation using anaerobic digestion as well as mixed gas to power a gas driven generator in order to further compress the gas for hydrogen removal. Although this patent heavily refers to mixed gas compressors and their use, it does not discuss the method for compression in any sort of detail.

Although much work has been done in research and development of methods to produce as well as scrub biogas, and compression is often mentioned, no work was found regarding the actual method of compression of the gas, which leaves our project many options of methods. In industrial uses, classic industrial air compression techniques are often used, however in this small scale, off the grid usage, different methods of compression and driving compression need to be determined.

PROJECT REQUIREMENTS

In order to find a solution to the previously described problem, it was necessary to gain information regarding the requirements specific to this project. The project requirements were obtained through a meeting on 15 January 2008 with our BLUELab contact, Jeffrey Schloemer. During the meeting, the project team discussed the need for a compressor, applications of implementation, and the resources available to a typical community in the Philippines. After the meeting with Schloemer, the project team discussed our newfound understanding of the problem, including what was expected of us and what we believed we could accomplish. In order to plan and prioritize our approach, we filtered out the requirements of the project versus the wishes of the sponsor. Ideally, we would be able to complete all of the requirements and wishes, but obviously the requirements take precedent because of constraints on time and resources. Table 1, below, was generated in order for the design team to get an idea of what the project requirements are and how important each requirement is as it relates to the project as a whole.

Requirement	Weight of importance to safety	Ease of implementation weight	Combined weight	**Possible Solutions**
$400 target	7	10	17	Low cost of materials without sacrificing safety
Overall system safety	10	6	16	Tank rupture valve, safe connections, user away from biogas
Portable tank volume	-	3	3	Reasonable tank capacity, tank easily carried
Ease of construction	5	8	13	Design simplicity, DIY construction, easy to be constructed properly
Pressure vessel safety	10	2	12	Factor of safety, rupture valve, pressure gauge on tank
Target pressure achieved	9	3	12	Pressure gauge on tank, possibly color-coded, warning whistle
Less sulfide in biogas	9	4	13	H2S scrubbing, steel wool
Universal container fittings	-	3	3	Standardized fittings, fittings easily available
Off-the-shelf materials	-	7	7	Materials easily accessibile
Ease of connections	8	4	12	Direct feed and splitter, valves easily managed and reliable
Human-powered compression	7	9	16	Easily operated by weaker users, user away from biogas
Less CO2 in biogas	5	10	15	CO2 scrubbing, potassium sulfide

Table 1. Diagram depicting each project requirement, the associated safety and ease of implementation weights (1=unimportant or easy, 10=important or difficult, respectively), and the related solution. '-' designates no weight.

The design requirements shown on the left of Table 1 were given a combined weight, which is a combination of safety and ease of implementation. For example, pressure vessel safety was given a combined weight of 12 because it is very important for safety (10), but relatively easy to implement (2); as opposed to less CO_2 in biogas, which was given a combined weight of 15 because of its moderate importance to safety (5) and high difficulty of implementation (10). Note that less CO_2 in biogas is the only design requirement that the project team is most likely to not implement into the final design. Although CO_2 scrubbing would be useful for easing compression, the cost of using a CO_2 scrubbing system is too high. For this project, keeping an inexpensive, simple design was key, which essentially rules out the use of an expensive, intricate CO_2 scrubbing system. Engineering specifications were generated in order to complete the design requirements. The "combined weight" of the design requirements can be viewed as "importance of requirement", with the exception of CO_2 scrubbing. This version of a QFD lacks a correlation matrix, which would help relate the solutions with each of the project requirements. However, this team's experience with QFD correlation matrices is that the values seem to be assigned too arbitrarily, making the QFD like table shown above much more straightforward and useful.

ENGINEERING SPECIFICATIONS

In order to meet the design requirements listed above, engineering specifications were generated. For now, the engineering specifications are relatively broad (less than [<], greater than [>], approximately [~]) and are shown in Table 2, below.

	Specifications	**Targets**
Cost	< $400	$200
Compression pressure	~ 50 psi	30 psi
Tank rating (safety)	> 100 psi	200 psi
Reasonable user input	< 50 lb	25 lb
Compression volume	from 14.5 gal to 5 gal	from 14.5 gal to 5 gal
Sulfide concentration	< 3%	0%
Assembly ease	< 20 hours	10 hours
Accessibility	no more than 2 distributors	1 distibutor
Portable tank volume	max transported to 5 gal	7 gal
Reasonable work in	< 300 strokes	150 strokes
Lifespan of system	> 10 years	15 years
Tank weight	< 20 lb.	7 lb.
Work in	< 0.3 Hp	0.1 Hp
Compression time	< 10 min	5 min
Compressor efficiency	>10 %	50%

Table 2. Engineering specifications (and associated targets) to be met in order to fulfill design requirements.

The engineering specifications are based on the need for a simple, inexpensive, man-powered compression and storage system. Note the specification for reasonable user input is < 50lb and targeted for 25 lb. This resulted from a change during our design process and is further explained in the Parameter Analysis section. Also worth noting are specifications for compression volume (14.5 to 5 gal) and compression pressure (~ 50 psi). These two specifications are largely dependent on what size of tank is available. For example, if a 5 gallon (19 L) air tank is used, the biogas must be compressed to ~ 50 psi. If a higher volume tank, 7 gallon (26 L), was used, the gas would only need to be compressed to ~ 35 psi in order to store the same amount of methane. The tank rating (> 100 psi) can accommodate both scenarios; however, the minimum tank size should be 5 gallons, so as to not infringe on the generous safety factor. The higher the tank volume, the easier it is to compress the biogas, but the harder it is to transport the tank. Piston compression is governed by equation 1, below.

$$\frac{P_1 \cdot V_1}{T_1} = \frac{P_2 \cdot V_2}{T_2} \qquad \text{(Eq. 1)}$$

P_1 is the pressure of the uncompressed biogas, which is slightly above atmospheric pressure (~16 psi). V_1 is about equal to 55 L (14.5 gal), the uncompressed volume of biogas in our case. V_2 is the volume of the storage tank (≥5 gal), and P_2 is the final pressure. T_1 and T_2 are usually the same (making temperature a negligible part of the calculation), but a worst-case scenario consists of compressing biogas in an extremely cold environment, and then moving the storage tank into an extremely hot environment. This would create large a pressure on the storage tank, and that needs to be accounted for. For example, in the tropical climate of the Philippines, the record low temperature is 12.2 °C and the record high temperature is 42.2 °C [15]. In this case, P_2 would be ~160 psi. Most air tanks have a pressure rating of 125 psi, but this isn't a huge cause for alarm because these temperatures are extremes and took place in different months and years. Obviously, these temperatures were air temperatures, and a tank sitting in the sun could get much hotter than the temperature of the air. This is why air tanks are equipped with blow–off valves (triggered at ~ 140 psi) that will release the contained gas if such extreme pressures are reached. Releasing of biogas is not ideal, but is better than the explosion of a tank. Our design team also recommends painting the air tank a "light" color such as yellow or white for two reasons. The first reason is that the tank will absorb less of the sun's heat; the second is that the light color will serve as a warning to users who may confuse the biogas filled tank with one filled with air. The climate in the Philippines is extremely stable, with average high and low temperatures only varying by 12 °C yearly. The chance of such an extreme temperature flux is slim, but accounted for in the fact that the tanks will be painted a light color and that the tanks are equipped with blow off valves.

The higher the quality of the compressor, tank, and fittings, the more expensive the system will be, the fewer replacements it will require, and the longer it will last. Lifespan is also related to ease of maintenance, which will depend on how available supplies are. The design requirement "off the shelf materials" entails that all materials can be found easily, making for quick repair and increased lifetime. Inexpensive components will comprise the majority of the system, due to the fact that the target group for biogas compression is more financially suited to incur small initial costs along with small maintenance costs as opposed to large initial costs. In order for inexpensive upkeep to be possible, material accessibility will be important. Lifespan is also related to how many components are involved in the system. Obviously, with fewer components involved, we lower the chance of failure. For the purpose of this project, inexpensive components comprise the majority of the system.

The work required to compress biogas is based on time and tank size. Table 3, below, outlines a few extreme cases and shows that they are both viable. Work required (W_{in}) is a function of the final pressure multiplied by the change in volume, as shown in Eq. 2, below. Work was then converted to power using a time of 60 seconds for compression, which relates to an upper estimate of input power, and then a time of 5 min (300 sec) which is more realistic. Both cases are viable candidates for human power: according to Ohio University, a healthy human can sustain 0.4 Hp for 10 minutes before becoming exhausted [16]. As seen in Table 3, it is expected that the power required for compression will be far below that threshold.

$$W_{in} = P_2 \cdot (V_1 - V_2) \quad \text{(Eq. 2)}$$

Tank Volume / V_2	P_2	W_{in}	Power (60 sec)	Power (5 min)
5 gal	50 psi	9,500 ft-lb	0.28 Hp	0.06 Hp
7 gal	35 psi	5,165 ft-lb	0.15 Hp	0.03 Hp

Table 3. Varying conditions for compression showing that the worst-case scenario, gas compressed to 5 gal in 60 sec., is achievable and any other variance of conditions will make compression easier.

The Figures for work and power found in Table 3, above, were calculated using 100% compressor efficiency. Note that for a 7 gallon tank, it would be possible to compress 55 L of biogas in 5 minutes even if the compressor efficiency was as low as 8%. As this figure is conservative, assuming a human will become exhausted in 5 min while sustaining 0.4 Hp, as opposed to 10 min, compression is definitely achievable even given poor efficiencies.

CONCEPT GENERATION

Initially, the most important principle to be was the compression mechanism. Various forms of gas compression were reviewed and are summarized in Figure 3.

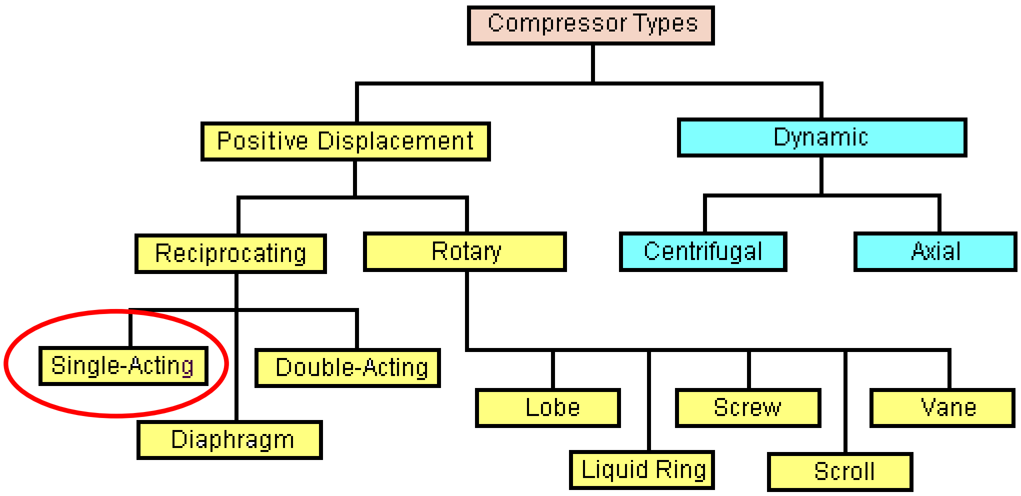

Figure 3: Available mechanisms of gas compression.

The scope of compression mechanisms is wide but was quickly narrowed by comparison with the requirements of our application. Ideally, we need to identify a compressor with few simple parts that are inexpensive and easy to manufacture or obtain in order to support simplicity of implementation. Also, the compressor must be easy to operate manually since it will be used in off-grid application. Lastly, many of the compressors available are intended for industrial use and produce output pressures that far exceed our needs. Dynamic pumps were eliminated immediately because they have large power requirements and produce extremely high pressures on the order of 10,000 psi. The more favorable compression method was determined to be positive displacement (e.g., piston-cylinder, rotary screw). These compressors were researched and further narrowed based on our requirements. Most favorable compression methods were determined to be the rotary screw compressor, the reciprocating compressor and the scroll compressor due to their simplicity of implementation [10, 11].

The rotary screw compressor, shown in Figure 4, is a positive displacement machine in which a male rotor pushes air along a female rotor into smaller and smaller volumes. Their application can range from very low pressures to very high pressures. It is useful because it can be utilized as either a stationary or portable compression device, but for best results it must be oil cooled, which involves a more complicated design. Though all designs could benefit from cooling, the rotary screw compressor requires it as a necessity for comparable performance.

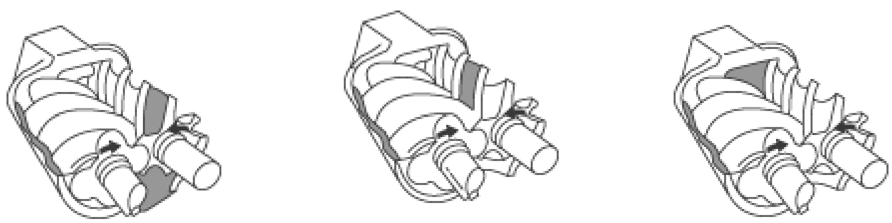

Figure 4. Schematic of Rotary Screw Compressor [12]

The reciprocating compressor, shown in Figure 5, is essentially a piston where gas is brought into a cavity and the cavity is physically reduced in volume. It can also be used in either stationary or portable design, which is useful, but the discharge pressure is generally lower than a rotary screw and this method can be noisy. There are few components, all of which are relatively simple. Another point that was noted is that reciprocating compression is the method also used in bicycle pumps [10].

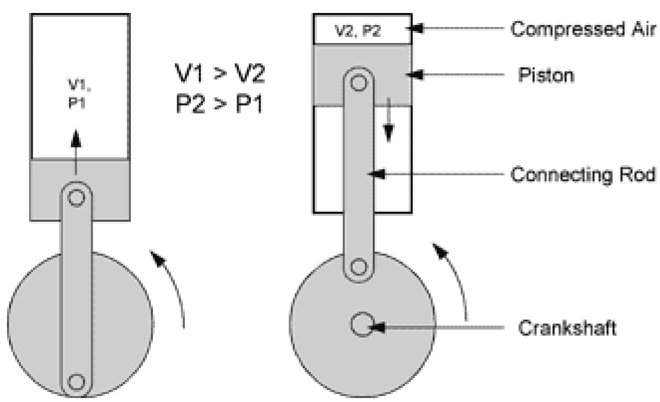

Figure 5: Schematic of Reciprocating Compressor [13]

Lastly, scroll compression is a relatively new form of compression in terms of its use. In this compressor, shown in Figure 6, a concentric relief coil moves in a circle in relation to another concentric relief coil, resulting in volumetric reduction and consequently compressed gas contained within the coil. This compression mechanism has few moving parts although they are not simple to fabricate.

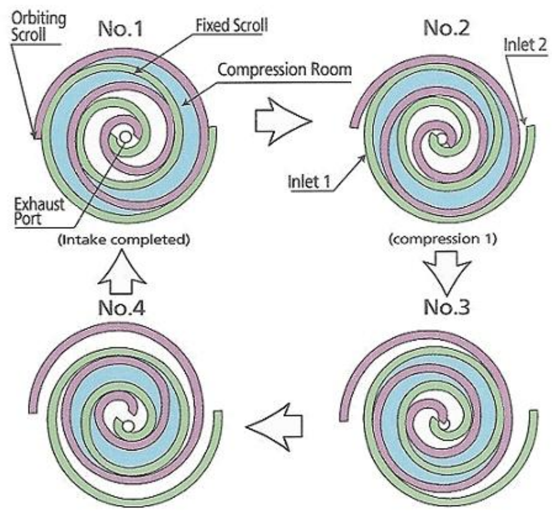

Figure 6: Scroll Compressor Schematic [14]

Expanding on these general concepts, our team held a brainstorming session which resulted in approximately 25 unique compression mechanisms that would potentially be feasible in our application. Notable compression concepts as well as other proposed system features are detailed below.

A Scroll Compressor is normally a pump used in industrial applications; however, it could be useful in our application because it is smooth, quiet and reliable. Other benefits of the scroll compressor are that its compression process is more continuous, has fewer moving parts, but does require more rotations of a crankshaft for rotation. This compressor is more than capable of achieving the 50 psi required for our application. The main drawback to this compressor is the fact that the necessary parts are expensive, have complex geometries, small tolerances, and are often very complicated to machine [11].

A modified bicycle pump is a simple compression mechanism that is available in the target area of implementation. Modifications would serve to make compression easier in the higher pressure regions. One way this can be achieved is through the mechanical advantage of a lever. Another method would be to fix the piston to the small gear on a bicycle. This would utilize the mechanical advantage associated with pedal power, and furthermore, the muscles in human legs are stronger than those in arms, which are used to operate conventional bicycle pumps.

Some other modifications would require a new piston-cylinder pump to be fabricated, rather than the implementation of an existing one with alterations. One such modification is scaling up the bicycle pump to allow more gas to be compressed with each stroke. Another is to use dual-stroke technology in which there are two air chambers and gas is delivered on both the push and the pull stroke of the pump. This allows the desired pressure to be achieved in fewer strokes and less time. The technology of Dual Stroke internals is inherent in the Blackburn Air Tower 5, which is capable of filling a bicycle tire to 100 psi in 10 strokes. It also features two modes: a high volume mode which displaces a maximum amount of air, and a high pressure mode which uses only one air chamber to reduce pumping effort [18]. We would likely model our pump after this design; however, the retail value of this pump is $100 which is far more than the cost of most bicycle pumps. Also, this design is not likely to be found commonly in the Philippines.

A Lead Screw Piston is similar to the previously mentioned bicycle pump, except it utilizes a lead screw and a large handle to provide a rotational mechanical advantage when the pressure is high and a large amount of force is required. This piston-cylinder system would be scaled up to increase the chamber volume and minimize the amount of necessary strokes. The lead screw would initially slow down the process of compression because simple, linear strokes are more direct than rotation, but when the piston becomes difficult to compress, the lead screw would aid in compression and weights on the handles (such as rocks) could be used to further decrease the force required.

A Bellows System is another simple compression method that requires minimal, inexpensive materials to build. A hand-operated bellows is the most common; however, in our situation we would use a foot-operated bellows in order to deliver more force and to keep the gas as far from the face as possible, for extra safety precaution. Concerns with this system are that it is limited to the amount of pressure it can produce, because standard bellows are meant to be used in ambient pressure applications.

Manual Volume Reduction of the Bladder could be achieved with a simple tool like a rolling pin. Once the bladder is full, it could be passed through two rolling pins, similar to the way pasta dough is passed through a pasta roller. This would force the gas into a container with less volume until the proper compression is achieved. Concerns with this system are the fatigue of the bladder material due to constant deformation, and also the effort involved in compressing in the high pressure region, since there is no notable mechanical advantage.

Natural Elements are commonly used in many places throughout the world to create power. In our case, we would use a design similar to a windmill or waterwheel to harvest this natural energy. This would eliminate the need for man power altogether, but would greatly restrict the areas of implementation. For this system to work, it would need to be placed near running water or in an area that usually experiences substantial amounts of air movement.

Playground Fixtures are desirable because they provide amusement to children who power the system without even realizing they are doing work. This relieves the burden from adults who likely already have an abundance of work to do. This compression mechanism would be implemented in the form of a see-saw, merry-go-round, or swing set. This idea was inspired by the Play Pumps organization, which utilizes this concept to supply clean water to African villages. This project would be much larger and more involved than previously discussed mechanisms and would require many materials. There is also a potential safety hazard in children playing so close to the gas all day. This could be avoided by relocating the pump with extensive lengths of piping, which would further add to the list of materials.

Other possible features include a whistling blow-off valve to give an audible indication that the maximum pressure has been reached. It will either blow off air, or blow biogas back into the digester. Another proposition is to use rubber hose after the compressor instead of PVC piping, for a higher pressure rating and increased versatility and mobility of component configuration.

To provide the options of both compression and direct feed, we thought about implementing a splitter in the line before the compressor. This would add additional versatility to the system and would provide quick access to a direct biogas source.

CONCEPT SELECTION PROCESS

Concept selection was largely regulated by the fact that every component of our compression / storage system must be inexpensive and readily available. In order to store the compressed biogas, two options immediately emerged – air and propane tanks. Both are readily available, refillable, inexpensive, safe, and have standardized fittings (connectors, hoses, valves). After choosing a tank, it was then possible for our design team to choose a compressor and begin testing. H_2S scrubbing was not part of the concept selection process because of its standard, straightforward design and ease of implementation. In this section, the tank will be discussed before the compressor, to mirror our concept selection process, which started with the tank and moved back to the compressor.

Tank Selection After our brainstorming session and an extensive product search, air and propane tanks emerged as the only feasible options for gas storage. The price for other types of refillable tanks, such as natural gas and carbon dioxide tanks, was not reasonable for this application (> $200). Table 4, below, outlines the pros and cons of both air and propane tanks.

	Air	**Propane**	**Best option**
Cost	~ $25	~ $30	Air
Pressure rating	125 psi	> 200 psi	Propane
Refillable	Yes	Yes	Tie
Safety	Blow off/check valves, coated interior	Blow off/check valves	Air
Volume	5 gal and up	4.7 gal and up	Tie
Pressure created	< 50 psi	< 55 psi	Air
Portable	Yes, weighs 7 lb for 5 gal	Yes, weighs 22 lb for 4.7 gal	Air
Fittings	Schrader valve, very standard	Reverse threads, less standard	Air
Accessibility	Most hardware stores	More "specialized" stores	Air
Considerations	Paint white, keep out of sun	Store upright, keep out of sun	Tie

Table 4. Pros and cons of implementing air vs. propane tank. Air is shown to be a better candidate for this application, winning or tying 9 of 10 categories.

As seen in Table 4, above, an air tank is well suited for this application. Note that all air tanks have a coated interior, which protects the tank from being corroded by water and other elements found in biogas. The fact that propane tanks have a higher pressure rating is not a major concern, because the 125 psi rating of air tanks is more than adequate considering the pressure in the tank is not expected to exceed 50 psi. Air tanks and the associated fittings are generally more available than propane tanks, as propane supplies require a specialized distributor, which we were unable to locate or identify in the Philippines. The selection of a storage tank before the compressor was necessary, as it forced us to think about the compression and storage process as a whole. For example, what fittings were needed for which type of tank, and how available all components would be.

Compressor Selection The engineering specifications that had the most bearing on selecting a compressor include cost, safety, accessibility, lifespan, and efficiency. It was extremely important to balance lifespan and cost. An inexpensive compressor is desirable, but it also has to be reliable.

Table 5, below, outlines our top five designs and their associated pros and cons. The following Table 6 scores each pump against the other pumps in the categories of cost, safety, accessibility, lifespan, and efficiency. It becomes clear that the modified bike pump is the best design because of its low cost, high safety, and moderate efficiency.

Compressor type	Pros	Cons
Scroll compressor	Efficient	High tolerances, expensive, difficult to machine
Modified bike pump	Inexpensive, reliable, user far from biogas	Poor quality compnents shorten lifespan
Leadscrew piston	Lower user input	Expensive, difficult to machine
Playground fixtures	User away from biogas	Injury, users may not cooperation
Natural elements (sun, wind, water)	No human input	Expensive, avilability of resources

Table 5. The pros and cons associated with each compressor type.

Compressor type	Cost score	Safety score	Accessibility score	Lifespan score	Efficiency score	Best option
Scroll compressor	3	4	4	1	1	13
Modified bike pump	1	1	1	3	3	**9**
Leadscrew piston	2	5	3	2	2	14
Playground fixtures	4	3	2	5	5	19
Natural elements (sun, wind, water)	5	2	5	4	4	20

Table 6. The score (1 being the best) for each compressor type in individual categories. Modified bike pump is best suited for this application, as shown in the "best option" column, a summation of the previous columns.

The scores in Table 6 were generated based on Table 5 and the concept generation section above. Cost, safety, accessibility, and accessibility have the most bearing on the overall compressor selection. Lifespan and efficiency aren't necessarily unimportant, but high lifespans and efficiencies are associated with compressors that have high costs, which isn't possible for this project. The ideal compressor will have low cost, high safety and accessibility, and a moderate lifespan and efficiency. The modified bike pump was the best option for this application because of its balance with the previous criteria. The full design based on the "modified bike pump" will be described in the design description section.

SELECTED CONCEPT TESTING

Testing Procedures aimed to distinguish between different pump models regarding several different aspects of use that were physically carried out. Specifically, we focused on ease of pumping, number of strokes to reach 50 psi, heart rate increase, and whether or not the pump could reach the target pressure. Three different bicycle tire pumps were tested; one basic upright cylinder hand pump (Air Master, Slime), one horizontal cylinder foot pump (GS foot pump), and one multi-volume upright cylinder pump (Blackburn Airtower 5). The three hand pumps ranged widely in price and pressure rating, and the foot pump was standard. The specs of each pump are located in Table 7, below. Each pump was successively connected to the air tank, initially at 0 psi. Next, each team member took turns pumping the tank to 50 psi to incorporate strength and gender variability in the sample. Three hand-operated bicycle pumps and one foot pump were tested.

Model	Pressure Rating	Price	Features
Air Master hand pump	70 psi	$8.00	Below standard, single chamber
Slime hand pump	70 psi	$20.00	Standard, single chamber
Blackburn Air Tower 5 hand pump	160 psi	$100.00	High quality construction, Dual-chamber, high pressure/ high volume modes
GS foot pump	100 psi	$20.00	Standard, double barrel
Air Stream air tank	125 psi	$30.00	Standard, built-in pressure gauge

Table 7. Specifications of pumps and air tank tested

Bicycle pump testing results verified that pumping the 7 gallon air tank to 35 psi (as explained, the bike pumps were used to compress air to 50 psi) with a bicycle pump was both possible and practical. The Blackburn Air Tower 5 far outperformed the other pumps in almost every measured aspect. It was the easiest hand pump to use, it took the least number of strokes, and it took the least amount of time with each user completing compression in under 5 minutes. Appendix A contains details of these test results. Every pump excluding the Blackburn took more strokes to reach each pressure checkpoint and failed at a pressure below 35 psi. In every case, failure occurred at the attachment of the hose to the body of the cylinder or the hose to the Schrader valve. The standard hose attachment found on these three pumps was very poorly constructed and quite different than the one found in the Blackburn pump. The Blackburn used a similar attachment method but with an additional threaded, plastic fitting which screwed onto the assembly to create a force to hold it together. It was very apparent that this attachment was much more durable because the hose cannot separate from the cylinder while the cap is in place; the cap serves as an additional barrier to delay failure. Of course, the exact lifetime of this hose attachment can only be speculated as it would require long-term testing to determine. This hose was also attached in an uncommon location on the top of the cylinder, pointing at the ground. This arrangement is desirable for our application because in the event of a leak, we would want the gas pointing away from the user’s face.

Other valuable information was gained from pump testing besides determination of the model which performed the best. We discovered the need for stability, or possibly a stationary pump, because the two standard hand pumps were unstable against the ground and made pumping much more difficult and strenuous. Another simple, but impacting concept is that a larger chamber volume displaces more air and significantly reduces compression time and required number of strokes. In the higher pressure region of compression it is desirable to compensate for this larger volume by implementing a dual-chamber system with the ability to turn off one chamber, or switch “modes”, to reduce volume and therefore reduce pumping effort. From testing, we found that near 40 psi, pumping gets rather difficult, and that is when the high pressure mode was used. The design should also be ergonomic, unlike the tested foot pump which was very awkward to use, and it should incorporate a mechanical advantage to reduce the intensity and dependence on arm muscles.

Fabricated piston-cylinder testing was required after preliminary bicycle pump testing in order to verify that off-the-shelf materials and simple fabrication techniques could create an adequate seal and operate with a reasonable input force. We used a small section of black pipe, cast iron end caps, and a steel piston with an O-ring to create the seal. Standard, black bearing grease was used for lubrication. The creation of this simple piston-cylinder pump verified that fabrication is feasible and an adequate seal can be created. Design changes were made as a result of this testing, including material and lubrication changes. The bearing grease proved to be too viscous for our application, and the black pipe had a rough surface finish which deteriorated the O-ring and required high input force to overcome. With this affirmation we were able to move on to our final prototype which will require users to stand and apply a downward force with both arms.

ENGINEERING DESIGN PARAMETER ANALYSIS

As previously stated, the purpose of this system is to provide a means for compressing biogas using only off-the-shelf, inexpensive materials. Based on the literature search and preliminary testing, a modified piston-cylinder that requires the user to stand and apply a downward force with both arms was chosen as our final design. In order find a balance between cylinder size, required force for compression, material used, and all other engineering specifications, it was necessary to gather information on the expected forces related to the system and apply the laws of thermodynamics and statics. Force and stress analyses were performed and resulted in conservative, safe estimates for dimensions. A Finite element analysis (FEA) was performed to confirm calculations and to gather information related to the stress distribution in the frame.

Expected Input Force In order to determine what range of input forces could be expected, it was necessary to gather information on the weight of a human. The system must be designed to withstand the high stresses caused by a very heavy individual's input and still be able to compress biogas given input from a very small individual. The average adult weight ranges from 100 lb (5th percentile) and 270 lb (95th percentile) [19]. Using this information, 300 lb will correspond to the maximum input force and 30 lb will correspond to the minimum input force in order to be conservative in our calculations. The actual force that is applied to the pistons will depend on the ratio (L+d)/d defined in Figure 7, below. Appendix C explains that even given a one-time force of 3,000 lb, the compressor would not fail. Under normal operating conditions, the biogas compressor should never require an input force of greater than 30 lb. However it isn't always safe to assume that people will be operating the compressor exactly how it was intended, so a safety factor of about 10 is incorporated into the final design.

Cylinder size determination brought on the realization that there is a tradeoff between the force required to compress biogas and the amount of time spent compressing biogas. That is, if the input force is high, the time spent compressing the biogas will decrease. Also, the smaller the cylinder, the lesser the force required when compressing the biogas, however, more time and more strokes are required for compression. This will affect the dimensions that will be determined around the engineering specification that requires compression to be completed in 5 minutes. This means that the cylinder size should be such that the weakest person (30 lb input or less) can compress 55 L (14.5 gal) of biogas down to 20 L (5 gal) in less than 5 minutes. The calculations for this are based on only one cylinder because it requires more force to compress 3 cylinders at a time. Weaker users can choose to use 1, 2, or 3 cylinders depending on compression difficulty. It is conservative to base this calculation on only 1 cylinder, because even the weakest user will feel little resistance and be able to use all 3 cylinders during the initial, low pressure compression stage. The details of the calculations are described in Appendix C. The result of these calculations were then compared with materials that were commonly available from manufacturers (like McMaster-Carr [20]) and the resulting cylinder size was one that was 1.87 inches inner diameter, D_i, 2 inches outer diameter, D_o, and 12 inches in length, l. The cylinder will be made of drawn-over-mandrel steel as explained in the material selection section below.

Piston-Cylinder Lubrication After testing our preliminary pump, it became clear that our choice of lubricant needs to be specialized to best accommodate the needs of this application. Choosing a lubricant is a matter of assessing the lubricant properties needed to provide adequate film thickness under normal operating conditions. Pertinent considerations to ensure proper lubrication are the temperature range, the load, the relative velocity between the surfaces in contact, the surface roughness of the components in contact and the viscosity of the oil. Table 8, below, shows various relationships amongst these relevant conditions.

Factor	**Application**	**Intended Viscosity**
Temperature	High temperature	High
	Low temperature	Low
Load	High load	High
	Low load	Low
Velocity	High speed	Low
	Low speed	High
Surface Roughness	High surface roughness	High
	Low surface roughness	Low

Table 8: Relationships among operating conditions and optimal lubricant viscosity.

The information in this table was generated by lubrication experts within Holcim Inc., an international cement manufacturer. It refers to extreme conditions typically found in the plant environment. A high temperature is considered to be greater than approximately 90°C (194°F), a high load is considered to be greater than approximately 500 lbs, and high speed refers to approximately 100 rpm or greater, whereas low speed refers to approximately 30 rpm or below. From the table of optimal lubrication viscosity in set operating conditions, it is clear that low viscosity oil is desired, given a low operating temperature of an estimated 70-110°F (21-43°C), a low load on the order of 100 lbs, and a low to medium speed of about 30 strokes/min, including both upward and downward strokes. These applications point to low viscosity oil, thus, to match the final application with low viscosity oil, surface roughness must be minimized as much as practically possible. The higher the asperities, the greater the degree of contact, wear rates, and viscosity required of the lubricant [18]. In other words, a smooth surface is best accommodated by a thinner oil. An additional reason why low viscosity lubrication is ideal in our application is that manual force is used rather than a motor, and the higher viscosity the oil, the greater the force required to move the piston. A lower viscosity oil will aid in compression.

Mobil 10W hydraulic oil is a low viscosity oil with additional features which will benefit our application. It has a high viscosity index which means that its viscosity changes very little over a wide temperature range. A low viscosity index (VI) is generally considered to be in the range of 0 to 40, and a high VI is generally considered to be in the range of 80 to 120; Mobil 10W hydraulic has a VI of 107. This is ideal because in our application, the pump may go through extended periods of use and non-use, and it is also likely to be placed outdoors and subjected to fluctuating ambient temperatures. A high viscosity index will aid in keeping the properties and performance of the oil more consistent. It offers good protection against oil thickening, high temperature deposits, varnish, and oil degradation. It retains effective film thickness at high temperatures and is compatible with many other oils in case of unplanned mixtures [24]. Additional details regarding this particular lubricant can be found in Appendix B. It should be noted that this oil is ideal for our application and is used in our prototype; however, there are several other comparable lubricants available that would match our application and perform just as well.

Lever Arm Shown in Figure 7, below, is the free-body-diagram for the compression system. It was used primarily to determine the ratio (L+d)/d and the dimensions of certain aspects of the system.

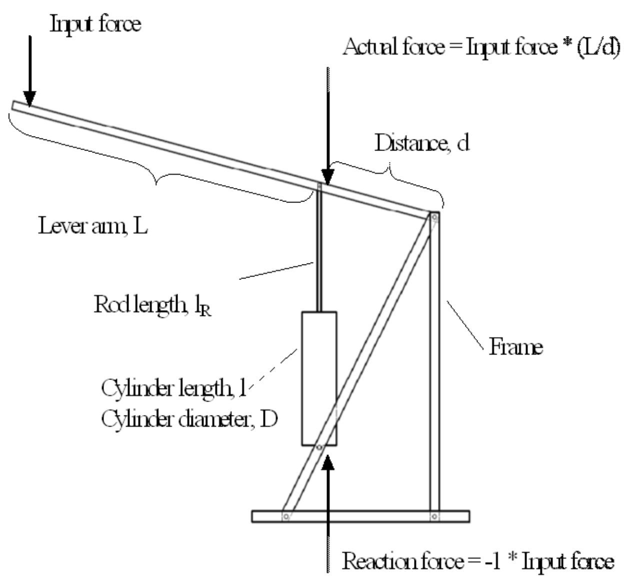

Figure 7. Right side view of the piston and stand; forces and dimensions to be determined.

A detailed stress and force analysis is shown in Appendix C; the results of which are shown in Table 9, below.

Cylinder inner diameter, D_i	Cylinder outer diameter, D_o	Cylider length, l	Rod length, l_R	Lever arm length, L	Distance, d	(L+d)/d
1.87 in	2.0 in	12 in	16 in	37 in	8.5 in	5.3

Table 9. Results of stress and force analyses from Appendix C showing that (L+d)/d is 4.33.

The inner and outer diameter of the cylinder is McMaster-Carr's specification for drawn-over-mandrel steel pipe [20]. It was also assumed that low-alloy mild steel, which we will approximate as 1010 steel, was used for the frame, piston, and plunger. This is a good approximation of the actual steel that will be used because 1010 steel has a relatively low yield strength, σ_Y, when compared to other steels of higher carbon concentration. Cylinder length was set to 12 inches in order to increase the area of highest efficiency and easiest manipulation that the plunger can work through. In our initial prototyping, a cylinder length of 6 inches was used. The 6 inch cylinder only had about 3 inches high efficiency zone in between each end of the cylinder that allowed the plunger to move freely. This was due in part to inefficiencies in the type of steel pipe used (which will be addressed in the materials section below) as well as the plunger entering into the end-caps and protruding from the cylinder. This is accounted for by incorporating pegs onto the piston as described below and shown in Appendix D. By increasing the cylinder length to 12 inches, the high efficiency zone is also increased. The quantity (L+d)/d was set to 5.3 to account for the weakest input given a safety factor. The lengths d and L were set to 8.5 inches and 37 inches respectively in order to ensure that the frame will not break when a large moment is applied. The distances L and d control how much of the input force is applied to the cylinders – if the force is too high the frame will be under a severe amount of stress and if it is too low compression will be too difficult. Therefore, the distances L and d were determined as further described in Appendix C.

The moment arm will also need a cross sectional area of at least 0.036 in^2 (the final design's beam cross section is 0.25 in^2). This is also described in Appendix C. The material for the lever arm will be mild steel, the same as that of the frame as explained below. That said, the lever arm should not be excessively heavy or too light. If too heavy, the lever arm can weigh on the system, causing the frame to warp over time, and put too much strain on the user. If the lever arm is too light it might be too easily bent or deformed. So, the lever arm should be made of a lightweight, strong material such as the mild steel described in the material selection section below.

Please also note that when assembling the lever arm, it can be lengthened or shortened in order to retro-fit it to specific users. Taking into consideration machining and fabrication, this would be a very minor undertaking. However, for the general case the dimensions in Table 9, above, will be more than suitable. With the dimensions in Table 9 determined, we can proceed to dimension range of motion and the rest of the frame.

Range of Motion and Frame Dimensions In order to provide the user with a comfortable range of motion, the lever arm should be moved as little as possible either up or down from a completely horizontal position. Knowing the length of the lever arm, it will be necessary to choose frame dimensions and an angle, θ, concurrently as to make the extreme heights for the lever arm reachable and workable for the user. When the lever arm is at the bottom most point of its motion, it is important that it is a reasonable height above the ground. Therefore, the cylinders should be 24 inches off of the ground. Anything less would put too much strain on the user, while anything higher than 24 inches would require the user to reach too high at the top of the stroke. The angle theta was chosen in order to allow for the piston to move completely in and out of the cylinder when the lever arm is lifted up and down. The bottom dashed line in Figure 8, below, corresponds to the piston being all the way down the cylinder, completing the lever arm's range of motion.

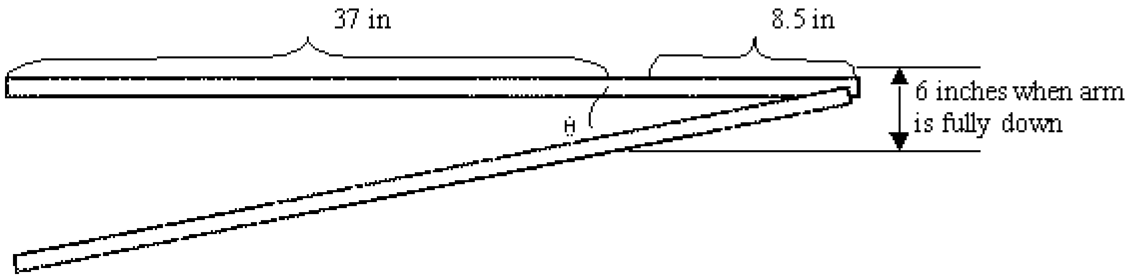

Figure 8. The proposed compressor's range of motion and some relevant dimensions. θ was determined to be 45 degrees.

Choosing theta (θ) is most easily done when concurrently choosing the height for the frame. The frame must be high enough to account for the length of the lever arm not hitting the ground at its bottom point. The length marked "6 inches when arm is fully down" is necessary for the piston to be able to move completely through the 12 inch piston. This way, when the lever arm is horizontal, the piston will be 6 inches through the cylinder. When the lever arm is rotated θ degrees above horizontal, the piston will complete its motion through the cylinder. Theta was determined to be 45 degrees as explained in Appendix C. This was derived as a combination of the need for the lever arm to be about 24 inches above the ground at the bottom of the stroke, but also out of the need for the lever arm to not be unreasonably high at the top of the stroke. At the bottom of the stroke, the lever arm will hover 24 inches above the ground. The design team made this decision because setting the lever arm too high would make the height of the lever arm at the top of the stroke unreachable, as mentioned previously. Also noted is the fact that when testing bike pumps, the most crucial range for compression (as far as where the maximum force is required) is near the bottom of the stroke. With the bottom of the lever arm's motion set to a height 24 inches, the angle θ equal to 45 degrees, and the lever arm at 45.5 inches long, the maximum height for a stroke at the end of the lever arm is a little over 7 feet. However, it isn't entirely necessary for the piston to be extended this far, and there is very minimal user force required to detract the piston. Therefore, users can position themselves up on the lever arm and work from a shorter distance, making the height of 7 feet more manageable. The material for the frame will be mild steel, as explained in the material selection section below.

Other Frame Dimensions The frame must be able to support 3 cylinders and allow for piston movement through each of the cylinders. Each cylinder will have a hose barb (which is about 1 in long) and a tube (which needs at least 1 in for clearance) coming out of the bottom of it. Therefore, the cylinders should be at least 4 inches off of the ground. As stated previously, the base of the compressors will sit at least 24 inches above the ground providing ample room for tubing and fittings. The width of the frame will be 2.5 feet or 30 inches. It must be wide enough for 3 compressors to fit comfortably side by side. Each cylinder is 2 inches outer diameter, and must have some space in between them. As mentioned previously, it will be desirable to allow users to move up and down the lever arm as they choose. That is, allowing the user to choose to use the mechanical advantage when it is needed and not using the extra length when compression is easy or when detracting the lever arm. So, the width of the frame must be wide enough to accommodate the width of a typical human and portion of the wing span, which is about 2.5 feet wide. The cylinders must be evenly spaced on the frame to ensure balanced forces. Knowing the frame dimensions, (L+d)/d, the lever arm length, the cylinder dimensions, and the range of motion, all other dimensions fell into place easily. The dimensioned drawings are shown in Figures 9 and 10.

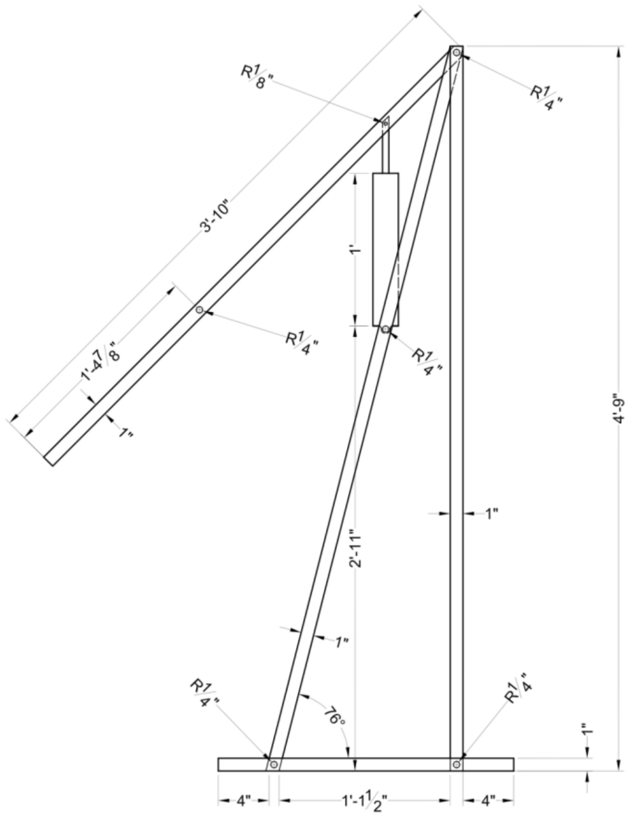

Figure 9. Right side view of compression system with final dimensions.

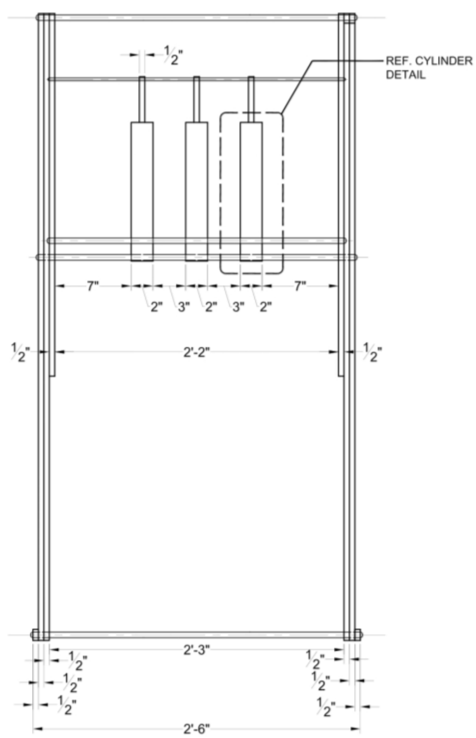

Figure 10. Front view of compression system with final dimensions.

Material Low alloy mild steel was used in the calculations above because of its availability, low cost, and its suitable material properties. Because all of the calculations were done using this steel and the results are realistic, low alloy mild steel, such as 1010 steel is suitable for this application. Steel with a high alloy content is more expensive than 1010 steel, but doesn't otherwise possess any qualities, save for weld-ability, that would make it a better option than 1010 steel. The properties of 1010 steel are shown in Table 10, below. If another material is used to reproduce this frame, the material properties shown below should be viewed as benchmarks.

Density	2.78E-4 lb/(in ^{3})
Young's modulus	27.5E3 ksi
Ultimate tensile strength	53 ksi
Yield strength	44 ksi

Table 10. Material properties associated with low alloy, 1010 steel. [21]

The material used for the cylinder should have as good a surface finish as possible to ensure a good seal between the piston and the cylinder. Again, the material properties for low alloy steel make low alloy steel a suitable option for this application as long as it is processed in a way that leads to a high quality surface finish. For a more detailed version of why this mild steel was chosen for the lever arm, frame and cylinder (as opposed to other materials) see Appendix E.

Another factor that was considered when choosing steel was the environmental impact of producing the material. When compared to using aluminum for the frame, steel had almost half the emission generation. The complete environmental analysis can be reviewed in Appendix F.

Stress Analysis Using the dimensions, material, and forces described above, a figure for stress distribution was generated using FEA (Altair Hypermesh). Figure 11, below, shows the stress distribution as seen from the right side of the frame. The stresses shown in the figure correspond to an input force of 300 lb, which will never be required to operate the system. Though, Figure 11 shows that even if it is, any mild steel will be easily able to resist the stress. The units of stress are in psi.

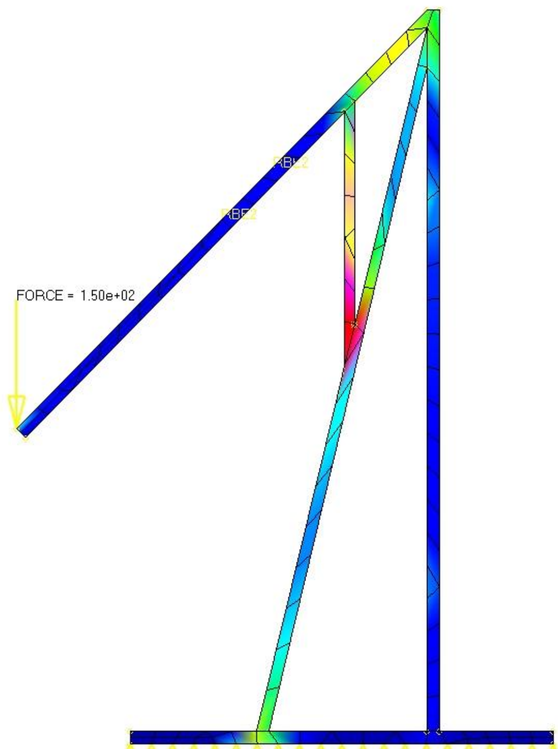

Figure 11. Maximum stress distribution for the right side of the compressor frame. The maximum stress is shown in red (light grey) and is ~6 ksi – well below the yield strength for the suggested steel.

Shown above is the stress analysis for the frame. The stresses applied to the rod that supports the three piston cylinders is detailed in Appendix C. The steel rod's dimensions were determined based on the expected stresses. Obviously as the rod's diameter increases, the stresses in the rod will be smaller, but it will also be more expensive. A 0.5 in diameter rod was chosen in order to optimize cost and minimize stress.

It should be noted that the frame is made entirely of steel, it will likely be considerably heavier had it been constructed from a less dense material. However, as explained above and in Appendices E and F, steel is the optimal material for this frame. The frame will need to be welded to ensure that it is joined together in a way that does not significantly compromise the material properties of the steel. Also, the biogas compressor does not need to be moved often (ideally just once to get it to the digester), making the weight of the compressor even less of an issue. Because the compressor frame needs to be welded, disassembly is not an option. However, that does not mean that it isn't easily maintained (e.g., the end caps on the compression cylinders can be removed giving access to the o-rings and pistons). The final compressor weighs 87 pounds, which means that it would need to be team lifted or transported using some sort of cart or dolly. Transportation of the entire system is feasible but requires some planning.

Our calculations were done extremely conservatively and have meshed together well. All components, including: θ, (L+d)/d, 1010 steel, and other dimensions noted, must work together for this system to work. Based on the above justifications and the explanations provided in

Appendix C; this design team feels confident that our assessments have lead us to a cohesive final product that meets all of the project's specifications.

DESIGN DESCRIPTION

The pump design can be broken into three different main categories: first, the scrubbing of H_2S, next, the actual pump, and finally, the storage container for the biogas. There is also the optional portion of CO_2 scrubbing, which we are not including in our final prototype.

Connection to the digester is achieved through an outlet gas pipe located near the top of the digester. This system outlet pipe is often PVC piping attached with a hose clamp, although the outlet pipe size is not of great consequence, a converter barb must be used to connect the digester to the ½ " flexible PVC pipe. One end of the barb must be ½ ", the other must be the size of the pipe in use with the digester. Multiple barbs and hose sections can be used to step the pipe diameter down as well; this set up is up to the user's needs.

The H_2S scrubbing mechanism is based on the example presented in our literature review (see Figure 2 above). The design includes a glass bottle filled with steel wool to act as an H_2S scrubber. The glass bottle will be sealed with a metal screw-on top, which has two holes, one for an inlet tube, which will reach to the bottom of the bottle. The other hole is for an outlet tube, which will reach just beyond the seal so that the gas must move through the length of the bottle before it is outlet. Both holes are sealed with caulk, or a similar sealing agent. The biogas will pass through this setup before entering the compressions system, and the pump will act as the driving force to move the gas through the steel wool.

The pumping mechanism design established is based on our experimentation. After testing the previously mentioned bicycle pumps, a set of design requirements and desires was established as follows:

- Inclined "foot pump" mechanism
- Relatively large cylinder volume
- Multiple cylinder design

The pump design includes three cylinders that are supported to stand vertically by a simple A-frame, based on our idea for the "inclined foot pump" design. The design is not foot -operated, but will have an A-frame which help the cylinders to remain up-right, and a long lever arm which the operator will pump using their hands use in order to control the system.

The cylinders themselves rotate around a rod near the middle of the A-frame base, and the end of each plunger is attached to the handle by a pin, around which it rotates. With this design, the heavy cylinder is kept relatively stationary, which is more structurally stable and requires less force than having the cylinder itself move with the lever. The long lever arm acts to give a mechanical advantage and moves the three plungers through the body of the cylinders. The three cylinders are used with on-off valves so that the user can determine how much work they would like to apply to the system by increasing or decreasing the number of cylinders on which they are performing work. This increases safety and allows them to vary the amount of work that they apply in order to compress the biogas.

These operations can be broken down into even further detail starting with the connection to the H_2S scrubber. The shorter tube in the scrubber should be connected to the valve system using flexible PVC piping. A hose barb can be used where necessary to make a connection if the hose from the scrubber is not long enough to reach the system. From the outlet pipe connection of the scrubber, the biogas moves to the pump inlet. The biogas is inlet through a one-way valve, which brings the gas into the bottom of the cylinder through a series of activated ball valves. Upon compression the gas moves back through this valve system and is outlet through a one-way outlet valve on the opposite side of the system, where it moves to the tank. The one-way valves allow the design to inlet and outlet through the same hole in the bottom of the cylinder, and have simplified the design (for details see Appendix J).

The valve system connects the volumes of all three cylinders and allows for the variable operation of the system. The cylinders are connected in parallel, and each has two ball valves. One of these valves controls flow to and from the ambient atmosphere, the other controls the flow of biogas from the inlet valve. For the cylinder to compress biogas, the biogas-controlling valve must be in the "on" position, and the ambient valve must be in the "off" position. The ball valve furthest from the cylinder will control the biogas, and the ball valve closest to the cylinder will control the ambient air entering the system. Once the tank contains enough compressed gas, compression will be come difficult and some of the cylinders can be disengaged in order to make pumping easier. In order to disengage a cylinder the biogas valve should be placed in the "off" position so that biogas is not pulled into that branch of the system, and the ambient air valve should be "on". This makes pumping easier because, with each stroke of the plunger, air is circulated in and out of the cylinder without creating pressure or a vacuum. When biogas is compressed by the system, it moves through the outlet one-way valve, which is connected to the storage tank.

The one-way valves chosen are basic half-inch brass swing valves because they will be able to operate under the low initial pressures of operation, have a relatively long lifetime, and were moderately inexpensive. The valves are not entirely ideal, but suit the needs of our design. Some gas may be able to move in an incorrect direction for a short amount of time until the valve closes fully. However, based on the combustibility of methane we do not foresee this creating large hazards or problems with the function of the system as a whole. The ball valves, pipe tees, nipples, hexes and other portions of the valve system were chosen to be brass for their availability as well as durability. A diagram of the system can be seen below in Figure 12 below. The cylinders are made of DOM (drawn over mandrel) steel, due to its durability and excellent interior surface finish, and steel nipples (1" l, 2" ID) were JB welded for connection to the black steel pipe caps.

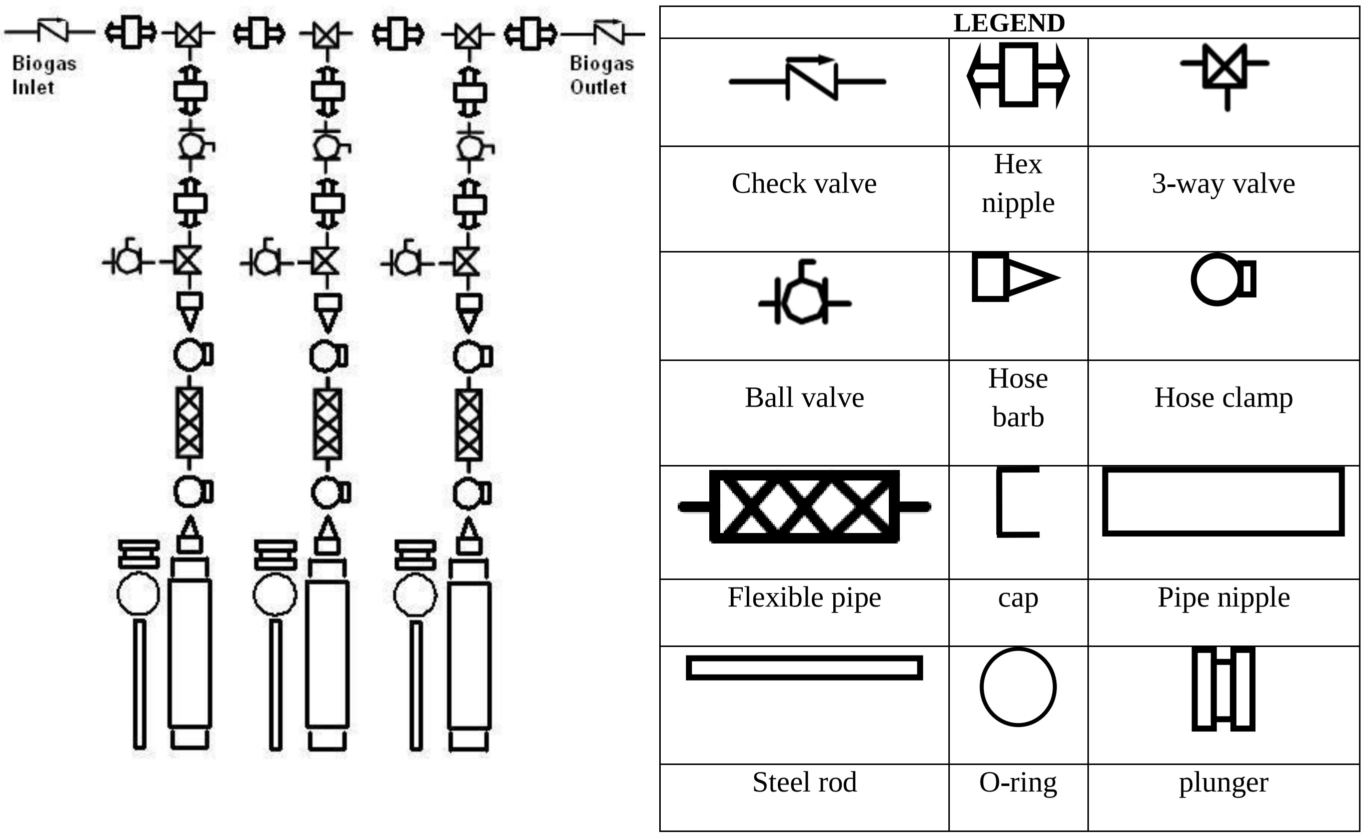

Figure 12. Schematic drawing of valve set up for compressor pump [25]

The cylinders will be connected by braided PVC to this valve system, which will rest stationary on a small wooden, raised platform (25" x 14 1/2" x 27") in order to reduce the strength and durability requirements of the frame, and the durability requirement of the PVC. A set of images can be found in Appendix G, which outlines what each valve looks like.

Each cylinder has a bottom cast iron cap, a top cast iron cap and a piston, all of which help attach the cylinder body to the frame and operating lever. The bottom cap has one ½" threaded hole, into which a hose barb is attached, and another [3/8"] threaded hole, into which a bent rod is attached. The bent rod is welded to a steel sleeve, through which the bottom rod is placed, consequently attaching the bottom of the cylinder to the frame. The top cap has only two holes, one of which is [3/8"], and allows the piston rod to move through the system, the other is a small hole which allows for air to enter the back side of the piston system, making pumping easier as a vacuum is not created. The two caps screw onto the DOM cylinder black pipe ends.

The plunger rod is 13" long, with a bent end, similar to the end cap design. The bent end is also welded to a steel sleeve. A rod, which connects to the lever arm, is fed through this sleeve, thus attaching the top end of the piston cylinder system to the frame, and providing a method of actuation for the system. Before the bend is placed in the plunger end, it must be inserted in the top cast iron cap. The plunger end is welded to a machined steel disk, and a 1/8th inch thick 2 inch OD O-ring is stretched around the disk. The plunger also has ½" pegs attached to each face to prevent motion beyond the range of the cylinder and into the cap. This system is lubricated with Mobil 10W hydraulic oil in order to aid motion, and in order to help create an even better seal in the cylinder itself. A schematic can be seen below in Figure 13, for dimensioned drawings see Appendix D.

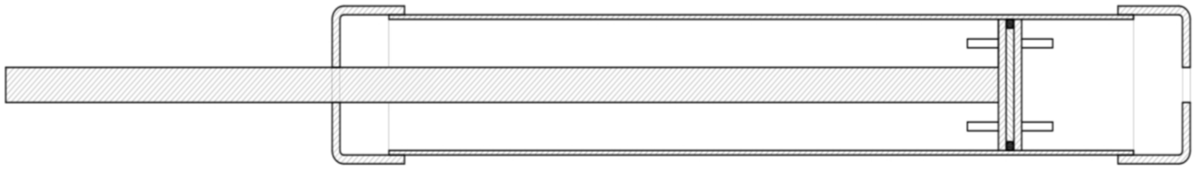

Figure 13. Schematic of piston-cylinder design

As the plunger is drawn through the cavity of the cylinder, biogas (or air, depending upon the valve set up) will be pulled into the cavity from the H_2S scrubber. The plunger is then forced down and the volume of the cylinder is reduced, consequently compressing the gas. With this force, the gas travels back through the tubing, this time routed to the outlet where it travels through braided PVC to the storage tank. The tanks is connected through a female Schrader valve connection, which is attached using a simple hose barb converter, as the connection to the Schrader valve is smaller than the braided PVC tubing. The cylinder system is supported by a simple A-frame system, which can be seen in the schematics below in Figure 14.

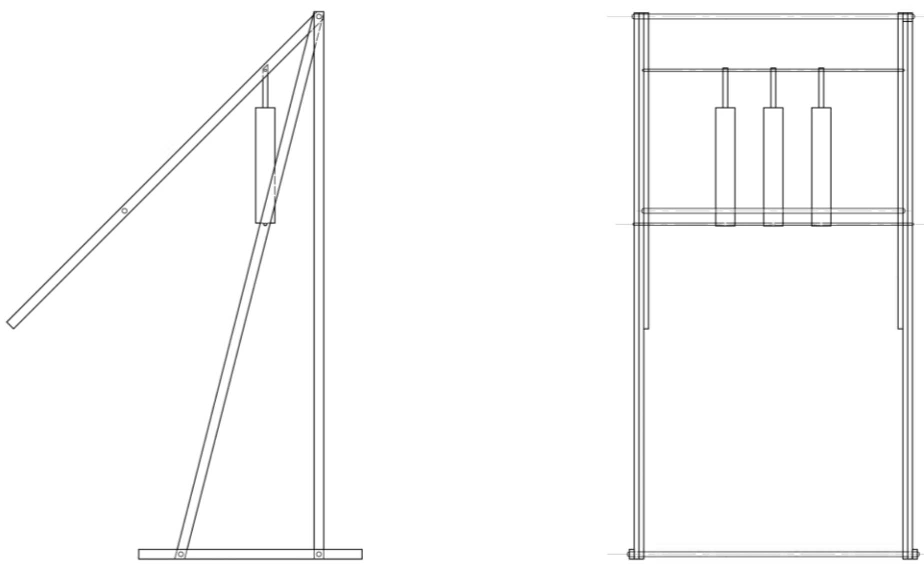

Figure 14. Basic schematic of frame set up

A fully dimensioned set of drawings can be found in Appendix D. The frame is supported by sand bags (210 lbs total were used for testing), in order to insure that it will remain in place during operation, this or another method of restraint should be used in order to keep the frame stationary. Due to the low surface area of the profile, we are not concerned with the affects of wind or additional external torques. A photographic image of the finalized prototype can be seen in Figure 15 below.

Figure 15. Photograph of finalized prototype of compressor design

High-pressure tank availability and capacity were researched in order to develop a recommendation for a tank to be used in conjunction with our pump. It was decided that an air, rather than a propane tank, would be desirable as air tanks include an inner coating to prevent corrosion of the inside of the tank. In this design and future testing a 7-gallon tank will be used. The tank should be white or pale yellow to prevent content confusion, and can be painted if necessary, in order to insure that as much heat energy as possible is reflected off the tank and not absorbed to expand the contents. This, and a large safety factor regarding the suggested pressure of compressed contents, will add to the safety of the gas tank in our design. The tank purchased also has a blow-off valve which preserves the tank pressure at 140 PSI to prevent failure and increase the safety of the system. A complete analysis of design safety is located in Appendix H.

Bill of Materials Included in Table 11, below, is an outline of the materials used in the pump design that was outlined above. The valves listed in finished materials comprise the valve system diagramed in Figure 12 above.

FINISHED MATERIALS					
# of Units	Part	Manufacturer	Product number	Price	
2	0.5" Brass check valve	Smith Cooper Int'l	01738191G	$6.49	
6	0.5" Brass Pipe Tee	Anderson Metal	3810108	$5.25	
13	0.5" Brass Hex Nipple	Anderson Metal	06122-06	$2.99	
6	0.5" Threaded Ball Valve	Smith Cooper Int'l	17208170G	$6.19	
6	Hose Barb Adapter- 0.5"barbx 0.5"MIP	Anderson Metal	17001-0808	$5.29	
6	2" Black Pipe Cap	Anvil Int'l	8700132452	$5.87	
1	7 Gallon Air Tank	Cambell Hausfeld	KT070003AV	$21.76	
RAW MATERIALS FOR CONSTRUCTION USE					
# of Units	Part	Manufacturer	Product number	Price	Use
1	10 ft Braided PVC tubing 0.5" ID	Anderson Barrows	RBVLI	$4.80	
1	3 ft DOM Steel Cylinder 2" OD	(n/a)		$23.62	Cylinder
2	3' W1 Tool Steel Rod, 0.25"D			$4.72	Piston Driver
1	6' 12L14 Carbon Steel Rod, 0.5"D			$9.31	Cylinder Support rod
6	Low-Carbon Steel Rectangular Bar .25"x1"x6			$16.27	A-Frame Material
3	6 Rubber O-Ring, 2" OD, .125" thickness			$0.70	
TOTAL COST				$334.34	

Table 11. Bill of materials for design construction

The optional CO_2 Scrubber is included as well, because in large-scale compression, removal of the CO_2 will result in more methane per cubic inch, as well as a cleaner burning fuel. It is not included in our final design as a necessary portion because the two simplest methods of extraction we found require toxic, expensive chemicals or a complicated design.

Hydroxide compounds react positively with CO_2 and are consequently often used in scrubbing mechanisms for the gas. The most popular are potassium hydroxide and sodium hydroxide, which are toxic and highly reactive with water. Great care should be taken if this method of scrubbing is used, and further research into the precautions that should be taken in dealing with the chemicals should be completed (another reason for not implementing it in a small scale setting). These chemicals are, however, available commercially and a special blend called Sodasorb [23], which is used in SCUBA systems and industrial applications, and can be ordered with the benefit that it changes color from white to purple as the capacity of absorption is exhausted.

The setup for the absorption mechanism should be similar to that of the H_2S scrubber, where the various hydroxide particles fill the volume of a jar or container, the sealed inlet tube reaches to the bottom of the jar, and the sealed outlet tub reaches just beyond the rim of the jar or container. Potassium hydroxide pellets can also be used in this set up. This scrubber should be attached inline between the H_2S scrubber and the compression system inlet.

Recommendations for scaling and alternative materials are fairly general. The design presented here covers the demands set for the scope of this project. It can easily be scaled up or down dimensionally, or by adding or removing cylinders. Generally the scaling will be linear, so unforeseen problems should not arise based on scaling. It should be said that prior to construction however, the Parameter Analysis section should be reviewed, and the equations and methods provided should be used to analyze the proposed scaled system. Additionally, increased weight and or applied force should be considered in the A-frame design.

For the design presented, the materials suggested are also those, which we found to be readily available; however other materials can also be used. For example, scrap metal can be used to construct the frame, but care should be taken to insure that it will be strong enough to endure forces applied. Additionally, for the cylinder we tried to find tubing that has a relatively finished interior surface and a reasonable cost. If DOM steel cannot be found, copper tubing has a sufficient inner surface finish. Black pipe or other steel pipe varieties can also be used, however the interior should be refinished so that it is smoother. PVC plastic piping should not be used in most cases, as the pressure rating provided is for comparably low ambient temperatures compared to the target region of the Philippines.

The valve systems and scrubbing systems are not necessary parts of the design if only a very simple compressor is desired. The cylinder should still be connected using brass hose barbs, and a system of Tees and nipples should be used in order to connect the cylinders to the inlet and outlet. This method would not include the ball valves, which allow for the variable volume option of our original design. The inlet of the valve system can also be directly connected to the digester, however we strongly recommend scrubbing H_sS, as it is highly corrosive to cooking systems.

FABRICATION

The entirety of our prototype was fabricated using very conventional and accessible tools. Our prototype design is a DIY project. With care, the final compressor can be constructed with tolerances that allow efficient compression.

Our design employs the use of three piston-cylinder pumps to compress the available biogas. All piston-cylinder descriptions on fabrication must be completed three times for compliance of our prototype design.

The pistons were constructed from 14-gauge mild sheet steel. Using a metal band saw, two 1.81" diameter and one 1.7" circle were cut out of the sheet. This was done using a compass. The circles were cut erring on the side of excess and then ground to the proper diameter using a pair of Vice-grips and a pedestal grinder. Any burs or rough edges left from grinding were then smoothed using the pedestal grinder and the wire wheel attachment for it. A file could be substituted for lack of a pedestal grinder. The two large circles then had 3 holes drilled approximately 1.25" equally spaced from the center. Once the pieces were drilled, the center was marked on each circle and the circles were clamped together, with the smaller diameter circle in the middle of the larger two. The workpiece was then clamped into a suitable vice, grounded, and TIG welded at the holes on top and bottom to fasten the three pieces together, this is in lieu of a resistance spot welder. Finally, one 3/8" hole was drilled in the very center of the plunger. Also, two 3/8" holes were drilled in the disk, one on each side from the center hole, approximately 0.5" from the edge of the center hole.

The piston rod was fabricated from 3/8" mild steel rod. The piston rod was cut down to a length of 18". The piston rod was inserted until it was flush with the flat plane of the piston and then TIG welded in place, making sure to create airtight seals. To limit the travel of the piston, two 3" pieces of 3/8" rod will be inserted into the 3/8" holes to the side of the center hole and TIG welded at the center. These will act as stoppers to keep the piston from traveling into the cast iron end caps. They will be inserted into the 3/8" holes until approximately ½" is sticking out from either end. A picture of a finished plunger can be seen below in Figure 16.

Figure 16. Completed plunger with O-ring securely seated and stoppers added.

The cylinders were constructed from 12" sections of DOM pipe cut to length using a band saw. Because the pipe had a slightly smaller inner and outer diameter than standard 2" black pipe that our fittings were dimensioned for, somewhat unconventional methods were used to produce threads on either end. Three 2" close nipples were cut directly in half, producing two threaded pieces that were compatible with our cast iron fittings. Each one of these threads were de-burred and then cold welded to the ends of the 12” DOM pipe sections using JB-WELD. Conventional welding’s HAZ creates oxidation that will ruin the inner surface finish of the DOM pipe as well as causing distortion that might inhibit a proper seal. Care was taken to preserve the threads during both cutting and cold welding.

2” threaded cast iron end caps will close the cylinder for our system. To allow the piston rod to move in and out of the cylinder, one end cap was drilled with a 3/8” hole using a drill press. Another hole, ¼” in diameter, was drilled on one side of the end cap to prevent a vacuum from forming during compression and also provide an inlet for lubricating the piston. The other end cap was drilled and tapped using a ½” HSS twist drill bit and a ½” standard NCT tap. A 3/8” hole was drilled on the very outer edge of the same end cap and threaded with a standard 3/8” NCT tap. A picture of the cylinder, end cap, with inserted hose barb can be seen below in Figure 17.

Figure 17. End cap with hose barb and sleeve attached.

To allow both the plunger and the cylinder to rotate freely throughout the entirety of the displacement, sleeves had to be secured to each end that would fit snugly over the ½” steel rods. The sleeves were constructed from 4” segments of ½” ID steel pipe cut to length on a bandsaw. To secure the sleeves on the end of the plunger rod, a 3/4” inner diameter hoop was bent into the end of the rod. Before this was done, the end cap with the 3/8” and ¼” holes was inserted onto the rod and allowed to rest on the stoppers of the plunger. Then the hoop was bent; this was accomplished using an oxy-acetylene torch and pliers to heat the steel to increase its’ ductility and then bend the circle in. Once the circle was formed and cooled, the 4” segment of pipe was centered into the circle and TIG welded in place. Because the end cap for the cylinder assembly is cast iron, the steel sleeve could not be welded directly to it. A 4” piece of the 3/8” rod was cut, the end bent into a ¾” inner diameter circle using the same method as before, a 4” piece of ½” ID steel tube welded to the inside of the circle, and the end of the rod threaded using a 3/8” standard NCT die. The threaded end of the rod is then screwed into the 3/8” tapped hole on the cast iron end cap and the threads are sealed with JB-WELD. This created a strong airtight seal. These are pictured in Figure 18, below.

Figure 18. Sleeves for the cylinder to rotate freely on the lever arm and frame.

Once the piston/cylinders were completed the frame was constructed. The detailed CAD drawing of this system can be seen in Appendix D. The frame and lever arm were made from ¼" thick by 1" wide mild strip steel (1018) and was welded together according to Figures 9 and 10. The welding was accomplished using a 110V portable MIG welder with 75/25 argon/CO_2 shielding gas. The frame itself is stationary but the lever arm as well as the piston/cylinders will not be static. All of the frame should be welded together except for the three ½" solid steel rod that the piston/cylinder assembly and lever arm rotate on, see Appendix D for reference. The lever arm had ½" holes drilled at the ends and slid on the ½" rod. Then the rod was welded in place. Before welding the other two rods in place, the plungers and end caps were slid on the upper rod and the cylinders and end caps were slid on the lower rod. To facilitate this, it was easiest if the plunger and cylinder were separate at this point. Once the piston/cylinders were aligned properly on both the frame and lever arm, both rods were welded in place. Before the valve assembly was attached the frame, lever arm, and any nonmoving parts were sprayed with no-rust enamel paint. The moving joints were generously lubricated with the same hydraulic oil used in the cylinder. Our painted prototype is shown in Figure 19, below.

Figure 19. Prototype painted with "no-rust" enamel paint to prevent corrosion.

After the frame was complete with the cylinders in place we began assembling the hose, fittings, and valves necessary for the system. A complete schematic of our setup can be seen in a later section, The Pumping Mechanism. We connected the fittings and valves via close nipples and Teflon tape. All of our fittings and hoses are ½” in diameter. The pistons were connected to the valves and pressure vessel via a ½” hose barb that connects the 2” cast iron end cap that was drilled and tapped, to the brass inline valves. This connection was made using a ½” hi pressure, nylon braided PVC line. The PVC lines were connected to the hose barbs using stainless steel hose clamps, and were tightened with a standard screwdriver. A Schrader valve was connected to flexible, high pressure hosing and used to connect the valve assembly to the actual pressure vessel. A close nipple, ½” to ¼” hose barb was used to connect the high pressure nylon braided PVC line to the smaller hosing the Schrader valve was on. This valve setup rests on a 27” tall wooden platform that was constructed using ¾” plywood. The valve setup can be seen in Figure 20, and the final valve setup in its entirety is shown in Appendix G.

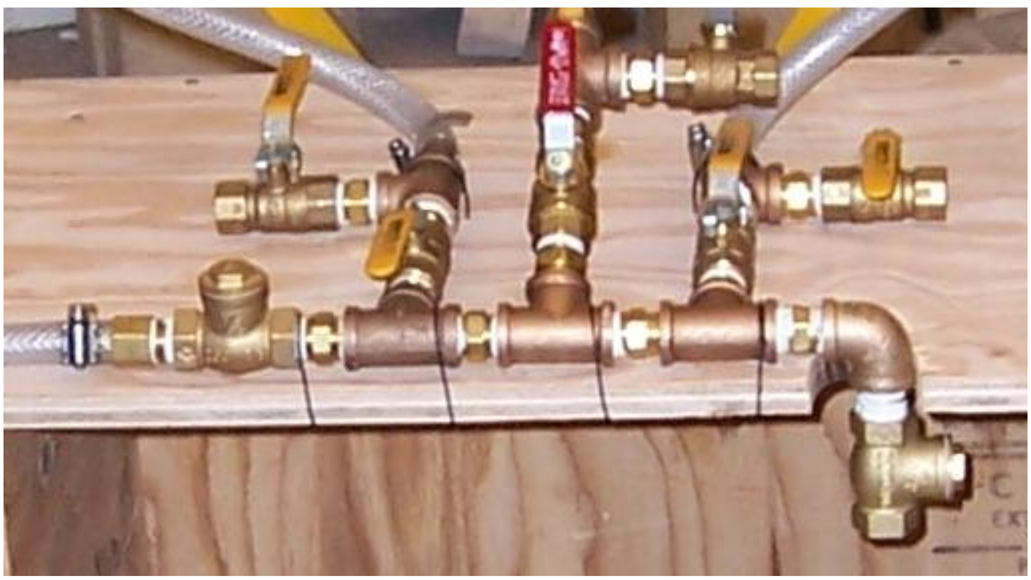

Figure 20. Valve setup for the all three piston-cylinders.

To create the hydrogen sulfide scrubber for the inlet of compressor, we utilized a standard mason jar with a tight fitting lid. We drilled two holes, the size of the outer diameter of the high pressure PVC hose, in the top of the lid. Then the hoses were inserted through the top of the lid, as described literature search above, and caulked to form an airtight seal. The jar was then filled with steel wool and the cap resealed. A picture of the finished H_2S scrubber can be seen in Figure 21.


Figure 21. H_2S scrubber and associated hosing.

For our prototype design most tolerances need to be relatively tight since we are dealing with compressing gas. The piston must be have a tight tolerance so that it can easily travel within the DOM cylinder, yet also hold the O-Ring very securely. This seating of the O-Ring is crucial in attaining a proper seal that will allow the biogas to be compressed. All of the fittings, valves, and hoses must be secured together using Teflon tape to create strong, airtight seals. Biogas is combustible and a greenhouse gas, hence every measure was taken to prevent leaks. User safety is of the utmost importance, so all welds, joints, and fittings need to be properly done as well as critically evaluated once after the compressor is built. Although we only produced one prototype, our design was fabricated using conventional and appropriate techniques. A discussion of this can be found in Appendix I.

VALIDATION

As the final step in our design process, we performed tests to insure that our constructed prototype met the specifications that were laid out at the beginning of the design process. A list of these requirements can be seen in Table 1. Many of these targets did not require any experimentation and could be evaluated by simple inspection of the final design. For example, having a $400 price goal requires simple addition of the costs of each of the components. Other specifications that do not require experimentation include: using standardized fittings, implementing human power, and using an air tank with a certain capacity.

Some requirements involved extensive calculations to predict whether the specification would be met. Pressure vessel safety, compression pressure, and compressor efficiency were all calculated and determined to be well within the specifications given by our sponsor. To validate the strength of the A-frame, an FEA model was created to verify that the design can handle the locations of high stress, as can be seen in Figure 11. Additionally, we are including H_2S scrubbing as a part of our system. Based on a literature search, the addition of an H_2S scrubber will serve the intended purpose as it is a very established art.

The remainder of the specifications set forth by our sponsor needed either minimal testing to verify or required that our final prototype was constructed to perform the tests. A list of these remaining specifications can be seen below in Table 12, below, along with the way that they were tested for, and whether or not they were actually achieved by the prototype. To verify the compression time, each group member operated the prototype and recorded the pressure at 30 second intervals. 25 psi is achieved relatively quickly, with 35 psi being achieved within the 10 minute specification, as can be seen in the two compression curves in Figure 22 on the following page. After testing, we feel confident that all of our specifications have been met, verifying the validity of our design.

Specification	Validation Method	Achieved?
Off the shelf materials	Purchased common materials from 1 hardware store	Yes
Tank pressure/weight	Utilized a tank with the required ratings	Yes
Time to stroke to capacity	Pumped with the Blackburn, achieved in 5-10 minutes	Yes
Lifespan of materials	Used durable steels & cast iron to easily last 10 years	Yes
Ease of construction	No special assembly methods, easily achieved by 5 people in < 20 hours	Yes
Compression to 35 psi	Achieved with normal pumping in < 10 minutes	Yes
Compression time/stroke #	Tested final prototype, achieved 25 psi in < 5 minutes and 35 psi in < 10 minutes, ~20 strokes/min	Yes

Table 12. Validation table for engineering specifications.

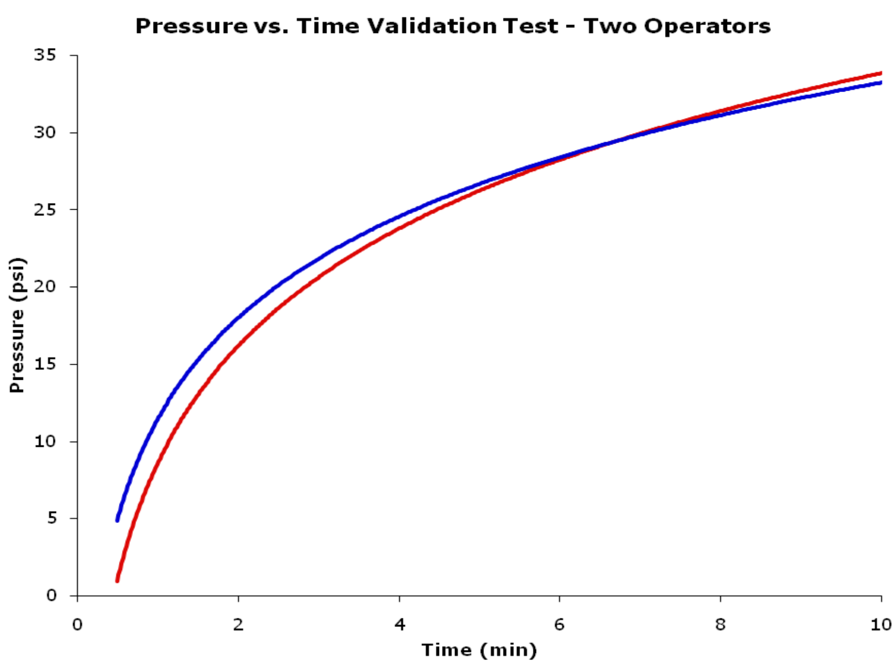

Figure 22. Compression with prototype for two different operators, taken at 30 second intervals.

BUDGET

We had an expenditure limit of $400, which is meant to cover all aspects of the project. We were able to obtain more funding however, through proposals to our sponsor for increased funding during our testing phase. During the course of the semester, we spent $598.56, which was over budget because of the high cost of our testing phase, and miscellaneous costs incurred from learning the fabrication method.

For testing, we believed that it was necessary to fully understand the current compression mechanism in different bike pumps available on the market. Therefore, we purchased two different hand pumps, a foot pump, a dual stroke pump, and a seven gallon air container. As the Blackburn Airtower 5, our dual stroke pump, was one of the best hand compressors on the market, the total bill from our testing phase was $173.28.

To fabricate the valve system of our prototype, we made a schematic of the system, as seen in Figure 12, and then drove to Stadium Hardware to purchase the appropriate pipes, connections, and tubing. The bars of 1010 steel for the A-frame were purchased directly from Alro Steel, while the smooth DOM pipe was ordered from an online distributor. The total cost of fabricating the prototype was $425.28, but as there were miscellaneous costs related to learning the details of assembly, we are confident that the compressor can be constructed for $350 with the parts outlined in Table 11.

SUMMARY AND CONCLUSIONS

Design critique After construction, our prototype verified that our design was marketable to developing countries. The plungers' O-ring seal was sufficient with no leaks and compressed the gas to high pressures as we had predicted. It was relatively easy to compress the tank to 25 psi, with 35 psi still attainable within the 10 minute specification from our sponsor. While we required additional money for testing purposes, the compressor can be constructed for around $350 from common parts at any hardware store.

While successful, there were a few things that could have been improved with our final prototype. The A-frame was a bit too large and therefore it was difficult to achieve a full stroke to the maximum height. As stated previously, the A-frame can be scaled to the size of the anticipated user. The frame wasn't stationary, and would vibrate or rock if it wasn't firmly held in place by sandbags. However, in a real application the frame could easily be staked down, sandbagged, or made stationary through other means. The biogas compressor isn't meant to be moved often, so in some circumstances it might be desirable to permanently fix it to the ground. While pumping at very high pressures, the center rod was bending noticeably, although our calculations showed that it wasn't close to yielding. A pair of supporting steel strips would reduce the bending significantly.

Recommendations Because of the success of our prototype, we recommend that our design be implemented with an actual biogas digester. We were not able to test the H_2S scrubber, but it is an existing technology that is required for safe operation of our design (e.g., to ease compression and protect cookware). Also, if possible, the gas in the tank would be more energy efficient if a CO_2 scrubber was incorporated into the process, as mentioned above, but this is neither a necessary nor cost effective addition.

Before widespread installation, we recommend drafting an instruction manual to inform the users how to operate the on/off valves, as well as inform them of the possible dangers when compressing biogas. Appropriate safety warning stickers (detailed in Appendix H) should also be included, in addition to those already in place, for those nearby when the pump is in operation.

To address the A-frame size, it could be improved my making it shorter, which would lower the center of mass and reduce vibrations. The stability can be corrected by anchoring the frame to the ground or weighing down the edges, as we chose to do with sandbags. The bending center rod could be corrected by using a thicker bar, or supporting it with additional welds to the frame.

This design team also recommends painting the final product with “no-rust” paint. It is strongly recommended that maize and blue be used as opposed to colors like scarlet, grey, white, and green.

Conclusion To better utilize the energy source that is provided by biodigesters, we designed a system that is able to compress biogas from a biodigester in developing communities using an off-grid power supply. After extensive research and meetings with the BLUELab group, our initial sponsor, we determined that this system must use off-the-shelf materials and be easy to assemble. In addition, since methane is the fuel source, our design must scrub the biogas of other gases, specifically hydrogen sulfide that is corrosive to steel. We have also suggested the possibility of carbon dioxide scrubbing, as well as using a splitter to allow a compression line and a direct feed line from the biogas reservoir. We were tasked to create a system that is simple, safe, and cost under $400 to create, all of which has been accomplished.

After exploring many options of physical input, we determined that the most feasible compression method is a piston-cylinder system, similar to a bicycle pump. We also determined that a standard air tank is ideal for this application because it is easily available, inexpensive, portable, has standard fittings, and will resist corrosion from the biogas better than other types of standard tanks. After testing several bicycle pumps with varying pressure ratings, we determined that it is feasible to pump the 7 gallon tank to 35 psi, which will provide users with approximately 6-8 hours of cooking and heating. Results of testing caused us to focus on a multiple-chamber model to achieve high volume at the desired pressure in the fewest number of strokes. This should also allow us to add a high pressure mode in which the user can shut off a chamber for less volume displacement and easier compression. We also incorporated a mechanical advantage through the addition of a long lever on the pump to aid the operator during compression

Our final design was fabricated using very simple and conventional construction processes. The plans for our prototype will be available in a Wiki for anyone to access. It was constructed in a very reasonable amount of time (<20hrs.). Also, the cost of our final prototype will be below $400 dollars when assembled according the plans outlined in this report.

Our design and final prototype worked extremely well and we were able to validate it through heavy testing. We feel that our design is ready to go on to the next stage and be implemented in applicable situations. Hopefully, because of the practicality and success of our project, developing countries will be able benefit from our design.

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- Stadium Hardware – Ann Arbor, MI
- Zach Jacobson-Weaver of UM's Sculpture Studio

Thanks so much for everyone's dedication, focus, and hard work!

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Note: All patent information was found using www.uspto.gov

APPENDIX A: Detailed Results of Pump Testing

Blackburn Air Tower 5:

Note: Switched to high-pressure mode at 100 strokes (≈ 40-45 psi)

Team Member	Results
Dave	Resting HR: 80 beats/min Final HR: 115 beats/min Total strokes to 50 psi: 146 Observations: Veins visible at 23 strokes, achieved 40 psi in 90 strokes.
Adam	Resting HR: 60 beats/min Final HR: 85 beats/min Total strokes to 50 psi: 140 Observations: Achieved 40 psi in 90 strokes.
Tim	Resting HR: 75 beats/min Final HR: 125 beats/min Total strokes to 50 psi: 138 Observations: Stated he was tired at 34 strokes which was 21 psi.
Jess	Resting HR: 85 beats/min Final HR: 145 beats/min Total strokes to 50 psi: 148 Observations: Began breathing hard at 40 strokes, arm muscles tired.
Alisyn	Resting HR: 75 beats/min Final HR: 160 beats/min Total strokes to 50 psi: 163 Observations: 25 psi at 55 strokes, 31 psi at 75 strokes.

APPENDIX B: Lubrication properties

Typical properties of Mobil 10W hydraulic oil are detailed in the table below.

Mobil Delvac Hydraulic 10W	
SAE Grade	10W
Viscosity, ASTM D 445	
cSt @ 40ºC	37.7
cSt @ 100ºC	6.1
Viscosity Index, ASTM D 2270	107
Sulfated Ash, wt%, ASTM D 874	0.5
Total Base #, mg KOH/g, ASTM D 2896	4.0
Pour Point, ºC, ASTM D 97	-30
Flash Point, ºC, ASTM D 92	232
Density @ 15ºC kg/l, ASTM D 4052	0.877

Table B1: Properties of Mobil 10W hydraulic oil [24]

APPENDIX C: Parameter Analysis

Cylinder Size:

This is a conservative calculation done for 1 cylinder at 50 psi. We will have at least one cylinder working, and we never expect the pressure to exceed 50 psi.

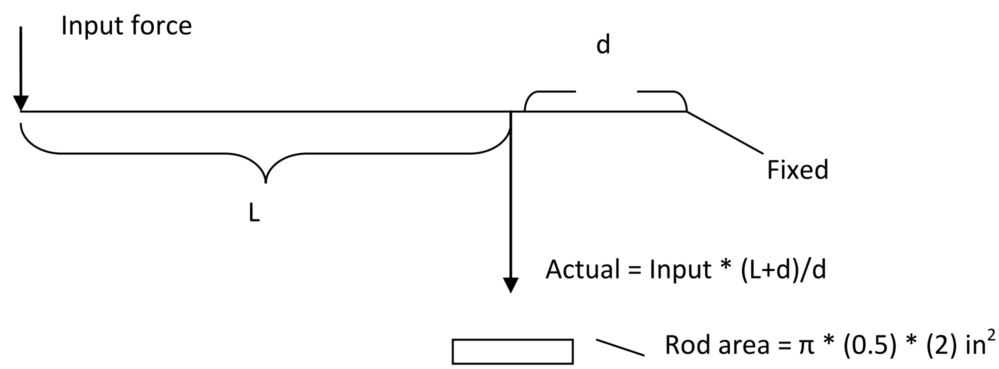
Volume of biogas to be compressed: 55 L = 14.5 gal
Potential volume of 1 cylinder: $\pi * (D_i^2/4) * l$
D_i: guess 2 inches
L: guess 12 inches
Stroke rate: 1 stroke in 3 seconds = 100 strokes in 5 minutes
Goal: Compress 14.5 gal of biogas in 5 minutes

Volume seen by proposed cylinder in 5 minutes = $100 * \pi * (2^2/4) * 12 \text{ in}^3 = 3{,}770 \text{ in}^3$

$3{,}770 \text{ in}^3$ = 16.3 gallons (> the needed 14.5 gal)

This is greater than the needed 14.5 gallons, so this works. We do need to investigate the stroke rate, as no similar compressor exists on the market. However, given the conservative nature of this calculation, we can feel confident continuing.

Simple model of lever arm and rod supporting 3 cylinders:



(L+d)/d:

Max input force: 300 lb
Min input force: 30 lb
σ_Y steel rod: 44,000 psi

Max force on rod (lbs) = 300 * (L+d)/d
Area of rod (in^2) = diameter of rod * outer diameter of cyl * 3 cyl = (0.5 in) * (2 in) * 3 = 3 in^2

Max stress on rod (psi) = (Max force on rod) / (Area of rod) = 100 * (L+d)/d

(L+d)/d = (44,000) / (100) = 440

This is an ***upper limit*** for (L+d)/d. Obviously, it would be outrageous to have L 440 times longer than d.

Min force required to compress 3 cylinders = 3cyl * P_2 (V_i-V_0) = 1560 lb-in
P_2 = 50 psi, this corresponds to the maximum amount of pressure expected in the storage tank
$V_i = \pi * (D_i^2/4) * l = 10.4\ in^3$ = Volume of a full cylinder
D_i = 1.87 in
l = 12 in, in order to get a ballpark number for (L+d)/d this estimate was made using engineering judgement. It really won't matter what this is set to, as long as the rest of the dimensions are set to accommodate for this.

Assuming that the weakest person can only apply 30 pounds input force, or 30 * (L+d)/d pounds actual force, through 12 inches,

(L+d)/d = (Min force to compress 3 cylinders) / (30 lb * 12 in) = 4.33

This a ***lower limit*** for (L+d)/d.

(L+d)/d is assigned the value of **5.35**, which is close to the lower limit value. The calculation for lower limit (L+d)/d was done very conservatively in that it was assumed that the tank would have 50 psi in it during each stroke. The design team never expects the tank to need to be compressed over 50 psi. Compression will be much easier during the initial, low pressure stages of compression. Therefore, the lower bound value of 4.33 for (L+d)/d already has a very conservative safety factor associated with it. (L+d)/d was found in combination with theta and the other dimensions. They all need to be cohesive.

Given a high input force, will the moment arm fail?

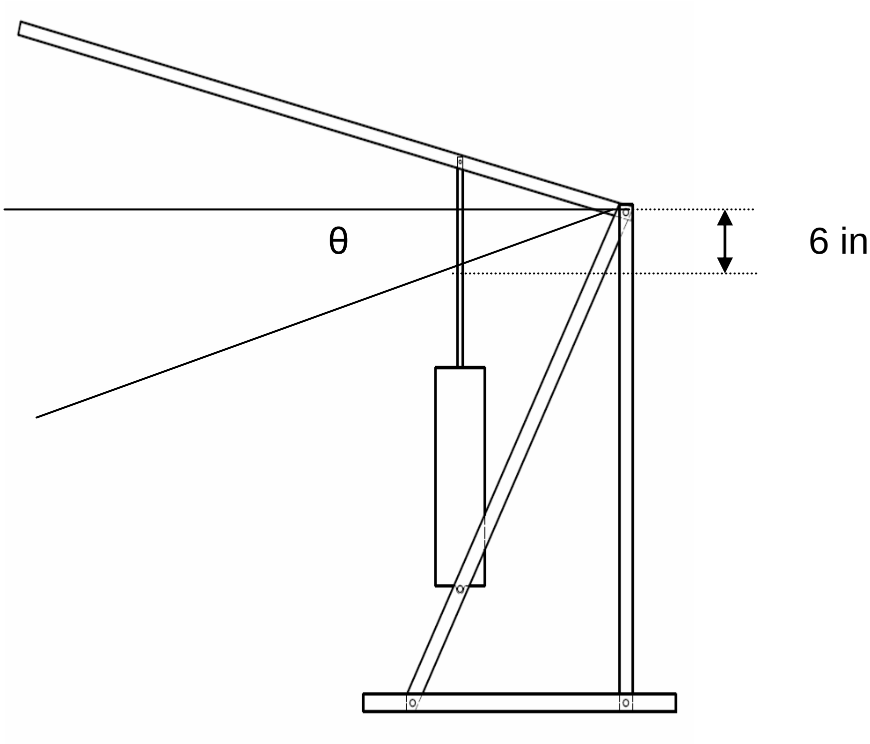
Max input = 300 lb * 5.3 = 1600 lb
σ_Y steel rod: 44,000 psi

Minimum area for the moment arm to not fail = 1600 lb / (44,000 psi) = 0.036 in^2

We expect the cross sectional area to be at least this big, if not at least 10 times larger.

Choosing theta to be 45°

For the piston to completely traverse the cylinder, the perpendicular distance from the connection point of the plunger to the axis of rotation, shown below, must be six inches.



It is also noted that theta should be as close to zero as possible to ensure more of an up and down compression stroke as opposed to a back and forth stroke. Also, theta was limited by the height of the stand (the lever arm hitting the ground if too long) as well as how low the lever arm should hover above the ground. That said, the design team hypothesized that θ would be near 45°.

For $\theta > 45°$:

$(L+d)/d = 5.3$

The lever arm would be situated at an angle that is almost straight up and down when resting at the bottom of the stroke. Say, if θ = 60°, the lever arm would be oriented at 60° with respect to the ground. This would mean that the frame would have to be tall and narrow, making in instable. Also, this would require more input from the user to complete each stroke.

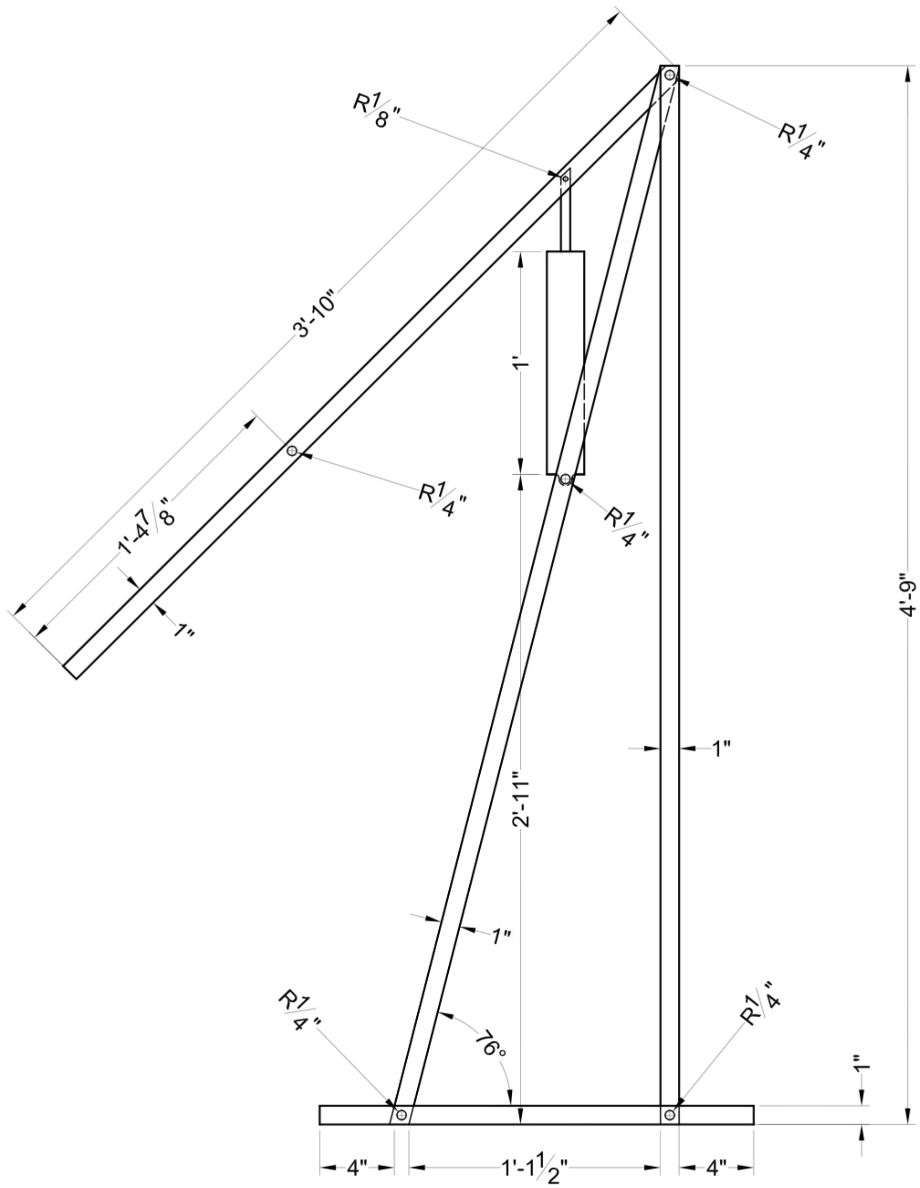
If $\theta < 45°$:

Say if θ = 30°, the connection of the plunger to the lever arm would have to be 10 inches or more away from the axis of rotation, making the lever arm distance on the order of 55 inches. This added distance isn't justifiable, because the same mechanical advantage can be achieved using less steel.

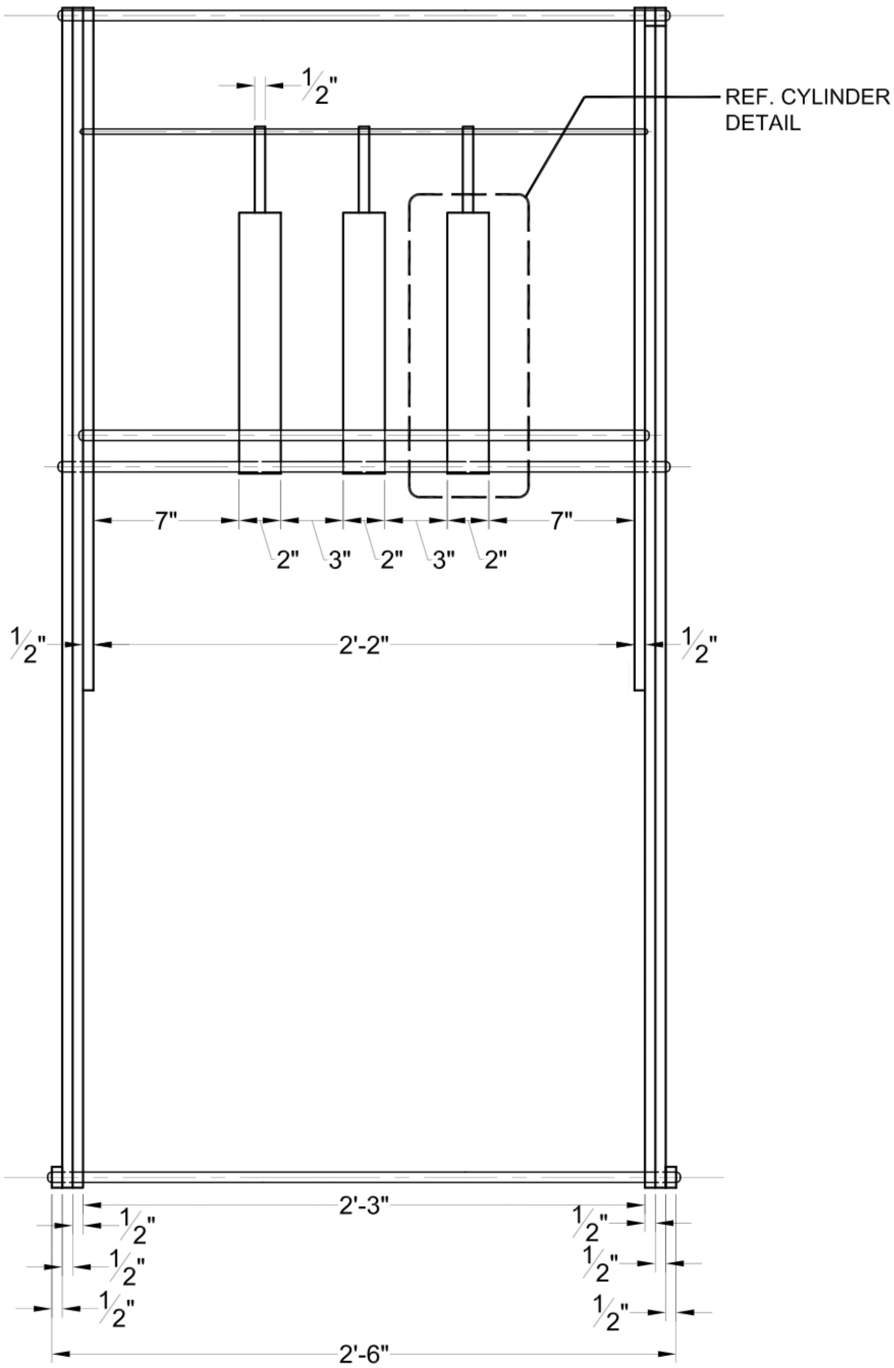
Based on the problems associated with making theta greater than or less than 45 degrees, theta was set to 45 degrees.

APPENDIX D: Dimensioned drawings of A-frame and cylinders

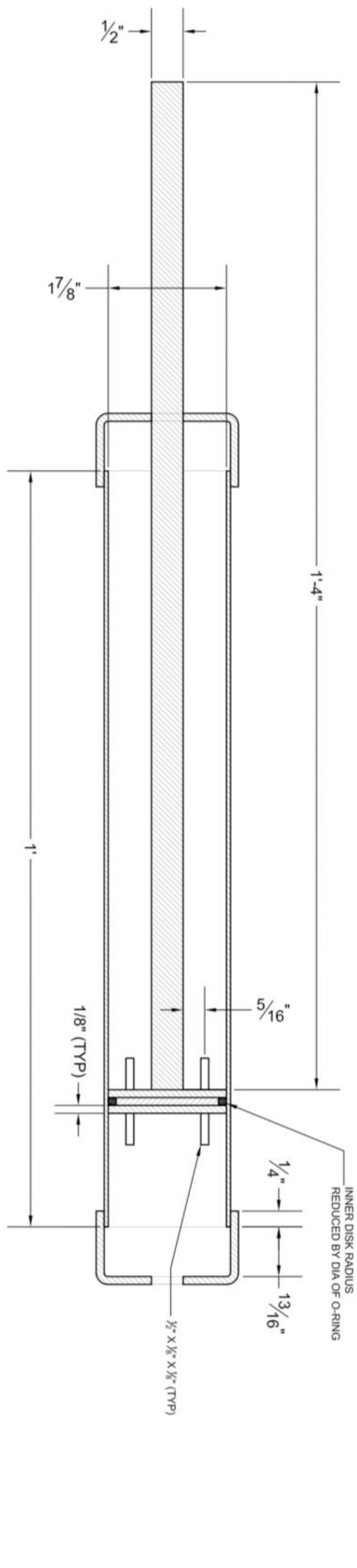
Right View:



Front View:



Cylinder Detail:



APPENDIX E: Material Selection

This Appendix entails the material selection process for two most important components of the biogas compressor: the frame that holds the three piston-cylinders and the actual cylinders.

Compressor Frame

The function of the compressor frame is to support the three cylinders as the gas inside of them is compressed. The frame should be able to withstand very high amounts of stress and should be able to withstand that stress given a very generous safety factor. The pieces of the frame need to be joined together in a way that keeps the integrity of the material, and the material's properties, intact. That is, all components of the frame should be made of the same material. For example, if wood were appropriate for the frame, the entire frame would need to be made of wood for purposes of joining (e.g., nailing and screwing). Likewise, if steel were chosen, the entire frame would need to be steel in order for the different pieces to be welded together. The chosen material must be very accessible, as noted in our project specifications. It must also be machine-able (e.g., diamond has an extremely high yield strength but is not easily machined).

The frame is most likely to fail in shear – explained in the engineering parameter analysis section, above. As shown in the Figure 11, a FEA was used to quantify the amount of stress at every location in the frame. As mentioned in the parameter analysis section of this report, the material for the frame should not have a yield strength smaller than 44ksi. The material should also be as inexpensive as possible. It can be predicted that as the yield strength of a material increases, as does the cost. Therefore, one could also foresee that the material of best fit for the frame will have a yield strength near 44 ksi; it shouldn't be much higher than 44 ksi order to keep material cost as low as possible. The CES Edupack was used to generate Figure E1, below, which is a plot of material price versus yield strength for bulk materials. All AISI steels show a high yield strength for a low cost.

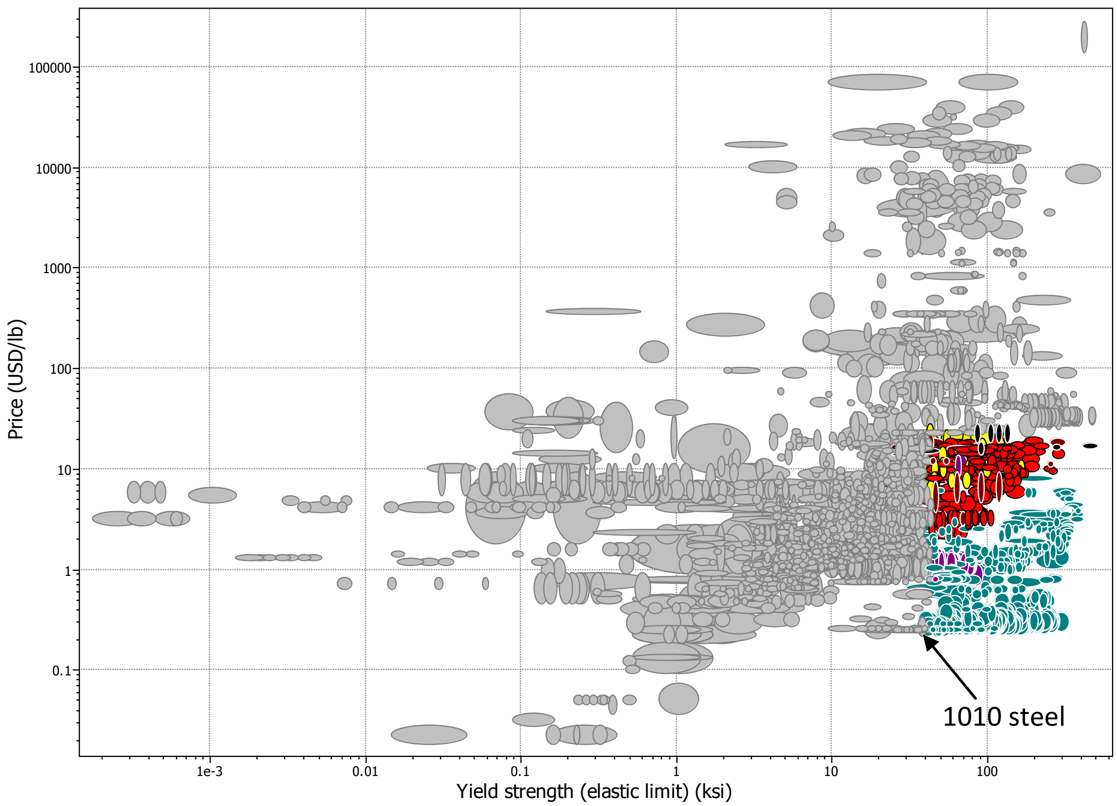


Figure E1: Price ($USD/lb) versus yield strength (ksi). 1010 steel has a low price and an appropriately high yield strength. It is also weld-able, machine-able, and easily accessed.

Based on the results of the CES software (shown in Figure E1), and using the logic described in the first two paragraphs, the top five choices (in order of rank, 1 being best) for frame materials are as follows:

1. AISI steels
2. Aluminum alloy
3. Bronze
4. Nickel-Silver alloy
5. Copper

Using the CES software it is easy to choose AISI steels as the material for the compressor frame based only on cost. Digging deeper, AISI steels become an even more attractive candidate for the frame material. AISI steels are very machine-able and weld-able. [E1] It is also noted that AISI steel is listed as “Above average” with respect to durability and “Good” with respect to rust resistance according to the CES Edupack. Knowing that AISI steels are weld-able, machine-able, and durable the two factors important to choosing a type of steel within the AISI steels are cost and yield strength. At a local steel supplier, Alro Steel, it was discovered that AISI 1010 and AISI 1018 were the two cheapest and most commonly carried steels. AISI 1010 steel was cheaper than 1018 (about half the price) and met the minimum yield strength requirement of 40 ksi with a yield strength of 44.8 ksi. AISI 1010 steel is the best option for the compressor frame because it can withstand a large shear stress, is cost-effective, weld-able, machine-able, and easily accessed.

Compression Cylinders

The function of the compression cylinders is to contain gas that is to be compressed while not impeding the compression process. The ideal cylinder will allow a piston to move up and down the inside of the cylinder with minimal resistance. The ideal cylinder will have an associated hoop stress (or pressure rating) large enough to withstand the pressure created inside of the cylinder given a generous safety factor. The cylinder should also be low cost, accessible, and machine-able (similar to the compressor frame). The ideal cylinder will also have as low a thermal coefficient of expansion (α) as possible. That is, when the temperature of the cylinder changes, its volume will change minimally.

As explained in the engineering parameter analysis section, the pressure in the cylinder is never expected to exceed 50 psi. That said, extreme temperature fluctuations can cause the cylinders to experience a larger pressure than 50 psi (~100 psi or more). When considering the pressure rating given to a specific type of cylinder, it is important to consider what temperature range that pressure rating is for. That said, the ideal cylinder will have a pressure rating of at least 200 psi in a temperature range of 65 to 95 °F (the average high and low temperatures for the Philippines [E2]). As said in the previous paragraph, when choosing a compression cylinder it is also important to maximize the smoothness of the surface finish, minimize cost, maximize accessibility, maximize machine-ability (the cylinders will need to be cut to length), minimize material weight, and minimize the coefficient of thermal expansion (α). As is shown in equation E1, below, the coefficient of thermal expansion needs to be minimized in order to ensure that the cylinders do not significantly expand during compression.

$$\Delta V/V_o = \alpha \cdot \Delta T \qquad \text{(Eq. E1)}$$

Using the CES Edupack, research on differing types of pipes, and talks with technical experts (at hardware stores, material suppliers, and the machine shop) were used to generate the following list of the top five choices. In order to narrow down the list into 5 types of piping, the accessibility of types of piping was assessed at local hardware stores. For things like "surface finish," which aren't quantifiable, good engineering judgment was used. For quantifiable items, McMaster-Carr, Kalpakjian/Schmid, or the CES Edupack was used. Table E1 shows the top five choices for compression cylinders in order of rank (1 being best) and the breakdown of individual rankings (1 being best) to show the reason for the overall ranking.

Cylinder material	Cost rank	Surface finish rank	Thermal expansion rank	Machine-ability	Pressure rating within temp. range	Material weight
1. DOM steel pipe	1	2	1	3	1	3
2. Cast iron pipe	2	5	3	2	2	2
3. Copper pipe	5	3	2	5	3	5
4. Brass pipe	3	4	4	4	4	4

5. Plastic pipe	4	1	5	1	5	1

Table E1: Rankings (1 being best) for top five compressor cylinder material possibilities. DOM steel pipe is the clear winner, consistently being atop of the other four options.

As shown above, drawn-over-mandrel (DOM) steel pipe meets all of the requirements set out for a compression cylinder. In Table E1, above, it is seen that DOM steel beets the other four choices in 3 of 6 categories. In the categories it loses, the associated winner is always an unsuitable candidate in at least one other category. DOM steel pipe is a well-suited candidate for the compression cylinder material because it is capable of withstanding pressures of over 750 psi (a safety factor of at least 15) even when threaded, is the cheapest of the five materials, has a near perfect surface finish (allowing for minimal wear on the piston and a high ease of compression), has the lowest thermal expansion coefficient, is machine-able (as explained in the compressor frame section), and is not too heavy for the frame to handle (weighing only ~1 lb. per cylinder). For these reasons, and because DOM steel pipe meets all of the requirements for a compression cylinder laid out before (e.g., accessibility, etc), DOM steel pipe is the best option for the material of the compression cylinders.

APPENDIX F: Design for Environmental Sustainability

Based on our Material Selection Analysis, there were several different material choices for constructing the A-frame. Because of on material properties, the two most likely candidates were AISI 1010 steel and aluminum alloy. SimaPro didn't have either of these materials, but the closest equivalents were "Steel low alloy ETH U" and "Al 99 I", and were therefore used in the environmental analysis.

In order to compare the environmental impact of using different metals, it was necessary to first calculate the mass of each metal that was required. Because steel has a larger density than aluminum, the dimensions of the A-frame were analyzed to determine the volume of metal required, and the results can be seen in Table F1, below.

Shape	Length Required	Volume
1"x 0.25" bar	59" x2, 46" x2, 57" x2, 24" x2, 30" x2, 48" x2	132 in^3
0.5" pipe	6" x2, 30" x2, 26" x2, 4" x3	27 in^3

Table F1. Amount of material required for A-frame base.

The total volume of metal required was 159 in^3, or 2605.5 cm^3. As the density of Aluminum is 2700 kg/m^3, with the density of steel being 7850 kg/m^3, this equates to 7.03 kg of aluminum and 20.45 kg of steel. The amount of emissions generated from manufacturing this material can be seen in Figure F1 below. That forms of emissions are separated into raw material, air emissions, water pollution, and solid waste generated.

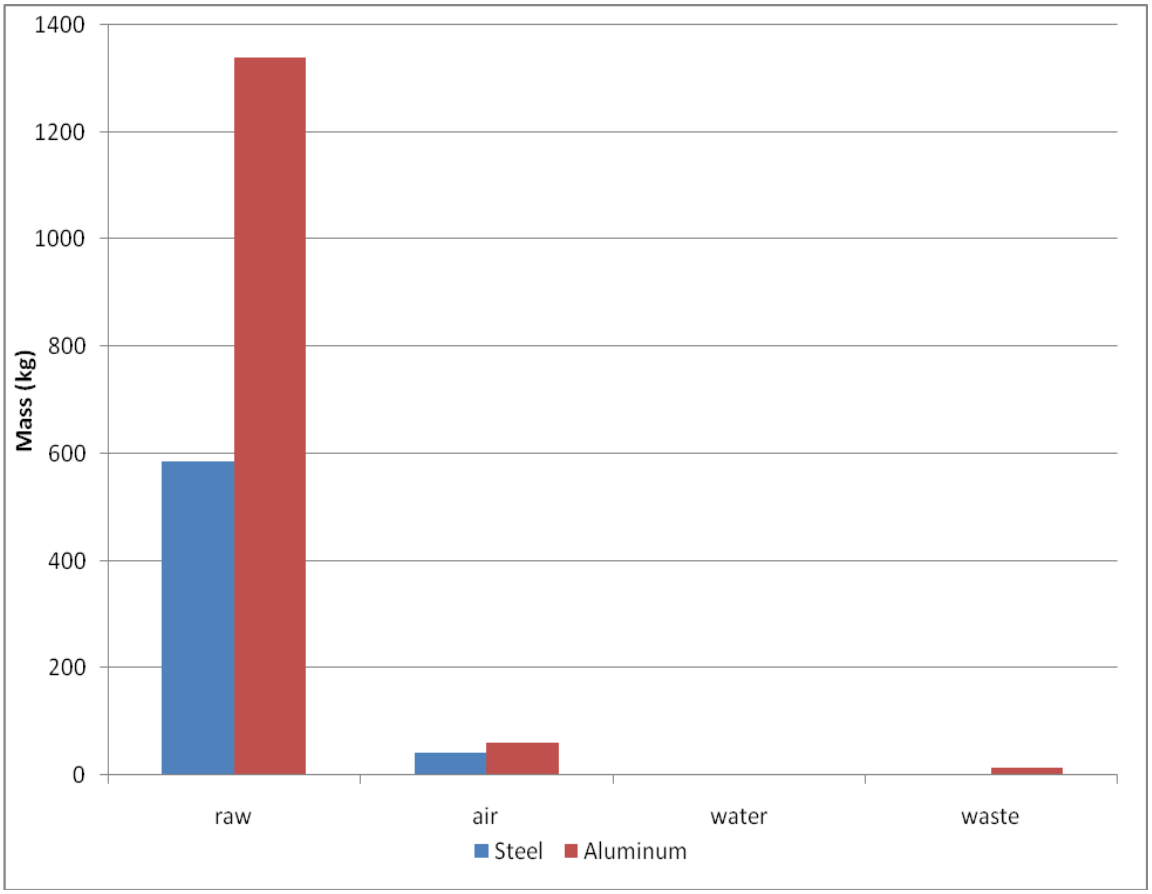


Figure F1. Emissions generated to manufacture the materials needed to fabricate the A-frame base.

For each of the emission categories, aluminum has a greater environmental impact than steel, even though a greater mass of steel is required. After running an EcoIndicator 99 analysis in SimaPro, the results were displayed graphically and can be seen in Figures F2 through F4. Figure F2 displays the relative impact of each material in terms of their disaggregated damage category. This is an easy way to visually determine how each metal compares in 10 separate environmentally impacting categories. Figure F3 compares the impacts of using the two metals in the general categories of "human health", "ecosystem quality", and "resources", with Figure F4 directly comparing the metals with the sums of these categories.

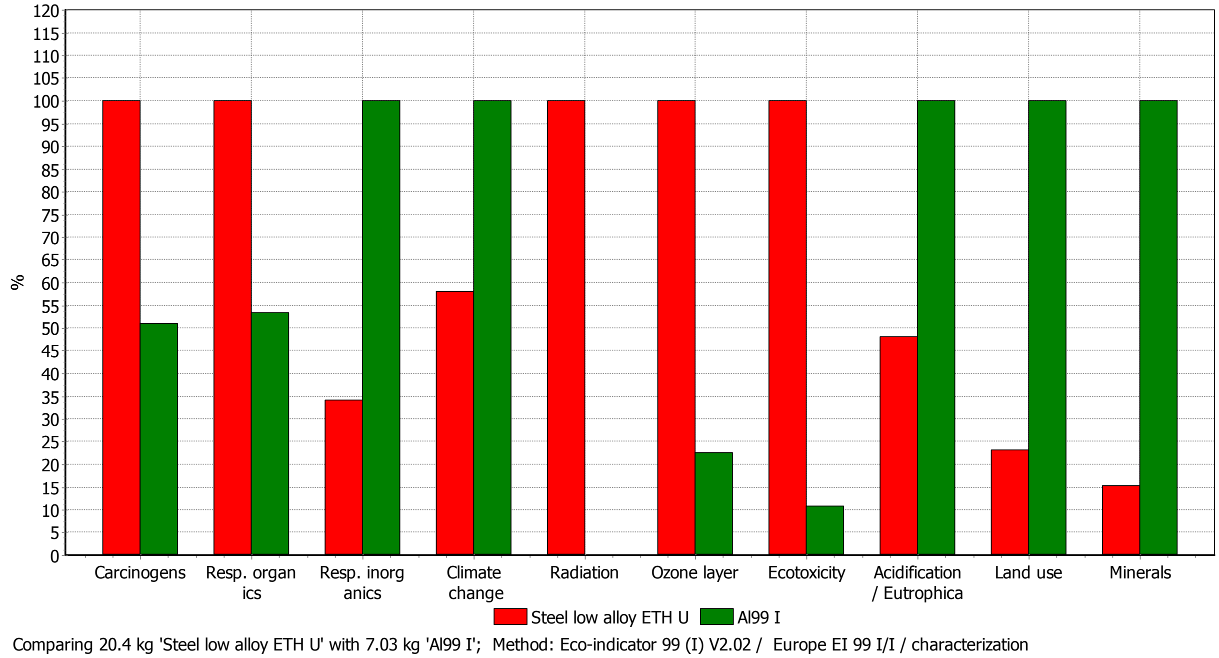


Figure F2. Material impact in disaggregated damage categories.

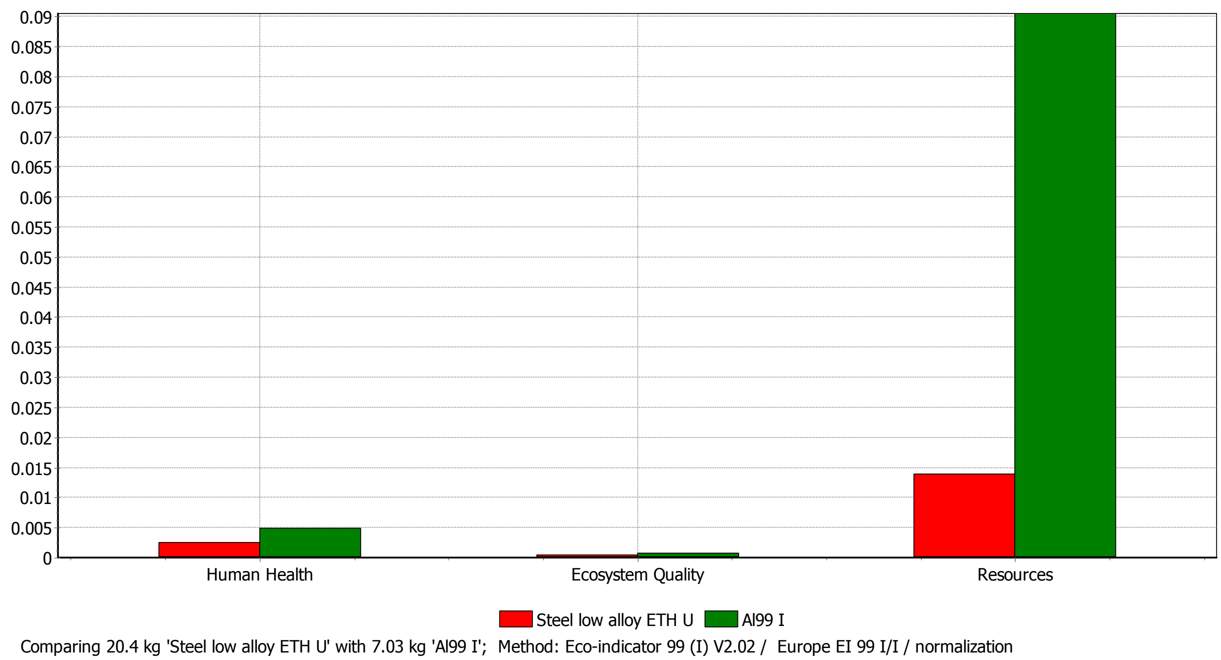


Figure F3. Material impact in normalized scores for human health, ecosystem quality, and resources.

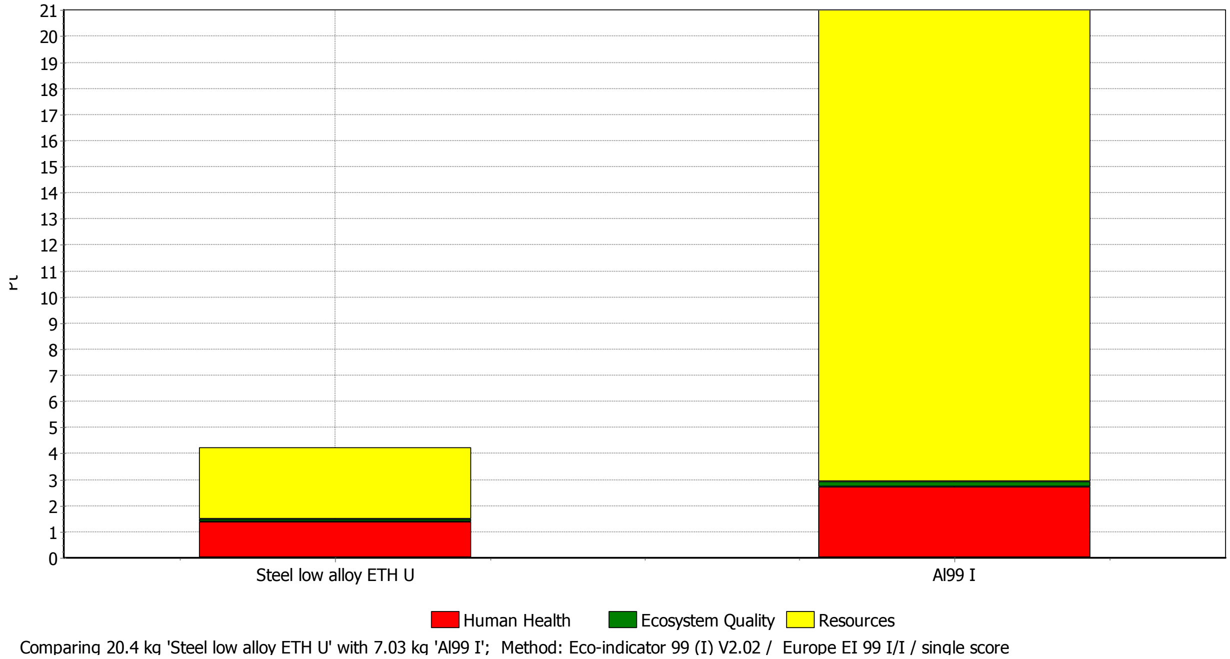


Figure F4. Material impact using single score comparison points.

Based upon the EcoIndicator 99 analysis, the Aluminum has a significantly greater environmental impact than the 1010 steel. While the steel is worse in half of the disaggregated damage categories, the aluminum's qualities have a greater impact on human health, ecosystem quality, and resources. When directly compared to each other in Figure F4, Aluminum is 5x worse for the environment than steel when constructing the A-frame for our prototype.

When considering the full life cycle, both materials are comparable in terms of environmental impact. Neither harmfully degrade in nature, and both are easily recycled at the end of their lives or take up an even amount of space in a landfill. However, we still believe that steel is the better choice for our prototype due to its smaller impact on the environment, greater strength, cheaper cost, easiness to weld, and wider availability.

APPENDIX G: Photographic images of valves and valve set up

Pipe Tee

Hex Nipple

One Way Valve (arrow points in direction of movement)

Hose Barb Adapter- 0.5"barbx 0.5"MIP

Threaded On-Off Ball Valve

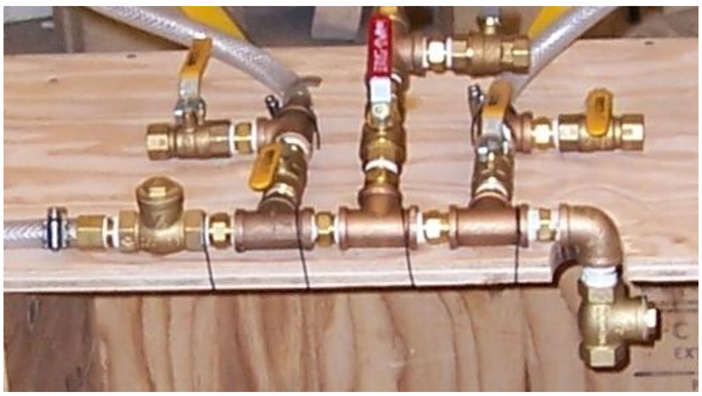


Image G1. Valve setup for entire design

APPENDIX H: Design for Safety

Failure Modes and Effects Analysis (FMEA) is a process used to identify hazards, calculate risks and design for safety. In an FMEA analysis, a Risk Priority Number (RPN) is calculated for each component based on likelihood of failure to occur, severity, and failure detection before release. The highest RPN values are of the biggest concern (RPN >100 indicates failure will occur). Corrective actions are developed and implemented and the RPN is recalculated and expectedly reduced.

A similar analysis, the risk assessment process is a more subjective approach which uses framework solutions and aims to make risks "As Low As Reasonably Practicable (ALARP)". This process utilizes task-based hazard identification, a useful approach that focuses on what people do and the risks/hazards associated. The risk is ranked based on severity and probability of occurrence. The goal is to subjectively identify acceptable and unacceptable risks and accept the fact that there is no such thing as zero risk. Each hazard is addressed and can be reduced through a framework of design changes, guard systems, warning systems, training, or use of personal protective equipment. The analysis is complete after all hazards have been fully addressed and risks are considered to be acceptable and "ALARP".

We used the risk assessment process to design for safety by identifying potential hazards and implementing methods for significantly reducing risks. With the aid of DesignSafe software, we feel confident that no safety hazard has been overlooked. DesignSafe software provides a systematic method for conducting risk assessment on many types of projects and systems. In the case of our biogas compression system, the major risks include flammable gas, sodium hydroxide, varying system pressures, and moving mechanical parts. The risks apply to the user, who will be in very close proximity to the system and the storage tank while pumping. After using DesignSafe software, we encountered some unexpected risks, all of which were less severe than the major risks we had already identified. These risks include trips/falls, mechanical fatigue and break up during operation, and ergonomics, that is, the user over-exerting or using poor posture while pumping. In our analysis, since zero risk is not possible, we implemented practical measures and considered a risk level of "Low" to be acceptable. The detailed DesignSafe report is shown on the following page.

designsafe Report

Application:	Biogas Compression	Analyst Name(s):	Jessica Leginski
Description:	Project 29: Safety/risk assessment for the biogas compression system. Based on user in the Philippenes, assuming compliance of construction and usage recommendations of the system.	Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:	Gerardo Baron, our contact in the Philippines, various web sources (hydrogen sulfide scrubbing, effects of methane on health, and other related studies), pressure ratings of each component come from various manufacturers, testing and user interviews.		

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
All Users All Tasks	mechanical : fatigue There are rotating parts and parts moving relative to each other that will be susceptible to wear and fatigue. Improper lubrication can accelerate wear.	Minimal Remote Possible	Low	other design change, use lubrication on moving parts to reduce mechanical wear. Include replacement indications in instruction manual.	Minimal Remote Unlikely	Low
All Users All Tasks	mechanical : break up during operation If something (after the compressor) breaks during operation, for example the valve connection to the storage tank which is repeatedly used, it will be under pressure (<50 psi).	Minimal Remote Possible	Low	warning label(s), instruction manuals. Hose barbs and other known weak points should be checked regularly and tightened. If there is a gas leak, the user must leave the area and seek maitenance personnel to patch leak until a permanent fix.	Minimal Remote Unlikely	Low
All Users All Tasks	slips / trips / falls : trip Could trip on hose, valve assembly which will be laying on ground.	Minimal Occasional Unlikely	Low	other design change. Place valve assembly beneath frame and use flexible hosing that can be moved against a wall or out of the way.	Minimal Remote Unlikely	Low
All Users All Tasks	slips / trips / falls : instability The frame could fall over depending on forces exerted by user and direction of force.	Minimal Remote Unlikely	Low	other design change. Design shape of frame with extended legs to make it very difficult to push over.	Minimal None Negligible	Low
All Users All Tasks	ergonomics / human factors : excessive force / exertion If all cylinders are active in the high pressure zone, or if the user chooses to use a short lever arm, excessive force and exertion may be required.	Slight Remote Possible	Moderate	warning sign(s), warning labels, instruction manuals. These will advise users to turn off one or more cylinders if the work seems difficult. Also will advise to use lever arm at its end, and to use their weight more so than using their back.	Slight Remote Unlikely	Low
All Users All Tasks	ergonomics / human factors : posture If a person uses bad posture during pumping, they could potentially injur themself.	Slight Remote Possible	Moderate	warning label(s), instruction manuals. See above. Post sign on system to demonstrate proper posture.	Slight Remote Unlikely	Low
All Users All Tasks	ergonomics / human factors : repetition Pumping involves repetitive motion, user could strain themself.	Minimal Occasional Probable	Moderate	warning label(s), instruction manuals. See above.	Minimal Remote Possible	Low

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level
All Users All Tasks	ergonomics / human factors : duration Compression was designed to take <5 minutes, however, depending on user it could take longer and user could become fatigued.	Minimal Remote Possible	Low	warning label(s), warning sign(s). Similar to warnings on exercise equipment. "If you become dizzy or fatigued, take a break and hydrate."	Minimal Remote Unlikely	Low
All Users All Tasks	fire and explosions : flammable gas Biogas is flammable, with a system malfunction or leak and a spark, it is possible for system to ignite.	Serious None Unlikely	Low	instruction manual, warning sign(s) that warn of flammable gas and advise to keep away from flame or spark. NO SMOKING.	Serious None Unlikely	Low
All Users All Tasks	environmental / industrial hygiene : emissions Leak, malfunction, or explosion of the system will result in biogas emisson (Methane, CO_2, H_2S)	Minimal Remote Unlikely	Low	special tools or fixtures (teflon tape used to prevent loosening or leaking), audible alarm or sounds (gas detectors, if available), warning label to warn of unusual smells or sounds, instruction manuals. Environmental effects negligible due to size.	Minimal None Unlikely	Low
All Users All Tasks	chemicals and gases : carbon dioxide CO_2 is present in biogas. In case of leak, severity depends on implementation of CO_2 scrubber.	Minimal Remote Possible	Low	See "emissions" above. Also, recommend CO_2 scrubber in design.	Minimal Remote Unlikely	Low
All Users All Tasks	chemicals and gases : Methane Non-toxic, by itself. Extremely flammable. Failure mode is a leak or explosion.	Minimal Remote Possible	Low	See "emissions" above.	Minimal Remote Possible	Low
All Users All Tasks	chemicals and gases : hydrogen sulfide Toxic gas. Is present in biogas. In smallest concentration, smells of rotten eggs. Medium concentrations cause eye irritation, highest concentration results in death.	Serious Occasional Possible	High	warning label(s) describing egg smell. other design change. Implement required hydrogen sulfide scrubbing to remove from the biogas before compression. If a high pressure leak occurs, the H_2S will already be gone.	Slight Remote Unlikely	Low
All Users All Tasks	fluid / pressure : explosion / implosion Possible explosion of tank or connections. Pressurized gas is flammible which increases risk. Tank is exposed to fluctuating ambient temperatures.	Catastrophic Remote Unlikely	Moderate	other design change. Do calculations of tank safety factors, using largest recorded temp difference in Philippines. Use warning labels on tank pressure meter, include in user manual. In system, hose barb is weak point and will fail before explosion.	Catastrophic None Negligible	Low

APPENDIX I: Manufacturing Process Selection

Although we created just one prototype for our design a realistic production value might be closer to 10,000 units. Many developing nations have access and currently use biogas as a source of fuel; India, Philippines, Costa Rica, and Africa to name a few. Our prototype was very successful in accomplishing the goals that we set out to achieve, namely compressing biogas up to 35 psi in a 7 gallon air tank, therefore it could become a very common accessory in addition to the biodigester. Although we have geared our project to be a DIY construction, we can still validate the production methods we used to fabricate our prototype. To do this we will look at two components of our prototype: the frame and the plunger, and analyze the methods we used for construction.

The frame was constructed out of low carbon, low alloy steel. It was MIG welded together using a relatively portable 110 V MIG welder with a 75/25 mixture of argon/CO_2 shielding gas. Flux cored welding wire could have been used instead of shielding gas. To analyze this we have used the CES manufacturing process selector to rank various joining processes. Figure I1 below shows various joining processes, that will accept shear stress and the setup time that is required from each.

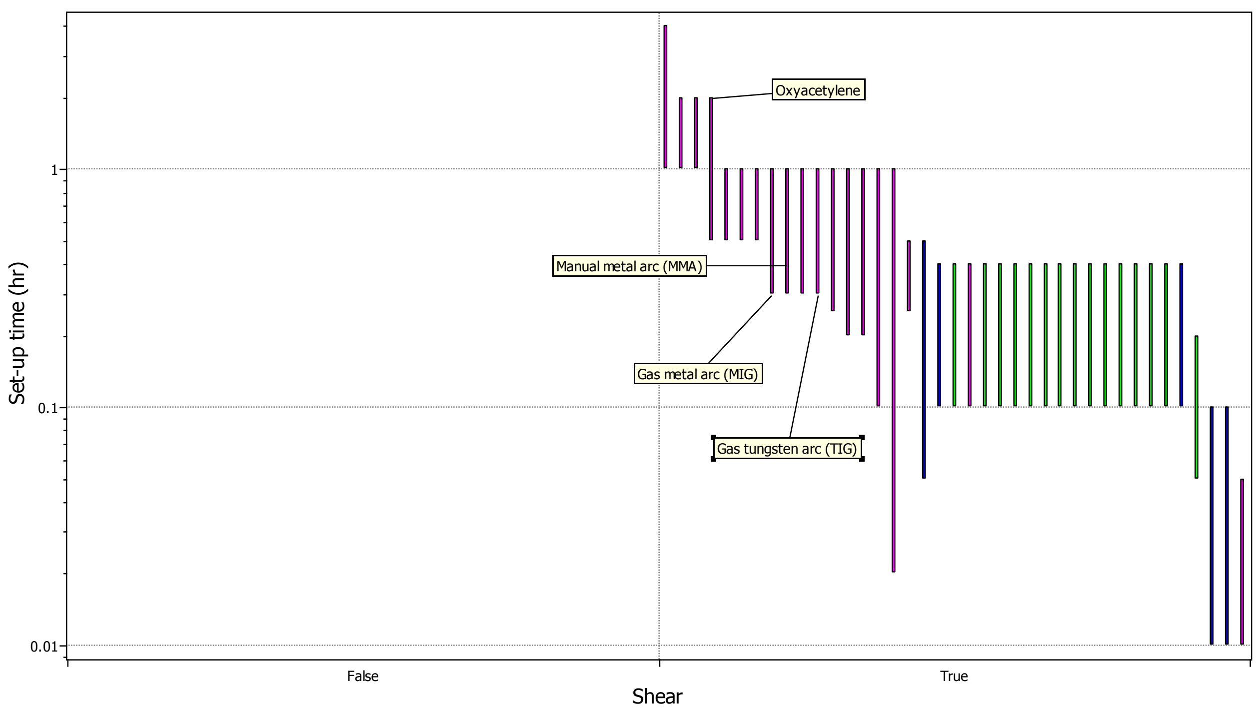


Figure I1. Various joining process that allow for shear stress.

The CES program ranked MIG welding to be higher in setup time than other joining methods that will accept a shearing load. While this may be true, MIG and other types of arc welding that require higher setup times will allow a greater factor of safety in the joining processes than other methods such as riveting, bolting or gluing.

Another test we performed in CES was to analyze the time required to cool down the part as seen in Figure I2 below. In this analysis, MIG welding did relatively well, beating out adhesives by an order of magnitude and not being too far behind some of the weaker joining methods such as soldering.

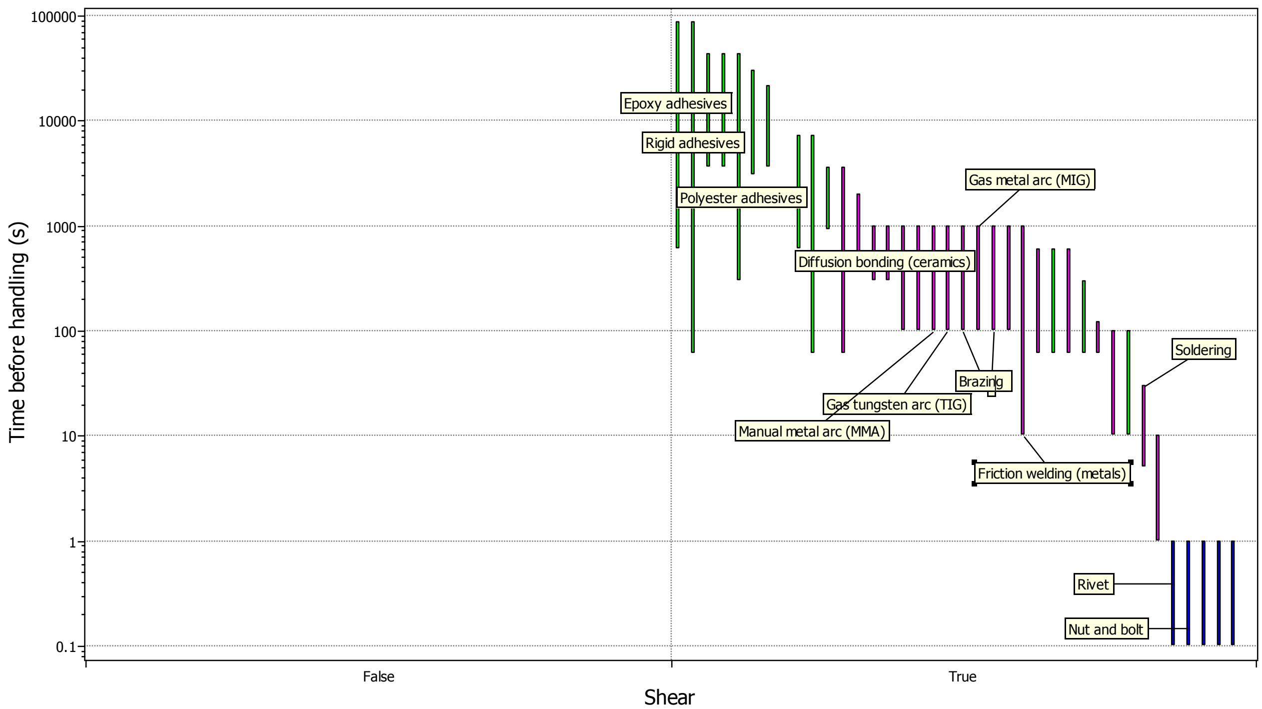


Figure I2. Cool down time after process for various joining methods that will allow shear stress on joint.

Although there were other methods available to us to join our frame together, none offered the robustness as well as the convenience that we found in a MIG welding setup.

The next part of our prototype we chose to analyze using the CES manufacturing process selector was our choice of plungers. We chose to use three separate pieces of steel and weld them together forming a seat for the O-ring. Once we performed an economic batch size analysis, seen in Figure I3 below, we learned that at higher production volumes turning and other machining processes become viable options for production. If we were going to manufacture our product and send it to the appropriate places, turning would become a very good option for our production volume. Since we are gearing our project for a DIY construction, where people will be constructing the prototype themselves, turning is not a viable option. Lathes are not a common enough tool that we can count on developing nations having access to them to construct the pistons for our design.

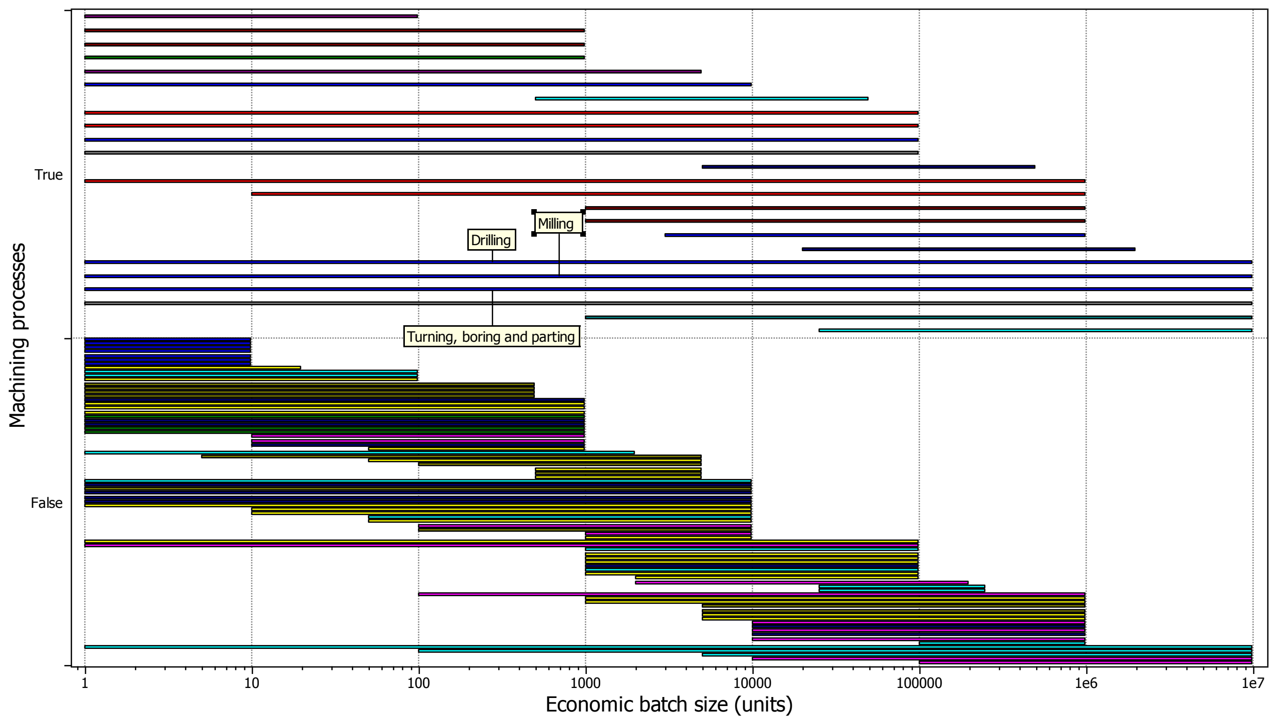


Figure I3. Economic batch size vs. the various machining processes available.

APPENDIX J: Design for Assembly Analysis

Frame Design Analysis

Total Pieces for Construction	18
Total Parts over 4 ft long	4
Non-welded Connections (Slide in place)	2
Number of Welds	19
Approximate time to construction	8 Hours

The total number of pieces in the frame should not be reduced for the sake of stability. Some connections could be connected with threaded rods and nuts and bolts, however the simplicity and strength of the welds provide the necessary strength for the frame, and should be incorporated where possible.

Cylinder and Valve System Analysis

Part #	# Of times the operation is carried out consecutively	Alpha, beta	Two digit manual handing code	Manual handling time per part	Two digit manual insertion code	Manual insertion time per part	Operation time (seconds)	Operation cost (cents)	Figures for estimation of minimum parts	Name of Assembly
1	3	180, 0	0,0	1.13	3,2	4	15.39	6.16	3	Cylinder
2	3	360,180	2,0	1.8	3,2	4	17.4	6.96	3	Plunger
3	14	180,0	0,1	1.43	3,2	4	76.02	30.41	8	Hose clamp
4	6	180, 360	2,0	1.8	3,2	4	34.8	13.92	6	Pipe Tee
5	12	360,0	1,0	1.5	3,2	4	66	26.40	8	Hose barb
6	6	360,0	1,0	1.5	3,2	4	33	13.20	6	End cap
7	12	180,0	0,0	1.13	3,2	4	61.56	24.62	6	Ball valve
8	10	180,0	0,0	1.15	3,2	4	51.5	20.60	10	Pipe nipple
							355.67	142.27	50	
							TM	CM	NM	
						Design Efficiency		0.421739253		

Table J1. Valve-cylinder assembly before redesign

Prior to the redesign, the biogas was inlet through the top of the cylinder, and outlet through the bottom, requiring a more complicated piston-plunger design. This design also required two sets of ball valve systems in order to allow for switching the inlet biogas "on" and "off", as well as to switch the outlet to act correspondingly.

With the redesign an inlet and an outlet one-way valve was implemented, resulting in the outlet and inlet operating through the same cylinder orifice. With the inlet and outlet flowing through the same valve system, the number of ball valves and connectors was severely reduced saving both time and cost in the design, and increasing the design assembly efficiency.

Part #	# Of times the operation is carried out consecutively	Alpha, beta	Two digit manual handing code	Manual handling time per part	Two digit manual insertion code	Manual insertion time per part	Operation time (seconds)	Operation cost (cents)	Figures for estimation of minimum parts	Name of Assembly
1	3	180, 0	0,0	1.13	3,2	4	15.39	6.156	3	Cylinder
2	3	360,180	2,0	1.8	3,2	4	17.4	6.96	3	Plunger
3	8	180,0	0,1	1.43	3,2	4	43.44	17.376	8	Hose clamp
4	6	180, 360	2,0	1.8	3,2	4	34.8	13.92	6	Pipe Tee
5	8	360,0	1,0	1.5	3,2	4	44	17.6	8	Hose barb
6	6	360,0	1,0	1.5	3,2	4	33	13.2	6	End cap
7	6	180,0	0,0	1.13	3,2	4	30.78	12.312	6	Ball valve
8	10	180,0	0,0	1.15	3,2	4	51.5	20.6	10	Pipe nipple
9	2	360,360	3,0	1.95	3,2	4	11.9	4.76	2	One way valve
							282.21	112.884	52	
							TM	CM	NM	
						Design Efficiency		0.552779845		

Table J2. Valve-Cylinder assembly after redesign

TEAM MEMBER BIOS

Dave Baron was born and raised in Battle Creek, Michigan and spent his earlier years at Lakeview High School and the Battle Creek Area Math and Science Center. After getting his

acceptance letter from the University of Michigan, he couldn't wait to get out of "Cereal City USA" and move 70 miles east to Ann Arbor. When taking a tour of U of M's campus, Dave still had no idea what to major in, and decided to seek the tour guide's input. After being informed that an engineering major would require many cold nights on the distant North Campus, countless hours in group meetings, and classes full of dudes, Dave's curiosity piqued and he decided to enter the college of engineering. While at the University, Dave has been an active member of the Michigan Fencing Club and has used his 10 years of experience to help them maintain their National Championship title for the past two seasons. He also is a member of the Michigan Snowboard Club and enjoys spending MLK and Spring Break in the fresh powder of Canada and Colorado. Like most other Mechanical engineers, Dave is also a member of ASME, but never attends any of the meetings or events. Having spent his entire life in Michigan, Dave decided that the best way to fully enjoy college was to take a break and study abroad to complete his German minor. After becoming fluent in the language and having the best time of his life for seven months, he is currently finishing up his last semester at the University of Michigan. While in Germany, Dave became interested in the different lifestyle and how Europeans utilize and conserve the environment in every aspect. After seeing hundreds of wind turbines and discovering that Germany is the leading producer of wind energy in the world, Dave plans on utilizing his U of M education by working in the renewable energy industry. After graduation, Dave plans to work at a nuclear power plant in Iowa for a few years until he can complete his MBA and move to either the west coast or Europe to work with wind turbines.

Jessica Leginski was born in Ann Arbor, MI and lived there until she graduated from Dexter High School in 2004. She played varsity softball for four years and actively participated in

Student Council and the National Honor Society. Now a senior at the University of Michigan, she was a member of ASME for two years and the Michigan Snowboard Club for three years. Her experiences in the undergraduate engineering program include designing and building a pneumatically controlled mechanical arm, a contemporary, expandable iPod dock, and the redesign of a surgical suturing device. Her academic interests lie in system optimization, design, technical communication and manufacturing. In the summer of 2007 she completed an internship at Holcim (US) Inc. at the plant in Dundee, MI, and now works there part time. She has accepted a full-time position with the company, which will begin after she graduates in April 2008. Her hobbies include snow sports, softball, running, raising domestic animals, video games, and playing piano and guitar. She loves thrill rides and haunted houses but is deathly afraid of sharks, bears, and squid. She has a younger brother and her parents recently moved to Nashville, TN. Her goals include world travel, working overseas, getting an MBA, SCUBA diving, and raising a family one-day.

Tim Murphy is from Gaylord, MI and is interested in mechanical engineering because of its broad spectrum and focus on critical thinking; making it useful in all aspects of life. Tim has

always been interested in attending law school, but after four years of undergraduate work, a year or two off seemed like an excellent idea. When Tim was offered the opportunity to gain useful patent law experience by working as a patent examiner at the USPTO, he jumped at the opportunity. Tim will be moving to the Washington D.C. area in late May, but not before a three-week trip to Europe (Frankfurt to Madrid) with his brother Dan, an LSA junior. Tim enjoys music, movies, and skiing… and $2 pitchers at Mitch's, which are available on Mondays and Wednesdays.

Adam Smith (see goofball below) was born on April 12, 1986 unfortunately in Edmond, OK. At the age of two, he moved from Oklahoma to Wisconsin for a year and then to Northeast Texas

(sigh of relief), where he would stay until leaving for college in 2004. He is currently a senior Mechanical Engineer at the University of Michigan, planning on graduating in April 2008. After college he hopes to work…somewhere. Ideally with hot metal and loud noises. He was introduced to engineering at an early age with Lincoln Logs and Erector Sets, and would soon find himself pursuing other healthy activities in later years including: potato cannons, pneumatic air cannons, fireworks, anything loud and destructive. In more recent years Adam has found himself enjoying lamer activities such as, running, biking, and hanging out (imbibing) with friends. After his initial ME 450 proposal for recreating Spider-Man's web-shooters was shot down, he looked for another project to be excited about and found himself pining to be on Team 29.

Alisyn Malek is a fifth year student here at the university dual majoring in German and Mechanical Engineering. She grew up in Brighton, Michigan primarily playing basketball and studying as well. Originally she believed that she would go into the field of architecture and acoustics, but after her experience of living in Germany's solar energy capital she decided to change her direction towards renewable energy. She hopes to gain work in a field relating to renewable energy, anywhere from the policy to the technical design. She is currently working to Figure out how to combine her desire to help the environment and provide the American public with more renewable energy in a graduate degree; she will most likely continue her studies here at the university. In addition to her studies she works at an outdoor outfitters in the hopes of replacing her old backpacking tent and other gear to support her backpacking hobby. She hopes eventually to hike the Pacific Northwest Trail as well as the Appalachian Trail. Usually she is also a music enthusiast, but since moving in with two musicians she has curbed her appetite for listening to music and has learned to appreciate silence. In the future, engineering will be her day job, but she hopes to continue pattern creation and clothing and quilt construction, as sewing is another hobby she enjoys. She also has an odd affinity for goats, and hopes to establish her own goat farm in the more distant future.